Abstract book

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GOBIERNO
DE ESPANA
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DE ECONOMIA
Y COMPETITIVIDAD
EUROPEAN SEMICONDUCTOR LASER WORKSHOP

MADRID, SPAIN, SEPTEMBER 24TH & 25TH 2015

UNIVERSIDAD CARLOS III DE MADRID

ABSTRACT BOOK
Framework

Following a long tradition, we are very pleased to inform you that the next European Semiconductor Laser Workshop will be held in Madrid-Spain, on September 24th & 25th 2015, just before the 41st European Conference and Exhibition on Optical Communication (ECOC-2015) (September 27th – October 1st. 2015 in Valencia Spain).

The workshop will take place at Universidad Carlos III de Madrid (UC3M), Campus “Puerta de Toledo”. The workshop provides the opportunity for informal discussions about recent advances and achievements in the field of semiconductor laser diodes, related devices and their applications. The workshop is arranged in the form of invited talks, contributed presentations, both oral and poster. We warmly welcome you to attend this workshop and promote fruitful discussions.

Beside its outstanding technical interest mentioned above, the European Semiconductor Laser Workshop 2015 takes place at Madrid city center (also known as Madrid of the Austrians or the Habsburgs). Is a name used for the old centre of Madrid, built during the reign of the Habsburg Dynasty, known in Spain as Casa de Austria. Puerta de Toledo is known for hosting El Rastro de Madrid which is the most popular open air flea market held every Sunday and public holiday. The area is trendy and festive with many small bars and restaurants where you can drink “Cañitas” and “Tapitas” (small beers and snacks) and has managed to retain much of its village ambiance.
Chairmans

Dr. Guillermo Carpintero del Barrio
Dr. Horacio Lamela Rivera

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Cristina Masoller - Universidad Politecnica de Cataluña
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Angel Valle - Universidad de Cantabria
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Robinson Cruzoe Guzman - Universidad Carlos III de Madrid

Fabian Vinicio Corral - Universidad Carlos III de Madrid

Carlos Diego Gordon - Universidad Carlos III de Madrid

We thank you for your interest in the Workshop
The Organizing Committee
Detailed program
## PROGRAM

### ESLW 2015

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<td>1 Department of Physics, Chungnam National University, Korea / 2 Department of Information Display, Kyung Hee University, Korea</td>
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<td>1 INA, CINSaT, University of Kassel, Germany / 2 CEP, CINSaT, University of Kassel, Germany / 3 Electrical Engineering Department, Technion - Israel Institute of Technology, Israel</td>
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### SOCIAL PROGRAM

- **Visit Museo de la Reina Sofia**: Bus Service, the bus leaves at 18:00 from Puerta de Toledo
- **Dinner, Posada de la Villa Restaurant**: Bus Service, the bus leaves at 20:15 from Museo de la Reina Sofia
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Session ID, 1-1: Semiconductor lasers with high-order surface gratings for optical communications applications

Azat Abdullaev,1 Qiaoyin Lu,2 Weihua Guo,2 Michael J. Wallace,1 Marta Nawrocka,1 Frank Bello1, James O’Callaghan,3 and John F. Donegan1

1School of Physics, CRANN and AMBER and CTVR, Trinity College Dublin, Dublin 2, Ireland
2School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, China
3Tyndall National Institute, University College Cork, Ireland

Abstract: We have developed a laser platform based on high-order surface gratings. These lasers have simple fabrication, do not require re-growth and have the potential to show high wafer yields. The high-order gratings are formed along with the laser ridge. The performance of these lasers in a laser array structure will be outlined. We show tuning with 12 channels in the array over the full C-band with an SMSR over 50 dB. This laser platform has also been applied to a Vernier tuned system with tuning over 30 nm demonstrated.

1. Introduction

Wavelength tunable lasers are the main sources in future reconfigurable dense wavelength-division-multiplexed (DWDM) optical communication systems and sensing technologies. So far, different types of wavelength tunable light sources, including sampled grating distributed Bragg reflector (SG-DBR) lasers [1], external cavity lasers (ECLs) [2] and tunable distributed feedback (DFB) laser arrays [3] have been developed. Of these, tunable DFB laser arrays exhibit stable mode operation and have advantages in terms of reliability and integration with other photonic components in one chip. Nevertheless, DFB lasers require complex regrowth steps and need high resolution electron beam lithography during the fabrication. Recently, our group demonstrated a tunable 9-channel single mode laser array based on a high order surface grating with multiple slots where the slots are etched on top of the ridge waveguide [4]. Therefore, such lasers are regrowth free and can be fabricated by standard photolithography. Wavelength tuning range of 27 nm was obtained in these lasers with side-mode suppression ratio (SMSR) more than 35 dB. In our most recent work [5], we present a 12-channel slotted single mode laser array with improved slots design. A tuning range of more than 36 nm was obtained with SMSR more than 50 dB for all channels.

2. Device structure and characteristics

Fig. 1 (left) 3D schematic structure of the wavelength tunable single mode laser array based on slots. (right) Measured output spectra of the fabricated laser array with a driving current of 100 mA for all the 12 channels at 20°C under CW condition with the SOA unbiased.

The schematic structure of a tunable slotted single mode laser array is shown in Fig. 1 (left). Each laser in the array has a 2 µm-wide ridge waveguide and is integrated with a curved semiconductor amplifier (SOA). The lasers are electrically divided into two sections: the front section includes a group of slots and the back section consists of straight waveguide. This was done to remove the yield problem caused by the uncertainty of the cleaving position. An anti-reflection (AR) and high reflection (HR) coatings were applied to the front and back facets, respectively, to improve the laser performance in terms of the threshold current and output power. The 12 channel lasers operate at different wavelengths as shown in Fig. 1 (right). The different wavelengths are determined by changing the slot period. The slot parameters such as slot width, depth, number and period have been optimized in the design using the 2D scattering matrix method. The slot depth is 1.35 µm and the ridge height is 1.85 µm. For the trade-off between maximizing the reflectivity and minimizing the bandwidth of the reflection peaks while also ensuring that the laser cavity length is kept to a minimum, the slot number is found to be 24. In our previous work, we used uniformly spaced slots with the slot period around 9 µm which yields the reflection peaks having a free spectral range of 27 nm.
range (FSR) around 38 nm. This FSR is not enough to suppress the adjacent modes when the main reflection peak is not at the gain peak. We observed this behaviour when the SMSR dropped from 50 dB to 35 dB in our previous run [4]. To suppress this modes which are one FSR longer, in this work we used three different slot periods which are around 8.5, 9.9 and 11.4 µm. The designed lasers have the same fabrication steps as in [4] and the total cavity length of the cleaved laser array is about 590 µm which includes 400 µm of the laser length and 190 µm SOA section.

Fig. 2 Measured tuning behaviors of the fabricated laser array at a driving current of around 100 mA over the temperature range from 10°C to 45°C: (left) lasing wavelength vs. temperature; (right) SMSR vs. lasing wavelength.

The fabricated devices were tested under CW condition with SOA section left unbiased and were mounted on a copper heatsink the temperature of which was controlled by thermoelectric cooler (TEC). For wavelength tuning we kept a laser current at constant 100 mA and changed the temperature of TEC. Fig. 2 (left) shows the measured wavelength tuning versus the chip temperature from 10 to 45°C. The wavelength tuning of more than 36 nm was obtained between the range of 1532 and 1568 nm covering the full C-band. The measured SMSR of the laser array is shown in Fig. 2 (right). An SMSR of more than 50 dB was obtained for all channels which means that the non-uniformly spaced slots suppress the adjacent modes which are one FSR longer.

3. Conclusion

In conclusion, we presented an improved design of a 12-channel single mode laser array based on non-uniformly spaced slots forming a high-order surface grating. The fabricated devices exhibit a wavelength tuning of more than 36 nm covering the full C-band. An SMSR of more than 50 dB was achieved for all channels during the temperature tuning. The tunable laser array just needs a single wafer growth and can be fabricated by standard photolithography. In addition, in these structures the yield problem related with the cleaving position of the laser facets is removed.

4. References

Session ID, 1-2: Performance of a Three-Section Master Oscillator Power Amplifier at 1.5 μm

M. Vilera¹, M. Faugeron², A. Pérez-Serrano¹, J.M.G Tijero¹, M. Krakowski², F. Van Dijk² and I.Esquivias¹

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Abstract: The performance of new three-section master oscillator power amplifiers emitting at around 1.5 μm has been analyzed in regard with their application as laser sources for a differential absorption lidar. The devices incorporate a modulation section that can be separately driven thus allowing the required random modulation of the laser emission. The bent design of this section together with the tilting of the output facet ensures a stable single-mode emission in the entire range of driving conditions. At the required modulation frequency (12.5 MHz) a square wave emission profile with high optical modulation amplitude and 22 dB extinction ratio is obtained.

1. Introduction

The monolithic Master Oscillator-Power Amplifier (MOPA) architecture in which the master oscillator is a single-mode laser and the power amplifier a flared section is a promising laser structure for applications requiring high brightness laser sources with stable and narrow spectral width, such as free space optical communications, Differential Absorption LIDAR (DIAL), metrology and frequency doubling. An integrated MOPA incorporating a modulation section has been proposed as the transmitter unit of a DIAL system operating in the Continuous Wave Random Modulation (CW-RM) mode [1]. However, the conventional straight MOPAs are known to suffer from emission instabilities and frequency jumps thus compromising their performance [2, 3]. In facing this problem we have recently reported the fabrication of new three-section bent MOPAs showing stable emission in the 1.5 μm spectral region [4]. In this work we analyze the performance of these devices in regard with their use as laser sources of a CW-RM DIAL system for the remote detection of atmospheric CO₂.

2. Device Description and Experimental setup

The devices consist of a 1 mm long Distributed Feedback (DFB) laser, a 1 mm long modulation section and a 3 mm long 4° tapered amplifier. Their most remarkable feature is the bent geometry of the modulation section inserted between the DFB laser and the flared amplifier, which output facet is slightly tilted accordingly (Fig. 1). More details about epitaxial structure, geometry, and fabrication process can be found in [4]. The devices were characterized both under separate CW injection of each section and also under square wave excitation of the modulation section. Fig. 1 illustrates the setup for the square wave excitation: A CW current, I_{DFB}, drives the DFB section; I_{mod} is the superposition of two signals: a CW current, I_{MOD}, and a squared wave provided by a Pulse Pattern Generator at a variable frequency f_{vpp}. When required, the square wave excitation signal was amplified by an RF amplifier which provided a peak to peak voltage V_{pp} up to 25 V. Finally, a CW current source supplies I_{PA} to the amplifier section.

The total output power was measured by a large area thermal detector. For the spectral and temporal analysis a part of the output power was coupled into a lensed fiber and then split in two paths and directed to an Optical Spectrum Analyzer (resolution 0.05 nm) and to a 20 GHz optical module of a Digital Signal Analyzer. The measurements were performed at a constant temperature of 15°C.

3. Experimental results

Figs. 2 and 3 illustrate the device behavior under separate CW excitation. Fig. 2 shows the variation of the output power when changing the current of the modulation section when driven in CW regime. Although a clear reduction of the output power is apparent at I_{MOD} = 0, the complete extinction requires negative values of I_{MOD} due to carrier generation caused by the power injected from the DFB laser into the modulation section. The single peak spectrum shown in Fig. 3 is stable in the entire range of excitation conditions and the kinks and ripples in the P-I characteristics as well as the wavelength jumps and mode hoping effects plauging the spectra of straight devices [2,3] are absent.
4. Conclusion

The innovative design of a three-section MOPA at 1.5 mm incorporating a bent modulation section results in an improved performance in terms of spectral stability and modulation capability thus paving the way for its application as laser source for a LIDAR system for the remote detection of atmospheric CO2.

5. References


Acknowledgments

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Session ID, 1-3: Improved optical field stability in high-power laser diodes with multi-stripe gain distribution

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Abstract: The formation of the multi-stripe gain distribution in active region of high-power laser diode is shown as a method of stabilization of the emitted beam. The numerical design and the experimental results obtained for the multi-stripe gain laser diodes are shown.

1. Introduction

The current spreading is typically observed in the laser diodes (LDs) gain waveguide formed by ion implantation [1]. As a result of this effect, in that LDs the formed gain waveguide in lateral direction is wider than the formed stripe, but the gain induced by current spreading is smaller than the gain in area of main current flow. This allows shaping a gain distribution in the LD active waveguide. The improved stability of the emitted beam is shown as a result of introducing some low-gain stripes in the wide active region of the high-power LD. Improved stability is achieved because of the limitation of the filamentation [2] and the far-field blooming effect [3]. The numerical design and the experimental characterization of the multi-stripe gain laser diodes (MSG-LDs) are shown.

2. Multi-stripe gain design and numerical simulations.

Fig. 1 schematically shows the geometry and the gain distribution in MSG-LD. If the energy of the implantation (E_{impl}) and the widths of implanted stripes (s) are small enough, the current spreading effect ensures pumping in the whole region of the width w. However, the gain in the implanted stripes is smaller than in non-implanted stripes – as a result the active region is a set of N high-gain stripes which are separated by the N-1 low-gain stripes. The gain distribution in MSG-LD is similar to this in phase-locked array (PLA), but because of small differences between the effective refractive indices in the high- and low-gain stripes (n_{eff} = 0) the formation of the supermodes is expected to be suppressed.

Fig. 2 shows numerically obtained modal gain distributions in the wide stripe (WS) LD and in the MSG-LD. The MSG-LD contains N = 15 high-gain stripes of width d = 10 μm and which are separated by the low-gain stripes of width s = 3 μm. It is characteristic for the MSG-LDs that the one of the high order modes have higher modal gain than neighbors. The optical field distribution of this mode is the most similar to the gain distribution – so that this
mode will be called well-fitted mode (WFM). As it can be seen in Fig. 2, the proper design of the MSG-LDs leads to achieve lasing of the fundamental mode and WFM at similar threshold current ($I_\text{th}$). As a result, the beam divergence at low currents ($I$) is expected to be wider than in WS LDs but the widening with increasing $I$ should be restricted. The filamentation should be also restricted because of defined gain distribution.

3. Experimental results

The far-field distributions of the MSG-LD ($N = 15$, $d = 10 \, \mu m$, $s = 3 \, \mu m$) measured at different $I$ are shown in Fig. 3. Near $I_\text{th}$ there are two maxima, but between them the region of reduced light intensity is observed. This region is gradually filled, as the $I$ increases. This confirms that the WFM is excited near $I_\text{th}$ – like the fundamental mode. The measurements also show that the widening of the beam distribution is smaller than in WS LD (results are not shown here) [4]. Additionally, the angular position of all the local maxima is stable over the entire range of drive currents.

In Fig. 4 the stability map of the optical field distribution on the front facet of the MSG-LD is shown. The map shows the variations of the relatively intensity noise (RIN) in number points at the laser front facet. The distance between points is 5 μm, which is a resolution of the measurement method. In case of the MSG-LDs, the RIN fluctuates slower and the amplitude of this fluctuations is smaller than in WS LDs (map for WS LD is not shown here) [4]. The slower fluctuations are observed as areas of the same amplitude – the RIN forms “time islands” in the stability map.

Measurements shows that the filamentation and far-field blooming effect are suppressed and better beam stability has been achieved.

Figure 3: The lateral (in junction plane) cross-sections of the beam distributions in the far field

Figure 4: Fluctuation patterns of the MSG-LD

4. Conclusion

The multi-stripe gain laser diodes are presented as the devices emitting more stable beam than the standard wide stripe high-power laser diodes. The gain distribution shaping by the ion implantation and by the current spreading is shown. This method has been used to form active region of the multi-stripe gain laser diodes. As a result of, the current flow is better defined in the active region of the laser diode, and the modal gain of the higher order mode can be achieved. It is shown that this leads to limit power fluctuations caused by the filamentation effect, and the far-field blooming effect caused by excitation of high order modes at different drive currents.

5. References

Session ID, 1-4: Longitudinal Multimode Instabilities in Master Oscillator Power Amplifiers at 1.5 μm

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Abstract: We theoretically investigate a dynamical regime experimentally observed in monolithically integrated master oscillator power amplifiers emitting at 1.5 μm. It consists in large emission wavelength jumps (> 10 nm) from the Bragg wavelength to that of the gain peak. Our analysis is based on numerical simulations of a travelling wave model that incorporates spatial and thermal effects. We find that whereas the thermally-induced index changes are the responsible of the modal jumps between consecutive modes, the carrier-induced refractive index changes are the responsible of the jumps occurring between the Bragg wavelength and the gain peak.

1. Introduction

Monolithically integrated Master Oscillator Power Amplifiers (MOPAs) are semiconductor-based devices sources of high brightness light. MOPAs are promising candidates to be modulated at high speed, as required for applications such as LIDAR, free space optical communications and laser projection displays [1]. Monolithically integrated MOPAs usually comprise two sections: an index guided waveguide section (usually a Distributed Feedback (DFB) laser) that acts as a Master Oscillator (MO) and a gain-guided tapered Power Amplifier (PA) section. Ideally, the single lateral and longitudinal mode generated by the MO is injected into the PA section where it undergoes free diffraction and amplification keeping its initial beam quality. However, MOPAs exhibit instabilities that have been attributed to a combination of thermal effects and the residual reflectance at the amplifier front facet, leading to coupling of the MO modes and the modes of the full MOPA cavity [2,3].

Here, we theoretically investigate a dynamical regime experimentally observed in commercial MOPAs emitting at 1.5 μm [3]. The main feature of this regime is the large emission wavelength jumps (> 10 nm) occurring for low currents in the MO section as a quasi-periodic function of the CW current in the PA section. Our theoretical framework is a Travelling Wave Model (TWM) that naturally includes spatial effects (such as spatial hole burning and coupled-cavity effects) and multimode dynamics [4]. Thermal effects are included by considering the optical response of the Quantum Well active medium within the quasi-equilibrium approximation at finite temperature. The redshift of the gain peak and the changes in the background material refractive index are phenomenologically included in the model by thermal coefficients accounting for the self- and cross-heating effects of both sections. Although a description of the possible filamentation in the PA section requires at least a 2-D spatial model [2], good qualitative agreement has been obtained between the experiments and a 1-D TWM [4], showing that the wavelength jumps arise mainly from the interplay of longitudinal modes and thermal effects.

