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InP-Based Lasers and Photonic Crystals Devices for Integrated Photonics

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ABSTRACT
In this paper, some of the activities towards the fabrication of Photonic Integrated Circuits at the COBRA Research Institute are summarized. Firstly, rate equations are used for the understanding of instability and dynamics in multilongitudinal mode semiconductor lasers. Secondly, we report the results of our investigation on broad-bandwidth frequency comb generators based on novel mode-locked InAs/InGaAsP/InP quantum dot laser diodes. In addition, we will show the integration of two-dimensional pillar-based photonic crystal waveguides in an InGaAsP/InP photonic integrated circuit.

Keywords: nonlinear dynamics, InP, photonic crystals, modelocking, integrated optics laser, DBR gratings.

1. INTRODUCTION
The COBRA Research Institute at the University of Technology Eindhoven is active in research in semiconductor materials and semiconductor optical devices. The fabrication of Photonic Integrated Circuits (PICs) in which semiconductor lasers and photonic crystals structures can be built-in, allows photonic systems to be more compact and capable of providing higher performance than with the use of discrete optical components. In addition, they also offer the possibility of integration with electronic circuits to provide increased functionality.

It is well known that semiconductor lasers can be used as sources of nonlinear dynamics and transitions to chaos [1], as well as generators of picosecond and sub-picosecond optical pulses using mode-locked laser diodes (MLLDs) [2]. While for the fabrication of MLLDs the traditional material used has been either bulk or quantum well, new works are choosing quantum-dot (QD) and quantum-dash (QDash) materials with proved capability for MLLDs fabrication giving the advantages of a broader gain spectrum with lower spontaneous emission levels and threshold current [3]. Other works have also proved that QD material is also high-non linear, and therefore, very promising for the fabrication of chaotic lasers. It is understood that the main causes of dynamics in semiconductor lasers are the degrees of freedom of the electrical field and the population inversion [4]. This work will also present the use of the rate equation theory essential for the understanding of these dynamics. While Standard Lang-Kobayashi equations [5] can describe the dynamics of a single-mode laser, they are unsuitable for Fabry Perot semiconductor lasers, since several modes in the cavity can be excited. Therefore, the concept of mode competition has to be introduced.

In addition, two-dimensional photonic crystals have been subject of extensive research due to their potential for integration in photonic circuits. An example of such a device is a polarization filter. The polarization sensitivity of photonic crystals makes it possible to significantly reduce the foot print of polarization filters.

Furthermore, deep etched distributed Bragg reflector (DBR) gratings are also very useful building blocks for PICs. One of the main applications is the fabrication of single mode laser devices, although, as it will be explained in section 2, this single mode operation does not correspond to a unique internal mode oscillating, but to a combination of several modes.

In the next section, some relevant components of the dynamic theory will be presented; this will be followed by a section in which the observation of passive mode-locking in a two section QD laser operating at 1.55 μm will be evidenced. After this, the design and fabrication of DBR gratings and polarization filters will also be presented.
2. SPECTRAL THEORY FROM RATE EQUATIONS

Consider the case of a semiconductor Fabry-Perot laser device that can sustain two-modes (for example if losses in all other modes are much larger). Two different modes with amplitudes of the electrical field \( E_1 \) and \( E_2 \) and spatial cavity eigen-modes \( \psi_1 \) and \( \psi_2 \) are oscillating in the cavity and interacting with the same active medium. The total field inside the cavity is expressed by

\[
E(z,t) = E_1(t)\psi_1(t)\exp(i\omega_1t) + E_2(t)\psi_2(t)\exp(i\omega_2t),
\]

where \( \omega_1 \) and \( \omega_2 \) are the optical eigen-frequencies of both modes. In particular, the interference term \( E_1^*E_2 + c.c. \) will generate a beat note, i.e. an oscillation on the order of \( \Delta\omega = \omega_1 - \omega_2 \approx 2L \), where \( L \) is the laser cavity length. In the case of very fast diffusion process, any ripple in the carrier distribution is washed away, and the two modes interact by reciprocally depleting a common gain. However, for a finite value of the diffusion strength, some components of the inversion grating survive and aid in the mutual injection of field from one mode to the other. As a result of such parametric interaction, the modal amplitudes \( E_1 \) and \( E_2 \) oscillate at frequencies on the order of the intramodal frequency spacing \( \Delta\omega \). To demonstrate this explicitly, we simulate a two mode laser in steady state with identical parameters for the two modes. The spectral content of each mode and of the total field are shown in Fig. 1. Each one of the amplitudes \( E_{1,2}(t) \) oscillates predominantly at its own eigen-frequency, however they also contain substantial spectral contributions from the side mode.

\[
\text{Fig. 1. Optical spectrum of the electric field in a non-linear cavity. The total spectrum indicates the presence of two modes; however the power is distributed in a non-trivial way among mode 1 and mode 2 due to parametric interaction.}
\]

Still, the low frequency mode has more energy, which is a consequence of the specific form of our equations and a well-known phenomenon in the semiconductor laser community. This effect depends on the linewidth enhancement factor being large and positive for a semiconductor laser [6]. A smaller value of \( \alpha \) reduces the asymmetry, whereas, a negative \( \alpha \) inverts the effect (shorter wavelengths are enhanced).