In this contribution we further investigate theoretically the physical mechanisms involved in the observed dynamics using a 1-D TWM. In particular we focus our analysis on the role of the thermal effects and the carrier-induced effective index changes. We find that as the PA current is varied, the thermally-induced index changes are responsible for the switching between consecutive longitudinal modes; however, the large jumps from the Bragg wavelength to the PA gain peak stem from the carrier-induced changes in the effective refractive index.

2. Results

We focus on the conditions where the large wavelength jumps appear, i.e. having biased the MO close to its threshold while increasing the current in the PA. Fig. 1 shows the dependence on the thermal effects and the carrier-induced effective index changes for different cases distributed in columns. For each case, the optical spectra in two panels for different wavelength ranges and the RF spectra is plotted. The numbering of the cases are ordered from more to less effects taken into account, being the case with all the effects taken into account shown in Case 1. We refer the reader to [4] for the model details. Case 1 shows good agreement with the behavior reported in [3]. The MOPA threshold occurs for \( I_{th} \sim 0.7 \) A, and the lasing wavelength corresponds to that of the Bragg grating in the MO section. As the current in the PA section is increased, the emission wavelength exhibits a small redshift due to the thermal drift of the Bragg wavelength as the refractive indexes increase due to cross-heating. Further increasing the PA current the optical spectrum of the device changes dramatically, passing from narrow emission at the Bragg
wavelength to broadband emission at a much shorter wavelength that corresponds to that of the material gain peak in the PA section. In this regime the RF spectrum displays strong peaks at \( f = 17 \text{ GHz} \) and \( 34 \text{ GHz} \), which correspond to the FSR of the full MOPA cavity. Continuing increasing the PA current the wavelength jumps occur in a quasi-periodic way.

![Fig. 1: Numerical results: Dependence on the thermal effects and the carrier-induced effective index changes for different cases distributed in columns. \( I_{\text{tot}} = 54 \text{ mA} \). Limit cases: Case 1: All effects taken into account. Case 5: Thermal and carrier-induced index effects neglected.](image)

The role of the thermal effects and the carrier-induced effective index changes are separately investigated. The carrier-induced index changes are neglected by setting \( \text{Re}\{\chi_2\} = 0 \), the effect of the thermal redshift of the material gain is maintained, the coefficient \( \chi_2 \) of the effective group index is \( \Theta_{\text{eff}} \), and the temperature interchange between sections is accounted via self- and cross-heating coefficients, \( \theta_\text{CS} \) and \( \theta_\text{SS} \) respectively. Fig. 1 (Case 2) shows the behavior when \( \Theta_{\text{eff}} \) is set to zero. In this case for \( I_p \gtrsim 1.2 \text{ A} \) emission at the gain peak of the PA section appears together with relaxation at the Bragg wavelength. While varying \( I_p \), a 5 nm displacement of the gain of the PA section due to the thermal redshift of the band-gap energy can be observed. In this situation the RF spectrum shows peaks corresponding to the FSR of the full MOPA cavity. On the contrary if only \( \text{Re}\{\chi_2\} = 0 \), i.e. the carrier-induced index changes are neglected (Case 3), both the Bragg wavelength and the modes of the full MOPA cavity shift as a function of \( I_p \). In this case no emission at the gain peak of the PA section appears and the RF spectrum shows relaxation oscillations peaks at a few GHz when the modal jumps take place. A similar behavior is found when the cross-heating coefficients \( \theta_\text{SS} = 0 \) shown in Case 4. In this case the Bragg wavelength does not drift but the emission mode consecutively jumps as a consequence of the self-heating of the PA section. The wavelength jumps between consecutive modes found in Cases 3 and 4 are similar to those reported in [2] which are a consequence of the thermal drift of the modes. Finally, when \( \Theta_{\text{eff}} = 0 \) is set to zero (Case 5), the laser emits at the Bragg wavelength (around 1550 nm) for the whole \( I_p \) range.

4. Conclusion

We have theoretically analyzed the physical mechanisms involved in the large wavelength jumps observed in MOPAs. By separately analyzing the role of the thermal effects and the carrier-induced effective index changes, we have found that the thermally-induced index changes are the responsible of the position of the modes and the jumps between consecutive modes as a function of the current in the power amplifier section. Yet, the carrier-induced refractive index changes are the responsible of the jumps occurring between the Bragg and the gain peak wavelength.

5. References


Acknowledgments

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Session ID, 1-5: Dissipative Light Bullets in Passively Mode-Locked Semiconductor Lasers

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We demonstrate the existence of three dimensional dissipative localized structures in the output of a laser coupled to a distant saturable absorber. These phase invariant light bullets are individually addressable and can be envisioned for three dimensional optical information storage. An effective theory provides for an intuitive picture and allows to relate their formation to static auto-solitons.

The possibility of using light bullets (LBs), i.e. pulses simultaneously confined in the transverse and the propagation directions, has attracted a lot of interest in the last twenty years, both for fundamental and practical reasons. Optical confinement is ordinarily envisioned through a mechanism in which a Kerr self-focusing nonlinearity compensates the spreading effect of diffraction. Yet in this scenario, reminiscent of the conservative soliton theory, conservative LB are unstable and lead to a collapse [1] in three dimensions. Other confinement mechanisms were envisioned in systems far from equilibrium. However, while LB were predicted in semiconductor cavities [2, 3], it was later shown that the proper consideration of the dynamics of the active material leads to collapse [4].

Recently, we have shown [5] how phase invariant temporal LLS can evolve from passive mode-locking (PML). The PML regime leads to the emission of temporal pulses much shorter than the cavity round-trip and it is achieved by combining two elements, a laser amplifier providing gain and a nonlinear loss element, usually a saturable absorber (SA). The different dynamical properties of the SA and of the gain create a window for regeneration only around the pulse. For cavities with a large aspect ratio, as defined by the ratio of the gain recovery time and of the cavity length $r = \tau/\tau_g$, the PML pulses may become individually addressable and coexist with the off solution [5].

We establish in which conditions the transverse profile of these temporal LLS can self-organize yielding to a new robust LB formation scenario. Departing from previous approaches, the structuration mechanism exploits the existence of the active material temporal scales making our LB essentially multiple timescale objects. We present an intuitive theory that allows to understand the LBs as hybrids between the temporal localized structures described in [5] and the spatial diffractive autosolitons of [6].

We describe the PML laser using the generic delayed differential equation model presented in [7] which can describe both the pulsating regimes and the steady solutions. We work in the limit of low gain (G) and saturable absorption (Q) as to justify a first order approximation to the single pass evolution of the field profile. In this uniform field limit,

![Image of isosurface representation of a three dimensional LB](image)

FIG. 1. Isosurface representation of a three dimensional LB at which the Intensity (a), the real (b) and the imaginary parts (c) are $1\%$ of the maximal value. The multiple curves in (c) simply indicate that the LB are spatially oscillating objects.
the equation for the field amplitude \( E (r_\perp, t) \) reads

\[
y^{-1} \partial_t + 1 - i\Delta_\perp E (r_\perp, t) = \kappa \left( 1 + \frac{1-\text{i}\alpha}{2} G (r_\perp, t - \tau) - \frac{1-\text{i}\beta}{2} Q (r_\perp, t - \tau) \right) E (r_\perp, t - \tau),
\]

where \( \gamma \) is the bandwidth of the spectral filter, \( \Delta_\perp = \partial_r^2 + \partial_{\perp}^2 \) is the transverse Laplacian, \( \kappa \) is the fraction of the power remaining in the cavity after each round-trip and \( \alpha \) and \( \beta \) are the linewidth enhancement factors of the gain and absorber sections, respectively. In Eq. (1), the transverse space variables \( r_\perp = (x, y) \) have been normalized to the diffraction length. As such, the domain size \( L_\perp \) representing the dimension of the broad area laser becomes a bifurcation parameter. For large values of \( L_\perp \), we demonstrate in Fig. 1 the existence of stable three dimensional LBs.

Exploiting the seminal work of New and the fact that the LLS are composed of different variables evolving over widely different timescales, we show here that a method distinguishing between different layers of fast and slow evolution allows finding an effective equation for the transverse morphogenesis problem in presence of diffraction. We assume that the field reads

\[
E (r_\perp, \sigma) = A (r_\perp, \sigma) p (t), \quad p (t + \tau) = p (t)
\]

with \( p (t) \) an unknown short temporal normalized pulse profile and \( \sigma \) a slow time. Inserting Eq. (2) in Eq. (1), allow finding the effective equation for the transverse profile \( A (r_\perp, \sigma) \)

\[
\frac{\partial A}{\partial \sigma} = i\Delta_\perp A + Af \left( |A|^2 \right)
\]

The expression of the nonlinear function \( f \) considers the gain and absorption depletion during the fast stages as well as their exponential recovery. Equation (3) makes apparent the link between our approach and the work of [6, 8] for the case of static auto-solitons in bistable interferometers. In [6, 8], one assumes a monomode continuous wave emission along the longitudinal propagation direction, which allows, via the adiabatic elimination of the material variables, to find an effective equation for the transverse profile, yet with a different expression for the function \( f \). Following the method detailed in [8] in the case of a single transverse spatial dimension, we search for the solutions of static spatial LLS as heteroclinic and homoclinic orbits solutions of Eq. 3 as discussed in Fig. 2 in the case of a single transverse dimension.

In conclusion, we have shown that PML lasers with large spatial and temporal aspect-ratios display addressable Lasing Light bullets that are hybrids between temporal localized structures [5] and spatial auto-solitons [6].

Session ID, 1-6: Theoretical investigation of multi-mode dynamics and mode-locking in an inhomogeneously broadened laser

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Abstract: We consider a travelling wave model of an inhomogeneously broadened laser. Using an efficient numerical method we perform numerical simulations of this model to study the effect of inhomogeneous broadening on the properties of mode-locking regime in a two-section semiconductor laser and on the stability properties of a CW regime in a single-section laser.

1. Introduction

Quantum-dot and quantum-dash semiconductor lasers can be potentially used as the sources of ultra-short pulses for applications in optical communications [1]. Such lasers exhibit high inhomogeneous broadening of the gain medium due to inhomogeneity of the ensemble of quantum dots in respect to their size, shape and composition, which contributes significantly to the pulse shaping process. In quantum-dot lasers under the bias conditions the inhomogeneous broadening width at half-maximum (from 21 meV to 50 meV) is larger than homogeneous broadening width (19 meV). Two-section lasers with absorber and gain sections are typically used for generation of mode-locked pulses, however self-mode-locking can be observed in single section lasers [2]. In this paper, using a travelling wave we study numerically the effect of the inhomogeneous broadening width on the properties of the mode-locked regime in a two-section semiconductor laser. Using the same model, we demonstrate the appearance of a multi-mode instability in a single-section laser due to inhomogeneous broadening. Finally, we investigate dynamical properties of the laser devices using the reduced DDE model of an inhomogeneously broadened semiconductor laser.

2. Model

We consider the following travelling wave model of an inhomogeneously broadened laser

\[
\frac{\partial E^\pm}{\partial t} \pm \frac{\partial E^\pm}{\partial z} = -\frac{\beta}{2} E^\pm + \int_{-\infty}^{\infty} P^\pm f(\omega) d\omega, \quad (1)
\]

\[
\frac{\partial P^\pm}{\partial t} = (-\Gamma + i\omega_0) P^\pm + \frac{g}{2} N E^\pm, \quad (2)
\]

\[
\frac{\partial N}{\partial t} = j_0 - \gamma N + \Re(P^+ E'^* + P^- E'^*), \quad (3)
\]

where \(E^\pm(t,z)\) are the envelopes of the electric of counter-propagating waves, \(P^\pm(\omega,t,z)\) is two-level polarization, \(N(\omega,t,z)\) is population difference/carrier density, \(\beta\) describes linear internal losses in the intracavity medium, \(g\) is the differential gain/loss parameter, \(\Gamma\) is polarization decay rate, \(\gamma\) is population difference relaxation rate, \(j_0\) describes linear gain/absorption. The normalized spectral distribution \(f(\omega)\) most commonly takes the form of the Gaussian distribution with the inhomogeneous broadening width at half-maximum \(\sigma_0\).

We apply a spectral method based on Hermite functions for numerical simulation of the system (1)-(3), where the moments of polarization and population difference are introduced: \(\mathbb{M}_0 = \int \Re e^{i\eta_0} \phi(t), \mathbb{M}_1 = \int \Re e^{i\eta_0} \phi_0(t)\), and from (2) one can obtain the relation between the moments of polarization \(\mathbb{M}_2\). Finally, we derive a simplified delay-differential equation (DDE) model for the K-section semiconductor laser

\[
\frac{dA(t)}{dt} = (\gamma - i\omega_0)A(t) = \sqrt{\gamma} (A(t) - \tau) + \sum_{k=1}^{K} P_{ab}(t - \tau), \quad (4)
\]

\[
\frac{dP_{ab}(t)}{dt} = (-\Gamma_k + i\omega_0)P_{ab}(t) + i\sigma_{DE} P_{ab}(t) + \Gamma_k (e^{N_k(t)/2} - 1) (A(t) + \sum_{i=1}^{k-1} P_{ab}(t - \tau)), \quad (5)
\]

\[
\frac{dP_{ab}(t)}{dt} = (-\Gamma_k + P_{ab}\sigma_{DE}) P_{ab}(t) + i\omega_0 P_{ab}(t) + i\sigma_{DE} P_{ab}(t), \quad (6)
\]

\[
\frac{dN_k}{dt} = n_{ab} - \gamma_k N_k(t) - s[A + \sum_{l=1}^{k} P_{ab}^2 - |A + \sum_{l=1}^{k-1} P_{ab}(t - \tau)|^2], \quad (7)
\]
similar to the one proposed in [4], which assumes unidirectional propagation of the electrical field in the ring cavity and accounts phenomenologically for the nonlinear polarization and inhomogeneous broadening approximated by the first moment of polarization [5]. Here, $\tau$ is the cavity round-trip time, $A(t)$ is the electrical field amplitude at the beginning of the first section, $N(t)$ represents carrier density, $P_{0}(t)$ and $P_{1}(t)$ represent the zeroth and the first moments of polarization, correspondingly, and parameter $P_{2}$ approximates adiabatically the effect of the higher moments of polarization. Linear filtering width $\gamma$ in the equation (4) is used as the regularization parameter ($\gamma \gg 1$).

**Numerical study**

In our study of the dynamics of inhomogeneously broadened passively modelocked two-section lasers we choose the following parameters [4]: $\kappa = 0.3$, $\tau = 25$ ps, $\gamma_{1} = 1$ ns in the gain section, $\gamma_{2} = 5$ ps in the absorber section, $\Gamma = 250$ fs. We find both in the model (1)-(3) and in the model (4)-(7) that inhomogeneous broadening in the absorber section can suppress Q-switched instability of the mode-locking (ML) regime, and inhomogeneous broadening in the gain section can lead to another instability of the ML regime which is accompanied by the formation of the Lamb dip in the spectral profile of the pulse (see Fig. 1). Using the DDEBIFTOOL software package for the DDE model (4)-(7) we confirm that the real parts of the eigenvalues that correspond to the Q-switched instability stay below zero for high enough inhomogeneous broadening with the variation of the injection current, whereas the Lamb-dip instability of the mode-locked regime appears after a fold bifurcation.

Finally, we consider the model (1)-(3) for a single-section device and observe appearance of a multi-mode instability of the CW regime for high enough inhomogeneous broadening (see Fig.2).

![Figure 1: Bifurcation diagram for the varying inhomogeneous broadening width $\sigma_{0}$](image1)

![Figure 2: Multi-mode periodic pulsations in a single-section laser. Here $\Gamma = 3.3$ ps, $\gamma_{1} = 1$ ns, $\sigma_{0} = 1.6$ ps.](image2)

4. **References**


Session ID, 1-7: Temperature and current dependence of 1/f frequency noise in narrow-linewidth discrete-mode lasers

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Abstract: We report on extensive studies of the frequency and intensity noise spec.tra in discrete-mode AlGaInAs multiple QW lasers at 1.55 μm wavelengths. Our final goal is to understand the mechanism of 1/f flicker noise build up that leads to linewidth broadening at high currents.

1. Introduction

Wavelength tunable lasers for 40G and 100G coherent optical communications systems need to meet stringent requirements on narrow linewidth emission across the entire tuning range, with typical values of 300 – 500 kHz required in commercial systems. Higher capacities can be achieved in next generation systems by employing higher order modulation formats such as 16QAM or 64QAM, however, such systems will have even more stringent linewidth requirements [1]. For the majority of semiconductor lasers, the integral noise features such as the linewidth and RIN are defined by flicker (1/f) noise contribution, which is believed to be due to generation-recombination processes through recombination centers in defects (e.g. dislocations). In this talk we will report on 1/f noise dependence on the cavity length as well as driving current and temperature of the narrow linewidth Discrete Mode Laser Diodes (DMLD) and discuss the possible origin of these effects. DMLDs are interesting for communications and other applications as they can be designed for narrow linewidth emission and present an economic approach with a focus on high volume manufacturability of monolithic semiconductor lasers [2].