3. QD MODELOCKING LASERS AT 1.55 \( \mu \)m

The QD laser structure is grown on n-type InP (100) substrates by MOVPE, as presented in [7]. The QD wavelength is tuned into the 1.55 \( \mu \)m region through insertion of ultrathin GaAs interlayers. In the active region five InAs QD layers are stacked, separated by 40-nm InGaAsP layers with a bandgap corresponding to a wavelength of 1.25 \( \mu \)m (Q1.25). The QDs have a diameter of approximately 50 nm and a height of 4 nm – 7 nm. The QD layers are placed in the centre of a Q1.25 InGaAsP optical waveguiding core layer, which is in total 500 nm thick. The bottom cladding of this laser structure is a 500-nm thick n-InP buffer and the top cladding is a 1.5-\( \mu \)m p-InP with a compositionally graded 300-nm p-InGaAs(P) top contact layer.

Passive mode-locking has been observed in a two-section quantum dot laser operating at wavelengths around 1.55 \( \mu \)m. The total length of the device is 9 mm, with a saturable absorber (SA) of 270 \( \mu \)m. The laser has a lasing threshold current values of 660 mA to 690 mA for SA reverse bias voltages of 0 V to 4 V respectively. Passive mode-locking is studied by recording the electrical power spectrum using a 50-GHz photodiode and a 50-GHz electrical spectrum analyzer. The RF-spectra obtained for this laser show clear peaks at the cavity roundtrip-frequency of 4.6 GHz. In Fig. 2 the height of these RF-peaks over the noise floor is given as a function of the operation parameters, i.e. the SA bias voltage and the SOA injection current. A large, robust operating regime with RF-peak heights over 40 dB is found for values of the injection current of 750 mA up to 1.0 A and for values of the SA bias voltage of 0 V down to -3 V. This large operating regime makes the QD laser very promising for practical implementation.
4. PHOTONIC CRYSTALS POLARIZATION FILTERS

The strong polarization dependence of 2D photonic crystals [9] is used to investigate a TE polarization filter based on a pillar photonic crystal waveguide in a square lattice of high-index pillars. TM-polarized light is defined as the polarization that has its electric field vector parallel to the pillars, normal to the plane of the chip, and TE-polarization has its electric field vector in the plane of the chip. The device is integrated in a classical PIC on an InP substrate with a 500-nm thick InGaAsP core layer and a 1-μm-thick InP top cladding. The layer stack of the pillar photonic crystal is compatible with that of the classical PIC, and so is the fabrication technology. Details about the design and fabrication of the filter can be found in Kok et al. [10]. Fig. 3 shows a scanning electron microscope (SEM) image of the PhC structure after the ICP etch.

The measured transmission for both TM and TE polarization is shown in Fig. 4. The average transmission for TM polarized light is -8.7 dB. The losses are higher than was calculated in the 3D simulation, probably due to scattering and to the non-vertical sidewalls of the pillars, which can cause large substrate leakage. Both can be reduced by an optimization of the fabrication technology. The TE transmission is -26.5 dB, which is in agreement with the simulated transmission. More characterization details can also be found at Kok et al. [10].

5. DBR FABRICATION

For the deep etched DBR grating design, a double heterostructure consisting of an n-type InP substrate, 500 nm Q1.25 passive waveguide layer and 1.5 μm p-type InP top cladding (see Fig. 5) has been used. The measured reflectivities are shown in Fig. 6. In the graph, 1 grating pair corresponds to 1 trench in the waveguide (generating 2 reflections, one at the semiconductor-air interface and one at the air-semiconductor interface), 2 grating pairs are 2 trenches, etc. More details about the design, fabrication and characterization of these DBR structures can be found at Docter et al. [11].
6. SUMMARY

In this paper a summary of some of the activities of COBRA has been presented. The use of a multilongitudinal mode rate equation model has proved that using, for instance, a grating under grazing angle to separate the Fabry-Perot modes, does not correspond to a measurement of a single internal longitudinal mode. To achieve single device mode measurements, one must identify the mixture of the individual device modes in a single Fabry-Perot line and thereafter construct an adequate frequency filter to extract the exact modal content. Moreover, since the mixture is strongly dependent on the laser parameters, identifying the level of mixture may also aid in the measurement of the laser parameters. We have also presented 4.6-GHz, two-section QD-lasers emitting around 1530 nm.

Furthermore, it has been evidenced that a very short TE polarization filter can be realized in a pillar photonic crystal. The fabrication process is compatible with that of a photonic integrated circuit based on conventional waveguide technology. This device, based on a simple design concept, can be used to define the state of polarization in a photonic integrated circuit, improving its stability and performance.

Last but not least, we developed a simple and robust fabrication technology for the fabrication of deep-etched DBR gratings. We have fabricated low loss deep etched waveguides, with DBR gratings that show reflections up to 80%.

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