2. Laser structures

The AlGaInAs Multiple Quantum Well (MQW) lasers were grown on n-type (100)-InP substrate in an MOVPE reactor at low pressure. The MQW structure consisted of five compressively strained (1%) 5 nm-thick AlGaInAs quantum wells and six slightly tensile strained (0.2 %) 8 nm thick AlGaInAs barriers. The MQW was sandwiched between two 200 nm-thick AlGaInAs Separate Confinement Heterostructure (SCH) guide layers. A 2 μm thick p-InP layer was grown on top of the SCH followed by a 200 nm thick highly p-doped InGaAs contact layer. Single wavelength operation in DMLDs is achieved by introducing shallow-etched (DBR-like) features positioned at a small number of sites distributed along the ridge waveguide [2]. DMLD samples with cavity length from 1.5 to 3 mm have been fabricated and tested. Frequency noise (FN) was measured using all-fibered Mach-Zehnder interferometer (MZI) as a frequency-amplitude converter. The output of the MZI was analyzed with a fast detector and a spectrum analyzer. Another detector was used for simultaneous acquisition of the relative intensity noise (RIN). Acquired FN and RIN spectra were analyzed and the contributions of the white and flicker noise were extracted. The linewidth was estimated by integrating the FN power spectral density (PSD). Additionally, the linewidth measurements were performed with the frequency-shifted self-heterodyne technique.

3. Results and discussion

For the majority of single-mode semiconductor lasers, the linewidth is mostly defined by the flicker FN contribution with the spectral power density decaying as 1/f in the noise spectrum (the first term in

\[ FN(f) = \frac{h_1}{f} + h_0 \]

). Only at high frequencies \( f \), the white noise with constant PSD \( h_0 \) dominates.

White noise has been widely studied in various lasers and comprehensive models have been elaborated for semiconductor lasers [3]. In our DMLD, white RIN almost follows the expected behavior, within the accuracy of the noise excess factor \( \chi \) [Fig.1(a)]. The increase of the factor \( \chi \) with the cavity length can be attributed to the behavior of the spontaneous emission factor \( \beta^2 \) into the lasing mode (values are shown in the figure legend). White FN PSD [Fig.1(b)] shows reasonable agreement with the modified Schawlow-Townes expression [3], exhibiting a linear decay with the pump current \( h_0 \sim l/l \).

In contrast, very little attempts were reported in literature to build a comprehensive theory for flicker noise in semiconductor lasers [4]. Measured flicker RIN PSD (Fig.2(a)) decays with the pump current \( I \), which is opposite to the expected exponential growth with the output power [4]. We did not find a rigorous theoretical model for the flicker FN PSD. Measured coefficient \( h_{-1} \), which is the FN PSD extrapolated to the Fourier frequency of 1 Hz, in
laser samples of different cavity length exhibits a minimum at almost the same output power level [in Fig.2(b), left axis, all samples were tested at the same temperature]. At these operation conditions, all laser samples exhibit narrower linewidths. With further increasing driving current, the flicker FN [Fig.2(b)] increases and the laser linewidth broadens. Noting that the white FN ∝ 1/I in Fig.1(b), we conclude that variations in the product of squared linewidth and current FWHM ∝ I should reveal the flicker FN contribution. Our measured data confirm this correlation [Fig.2(b), right axis]. Therefore we study the current and temperature dependence of flicker noise contribution by measuring the integrated linewidth in the self-heterodyne setup. Fig.3(a) shows the results obtained in a DMLD with cavity length 1.5 mm for three different pump currents (curves) and temperatures (see data labels). There is an optimal operation point with the lowest flicker FN, which is at 200 mA and 30°C in the particular sample. The location of local minima shifts symmetrically with the laser temperature and/or current detuning. Such behavior cannot be attributed to generation-recombination processes. This behavior much resembles the lasing mode pulling from the DBR mode due to the spectral gain profile and DMLD cavity. Indeed, we find that 1/f FN is correlated with the wavelength difference of the lasing mode and the power-weighted mean wavelength of the amplified spontaneous emission into other cavity modes [Fig.3(b)].

4. Conclusion

In conclusion we believe we bring an important piece of experimental data that allows one to build a realistic model for the frequency flicker noise in a semiconductor laser.

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5. References

Session ID, 1-8: Directive emission from multimode lasers with subwavelength transverse dimensions

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Abstract: Here we propose an approach to obtain directive radiation from multimode lasers with subwavelength transverse dimensions and the length much larger than the wavelength (wire lasers). The approach is based on the use of a spherical lens producing the image of the laser due to the interference of radiation from the distribution of sources along the laser waveguide. The image of a slow mode of a wire laser consists of two maxima with position and width independent on the mode parameters. A narrow beam can be formed by choosing the lens parameters leading to overlap of the two maxima, or by separating one of the maxima with a diaphragm.

1. Introduction

A large group of lasers based on semiconductor nanowires, plasmon waveguides, and multi-quantum-well structures have wire geometry with transverse dimensions smaller than the emission wavelength and a length much larger than the wavelength. The spatial structure of wire laser radiation differs drastically from that of conventional lasers with large apertures. It was found to be highly divergent, with strong intensity modulations observed both in far [1] and near field [2], with the pattern of modulations more dense for longer lasers. It was shown that the far-field pattern of wire lasers is formed by the interference of radiation from the longitudinal distribution of sources along the laser waveguide [3] and is similar to that of antennas of traveling wave. Directive emission from wire lasers with narrow, almost axially symmetric beam along the laser axis has been achieved experimentally using gratings with appropriate periodicity, acting as a discrete array of phased sources along the laser waveguide [4–7]. However, this approach is applicable only to single mode lasers, as the conditions of directive emission and the angle between the radiation maximum and the laser axis depend on the longitudinal phase velocity of the mode. Thus it does not solve the problem of directivity of wire lasers operating in multimode regime required for various applications including generation of short pulses. Here we propose an approach to obtain a directive beam from a multimode laser with subwavelength transverse dimensions and the length much larger than the wavelength. The approach is based on the use of a spherical lens producing the image of the laser due to the interference of radiation from the distribution of sources along the laser waveguide. We show that the structure of the field in the vicinity of the image of a slow mode of a wire laser does not depend much on the mode parameters and enables the formation of a narrow beam from a multimode wire laser.

2. Calculation method

Calculation of the image of a wire laser cannot be performed with the standard aperture diffraction methods, which have been used to develop the beam shaping techniques for the lasers with the apertures much larger than the wavelength, since a considerable part of radiation of wire lasers propagates outside the laser waveguide. This part of the radiation carries information about the longitudinal structure of the laser mode and enables the formation of the laser image. The influence of the longitudinal structure of the waveguide on the radiation distribution can be adequately described using the approach based on the equivalence of displacement currents in dielectrics and conductivity currents [3]. Radiation field of a wire laser is expressed within this method in terms of the field values inside the volume of the cavity, enabling the account of the influence of laser length on the field structure. Further we calculate the transformed radiation field using Fresnel integral over the aperture of lens and the aperture of the diaphragm placed in the plane of one of radiation maxima of the wire image.

3. Results

The structure of the image field of a wire laser placed on the axis of a spherical lens obtained in paraxial approximation is a multiple of two factors: the spherical wave from the center of the lens and a structural factor. The latter depends on the two dimensionless parameters: the laser length normalized to the lens axial resolution Δ and the phase shift between the laser mode and free space radiation travelling along the laser waveguide Φ [8]. The structural factor of slow modes with large negative Φ typical for wire lasers has two maxima with uniform phase
corresponding to the images of the ends of the laser waveguide. Each of the maxima contains half of the radiation power collected by the lens. While the field outside of these maxima strongly depends on the mode phase velocity, the field within the maxima does not depend on the mode structure. Narrow beam can be obtained when the laser is placed with one end in focus of the lens with 1<λ<1.5, when the two maxima overlap (Fig. 1.). The divergence of such beam is determined by the ratio of the wavelength to the lens radius, and the minimum beam spot size is close to that of the image of a point source located at the laser end. However, the fraction of the laser power collected this way into a narrow beam is limited, and its maximum is about the ratio of the wavelength to the laser length. The level of the power collected into a narrow beam can be increased using a lens with a larger λ, producing the image with two non-overlapping maxima, and separating one of them with a diaphragm (Fig. 2.). In this case the maximum fraction of the laser power collected into a narrow beam does not depend on the laser length and is determined by the fractional area of the lens.

![Figure 1](image1.png)  ![Figure 2](image2.png)

**4. Conclusion**

We reported on the method of formation of a directive beam from a multimode laser with subwavelength transverse dimensions and the length much larger than the wavelength.

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**5. References**


Session ID, 1-9: High performances of very long (13.5mm) tapered laser emitting at 975nm

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Abstract: We have realised a very long (13.5mm) tapered laser emitting at 975nm, designed for the emission of ultra-short optical pulses (<1ps) at a repetition rate of 3GHz with an average optical power of 200mW at least, in a monolithic way. It is based on a laser structure grown by MOVPE, with Aluminium free active region, and designed for high gain, low internal losses and series resistance. The first results in CW operation at 20°C show a low threshold current of 1.27A and a high differential external efficiency of 0.55A/W for such a long mode.

1. Introduction: context of the laser diode development

The technology of Mode-Locked Semi-Conductor Lasers (MLSCL) is a promising candidate to be used in optical metrology systems for various space applications in the context of high-precision optical metrology, in particular for High Accuracy Absolute Long Distance Measurement (HAALDM). The following very challenging target performance requirements should be met: pulse duration<1ps, pulse repetition frequency (PRF) of 1-3GHz, PRF stability < 5.10⁻⁹, PRF tunability > 20MHz, average optical output power > 200mW, pulse energy > 200pJ, high spatial beam quality (M²<2.5). For PRF of 3GHz and pulse energy of 200pJ (resp.500pJ), the average optical power should be 600mW (resp.1.5W). We intend also to get compactness, integration of gain and absorber on the same chip, high wall plug efficiency and possibility to operate in hybrid mode-locking (ML) regime. Therefore, we have decided to address these targets (with PRF of 3GHz) by the design and fabrication of a very long (13.5mm) monolithic multiple-section edge-emitting mode-locked laser.

2. Laser diode structure

In order to get high power and wall plug efficiency on a very long laser cavity we have designed a structure with tailored doping for very low internal losses (~1cm⁻¹) together with low series resistance. The laser structure (shown in figure 1) is grown by Metal Organic Chemical Vapor Epitaxy (MOVPE). The laser comprises one compressively GaInAs 5nm thick quantum well (QW) for high gain in TE polarisation. GaInAsP Large Optical Cavity (LOC) is used for the waveguiding. Most of the field (90%) then propagates in the Al free active region [1], in order to get a good reliability. The external cladding layers are made of GaAlAs.

![Diagram of the Laser Diode Structure](image1)

*Fig. 1: Laser epitaxial structure

The tapered laser structure (shown in figure 2) comprises different sections. From the rear side to the front side the laser comprises an absorber section, an intermediate section and a tapered section. In the two first sections, index waveguide is provided by etching of a single mode ridge waveguide (RW), 3µm wide. The tapered section, which provides the gain, is not etched as the previous ones but is defined by a proton implantation outside of the tapered

![Diagram of the Tapered Laser Structure](image2)

*Fig. 2: Schematic diagram of the tapered laser structure

![Diagram of the SEL-ML Regime](image3)

*Fig. 3: SEL -starting passive ML regime (green domain) is stable against self-pulsations at below the red line plotted in the plane of normalized small-signal cavity gain g0 and absorption q0 [2].
part. The tapered angle corresponds to the free diffraction of the beam coming from RW part. The overall cavity length is 13.5mm, corresponding to the PRF of 3GHz. The tapered section is 4mm long. The intermediate section is used for spatial mode filtering, device length adaptation and also fine PRF tuning. The rear and front facets have received respectively a high reflectivity (>95%) and low reflectivity (<0.1%) dielectric coating for high power and high beam quality operation. The laser chips are then mounted on a Cu submount, in a P side up configuration. The laser is predicted to show a passive ML operation. The green colour scale in figure 3 indicates ML pulse energy variation. Self-starting ML is stable against low-frequency self-pulsations at below the red line plotted in the figure.

3. First results under CW operation

We present the very first CW results of these lasers where all the electrodes have been short circuited. The light-current characteristics (shown in figure 4) and the voltage-current characteristics have been characterised at different temperatures from 10°C to 40°C. The threshold currents are 1.17A, 1.27A, 1.43A and 1.65A, respectively, corresponding to characteristic temperature T0 higher than 200K. The external differential efficiency are quite high for such a long laser cavity with values of 0.59W/A, 0.55W/A, 0.51W/A, 0.47W/A, respectively, corresponding to characteristic temperature T1 better than 300K. At 20°C, an optical power of 1.5W is obtained at 4A. The series resistance has a low value of 37mΩ. Thanks to high efficiency and low series resistance, the wall plug efficiency measured at 20°C is 26% at 4A.

![Figure 4: Light-current characteristics at different temperatures](image)

![Figure 5: Evolution of the wavelength with the dissipated power at 10°C](image)

The wavelength evolution with temperature at a fixed current is 0.29nm/°C, typical value for Fabry-Perot lasers in this wavelength range. The wavelength evolution with the dissipated power (shown in figure 5), is linear with a slope of 1.7nm/W. The ratio of these two slopes gives an average thermal resistance of 5.9K/W, which is a low value for a P side up mounted laser.

4. Conclusion

We have reported on the fabrication of a very long multi-section tapered laser designed for high-precision optical metrology. The monolithic approach implies a very long cavity of 13.5mm for a PRF of 3GHz. Despite this cavity length we have demonstrated a high external efficiency of 0.55W/A in CW at 20°C together with an optical power of 1.5W at 4A.

The future work will be a comparative study on the laser heterostructure and electrode geometry impact on the beam quality and stability of ML oscillations.

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5. References


Session ID, 1-10: High-frequency pulsating dynamics in a laser diode with phase-conjugate feedback

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Abstract: We make the first observation of so-called external-cavity modes (ECMs) in a laser diode with phase-conjugate feedback. Predicted more than thirty years ago, these ECMs are self-pulsating dynamics with a frequency being harmonic of the external-cavity frequency. High-frequency self-pulsation is therefore achieved with a frequency being controllable by the feedback parameters and by the nonlinear optical material properties.

1. Introduction

A laser diode behaves dynamically like a damped nonlinear oscillator showing so-called relaxation oscillations. However there exist configurations including external optical feedback for which these oscillations become un-damped leading to self-pulsation and chaos [1]. This problem has been traditionally addressed in the context of conventional optical feedback (from an external mirror). However applications have driven a resurgent interest in analyzing configurations such as phase-conjugate optical feedback where the reflected field is dynamically filtered and self-aligned.

In contrast to conventional optical feedback (COF), there have been only few experiments analyzing the impact of phase-conjugate optical feedback (PCF) on laser diode dynamics. Experiments have shown several dynamical features that are common to time-delayed feedback laser diodes and therefore not specific to PCF, e.g. undamping of relaxation oscillations, coherence collapse and low-frequency fluctuations [2]-[4]. However, theory shows very distinct steady-state solutions and secondary bifurcations to chaos [5]. A laser diode with PCF admits only one steady-state solution which destabilizes to limit-cycle solutions of increasing frequency when increasing the feedback strength. These self-pulsating solutions have been called 'External Cavity Modes' (ECMs) because their frequency is a multiple of the external-cavity frequency. ECMs then exhibit secondary bifurcations to quasiperiodic dynamics and chaos. The search for these harmonic self-pulsation dynamics is of utmost interest for applications in optical signal processing and communication.

We report here on the first experiment showing ECMs in a PCF configuration, i.e. high-frequency self-pulsation at a frequency being super-harmonic of the external-cavity frequency. We will further analyze how the stability of these ECMs depends on the laser and feedback parameters, including the impact of the finite penetration time in the material generating phase conjugation.

2. Results

Phase-conjugation is achieved experimentally using four-wave mixing in a SPS photorefractive crystal [4]. The laser diode is an edge-emitting laser emitting at 852 nm. Figure 1 details the transition from stationary to self-pulsating solutions and further to chaos as the phase-conjugate mirror reflectivity R increases. The external-cavity length $L_e$ equals 22 cm. As R increases, the stationary output power bifurcates first to fast-fluctuating dynamics at frequencies close to the solitary laser diode relaxation oscillation frequency (not shown), which for slightly large R value bifurcate to more complex dynamics such as in trace (a)—when R=0.24%. The laser diode shows a pulsating dynamics with a rich frequency content but with a clear signature of the external cavity delay as visible from the regular peaks interspaced by 680 MHz = c/(2L_e) in the RF spectrum. Trace (a) is typical of a chaotic-like dynamics. For slightly larger feedback strength, regular self-pulsating dynamics is observed in (b) (frequency=1.36 GHz) and (c) (frequency=2.06 GHz), i.e. at respectively twice and three times the fundamental external-cavity frequency 680 MHz = c/(2L_e). A clear dominant peak at the corresponding frequency is visible in the RF spectra. These solutions are respectively called 'ECM2' and 'ECM3' to refer to a time-periodic solution pulsing at the second and third harmonic of the external-cavity frequency. For larger feedback strength, a route to chaos by period multiplying occurs: the third-harmonic self-pulsation undergoes period tripling giving birth to trace (d) in which it can be clearly seen that one on every three peaks is skipped compared to trace (c). In the RF spectrum the main frequency at 2.06 GHz stemming from trace (c) is encircled and peaks interspaced by 680 MHz appear. For larger feedback strength, the laser bifurcates to chaos (e).
Simulations of a rate equation model show very good qualitative agreement with the above reported bifurcation scenario [6]. We have performed a detailed mapping of the bifurcations that stabilize and de-stabilize these high-frequency self-pulsations, as a function of both the mirror reflectivity R and the external-cavity delay time. Interestingly frequencies of several tens of GHz well beyond the relaxation oscillation frequency are predicted for large values of R and the achieved frequency for a given value of R remains almost independent of the external-cavity length value. However these ECM solutions of high frequency disappear when the penetration time within the nonlinear optical material increases [7]. The filtered feedback PCF system then yields similar dynamics than an optical injection system with destabilized relaxation oscillation self-pulsations.

3. Conclusion

We have evidenced the existence of external-cavity mode (ECM) self-pulsation in a laser diode with phase-conjugate feedback, i.e. high-frequency self-pulsation at a frequency being harmonic of the external-cavity frequency. Phase-conjugation is achieved from four-wave mixing in a photorefractive crystal. These ECM solutions reach very high frequencies well beyond the relaxation oscillation frequency when increasing the phase-conjugate mirror reflectivity and their existence requires a small penetration time within the nonlinear optical material - typically corresponding to <1 cm long photorefractive crystal.

5. References

Session ID, 1-11: Quantum dot lasers with two-wavelength emission- Routes to improved modulation capabilities

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Abstract: Nanostructured quantum dot laser devices have the unique capability to show simultaneous two-wavelength emission due to their multiple confined states and their relatively slow carrier-scattering processes. Using a microscopic modelling approach, we discuss the necessary condition for the internal scattering processes inside the laser that enable two state lasing. Furthermore, we study the nonlinear dynamics of these devices and explore ways to optimize their performance under electrical current modulation. We predict a drastic increase of the ground state modulation bandwidth beyond the threshold of the excited state laser emission.

1. Introduction
Quantum dot (QD) laser devices are promising sources for a variety of applications, including telecommunication devices, mode-locked lasers, and single-photon sources. They have also been of interest for their theoretically predicted high modulation capabilities, however these have yet to be realized. In contrast to quantum wells and bulk heterostructures, their completely discretized energy spectrum gives rise to their various special properties, i.e. low threshold currents for lasing, high temperature stability and low linewidth. However, this also leads to their most prominent drawback: the carrier redistribution between these discrete levels is slow, when compared with quantum wells (QW). Thus, modulation capabilities are inhibited and despite many efforts, QD systems currently cannot compete with QW based devices. Nonetheless, the slow scattering also gives rise to the unique phenomenon of two-state lasing, i.e. simultaneous emission at two wavelengths. While normally lasing occurs by the recombination of carriers in the lowest energy state of the QD, recombination is also possible for higher bound states [1]. This can lead to excited state lasing and even the simultaneous emission on two very distinct wavelengths. As can be shown, this is only possible if a semi-decoupling of the charge-carriers within the localized states of the QD is preserved [2].

2. Small and large signal response
Our microscopically motivated rate-equation model is based on [3, 4] and includes the ground and first excited state, separate hole and electron occupation numbers, and accounts for inhomogeneous spectral broadening due to the spread in QD size. Fig. 1 shows the calculated maximum modulation frequency of the QD laser versus the electric pump current. We choose a QD laser with an energy spacing that allows for two-state lasing, as a very large spacing completely suppresses ES lasing while the enhanced ES filling for very small values leads to solely ES lasing.

Figure 1:
Maximum modulation frequency under periodic small signal current modulation (solid lines), i.e. 3dB-cutoff frequencies, versus pump current for ground state (GS) (light red) and excited state (ES) (dark blue) emission. Dashed lines depict the laser intensity at both wavelengths. The system exhibits a sharp increase of the GS modulation capability after the ES threshold.

We find a sharp increase in the 3dB cutoff-frequency of the GS lasing frequency that occurs when the two-state lasing starts. This surprising effect can be linked to the decreased slope of the GS light-current characteristic (dashed lines in Fig.1). To elaborate
how the large signal response is affected by this decreased slope. Fig. 2 shows the simulated large signal eye-pattern diagrams, for a modulation frequency of 4 GHz, below and above the ES threshold current (left and right panel, respectively). A dramatic improvement of the signal quality can be observed above the threshold current, which might be exploited for device applications.

3. Analytic approximations

We also investigated the robustness of the two-state lasing in QD laser devices against parameter changes. Here, we also found a small parameter region exhibiting ‘GS quenching’, i.e. two-state lasing that transitions to pure ES lasing for high currents. Over all, the carrier dynamics is crucial for the GS quenching while self-heating or gain reducing effects are negligible. With additional analytical approximations applied, our model shows that an electron-hole asymmetry is necessary to explain GS quenching and underlines the importance to model both carrier types separately. The analytic results can be seen in Fig.3 where the regimes of GS lasing (yellow area) and ES lasing (black line) are displayed in the parameter space of ES electron ($\rho^{\text{ES}}_e$) and hole ($\rho^{\text{ES}}_h$) occupation. Increasing the pump current (as done in Fig.1) changes the scattering processes and thus leads to variations of the carrier occupations and to variations in the lasing characteristics.

4. Conclusion

We report on the data transmission capabilities of QD lasers by using a microscopically motivated multi-population rate equation model. We present numerical results on the connection between two-state lasing and modulation properties of QD laser devices and discuss analytic approximations for parameter regions that allow for multi-wavelength emission. A sharp increase in the 3dB cutoff-frequency of the GS lasing frequency is found to occur at the threshold of the excited state emission that can be linked to the decreased slope of the GS light-current characteristic. Simulated large signal modulation eye diagrams also suggest dramatic improvement of the signal quality above the second threshold, which might be exploited for innovative device applications.

5. References

Session ID, 1-12: Double-state lasing in an InAs/GaAs quantum dot laser diode: microscopic mechanism

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Abstract: The microscopic mechanism of the double-state lasing at the ground state and the excited state in an InAs/GaAs quantum dot (QD) laser diode was investigated. The excited state lasing in the double-state lasing was found to take place not from the same QD group of the ground state lasing, but from a different QD group located outside the homogeneous bandwidth. This finding was possible by analyzing spontaneous emission from a window of a QD laser diode under lasing conditions, together with numerical simulations based on coupled rate equations incorporating QD micro-states.

Double-state lasing, simultaneous lasing at the ground state and the excited state, was reported in InAs/Ga(In)As QD laser diodes [1,2,3]. QD laser diodes lased only at the ground state at a low injection current. However, as the current increased lasing at the excited state developed, resulting in simultaneous lasing at both the ground state and the excited state. This behavior is quite different from that of a typical semiconductor laser and is also different from inhomogeneously broadened lasing. Double-state lasing was interpreted mostly to originate from slow carrier relaxation from the excited state to the ground state in a QD, which enabled the carrier build-up at the excited state under ground state lasing. We investigated the microscopic mechanism of double-state lasing by analyzing spontaneous emission from a window of a QD laser diode, together with numerical simulations using coupled rate equations incorporating QD microscopic states [4].

Three window structures were fabricated on top of the waveguide of a ridge waveguide QD laser diode by removing the gold layer in the windows using focused ion beam etching, as shown in Fig. 1. Spontaneous emission was collected from the window structure by a vertically aligned single mode fiber and its spectrum was measured using an optical spectrum analyzer.

Figure 1: A schematic diagram of a ridge waveguide laser diode with three windows on top.

The amplified spontaneous emission (ASE) spectra from a facet of the QD laser diode showed only ground state lasing up to 12 kA/cm² and eventually double-state lasing at 16 kA/cm². The lasing peak at the ground state coincided with the ASE peak and the signal outside of the lasing peak increased continuously with injection current. The increase of the outside signal is due to the inhomogeneously broadened gain of the QD system. However, the increase at the excited state is not from QD inhomogeneities, but indicates that the carrier density in the excited state increases to lasing regardless of the strong lasing at the ground state. In contrast to ASE, spontaneous emission depends only on the carrier density so that we can estimate the carrier build-up directly from the spontaneous emission spectrum. Spontaneous emission spectra obtained from the center window on the QD laser diode at high
current densities clearly showed clamping of the carrier density at the lasing wavelength, the continuous increase of the carrier density outside the lasing wavelength band at the ground state, and the significant carrier increase at the excited state. Double-state lasing was caused by a build-up of the excited state carrier density to excited state lasing under ground state lasing due to slow carrier relaxation from the excited state to the ground state, which was clearly observable in the spontaneous emission spectra at high current densities.

We carried out simulations using coupled rate equations and matched the simulation results with the measured spontaneous emission spectra. Inhomogeneous broadening in a QD ensembles was considered to investigate the microscopic details of double-state lasing. For the carrier dynamics, we employed the coupled rate equations used to simulate an InAs/GaAs quantum dot semiconductor optical amplifier [4].

![Figure 2](image-217x402 to 395x624)  
Figure 2: Calculated results of (a) the spontaneous emission spectra from the window and (b) the lasing spectra from a laser facet, as a function of the carrier relaxation time from the excited state to the ground state.

Figure 2 shows the simulation results of spontaneous emission spectra from the window and the lasing spectra from a laser facet as a function of the carrier relaxation time from the excited state to the ground state. The dip around the excited state peak was more significant when the relaxation time was fast. At a relaxation time less than 5 ps, excited state lasing was not observed since the carrier density could not reach the excited state lasing threshold due to the overall fast relaxation to the ground state. On the other hand, slow relaxation enabled the overall build-up of carriers at the excited state and the eventual excited state lasing outside of the homogeneous broadening band. The simulation results indicate that excited state lasing in double-state lasing did not proceed from the same QD group of ground state lasing, but from a different QD group located outside of the excited state band that corresponded to the ground state lasing band.

Session ID, 1-13: Widely tunable narrow-linewidth light sources based on quantum dot gain material for future high-capacitance coherent optical communication

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Abstract: The effect of the number of quantum dot (QD) active layers on the emission linewidth of 1.55 μm InAs/AlGaInAs/InP QD distributed feedback lasers was studied. A systematic reduction of the laser linewidth for structures with 2 and 5 QD layers, being consistent with a strong decrease of the linewidth enhancement factor for QD materials, was observed. The measurements showed a good agreement with device simulation results. For a 1.2 mm long QD DFB laser a minimum linewidth of 110 kHz was achieved. Continuous emission wavelength tuning of about 11.5 nm for a single device was obtained by on-chip temperature control.

1. Introduction

Judging from the ever-increasing growth in data rates, it is obvious that currently available transmission capabilities of fiber lines will not suffice in the long run. The solution could be the implementation of coherent optical transmission, which provides much higher spectral information densities using a variety of digital modulation schemes like phase shift keying (PSK), quadrature amplitude modulation (QAM), etc. Such high-capacity coherent optical telecommunication systems require narrow linewidth widely tunable single-mode-emitting light sources, which can be used like a local oscillator for reference signal generation and data recovery. A smaller laser linewidth allows better channel separation and phase resolution. Due to the inherently low linewidth enhancement factor (α-factor) and inhomogeneously broadened gain spectrum of quantum dot (QD) material, QD based distributed feedback (DFB) lasers can fulfill all of these criteria. We report on the emission linewidth of monolithically integrated 1.55 μm InP-based QD DFB laser arrays with tailored active region design.

2. Device fabrication and results

Lasers structures consisting of two and five QDs layers in active region were grown by solid source molecular beam epitaxy. The details on the growth and epitaxial design could be found elsewhere [1]. All lasers showed high modal gain of about 10 cm⁻¹ per QD layer. DFB lasers with a first order lateral grating, defined by e-beam lithography and a combination of wet- and dry chemical etching were processed with nominally similar geometry. Figure 1 shows an example of an integrated optoelectronic chip, consisting of four DFB lasers coupled by 3dB combiners. Laterally positioned micro heaters enable thermal tuning over a wide wavelength range. Additional contacts for pumping the couplers, in order to make them transparent, are also included. DFB lasers from each epitaxy wafer with a similar grating length measured from the cleaved backside facet were compared. The P-I characteristics for mounted lasers on a heat-sink (Fig. 2a) shows quite similar threshold currents of about 55 mA. Due to the lower number of active layers for lasers with two QD layers, the ground state gain is starting to saturate already at lower current leading to an earlier thermal roll-over and lower maximum output power.

Figure 1: Optical microscope picture of four arrayed QD DFB lasers with a 3dB couplers and integrated micro heaters.
of about 4 mW while the other laser exhibits more than 15 mW. Both lasers operate in single mode over the whole plotted current range with a side-mode suppression ratio of 40 dB and beyond.

Linenwidth measurements were performed by delayed self-heterodyne technique [2] with 10 km and 5 km delay lines for structures with 2 QD and 5QD layers respectively. In order to decrease current noise and yield an improved signal to noise ratio both lasers have been pumped using a battery source. The intrinsic linewidth was determined by fitting a Voigt line profile and extracting the Lorentzian part. In Fig. 2b the measured and simulated current dependent linewidths for both lasers are plotted. The theory based on a traveling-wave model along the laser optical axis coupled to a carrier rate equation was applied [3]. The difference in laser structure designs and the inhomogeneous size distribution of the QD layers were also part of the model. For the initial simulation the low injection alpha factor of 0.6 for wafer with 5 QD active layers was derived from the QD gain model which does not include wetting layer states. As one can see, the measured intrinsic linewidths clearly follow the simulations proving the strong impact of the active zone design and correspondingly the quantum dot gain function profile on the laser linewidth. Some underestimation of simulation data at higher injection currents could be related to the fact that increase of linewidth enhancement factor with rising of injection current is yet to be taken into account. This effect is expected to be more prominent for the wafer with 2QD active layers. The minimum linewidth of about 110 kHz was measured for a single 1.2 mm long QD DFB laser with 2 QD layers and without a coupler section on the rear facet. This value is about one order of magnitude lower than typical linewidths for QW lasers. Figure 2c shows the emission spectra of DFB laser with 5 QD active layers. By adjusting of gain and heater currents continuous single mode wavelength tuning over the range of 11.5 nm was obtained.

3. Conclusions

Systematic studies confirmed a dramatic effect of quantum dot material on the laser linewidth. Depending on the active zone design, i.e., by tailoring the QD gain function profile and linewidth enhancement factor, considerable reduction of the intrinsic DFB laser linewidth down to a few hundred of kHz and even below could be obtained. The experimental data are in a full agreement with theoretical consideration. In addition, due to the internal temperature compensation mechanism of QD material, a wide tunability range of about 11.5 nm for a single DFB laser could be achieved. Therefore such devices are excellent candidates as integrated reference lasers for future high-capacity coherent optical communication systems.

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4. References

Session ID, 2-1: A near thresholdless laser at room temperature

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Abstract: In this work we report room temperature (RT) continuous wave (c.w.) lasing at 1.3 μm in photonic crystal microcavities with a single layer of self-assembled InAsSb quantum dots (QDs) embedded in a photonic crystal microcavity. The laser exhibited ultra–low power threshold (860 nW) and high efficiency (β=0.85), thus operating in the near thresholdless regime.

1. INTRODUCTION

Laser emission using photonic crystal microcavities (PCM) has opened new ways towards very low threshold and highly efficient solid state lasers with also very small size. Recently, the term “thresholdless” has been used in the literature to identify lasers presenting two main features: a spontaneous emission coupling factor (β) close to 1 and low non radiative losses. Non radiative losses are reduced by several orders of magnitude at cryogenic temperatures, although they can never be completely suppressed. When the spontaneous emission factor β is equal to 1 every photon emitted by the device is emitted in the lasing mode. Such “thresholdless” lasers were proposed to be realized by combining QDs as light emitters and PCMs as high quality resonators. [1] That strategy was adopted to demonstrate near thresholdless lasing at low temperature (4.5 K) by using few QDs (between 2 to 4) as active emitters and a high β=0.85 with power threshold values of 124 nW.[2] In this work we show a RT continuous wave (c.w.) laser with emission characteristics close to those of an ideal thresholdless laser.

2. DESIGN AND FABRICATION OF THE DEVICES

We have designed a PCM that consisted of a hexagonal lattice of air holes with 9–missing holes along the ΓK direction (i.e., L9–PCM) fabricated on a GaAs suspended slab containing a single layer of InAsSb QDs.[3] Fig. 1a shows a photoluminescence spectrum of an L9-PCM fabricated on this epitaxial material. Four sharp resonances are observed and identified as the first high-Q even modes, being the e1 the fundamental lasing mode.

![Photoluminescence spectrum](image)

**Fig. 1.** (a) shows the PL spectrum at RT of the ensemble of QDs outside of microcavities; it is also shown the spectral distribution of the optical modes of the L9-PCM. The design of the cavity was made to provide the fundamental mode with the best Q/V ratio and the optimum spectral matching to the emission of the QDs. (b) shows a SEM image of the cavity.
3. OPTICAL CHARACTERIZATION

Figure 3a shows the experimentally measured emission of the device versus the optical power used for excitation (LL-curve) in logarithmic scales. It is also represented the theoretical fittings to the experimental values using the laser rate equations for different β-values. The best fitting is obtained for β = 0.85. [4]

![Graph showing integrated power vs pump power and linewidth characteristics of the L9 photonic crystal microcavity (PCM) laser. Different coupling factors (β) are modeled through the rate equation model (blue lines) and the best fit, for β = 0.85 (red line). Grey region in (a) refers to the amplified spontaneous emission (ASE) region; lower powers define the photoluminescence (PL) region, and higher powers correspond to the lasing region. (b) Analysis of the differential efficiency calculated from the LL data (dots) and from the best fit for β = 0.85 (red line).]

Figure 3b presents both the experimental and calculated DE in our system; the latter corresponds to the best fit of the LL-curve. Below an excitation power of 3 μW an increasing of the DE is observed, indicating the lasing characteristics of the L9-PCM mode.

4. CONCLUSIONS

Efficient c.w. room temperature laser emission in the 1.3 μm window has been demonstrated for an L9 PCM containing a single layer of InAsSb QDs as active medium. We have analyzed the emission characteristics of the laser, and established a low pump absorbed threshold power as low as 861 nW and a β = 0.85. Such features may be key for low-power consumption associated to such kind of light sources that may improve future laser devices, optical interconnects, sensors and photonic integrated circuit technology.

ACKNOWLEDGEMENTS

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REFERENCES

Session ID, 2-2: High temperature operation of 1.55 μm InAs quantum dot lasers with high T₀ and T₁ values

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Abstract: InP based quantum dot lasers emitting at 1.55 μm have been developed with strongly improved thermal stability of the device characteristics. Broad area laser evaluation exhibits high modal gain of 14.5 cm⁻¹ through the ground state transition allowing laser operation up to 150 °C. Further improvement could be obtained by rapid thermal annealing. The impact on the laser performance will be presented. Record values in temperature stability of threshold current density (T₀ = 125 K) and (T₁ > 390 K at 80 mW) were observed. Constant slope efficiency over a temperature range of 95 K could be obtained.

1. Introduction

In the last decade, semiconductor quantum dot (QD) structures have attracted an impressive interest from both fundamental physics and potential optoelectronic device applications operating at 1.55 μm and beyond, mainly driven by fiber-based applications, such as classical optical communication [1]. Mainly self-assembled semiconductor QDs formed via Stranski-Krstanov growth mode have supplied a potent active medium for optoelectronic devices such as laser diodes and light-emitting diodes [2]. For laser applications, it is necessary to establish a high QD density with a homogenious size distribution and most likely round-shaped geometry [3]. This results in device related performance properties such as high temperature stability [4], reduced threshold current and increased spectral and differential gain [5] resulting in a high modulation bandwidth [6]. Recently we studied the impact of the growth parameters on the QD formation [7]. With optimized growth parameters an excellent size uniformity of QDs were obtained with a recorded ensemble photoluminescence linewidth of 17 meV at 10 K and high dot densities up to 6x10¹⁰ cm⁻¹. Also stacked QD layers showed a narrow linewidth of 26 meV, only slightly broadened by additional fluctuations caused by strain coupling between QD layers. These can enable an impressive improvement of 1.55 μm QD lasers exhibiting a high modal gain with a temperature-insensitive threshold current density. In this work first results from broad area laser evaluation are presented, where these improved QD material is implemented into laser diodes showing a big impact in the device performance.

2. Epitaxial laser structure

The presented lasers are grown on n-doped InP(100) by mean of a solid source molecular beam epitaxy system. The laser structure consists of six stacked grown at 490 °C with nominally 5 InAs monolayers and separated by 20 nm thick In₀.₅₂Ga₀.₄₈As layers. The detailed full epitaxial laser structure will be presented. All epitaxial layers, except the QDs, are lattice-matched to the InP substrate. Broad area lasers with 100 μm stripe width and cavity lengths varying between 0.25 and 1 mm were processed and characterized in pulsed mode regime. All cavities consist of as-cleaved facets.

3. Laser’s characteristics and temperature dependence

From the processed broad area lasers the internal characteristic parameters were evaluated from length-dependent threshold current density measurements and summarized in the Table 1. Values are shown before and after a rapid thermal annealing (RTA) process. A strong improvement in most of the parameters are obtained. The impact of the RTA will be discussed in the presentation. Figure 1 (left) shows the light output vs. the drive current of 292 μm long lasers. The temperature dependence of threshold current density was measured as shown in Figure 1 (right). A characteristic temperature T₀ of 125 K (15 to 45 °C) and 100 K (above 45 °C) could be determined while the characteristic temperature T₁ for a constant output power is 394 K over a temperature range of 15 - 95 °C. Only above a significant drop is observed presumably caused by a loss in carrier confinement in the QDs.
Table 1: The internal laser characteristics of the QD broad area lasers with 100 μm stripe width as grown and after using the rapid thermal annealing.

<table>
<thead>
<tr>
<th></th>
<th>as-grown</th>
<th>after RTA</th>
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<tbody>
<tr>
<td>Threshold current density (A/cm²)</td>
<td>1546</td>
<td>738</td>
</tr>
<tr>
<td>Internal quantum efficiency</td>
<td>0.52</td>
<td>0.37</td>
</tr>
<tr>
<td>Internal absorption (1/cm)</td>
<td>12.7</td>
<td>3.1</td>
</tr>
<tr>
<td>Transparency current density (A/cm²)</td>
<td>862</td>
<td>356</td>
</tr>
<tr>
<td>Modal gain (1/cm)</td>
<td>87</td>
<td>75</td>
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Figure 1: Left panel: Plot of the output power vs. the drive current in temperature range between 15 and 125 °C for the 292 μm long device. Right panel: Temperature dependences of threshold current density (black) and operation current at a power level of 80 mW (blue) show the extracted T₂ and T₁ values deduced from the linear fits of the semi-logarithmic curves.

4. Conclusions

With optimized InAs QDs the performance of laser diodes is improved significantly, mainly by the improved modal gain. By rapid thermal annealing further improvement in the material quality is obtained with significant impact on the device performance. Record-high characteristic temperature values of T₂ = 125 K and T₁ = 393 K could be obtained. As a result of the strong carrier confinement the devices can be operated up to 150 °C with a constant slope efficiency up to 110 °C. This temperature stability of this new type of QD laser material is well outperforming typical quantum well laser characteristics in this wavelength range and material system.

5. References

Session ID, 2-3: Do we understand the origin of the degradation of InGaN laser diodes?

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Abstract: We studied the InGaN laser diode, emitting in the blue region of the spectrum, characterized by anomalous temperature behavior. Thanks to epilaxial structure modification we observe the decrease in threshold current with the increase in temperature. Because of the non-monotonic temperature dependence of laser parameters, we can demonstrate a correlation of the degradation rate with nonradiative part of the total device current. We interpret the result as strong suggestion that the InGaN laser diode degradation process requires non-radiative recombination of carriers escaping from the quantum wells.

1. Introduction

The problem of the reliability of nitride (InGaN-based) laser diodes (LDs) is, in spite of intensive research poorly understood. In contrast to GaAs based devices, degradation leaves little structural traces in in the stressed structures. Paradoxically, the heavily degraded laser diode may show no extra defects explaining dramatic changes in its device properties. In the present paper we study a peculiar type of nitride laser diodes, which show negative $T_0$ characteristic.

2. Characteristic temperature $T_0$

$T_0$ is the purely phenomenological parameter describing the thermal stability of the laser diode. It can be found in the equation for the threshold current of a device [1], expressed as:

$$I_{th} = I_0 e^{T_0}$$

For the vast majority of the lasers, threshold current increases with the increase of temperature, what results in the positive value of $T_0$, usually in the range of 100 K – 200 K [2-4]. By modification of epilaxial structure of our devices we obtained a set of laser diodes characterized with strongly negative value of $T_0$. For these devices the threshold current decreases during heating in certain temperature range, as shown in Figure 1. In the case of laser diodes with negative characteristic temperature, we can quite easily tune the injection efficiency of holes to the quantum wells by varying the device temperature. Our study [5] shows that the internal efficiency of LD is governed by two processes: injection efficiency and thermal escape of carriers form the quantum wells.

3. Laser diode degradation.

To observe the degradation process of a devices with negative and positive $T_0$, we measured their driving current as a function of time and temperature for constant optical power. To describe the laser aging we use the degradation rate, which is defined as the driving current's slope:

$$\frac{\Delta I}{\Delta t}$$

Obtained results and calculated curves are shown in the Figure 2. The degradation rate of the laser diode measured for various temperatures shows quite complex character, which can be fully accounted for when we assume the proportionality of this process to the carrier escape from quantum well ($I_{rad}$) and to standard thermal activation factor ($e^{-\frac{E_t}{kT}}$):

$$\frac{\Delta I}{\Delta t} = D I_{rad} e^{-\frac{E_t}{kT}}$$

Here, D is a constant factor. Obtained results indicate the potential importance of the recombination processes occurring outside of the active region for the degradation process of InGaN laser diodes.
4. Conclusion

We reported on degradation of InGaN laser diodes characterized by strongly negative $T_0$ behavior. We observed a correlation between the degradation rate of a device and thermal escape of electrons from quantum wells. This result can be interpreted as strong suggestion that the InGaN laser diode degradation process requires non-radiative recombination (recombination-assisted degradation). Additionally this results indicates that the degradation process may not occur only in quantum wells.

5. References


Session ID, 2-4: Impact of InAlGaAs QW strain and output coupling on dynamic characteristics of 1.3-mm wafer fused VCSELs.

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Abstract: The impact of the strain in the active InAlGaAs QWs and output coupling on the dynamic characteristics of 1.3μm wafer fused VCSELs is investigated. Varying the strain from 1 to 1.6% improves the modulation bandwidth from 7 to 10 GHz at 3 dB cutoff, and with optimization of output coupling the bandwidth further increases to 12 GHz. This progress gives indications for achieving 25Gbps and higher modulation bandwidths with long wavelength wafer fused VCSELs for optical fiber data links.

1. Introduction

Vertical cavity surface emitting lasers (VCSELs) have important advantages compared with edge emitting semiconductor lasers such as low beam divergence, high fiber coupling efficiency due to circular output beam, low threshold current, low power consumption, single longitudinal mode emission, simple integration into one or two dimension arrays and on-wafer testing capability. VCSELs operating at <1μm wavelengths have established themselves as the ultimate low-power-consumption lasers for an increasing number of applications in data communications, active optical cables, computer mice etc. There are currently increasing needs for similar low-power-consumption lasers at longer wavelengths, especially for 1310 nm and 1550 nm optical communications networks, where the huge expansion in data traffic is facing severe limitations due to thermal management problems.

Among different approaches of long wavelength VCSEL fabrication, the wafer fusion approach [1] has an advantage allowing to combine high quality InP-based active and high reflectivity, low absorption GaAs-based distributed Bragg reflectors (DBRs). 1.3μm VCSELs fabricated with this technology yiled record single mode (SM) power and good performance compatible with 10 Gbps data transmission over SM optical fiber [2, 3]. It has been shown that InP-based 1300 nm VCSELs can operate at bandwidth in excess to 15 GHz [4]. To push further the modulation capabilities of wafer fused VCSELs, the differential gain of the active must be increased and, as shown in [5], higher strain in QWs can lead to higher differential gain. In this paper, the dynamic performances of wafer fused 1310 nm VCSELs with 1.6% QWs strain and optimized output coupling are presented.

2. VCSEL fabrication and characterization

The wafer fused VCSELs [1] comprise an InP based active sandwiched between two undoped GaAs based DBRs. The active region is grown by metalorganic vapor phase epitaxy (MOVPE) and contains several InAlGaAs, compressively strained QWs, 6mm in diameter buried tunnel junction (TJ) for current and optical confinement. The bottom and top DBRs contain 35 and 21 pairs, respectively. Processed VCSELs are top emitting and employ double intracavity contacting. Devices with QWs strain of 1, 1.3 and 1.6% have been fabricated and tested.

Static characteristics were measured at 20 and 70°C. Statistic analysis shows small changes in emission power, threshold current and slope efficiency. Most of devices are SM with side-mode suppression-rate (SMSR) more than 30 dB up to 8-10 mA, corresponding to more than 1.5 mW output power in the temperature range.

Dynamic characteristics were extracted from S21 measurements. From the fitting of S21 curves with the 3-pole transfer function, the resonance frequency fR and the 3dB cutoff frequency [6] have been extracted. Modulation bandwidth at -3dB increases from ~6±7 GHz to ~10 GHz with increasing QW strain from 1% and 1.6%. An important parameter used to estimate the modulation efficiency, the D factor [6], increased with strain from ~2.5±3 to 4 GHz*(mA)^1/2, but more data are needed to establish the statistics of this behavior.

At 1.6% strain, the 3dB modulation bandwidth for the highest QWs strain is close to 10 GHz, which is not sufficient for 25 Gbs operation. In [7] it is shown that by increasing output coupling of the VCSEL, the maximum of the 3dB cutoff frequency increases and moves to higher operation currents. For this, on one piece of double fused structure with 1.6% QWs strain, 3 pairs of the top DBR were removed prior to device processing.

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Figure 1 show light-current (LI) curves for two structures with different output coupling at 20 and 70°C. There are big improvements in power and slope efficiency, with only small increases in threshold current ($I_{th}$) at 20 and 70 °C

![LI curves](image1.png)

Figure 1: LI characteristics of VCSELs with 21 and 18 pairs of the top DBR for 20 °C (left) and 70 °C (right).

The D factor extracted from S21 is practically the same for both values of output coupling and it is close to 4 GHz*(mA)$^{-1/2}$ at 20°C. As shown in figure 2, the 3dB cutoff frequency increases with current up to 5-6 mA and 10 mA for devices with 21 and 18 pairs of top DBR, respectively.

![3dB cutoff curves](image2.png)

Figure 2: 3dB cutoff versus current at 20°C for devices with 21 (left) and 18 pairs (right).

4. Conclusion

We reported on fabrication of wafer fused VCSELs with modulation bandwidth close to 12 GHz by optimizing the output coupling and increasing the strain in the active QWs to 1.6%. Future work includes increasing the number of QWs and reducing the mode volume in order to go beyond 25-30 Gbps data transmission rates.

5. References

Session ID, 2-5: Dynamic characteristics of electrically pumped waveguide-coupled metal-cavity nanoLEDs


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Abstract: Future optical interconnects require ultra-small light sources working efficiently at ultrafast speeds. In this work, we investigate the high-speed dynamic characteristics of electrically pumped metal-cavity semiconductor nano-light-emitting diodes (nanoLEDs). The nano-light sources consist of a metal-cavity nanopillar coupled to a InP-waveguide on a III-V membrane bonded to silicon. We achieve sub-nanosecond electro-optical response showing potential for direct modulation at Gb/s speeds. The results represent a major step forward in providing efficient and ultrafast sources for optical interconnects.

1. Introduction

Reducing the energy consumption and increasing the density of interconnects have been identified as one of the major challenges in the development of future computing and communication systems. The future optical interconnects require light sources with areas below 10−2 m², and working efficiently (10−100 fJ/bit) at 10−100 Gb/s [1]. The first electrically-pumped metallic nanolaser was demonstrated in 2007 [2]. Since then, several groups reported lasing in sub-µm sized metal-cavity light sources. Nevertheless, high losses in metal-based cavities make it challenging to achieve lasing at room temperature and at the same time efficient coupling to a waveguide. Small size light emitting diodes (LEDs), on the other hand, are not limited by low-quality cavities, can operate without threshold, and can emit in a single spatial mode. Recently, approaches using photonic crystal cavities [3], and plasmonics [4] were demonstrated. Although all these efforts, nearly all the nanoLED proposals display negligible output power (pW-level) and ultra-low efficiencies (<10⁻⁷) providing great difficulties in measuring their predicted ultra-high-speed characteristics.

In this work, we investigate the high-speed dynamic characteristics of a new generation of electrically pumped waveguide-coupled metal-cavity nanoLEDs onto silicon operating at telecommunication wavelengths. We demonstrate nanoWatt output power at tens of µA bias levels at room-temperature with potential for direct electrical modulation at Gb/s speeds. The fast and ultra-small light sources reported here offer new perspectives in nano-light sources design strategies for future on-chip integrated nanophotonic circuits.

2. Description of the device

The small light sources consist of a nanopillar metal-dielectric cavity coupled to a InP-waveguide on a III-V membrane bonded to silicon, Fig 1(a), as first reported in [5]. The cavity consists of a semiconductor nanopillar (cross section of 300 nm × 300 nm) with an intrinsic InGaAs layer as active region. The pillar is covered with a SiO₂ layer and then encapsulated with a silver cladding to form a metallo-dielectric cavity which redirects a sizeable fraction of spontaneously emitted photons into a single guided mode (see [5] for more details regarding the device characteristics and fabrication). A representative light-current (L-I) curve of a nanoLED operating at room temperature is shown in Fig. 1(b). The devices provided a typical optical emission with nW output power at tens of µA bias levels, as measured from a grating coupler. When considering the efficiency of the integrated grating coupler and the bidirectional emission into the waveguide, this translates into a quantum efficiency of ~0.01 % for emission in the waveguide. The emission saturates with a current higher than 200 µA due to heating produced by the high resistance (~30 kΩ). The inset of Fig. 1(b) shows the typical electroluminescence spectrum peaked at around 1.525 µm. In what follows, we discuss the electro-optical pulse response of nanoLEDs samples under high-speed electrical modulation.

3. High-speed dynamic results

We employed a time-correlated single-photon counting spectroscopy technique to experimentally investigate the high-speed dynamics of the fabricated waveguide-coupled metal-cavity nanoLEDs. In the experiment, shown schematically in Fig. 2(a), we directly modulate the nanoLED using a pulse pattern generator (Anritsu MP1701A) with a periodic pulse train at repetition rates ranging from 2 Gb/s to 5 Gb/s with pulse widths varying from 250 ps to 100 ps, respectively, while setting a dc bias through a high-frequency bias-T. The electroluminescence was coupled
into a single mode optical fiber using a microscope objective and then guided to a superconducting single photon detector (SSPD). For the time resolved measurements, a histogram of photon arrival times was built by correlating the SSPD output with the pulse pattern generator trigger with a correlation card (Picoharp 300).

Figure 2(b) shows the light output when we modulated the nanoLED using a pulse pattern generator with a periodic pulse train at repetition rates of 2 Gb/s, 3 Gb/s and 5 Gb/s. The results show that the nanoLED replicates well the injected on-off periodic bit sequences. The bit stream has clearly resolvable off-pulses and the on-pulses at 5 GHz are around 100 ps, i.e. with identical pulse width of the injected pulses. Although the results correspond to a statistical measurement employing time-correlated single-photon counting, it show promising performance for further tests in short range telecommunication transmission using high sensitive photodiodes able to detect low-power optical signals.

4. Conclusion

In this work, we have investigated the high-speed dynamic characteristics of waveguide-coupled metal-cavity nanoLEDs employing time-correlated single-photon counting. Operating at room temperature and at ~1.55 µm, we achieved nW output power at tens of µA bias levels and sub-nanosecond electro-optical response showing potential for direct modulation at Gb/s speeds. The results represent a major step forward in achieving efficient and ultrafast nanoLED and nanolaser sources for on-chip optical interconnects.

5. Acknowledgments

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6. References

Session ID, 2-6: Wideband Chaos with Time-Delay Concealment in Three Cascaded Vertical-Cavity Surface-Emitting Lasers

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Abstract: Time-delay (TD) signature and bandwidth of chaos in three cascaded vertical-cavity surface-emitting lasers (VCSELs) have been investigated experimentally. The experimental results show that broad bandwidth with total TD concealment of chaos can be achieved in this configuration. The results agree well with the theoretical predictions.

1. Introduction

Optical chaos has many potential applications, such as chaos-based optical communications, physical random number generators and time domain reflectometry. Semiconductor lasers with optical feedback are most commonly used for generated optical chaos since they are readily available and are easy to operate. For the applications of chaos generated by optical feedback, there are two important parameters – chaos bandwidth and time delay (TD) signature. For chaos applications, a broad bandwidth with no TD signature is desirable. Several papers have considered chaos generation with either bandwidth enhancement or TD signature suppression. Previously, we have reported that both bandwidth enhancement and TD signature suppression can be obtained simultaneously [1], however, the TD signature was not totally concealed. Recent numerical simulations have predicted that by using three cascaded VCSELs wideband chaos together with TD concealment can be achieved [2]. We experimentally examined the bandwidth and TD signature of chaos generated by a system of three cascade VCSELs and the experimental results show that the TD signature significantly reduced. Wideband chaos with total TD concealment can be obtained in the total power of a VCSEL over a wide frequency detuning regime, which is in accordance with the numerical simulations [2].

2. Experimental setup

In the experiment, three commercial VCSELs were used as master laser (ML), intermediate laser (IL) and slave laser (SL). The ML was rendered chaotic by optical feedback when the feedback ratio was about -9.5 dB. The feedback round trip time was about 76.2 ns. The IL was also rendered chaotic at some frequency detuning range when it was subject to optical injection from the chaotic ML. The injection ratio was about -9.0 dB. The SL was subject to optical injection from the chaotic IL and entered chaotic dynamics. The injection ratio was about -4.0 dB. The frequency detuning between the ML and IL (Δf₁) and the frequency detuning between the IL and SL (Δf₂) were tuned by adjusting the temperature of the ML and the SL, respectively. The outputs of the VCSELs were detected by 12 GHz bandwidth photo-detectors and recorded using a 30GHz bandwidth RF spectrum analyzer and 4GHz bandwidth oscilloscope.

3. Experimental results and discussion

The conventional definition of chaos bandwidth is adopted as being the frequency difference between DC and the frequency which contains 80% of the power. The TD signature is quantified by measuring the peak value (C_T) of the autocorrelation coefficient at the feedback round trip time. The bandwidth and C_T of the chaos generated in the ML are about 2.4 GHz and 0.19, respectively. The peak at the feedback round trip time on the autocorrelation coefficient curve can be seen, so the TD signature is identified.

For the chaotic IL, the results are similar to those in [1] - the bandwidth of chaos increases significantly outside zero frequency detuning Δf₁, and the TD signature is greatly suppressed compared to that of the ML.

The bandwidth and TD signature of chaos generated in the SL are investigated. Three cases of chaotic optical injection are studied. In the first case, Δf₁ = -5.0 GHz, the bandwidth and C_T of chaos generated in the IL are about 4.9 GHz and 0.025, respectively. In the second case, Δf₁ = 0.2 GHz, the bandwidth and C_T of chaos in the IL are
about 2.3GHz and 0.03, respectively. In the third case, $\Delta f_1 = 3.3$ GHz, the bandwidth and $C_F$ of the IL chaos are about 3.3 GHz and 0.02, respectively. In all three cases, the TD signature can be seen from the autocorrelation coefficient curve. Fig.1 shows the chaos bandwidth of the SL as a function of the frequency detuning $\Delta f_z$. It is surprising that the chaos of the SL has the same minimum bandwidth of 2.4 GHz at around zero $\Delta f_z$ for all three cases. It is much lower than the bandwidths of the injection beam for cases I and III, where the bandwidths of cases I and III are 4.9 GHz and 3.3 GHz, respectively. The results indicate that the minimum bandwidth is decided by one or more intrinsic parameters of the SL. The relaxation oscillation frequency is one of possible parameters. Outside zero frequency detuning, the bandwidth of chaos increases with the increasing absolute value of the frequency detuning $|\Delta f_z|$ for all three cases. The difference between the three cases is that the bandwidth of chaos increases slightly faster with the increasing $|\Delta f_z|$ for the higher bandwidth of the injection beam.

Fig. 2 shows $C_F$ as a function of the frequency detuning $\Delta f_z$. Fig. 2(a), (b) and (c) are for cases I, II and III, respectively. In the experiment, the time traces of the IL and SL are recorded simultaneously. As expected, Fig.2 shows that TD signature is further suppressed for most of the frequency detuning range in three cases. In particular, for case I, $C_F$ is suppressed to less than 0.015 for wider range of the frequency detuning, where the TD signature has been totally concealed within the noise background. Fig.2 also indicates that the effect of chaotic optical injection on the TD signature suppression varies with different bandwidths of the chaotic injection beam. The higher bandwidth of the chaotic injection beam can suppresses the TD signature more effectively.

![Figure 1: The chaos bandwidth of the SL as a function of the frequency detuning.](image1)

![Figure 2: $C_F$ as a function of the frequency detuning.](image2)

4. Conclusion

We have reported on the bandwidth and time-delay signature of chaos generated in three-cascaded VCSELs. The results shows that the bandwidth of the chaotic injection beam does not have much effect on bandwidth of chaos generated in the SL; however, the higher bandwidth of the injection beam suppresses the TD signature better. A broad bandwidth chaos with complete TD concealment can be obtained in a system using three-cascaded VCSELs.

5. References


Session ID, 2-7: State-dependent delay dynamics in semiconductor lasers

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Abstract: We introduce and implement a semiconductor laser system with two external cavities of different length and disjoint spectral reflection. We demonstrate self-organized dynamical switching between states dominated by the individual cavities. This behavior is characteristic of state-dependent delay systems, a whole class of complex dynamical systems with a variety of applications in science and engineering. Semiconductor lasers can therefore be used as testbed systems to study the properties of such systems, even inspiring novel applications.

1. Introduction

Semiconductor lasers exhibit a characteristic amplitude-phase coupling described via the linewidth enhancement factor, therefore amplitude dynamics induces dynamics of the optical frequency as well. We exploit this relationship to implement experimentally a semiconductor laser system with two external cavities with different delay times, which are active, depending on the dynamical state of the laser. The two external cavities have disjoint frequency responses. In particular, we demonstrate a dynamical regime dominated by state-dependent delay dynamics in which the effective delay is intrinsically determined by the state (optical frequency) of the laser and the latter one depends on the delays active at each time interval [1].

A variety of important technological systems can be described with a state-dependent delay formalism, some examples are internet traffic, space communication, control theory, economics, turning processes, deep drilling, predator-prey systems, and blood-flow. Our implementation enables the use of semiconductor lasers as testbed systems to systematically study this type of dynamics that are relevant for a variety of fields and, at the same time, it might inspire novel applications for state-dependent delay dynamics.

2. Experimental Implementation

Our experimental implementation consists of a discrete-mode quantum-well semiconductor laser emitting at 1543 nm at temperature T=21.00 °C with threshold current Ith=12.00 mA. This laser exhibits single longitudinal-mode behaviour (with and without external optical feedback) with a side-mode suppression ratio larger than 35 dB and a longitudinal mode separation of 150 GHz. The current and temperature of the laser are stabilised to an accuracy of 0.01 mA and 0.01 °C, respectively. We have measured a linewidth enhancement factor ~2 using the Henning–Collins approach.

We have measured the spectral characteristics of our system with a high-resolution optical spectrum analyzer. The laser is subject to filtered optical feedback from two cavities of different length and disjoint spectral reflection ranges. As shown in Figure 1, each feedback cavity contains an independent fibre-loop mirror closed by a fibre Bragg grating (FBG) acting as frequency-selective reflector. The reflection bandwidths are 4.63 GHz for FBG1 and 5.69 GHz for FBG2, respectively. The centre frequencies of FBG1 and FBG2 have been detuned -4 GHz and -11 GHz with respect to the solitary laser frequency.

In order to assure the spectral isolation of the two filters, we have only considered those pump currents where the spectral gap between the two FBGs has an amplitude larger than 10 dB. We have determined in our experimental configuration that below I=1.08 Ith, the optical emission in the two filters can still be regarded as being independent (and with comparable spectral amplitudes and bandwidths in both filters). For currents above this value, this gap gradually disappears and the dynamics resulting from these spectral signatures cannot be considered spectrally separated anymore.

The intensity dynamics at different outputs has been measured with 13 GHz and 20 GHz bandwidths detectors and has been recorded with a 16 GHz analogue bandwidth oscilloscope with a sampling rate of 40 GSamples/s.
3. Experimental Results

The design of our experimental setup allows for simultaneous direct detection of the light emitted from the laser diode and of the light reflected from each individual filter. Figure 2(a-c) shows experimental time traces of the dynamics consisting of alternating periods of emission corresponding to feedback from FBG1 (P1 is active), FBG2 (P2 is active) or none of the filters (off state). The signature of this state-dependent delay dynamics is shown in Fig. 2(d) using the contrast function \( C(t) = (P_1 - P_2) / (P_1 + P_2) \). The contrast function of the 1 GHz low-pass filtered intensity time traces (red dots in Fig. 2(d)) is also shown. From both time traces of the contrast function, the switches between the states can be clearly recognised. In the low-pass filtered contrast function the fluctuations due to the influence of detection noise are eliminated. Those fluctuations do not represent actual switches between states and are mostly removed by the low-pass filtering, giving rise to the much smoother contrast function. Increasing further the injection current results in faster transitions between the different state-dependent delays.

In this system, the state-dependent delay dynamics results from the interplay between the laser bandwidth, the separation between the central frequencies of the filters and the bandwidth of the filters. In order to clearly distinguish the two states, the filter parameters must be chosen to minimize their overlap.

4. Conclusion

A self-organised erratic switching between different delay states has been demonstrated, that might be exploited to envisage novel technical applications. In particular key exchange and encryption systems, that utilise the synchronisation of delay-coupled lasers, could benefit from such switching [2]. Irregular jumps between filters induced by state-dependent delay dynamics could even enhance security without the need of externally controlled switching [3].

5. References


Session ID, 2-8: Experimental characterization of semiconductor laser dynamics by phase-space tomography

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Abstract: We have developed and experimentally implemented a method to simultaneously measure emitted intensity, optical frequency and population inversion of a semiconductor laser with high temporal resolution. Therefore, we can perform phase-space tomography of semiconductor laser dynamics using the relevant physical quantities. To illustrate the power of our approach, we apply this technique to a semiconductor laser with external cavity, exhibiting high-dimensional chaotic emission dynamics. We can identify so far unidentified trajectories in phase-space and identify the underlying physical mechanism.

1. Introduction

The characterization of the dynamical emission of semiconductor lasers is crucial for many of our today's laser applications. Nevertheless, so far, the characterization of the emission dynamics has often been restricted to the detection of the intensity dynamics. This has imposed a major limitation for its full understanding and when comparing to theory. The dynamics of the laser emission is best represented in the phase space, spanned by the laser's dynamical variables. For simple configurations, there may be only a few degrees of freedom, e.g. intensity, carrier density, and optical frequency, spanning the phase-space. If the laser is subjected to delayed feedback from an external cavity, the phase space has an infinite number of dimensions. Still, the projection of the dynamics on the space spanned by the variables intensity, carrier density, and optical frequency allows for an insightful phase-space tomography [1]. Phase-space tomography performed on such an external cavity configuration is presented in the following.

2. Experimental Technique

The experimental setup employed in our experiments is schematically depicted in Fig. 1. An openly mounted, single mode DFB laser diode (λ₀ = 1.543 nm) has been used in our experiments. Its emission is collected by a single mode optical fiber. Using an optical circulator, we form a fiber-based external cavity, representing a delay loop, in which an optical attenuator and polarization controller are used to accurately define the feedback conditions. A fraction of the collected emission is coupled out for detection and amplified by a semiconductor-optical amplifier (SOA).

The three physical phase-space dimensions of the laser are measured as follows. After amplification by the SOA, the optical signal is split, using one port to detect the intensity dynamics, and the other port to detect the optical frequency dynamics based on a heterodyne detection scheme [2]. For that, the laser emission is mixed with a narrow linewidth tunable laser source (TLS) serving as a reference tuned to a frequency of ν₀ + 1.8 GHz. We extract the optical spectrum of the laser using Fourier transformation on a sliding time interval. Both, intensity and heterodyne signals are detected using fast photo detectors with 20 GHz bandwidth. For the measurement of the carrier dynamics, we connect the laser electrically via a bias tee. Its low frequency port (dc–0.2 MHz) is used for biasing the laser. The bias tee's radio-frequency port output (0.2 MHz–12 GHz), corresponding to the dynamics of the forward bias, is electrically amplified and normalized to the dc bias (dV/N₀, V₀ = 0.8 V). For not too far above threshold and small dV, the laser’s junction capacity can be assumed constant, therefore, dV/N₀ ~ dN/N₀. All this information has been recorded simultaneously using a 40 GSamples/s digital real-time oscilloscope with 16 GHz analog bandwidth.

3. Applying Phase-Space Tomography

We illustrate the power of our approach by applying it to the characterization of a semiconductor laser with delayed optical feedback from an external fiber cavity. Although the characteristic feedback-induced phenomenon of Low Frequency Fluctuations (LFF) has been studied for a long time, thanks to this new method, we can gain new insights into the underlying mechanism of the optical feedback-induced dynamics and identify a before-overlooked case, the possible segmentation of the dynamical phenomenon into two or more independently developing segments.
In Fig. 2 we depict a trajectory of the laser dynamics induced by the feedback from the external fiber cavity in the three-dimensional physical phase space defined by intensity, optical frequency and carrier inversion (norm. bias drop). The laser exhibits fragmented intensity pulsations that are the consequence of fast alternations going back and forth between the solitary laser mode (SLM) region and the feedback-shifted high gain region (HGR), exhibiting large scale dynamics in all three dimensions while occupying a large volume of the phase space. The dynamics of this LFF connects the SLM to the HGR as for the usually observed LFF, however, fragmented into sections.

4. Conclusion

In conclusion, we demonstrate the simultaneous, temporally high-resolved, characterization of the three physical phase-space variables intensity, optical frequency, and carrier inversion of a semiconductor laser. This represents physically meaningful phase-space tomography of semiconductor laser dynamics that can be applied in many situations. To illustrate the far-reaching capabilities of this method, we identify a so far unreported modification to optical feedback-induced trajectories in the LFF regime.

Moreover, our approach facilitates a better characterization of semiconductor laser dynamics in general, and direct comparisons with theory, thereby allowing for optimization of semiconductor lasers and their operation in telecommunications and other applications.

5. References


Session ID, 2-9: Experimental and theoretical study of polarization switching in 1550 nm VCSELs subject to parallel optical injection

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Abstract: Polarization switching in a long-wavelength VCSEL under parallel optical injection is analyzed in a theoretical and experimental way. We find a novel situation in which injection locking of the parallel polarization and excitation of the free-running orthogonal polarization of the VCSEL are simultaneously obtained.

1. Introduction

Polarization switching (PS) and the underlying physical mechanisms in vertical-cavity surface-emitting lasers (VCSELs) subject to optical injection have attracted considerable attention in recent years [1-2]. PS in VCSELs has been usually obtained for the case of orthogonal optical injection: linearly polarized light from an external laser is injected orthogonally to the linear polarization of the solitary VCSEL. Just a few experimental works have shown that PS can also be obtained for parallel optical injection, that is, the directions of linear polarization of the injected light and the free-running VCSEL are parallel [1],[3].

In this work we obtain, experimentally and theoretically, PS in a single mode VCSEL subject to parallel optical injection around the frequency of the parallel polarization mode of the free running VCSEL. Our injection locking (IL) and PS characteristics are different to those previously found [1],[3]. We obtain a novel dynamical situation in which injection locked emission in the parallel polarization and excitation of the free-running orthogonal polarization of the VCSEL occur simultaneously.

2. Results

The parallel optical injection is achieved using an all-fiber experimental setup similar to that shown in [4] modified to consider a single optical injection. The light from a tunable laser (TL) (master laser) is injected into a commercial 1550-nm VCSEL (RayCan) via a three-port optical circulator. The first polarization controller (PC1) is adjusted to assure the parallel optical injection configuration. A second polarization controller is connected to a polarization beam splitter (PBS) to select the parallel and the orthogonal polarizations, which are analyzed by the power meters (PM) or the high-resolution optical spectrum analyzer (BOSA).

Our VCSEL operates in a single transverse mode regime with a threshold current of 1.66 mA at 298 K. The temperature and the bias current of the VCSEL are held constant at 298K and 3.043 mA, respectively. The free-running VCSEL emits in a linear polarization that we call the “parallel” polarization at the wavelength \( \lambda_p = 1540.88 \) nm. The orthogonal polarization (>30 dB weaker than the parallel polarization) is shifted by 0.23 nm towards the short wavelength side (\( \lambda_s = 1540.65 \) nm): the birefringence of the VCSEL is then 28.75 GHz. We characterize the optical injection by its strength given by the value of the power measured in the port 2 of the optical circulator, \( P_{in} \) and by the frequency detuning defined as \( \Delta \nu = \nu_{in} - \nu \), where \( \nu_{in} \) and \( \nu \) are the frequencies of the optical injection and the parallel polarization of the free-running VCSEL, respectively.

Figure 1 shows the experimental optical spectra of both linear polarization modes as the frequency of the master laser is decreased for a fixed value of the injected power, \( P_{in}=65,30 \) mW. The zero value of the frequency in the optical spectra has been chosen to correspond to the parallel polarization of the free-running VCSEL. The observed signal is the coherent addition of the VCSEL emission and the reflection of the optical injection from the front surface of the VCSEL. Fig. 1 (a) shows a time-periodic dynamics in the parallel polarization. As we decrease \( \Delta \nu \) we obtain injection locking in the parallel polarization as it is shown in Fig. 1(b): only one peak at the frequency of the injection appears in the optical spectrum. This regime is found from \( \Delta \nu = 0.86 \) GHz to \( \Delta \nu = 3.38 \) GHz. However, this situation changes from \( \Delta \nu = -3.38 \) GHz to \( \Delta \nu = -4.88 \) GHz where PS happens whilst the parallel polarization is still locked to the optical injection, as it is shown in Fig. 1(c) for \( \Delta \nu = -4.74 \) GHz. In [3] PS was also obtained for negative \( \Delta \nu \) but the orthogonal spectrum was locked to the injection. In [2] PS close to the parallel polarization of the free-running VCSEL was obtained for positive \( \Delta \nu \). If we decrease more the frequency of the
master laser for $\Delta \nu < -4.88$ GHz, the injection locking regime in the parallel polarization disappears (seen by the small black peak at the frequency of the free-running parallel polarization mode) while the orthogonal polarization mode remains excited, as it is shown in Fig. 1(d) for $\Delta \nu = -5.88$ GHz. The orthogonal polarization remains excited from $\Delta \nu = -3.38$ GHz to $\Delta \nu = -6.025$ GHz.

Fig. 2 shows the theoretical optical spectra corresponding to the situations described in Fig. 1. We have obtained our results by using the model and parameters in [4] modified to consider a single parallel optical injection, and different values of the linear dichroism ($g_0 = -0.3$ ns$^{-1}$) and of the optical injection strength ($E_{inj}=0.36$). Also a bias current of 3 mA and very small values of the intrinsic noise strengths in both master and slave lasers have been considered.

Good agreement is obtained between our theoretical and experimental results. In particular, Fig. 2(c) shows locking of the parallel polarization mode to the optical injection and excitation of the free-running orthogonal polarization mode of the VCSEL, similarly to Fig. 1(c). Our model also includes the effect of the reflected light at the VCSEL mirror. In this way the spectrum of this reflected light, that is the spectrum obtained when the VCSEL is off, is also shown in Fig. 2 with a green dashed line. Comparison between spectra of the parallel polarization and the reflected spectra shows that there is a significant VCSEL emission in the parallel polarization at the frequency of the optical injection.

3. Conclusion

In conclusion, we have investigated theoretically and experimentally the injection locking regime and the polarization switching in a single mode VCSEL under parallel optical injection when we inject around the frequency of the parallel polarization mode of the free-running VCSEL. We have found that simultaneous injection locking of the parallel polarization mode and excitation of the free-running orthogonal polarization mode of the VCSEL can be obtained.

5. References

Spatially extended nonlinear systems often admit multiple coexisting stable states, and fronts connecting them are fundamental in the understanding of pattern formation. We are investigating the pinning of domain walls in a space-like dynamical system with delay with a view on using robust localized structures as bits in information storage and processing applications. However, in the simplest case of a symmetric bistable system with a single dynamical variable $\psi$, the stable coexistence between two phases is merely achieved for a single value of the parameters, the so-called Maxwell point. Such a regime possesses little experimental significance since any deviation of the control parameter or any symmetry breaking effect implies that one of the two bistable phases will eventually invade the other in a way reminiscent of nucleation bubbles in first order phase transitions. As such, the dynamics of the fronts separating the two phases and how they interact is of paramount importance. It is known that there exist strong analogies between spatially extended and delayed dynamical systems [1] and it was recently shown [2] that the same phenomenon of phase coarsening occurs in delayed bistables. Recently, additional attempts [3] were performed in order to try and pin the domain walls via an external temporal modulation.

We are looking instead at stabilization via the intrinsic antiperiodic output in a delayed system. Indeed, it is maybe less known that delayed systems can generate antiperiodic output, i.e. temporal traces that get inverted after each time delay $\tau$, thereby inducing an effective periodicity $2\tau$. We demonstrate in this contribution how such an effect can be exploited in order to create motionless domain walls and prevent the coarsening phenomenon. We evidence experimentally and theoretically stable domains for a wide parameter range, that are insensitive to symmetry breaking effects. They exist even beyond the bistable regime and allow the writing and storing of information. We describe in Fig. 1 the experiment: a 1310nm Fabry-Perot Laser operated below threshold is simultaneously subjected to external injection and optical feedback after a round-trip time $\tau$. The full system is set close yet out of the bistable regime. We show in Fig. 2a) an experimental trace getting inverted at each round-trip. Figures 2b) and 2c) plot the space time diagrams with folding parameters equal to $\tau$ and $2\tau$. Noteworthy, one observes the nucleation of a pair of domain wall after having perturbed the system. Our results are well explained by rate equations with optical feedback but also by the modified normal form of the imperfect pitchfork bifurcation. In summary, we presented a first investigation of stable fronts in an injected semiconductor laser opening new possibilities for inexpensive information storage.

Session ID, 2-11: Control of Rogue Waves in Optically Injected Semiconductor Lasers

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Semiconductor lasers with cw optical injection display a rich variety of behaviors, including stable locking, periodic or chaotic oscillations, excitable pulses, etc. Within the chaotic parameter region it has been shown that the laser intensity can display extreme pulses (i.e., pulses which belong to the tail of a 1-shaped distribution of pulse heights), which were identified as deterministic optical rogue waves (RWs) [1].

Simulations of a simple rate-equation model have shown that the extreme pulses [Fig. 1(a)] can be completely suppressed via direct modulation of the laser pump current [2]. This occurs when the modulation frequency is close to the laser relaxation oscillation frequency, \( f_{\text{mod}} \) [Fig. 1(b)].

Here we show that, when RWs are not suppressed by current modulation, their likelihood of occurrence is controlled by the phase of the modulation. If the modulation is slow [\( f_{\text{mod}} \ll f_{\text{res}} \), Fig. 1(c)] the RWs occur within a well-defined interval of values of the modulation phase, i.e., there is a “safe” window of phases where no RWs occur. The most extreme RWs occur for modulation phases that are at the boundary of the safe window [Fig. 1(d)]. In contrast, when the modulation is fast [\( f_{\text{mod}} > f_{\text{res}} \), Fig. 1(e)], there is no safe phase window; however, the RWs are likely to occur at particular values of the modulation phase. Regardless of the modulation frequency, the waiting times between consecutive RWs are exponentially distributed [Fig. 1(f)].

![Figure 1](image-url)

**Fig. 1** (a) Simulated laser output vs. time when the modulation amplitude is 20% and the modulation frequency is 2.5 GHz. As in [2], a pulse is considered a RW if its height is higher than a threshold, \( I_{\text{th}} = 3I_\text{ave} + I_{\text{ave}} \), where \( I_\text{ave} \) is the mean pulse height and \( \sigma_\text{I} \) is the standard deviation of the distribution of pulse heights. The laser parameters are such that the intensity displays deterministic RWs in the absence of noise and modulation (\( I_0 = 2.4 \), \( \Delta \nu = 0.22 \) GHz, other parameters as in [2]; for these parameters the relaxation oscillation frequency is \( f_{\text{res}} = 4.5 \) GHz). (b) Number of RWs vs. the modulation frequency, \( f_{\text{mod}} \), and the normalized modulation amplitude, \( \mu_{\text{mod}} / \mu_0 \). The color code is plotted in logarithmic scale in order to increase the contrast of the parameter regions with a small number of RWs. In the white region (\( f_{\text{mod}} \) close to \( f_{\text{res}} \)) no RWs are detected. (c) Number of detected RWs and (d) mean RW height as a function of the phase of the modulation, \( \Phi \), when \( f_{\text{mod}} = 3.5 \) GHz. The error bars in (d) indicate the standard deviation of the distribution of RW heights. Note that RWs mainly occur during the first 3/4 of the modulation period; during the last 1/4 of the period, RWs are very unlikely to occur. (e) As panel (b) but when \( f_{\text{mod}} = 5 \) GHz. It can be observed that the RWs likely occur at specific values of the modulation phase. (f) Distribution of intervals between consecutive RWs. These results can be relevant for the study of RWs in other optical systems, where a similar response to external periodic forcing could be observed. It would be very interesting to investigate experimentally the transition from very slow modulation (when the variation of the laser current is adiabatic and the modulation phase plays no role), to fast modulation. We expect that, when the phase of the modulation starts affecting the RW probability, the shape of the distribution of the number of RWs will become asymmetric under the transformation \( \Phi \rightarrow \Phi - \pi \) (that leaves the value of the pump current unchanged). This hypothesis could be tested experimentally.

Session ID, 2-12: Deterministic optical rogue waves in a laser diode with time- delayed feedback

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Abstract: We experimentally observe extreme events in a configuration that combine optical nonlinearity with optical feedback. Indeed, the chaotic pulsing output of a laser diode with a phase-conjugate feedback shows high-intensity pulses that have the characteristics of extreme events or rogue waves. Increasing the feedback strength leads to a large number of such rogue waves with smaller replica at the periodicity of the external-cavity time-delay. To explain this experimental behaviour we demonstrate that a rate equation model of a laser diode that includes an instantaneous phase-conjugate feedback field reproduces qualitatively well the statistical features of these extreme events.

1. Introduction

Extreme events are single events of very high amplitude that can appear in a signal on a rare basis, thus breaking its otherwise smooth or regular evolution. Historically, the first extreme events were spotted in the ocean by sailors and were then described as huge lone (rogue) waves arising very high above the calm average water level without warning. Besides their first report in microstructured optical fibers showing supercontinuum emission [1], extreme events in optics have been shown in mode-locked lasers [2] and laser diodes with optical injection [3]. We report here on extreme events but in a nonlinear optical system driven by external feedback.

2. Results

We consider an experimental set-up where a laser diode is subject to external optical feedback from a phase-conjugate mirror. Depending on the feedback parameters (feedback strength, external-cavity length), the laser shows a rich and complex dynamics including chaos. Figure 1 shows an example of chaotic pulsing output where we identify high-intensity pulses well above the average signal level [4]. These events share similar characteristics to the rogue waves: 1) their intensity crosses the threshold for abnormal waves (abnormality index (AI) >2) (Fig. 1, left), 2) their occurrence leads to a significant deviation of the intensity statistics from a Gaussian distribution (Fig. 1, right); 3) the time between the extreme events is large in comparison with the system time-scales (so they are rare) and follows a log-Poisson distribution. These extreme events are driven by optical feedback in that the number of extreme events and therefore the deviation from a Gaussian distribution increases with the increase of the feedback strength (Fig. 1, right).

![Fig. 1. Extreme events in the temporal chaotic dynamics of a laser diode with phase-conjugate optical feedback. Left: high-intensity pulse crossing the threshold for abnormal waves (AI=2). Right: statistical distribution of the output power for increasing reflectivity R of the phase-conjugate mirror.](image)

To explain these experimental observations, we use a rate-equation model, inspired by Lang and Kobayashi equations [5] and adapted to the case of PCF [6] and we show that this model is able to reproduce the dynamical
features observed in the experiment [4]. Of particular interest is the influence of the delay and the feedback rate (a measure of the quantity of light that is fed back in the laser) on the number and statistics of time separating extreme events. Not only are the theoretical results in good qualitative agreement with the experimental observations, but they also allow to bring insight into the physics underlying the emergence of extreme events [7].

3. Conclusion

We reported on extreme events in an optical system with time-delay induced chaotic dynamics. The increased feedback strength yields an increased number of extreme events that fulfil the criterion relative to the AI, and exhibit statistics that show the typical long-tailed distribution. By contrast to other reported cases of extreme events, an extreme event pulse is anticipated and followed by pulses with delay periodicity that may exhibit extreme event properties when varying the feedback strength. The impacts of noise on the number of events and the statistics of the waiting times have been addressed by simulations of a rate equation model. These simulations performed for a laser diode with PCF reproduce qualitatively well the experimental observations of extreme event statistics, analogous to rogue waves.

4. Acknowledgements
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5. References
Session ID, 2-13: Photonic integrated circuits for low-noise microwave generation

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Abstract: Photonic integrated circuits have reached a level of maturity where they have now become an integral part of telecom and datacom networks. However, their performance is relatively low, compared to fiber-optics and discrete bulk optics counterparts, which is prohibitive for more widespread use. The invention of the ultra-low loss waveguide platform, with losses of < 0.1 dB/m, heralds a new range of applications for photonic integrated circuits. By combining this with silicon and/or indium phosphide photonics, improved performance can be achieved. I will discuss the opportunities that this technology offers for low-noise lasers and oscillators.

1. Introduction

The complexity of photonic integrated circuits (PICs) has increased exponentially over the last 25 years. With indium phosphide (InP) based technology still driving the roadmap for telecommunications, silicon photonics is rapidly catching up. Combining the active functionalities of InP-based photonics with the fabrication maturity of silicon photonics, the hybrid silicon photonics platform is the newest kid on the block [1]. The complexity of hybrid silicon PICs has grown to over 100 components per chip [2].

Despite the impressive advances in the field, PIC technology has only fulfilled a small part of the huge potential and quite often at a far slower pace than expected. In scientific literature a large range of possible applications can be found, ranging from spectroscopy, metrology, sensing and imaging, to applications in the field of microwave photonics. The reality is, however, that commercial applications and realistic prototypes are almost exclusively found in the fields of telecommunications and data communications.

In this paper I will argue that this is about to change. A recent key development is the invention of the ultra-low loss waveguide (ULLW) platform [3,4], and the possibilities to integrate these waveguides with active photonic components. This development opens up the field for PIC-based low-noise microwave generation, with in principle improved performance over current state of the art technologies.

2. Ultra-low loss waveguide technology and its integration with active photonics

The use of thin silicon nitride waveguides, as shown in Figure 1, has decreased the state of the art in waveguide losses significantly, by an order of magnitude [4]. Loss values below 0.1 dB/m have been reported [3], which is a world-record for integrated waveguides. The thin core, with typical dimensions of a few micrometer width and 40 – 100 nm height, has a small overlap with the optical mode, which reduces sidewall scattering and minimizes material loss [3].

ULLW technology can be combined with silicon, InP, or hybrid silicon PIC technology, using hybrid or heterogeneous integration. Hybrid integration refers to the combination of two (or more) processed chips or dies in a package, e.g., by butt-coupling of the facets [5]. The advantage of this approach is that the separate dies can be fabricated using the standard processes. The disadvantage, on the other hand, is that expensive and complex packaging is required. Especially the alignment of optical waveguides has a low tolerance, which requires accurate tools.

The alternative is to use heterogeneous integration, where the combination of technologies is achieved within the process flow. This reduces packaging cost, but at the expense of increasing the complexity of the process flow. The only known approach to combine ULLWs with (hybrid) silicon photonics, while preserving the low-loss performance, is to first fabricate and anneal the ULLWs and then, by means of wafer bonding, add the silicon photonic layer [6,7].

3. Opportunities for high-performance microwave photonic applications

The losses of 0.1 dB/m show for the first time the feasibility of some long-discussed applications. Microwave filters are typically made using waveguide, YIG or IC technology. Figure 2(a) shows the clear trade-off between
tuning range and filter bandwidth. Enabled by Q-factors close to 100M [8], PIC based filters can achieve in principle bandwidths down to around 1 MHz, while keeping the tuning range well into the 1 – 10 GHz range. The potential performance improvement is over an order of magnitude.

The high Q of ULLWs enables low-noise continuous-wave and mode-locked lasers. The analysis in [4] shows that mode-locked lasers with timing jitter values of 2 fs at 20 GHz (10 kHz – 10 MHz integration range) can be realized in theory. This is about three orders of magnitude lower than state of the art monolithic mode -locked laser diodes [9]. Such pulsed lasers can enable microwave oscillators. In Figure 2 (b) this performance is compared to a discrete-optics based oscillator [10], and to a state-of-the-art crystal oscillator.

Although the clear potential from a physical point of view is shown, the still remaining challenge is to design the PICs on the circuit level. A low-noise microwave generator is radically different from a monolithic passively mode-locked laser diode. The full integration of an oscillator will require multiple electro-optic stabilization and control loops. A clear awareness is required of the, sometimes fundamental, trade-offs, for example, between power and signal-to-noise-ratio on the one hand and nonlinearities in, e.g., photodetectors and waveguides on the other hand. To achieve this is a clear scientific and engineering challenge, but at least one with a potentially large reward.

![Figure 1](image1.png)

Figure 1 (a) Schematic and (b) scanning electron microscope picture of the ULLW cross-section. (c) Overview of planar waveguide propagation loss as a function of bend radius. Data are shown for wavelengths in the 1.3 – 1.6 μm range [4].

![Figure 2](image2.png)

Figure 2 Projected PIC performance, enabled by the ULLW technology for (a) microwave filters, with reference data taken from commercially available filters, and (b) oscillators, with reference data taken from [9,10].

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Session ID, 2-14: Optical Frequency Comb Generator based on a Monolithically Integrated Ring Laser

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Abstract: We report the demonstration of an optical-frequency comb generator based on a monolithically integrated ring laser. We have designed a device fabricated in a Multi-Project Wafer (MPW) run in an active/passive integration process from a generic building blocks. Chip fabrication has been carried out on the JePPiX technology platform, within the InP technology MPW run. A passive modelocked ring laser architecture is chosen, due to its ease of integration with other components to achieve photonic integrated circuits (PICs). The -10 dB span of the optical comb obtained is 8.75 nm (1.09 THz) with lines spaced by 10.1 GHz.

1. Introduction

Optical frequency comb generator (OFCG) has many applications including, among others, sources for dense wavelength multiplexing division transmitters to exploit the high bandwidth of single mode optical fiber [1,2]. Another utilization is the direct injection of an optical frequency comb signal to two monolithically laser diodes to generate the phase-stabilized carrier signal for the real-time error-free coherent wireless transmission link [3]

Some key requirements for a comb generator are a good spectral flatness, an equal frequency spacing, spectra width and a narrow linewidth for each comb-lines, to use in coherent systems. [4]

One type of optical comb aims to produce multiple optical lines with the frequency intervals defined by an external synthesizer. In this case, comb generation is achieved by successive phase modulation of the external laser reference line in an amplified recirculating loop. This modulation frequency is important as it determines the resulting optical comb spacing. The loop configuration is chosen for its proven performances in term of flat comb generation as demonstrated by published fiber ring implementations [5].

Also, it is possible to generate a flat top optical comb using a Mach Zehnder modulator [6]. In [7] it was proposed an InP based comb generator for optical OFDM transmission using a Mach Zehnder interferometer inside an amplified ring. But they demonstrate only 6-line frequency comb. In [8] it was obtained a 2.06 THz broadband comb that it had 70 lasing lines and was generated using a hybrid modelocked laser with gain flattening filter, but it was not completely flat.

Another type of optical comb is when using modelocked ring lasers that are integrated on a single chip. In [9] it was presented an optical coherent comb centered around 1542 nm with a 3 dB bandwidth of 11.5 nm.

2. Device

We have designed a device fabricated in a Multi-Project Wafer run in an active/passive integration process from a generic building blocks, including semiconductor optical amplifier (SOA), Saturable absorber (SA), passive waveguides (PWs), multimode interference (MMI) and phase modulators (EOMs). Chip fabrication has been carried out on the JePPiX technology platform, within the InP technology multi-project wafer run. A modelocked ring laser architecture is chosen, due to its ease of integration with other components to achieve photonic integrated circuits (PICs). So there is no need of facet mirrors.

The block diagram and photograph of photonic integrated circuit is presented in figure 1. The fully fabricated device has a round-trip cavity length of 8062 μm, corresponding to a frequency spacing of 10 GHz. The Mach Zehnder Interferometer (MZI) uses two 1000 μm phase modulator (EOM) to generate the frequency comb, one in each arm. Also, it uses two 370 μm semiconductor optical amplifier (SOA) with intermediate 20 μm saturable absorber (SA).

3. Measurements

To make the optical frequency comb the two semiconductor optical amplifier (SOAs) are biased at 62 mA drive current each one, -2.0 V bias on the saturable absorber; the phase modulators are biased at \( V_{\text{bias}} = -1.3 \) V. The average output optical power is 2 mW. The -10 dB span of the comb is 8.75 nm (1.09 THz) with lines spaced by 10.1 GHz as determined by the cavity length. The optical spectrum of the comb is shown in figure 1c.

The RF spectrum was recorded with an electrical spectrum analyzer (ANRITSU MS2668C) and it is shown in figure 2a) where the fundamental frequency is 40.86 dB over the noise floor. The fundamental frequency is found at 10.16 GHz which corresponds with the frequency spacing determined by the cavity length.

An autocorrelation trace of a picosecond pulse generated at 10.1 GHz are shown in figure 2b). Picosecond pulses with a pulse width of 21.2 ps (assuming a hyperbolic sech waveform) were obtained. Here we have employed an erbium doped fiber amplifier (EDFA, Nortel telecom FA14UFAC) to amplify the output signal prior to autocorrelation. The dotted curve is the experimental trace, and the solid curve is the theoretical fit. The FWHM of the intensity autocorrelation is 32.8 ps, which corresponds to a pulse width of 21.2 ps, in agreement with the theory.
4. Conclusion

In conclusion, we have demonstrated an optical frequency comb generator using an integrated ring laser with Mach-Zehnder Interferometer, fabricated in a Multi-Project Wafer run. 10.1 GHz spaced lines over a spectral width of 8.75 nm (at -10 dB) were achieved, at output optical power of 2 mW. It is not necessary to use a RF signal or an external laser to generate the comb. The device exhibits a remarkable flatness, a RF linewidth of 15.41 KHz and picosecond pulses with a pulse width of 21.2 ps (assuming a hyperbolic sech waveform). The spectral flatness it is important to have optical sources in DWDM systems.

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5. References


Session ID, 2-15: Widely Tunable MIR Sources

G. Maisons

MirSense, France

NO RECEIVED
Session ID, 2-16: Electrically pumped mid-infrared VCSELs using type-II quantum wells

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Abstract: We present concepts for InP- and GaSb-based buried tunnel junction vertical-cavity-surface-emitting lasers (VCSEL), using type-II quantum wells, for the spectroscopically interesting wavelength range above 2.5 µm. We recently demonstrated an InP-based VCSEL, operating in continuous-wave mode up to 10°C with an emission wavelength of 2.5 µm. Here we present the feasibility of extending this successful VCSEL concept to GaSb-based devices using type-II quantum wells for emission beyond 3.5 µm. A detailed analysis of the proposed active region using edge emitting lasers is presented followed by a design proposal for a VCSEL.

1. Introduction:

Tunable diode laser spectroscopy (TDLAS) is a highly sensitive optical gas sensing scheme [1], which exploits the property of gases to have a unique absorption spectrum. Various gases such as CO₂, SO₂, hydrocarbons etc. have distinct absorptions lines in the mid-infrared (mid-IR) spectral region between 2-6 µm. The need to make such sensors compact, portable and cheap, has increased the demand for highly efficient and electrically pumped semiconductor light sources such as VCSELs. The longest emission wavelength for an electrically-pumped InP-based VCSEL using type-I QWs is 2.36 µm [2], limited by material constraints. Longer emission wavelength was reported for a GaSb-based VCSEL at 2.63 µm [3]. However, a drastic increase in the emission wavelength using type-I QWs is very unlikely using any material system. Further extension of the wavelength is possible using type-II QWs as already demonstrated in edge-emitting lasers [4] and recently in an InP-based VCSEL [5]. Here we present two concepts for VCSELs using type-II QWs: an InP-based VCSEL emitting at ~2.5 µm and a GaSb-based VCSEL for emission above 3 µm.

2. InP-based type-II VCSEL:

Type-II quantum well lasers are an innovative concept to extend the wavelength range of InP-based lasers. In these lasers, the type-II band alignment between GaInAs and GaAsSb is used to spatially separate the electrons and holes to achieve emission below the bandgap energies of the constituent materials [5]. The presented VCSEL has 8 W-shaped type-II QWs, each with two GaInAs QWs confining electrons, surrounding a GaAsSb layer confining holes. The bottom epitaxial Distributed Bragg Reflector (DBR) is made of 45 pairs of undoped GaInAs/InP, resulting in a reflectivity of 99.9%. A lateral current injection scheme was chosen using a highly n-doped GaInAs contact layer placed in a node in the 3A cavity to minimize losses. The top dielectric DBR is formed by 6 pairs of evaporated AlF₃ and ZnS, with a reflectivity of 99.8%. Current confinement is achieved by a buried tunnel junction [6].

Figure 1 shows the optical output power versus current for a VCSEL with BTJ diameter of 9 µm at different heat sink temperatures. It works up to 10°C in continuous-wave (cw) mode and the maximum output power for this device is 300 µW at -18°C. Higher powers are expected at lower temperatures, but the setup is limited to -18°C. Further
improvement is expected from optimization of temperature stability of the active region (AR), mode gain offset and better thermal management.

3. GaSb-based type-II VCSEL:
The type-II broken-gap band alignment between InAs and GaInSb is ideal to form type-II W-shaped QWs in GaSb-based lasers, as successfully demonstrated in interband cascade lasers (ICL) [4]. However, cascading in VCSELs has not proved to be beneficial due to current spreading effects. Here we report a detailed study of a non-cascaded active region consisting of type-II QWs to be implemented in GaSb-based VCSELs for emission beyond 3.5 μm. The presented AR emitting at 3.94 μm was studied using edge-emitting lasers. The extrapolated pulsed threshold current density at infinite length for a 5 QW device at 15°C is 1.4 kA/cm² corresponding to 280 A/cm² per QW. This is the lowest threshold current reported for a single stage device at this wavelength. These edge-emitters operated in pulsed mode up to 65°C, limited by the setup. The T₀ is 40 K, which is comparable to the ICLs at this wavelength range [4].

A low-loss VCSEL design for emission beyond 3.5 μm was made and optimized using the active region characterization data. Figure 2 shows the variation in modal gain in the VCSEL with increasing current for 8 QWs. The performance of the designed VCSEL was simulated using the AR characterization data, giving an estimated threshold gain at 15°C of 5.8 cm⁻¹, which corresponds to a threshold current density of 3.2 kA/cm².

4. Conclusion:
Concepts for extension of the emission wavelengths of InP- and GaSb-based VCSELs using type-II QWs have been presented. A first demonstration of the InP-based VCSEL showed an extension of the emission wavelength to 2.49 μm which is impossible using type-I QWs on InP. It works up to 10°C in cw operation and there is a lot of scope for improvement with further optimization. For GaSb-based devices, an active region for emission beyond 3.5 μm was developed and characterized using edge-emitting lasers. A low-loss GaSb-based VCSEL was designed using the presented active region and the estimation of its performance is very promising for mid-IR emission.

5. References:
Session ID, 2-17: Widely tunable laser source operating at 2μm realized as monolithic InP photonic integrated circuit

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Abstract: A tunable laser operating from 2011 – 2042 nm realized as a monolithic InP photonic integrated circuit and fabricated within a multi project wafer run is presented. The laser is tuned using an intracavity filter based on nested asymmetric Mach-Zehnder interferometers with electro-refractive modulators. The device is intended for a single line gas spectroscopy and was designed and realized using a generic integration technology.

1. Introduction

The generic photonic integration technology platforms [1] provide application oriented specialists with means of design and fabrication of application specific photonic integrated circuits (ASPIc) at relatively low cost. The main factor defining the scope of potential applications results from the range of accessible wavelengths. For most of the platforms these are guaranteed at the wavelengths covering the telecom C-band around 1.55μm. Should other wavelength bands become available by such integration technology, it would become attractive for a wider field of applications. In particular the area of gas spectroscopy would benefit if the mid-infrared wavelengths at around 2μm become accessible due to the presence of stronger absorption profiles of several gas species. It has been demonstrated that such wavelengths can be generated and amplified using InP based strained quantum well [2]. A development towards implementation of such functionality using strained quantum wells into the COBRA active – passive integration technology platform was undertaken [3].

A tunable laser realized on a monolithic, indium phosphide (InP) photonic integrated circuit (PIC) operating at wavelengths range around 2027 nm is presented. For the wavelength tuning an intra-cavity filter based on nested asymmetric Mach-Zehnder interferometers (AMZI) with electro-refractive modulators (ERM) is implemented [4,5]. This enables a single mode operation of the laser and in combination with the gain bandwidth of the strained quantum well based layer-stack [3] provides a record tuning range of 31 nm.

2. Monolithic photonic integrated circuit

The ring laser cavity has an average physical length of 9 mm and its topology is shown in Figure 1(a). The cavity consists of several basic building blocks connected with deeply etched passive waveguides. The optical gain is provided by a 4 mm long semiconductor optical amplifier (SOA). The wavelength tunable filter inside the laser cavity is a nested configuration of asymmetric Mach-Zehnder interferometers (AMZI). The AMZI stages are formed by passive waveguides and multimode interference couplers (2x2, 1x2, MMI) with 2 mm long ERM sections added in each branch in order to enable its tuning. Two inner AMZI stages of the filter have photodiodes (PD) added on both sides of each stage for on-chip monitoring and calibration functionalities. The ring cavity is closed with passive waveguides and the signals are coupled out from the laser cavity with two 1x2 MMI elements. The light is routed to the output ports which are angled with respect to the cleaved edges of the chip to reduce reflections. The resulting mask layout for one device occupies an area of 3.4 mm2 as is shown in Figure 1(b). The chip was designed following the generic integration approach using the COBRA long wavelength extension of COBRA active-passive technology [1] and the laser cavity is defined using a predefined set of basic building blocks (BB) [1, 4]. The chip was fabricated within a multi-project wafer (MPW) run using NanoLab@TU/e cleanroom services [6] using a long wavelength generic integration technology developed at the COBRA research institute.
3. Experimental results

The fabricated chip is mounted on an aluminum block and all electrical contacts are wire bonded to a signal distribution printed circuit board (PCB). The sub-mount is temperature stabilized with a passive water cooling system at 18°C. Optical signals are collected with an antireflection coated lensed fiber and fed with a standard single mode fiber and via an optical isolator to the measurement equipment. An extended InGaAs amplified photodiode was used to record the total optical output power coupled into the fiber as a function of bias current injected into the SOA section. The LI characteristic shows the lasing threshold point to be at 350 mA (3.34 kA/cm²). A Yokogawa AQ6375 optical spectrum analyzer with a 0.05 nm resolution was used to record the optical spectra for different sets of reverse bias voltages applied to the ERM sections with the SOA current and temperature being constant at $I_{SOA} = 500$ mA and $T = 18$°C respectively, which are presented in Figure 2. The laser provides single-mode output (side mode suppression ratio of more than 30dB) with the wavelengths range centered at around 2027 nm and spanning over 31 nm.

4. Conclusion

A fully functional photonic integrated circuit realized using monolithic active-passive integration technology at wavelengths around 2μm has been presented. The laser provides a single longitudinal mode output at wavelengths around 2027 nm and with a record tuning range.

5. References


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**Figure 1**: (a) Schematic diagram of the photonic integrated circuit based tunable ring laser featuring an intracavity tunable wavelength filter based on nested asymmetric Mach-Zehnder interferometers indicated with a dashed box. (b) Mask layout of the laser cavity with area of 3.4 mm².

**Figure 2**: Optical spectra recorded for different sets of reverse biases applied to the ERMs. Both the injection current into the SOA section and temperature were kept constant at $I_{SOA} = 500$ mA and $T = 18$°C respectively.
Poster ID, 1: Analysis of the effects of periodic forcing in the Spike Rate and Spike Correlation's in Semiconductor Lasers with Optical Feedback

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Abstract: Semiconductor lasers with optical feedback are excitable devices when operate in low frequency fluctuations regime[1]. We investigate how the dynamic of a laser process weak forcing through a direct modulation of the pump current. We used the ordinal symbolic analysis[2] to study how the time correlations (between several consecutive laser spikes) change with the spike rate. Our results show that higher spike rates wash-out the effects of the modulation in time correlations [3]. The variation of the probabilities of the symbols with the modulation frequency allows to identify different noisy phase locking regimes[4]. Simulations using the Lang-Kobayashi model have good qualitative agreement with experimental observations.

References


Poster ID, 2: Towards high indium content nitride laser diodes

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Abstract:

In the present work we discuss different approaches to obtain long wavelength (>450 nm) InGaN based laser diodes. We show a number of strategies used to mitigate the material and design issues related to such structures. In particular we focus on: the reduction of internal electric field via the use of non polar growth planes or/and by application of staggered quantum wells. We discuss the problem of strain related defects and finally the problem of thermal degradation of high indium QWs after the high temperature overgrowth of p-type AlGaN layer.

1. Introduction

Nitride-based optoelectronic devices, such as light emitting diodes (LEDs) and laser diodes (LDs), are commonly grown along polar GaN (0001) direction¹. A consequence of such a design is the presence of strain-induced piezoelectric fields manifesting itself in a phenomenon known as the Quantum Confined Stark Effect (QCSE)¹. QCSE consists in the reduction of holes and electrons wavefunctions overlap and subsequent lowering of their radiative recombination rates and their recombination energy. It is, however good to remember, that the non-radiative recombination rate is also increased by QCSE, making the question of final efficiency of such device disputable². However, we can avoid all the above effects by choosing an other than (0001) growth plane like e.g. (20-21) semi-polar surface³. Indeed, in the last years a number of groups have succeeded in the demonstration of blue and green laser diodes grown on various semipolar and non-polar GaN orientations⁴⁷. These results show that using different that c-plane GaN plane is very promising way to obtain long wavelength and efficient laser diodes. However semipolar GaN planes are not so easy in application in growth of laser diodes structure. We have to deal between smaller incorporation of indium on semipolar planes and smaller critical thickness in comparison to standard c-plane. InGaN and AlGaN layers grown on semipolar GaN tends to faster relaxation and defects formation.

2. Semipolar (20-21) laser diodes structures

We fabricated green-light-emitting laser structures on a (2,0, 2,1) semipolar GaN substrate. Using cathodoluminescence mapping, X-ray diffraction, and transmission electron microscopy, we revealed the formation of relaxation defects within InGaN waveguides and AlGaN claddings. The observed defects in the AlGaN layers are stripe-like and extend along the "a" axis, but in the InGaN layers, they form a characteristic checkered pattern (Figure 1)

![Image](image.jpg)

Figure 1. Cathodoluminescence panchromatic maps: a) are with losley space SiN stripes , b) boarder between losley and dense spaced stripes, c) 50nm distance between SiN stripes.
We demonstrate that using the selective area growth method we can effectively suppress the formation of both types of defects, thus enabling the fabrication of defect-free green laser structures on semipolar GaN substrates.

3. c-plane long wavelength laser diodes

The most common way to obtain high indium content layers in MOVPE is to decrease temperature in the reactor. However this solution results in large difference in growth temperature between QWs and p-type AlGaN layer. (250°C). This difference results in the thermal degradation of QWs. Figure 2 shows cathodoluminescence monochromatic maps taken at QWs (448nm) wavelength. Dark areas correspond to defects results after p-AlGaN growth.

![Figure 2. Cathodoluminescence monochromatic maps (QWs wavelength ~ 448nm). Dark are correspond to degraded QWs.](image)

We show that replacement p-AlGaN by low temperature p-GaN can give promising results in achieve homogeneous InGaN QWs.

4. Conclusion

We conclude that using selective area epitaxy it is possible to avoid extended defects propagation on semipolar (20-21) GaN plane. Defect free structure is necessary to achieve good performance laser diodes on this, semipolar directions.

5. References