# Spectral Investigation of the Operation of Multi-longitudinal Mode Semiconductor Ring Lasers

**S.Beri[1,2], O. Raz[1], E.A.J.M. Bente[1], Y.Barbarin[1], S. Anantathanasarn[1], R. Nötzel[1]**
**H. J. S. Dorren[1], M.K. Smit[1]**
*1: COBRA Research Institute, Eindhoven University of Technology, PO. Box 512, 5600MB – Eindhoven, The Netherlands*
*tel:+31 (0) 40 247 3521 fax:+31 (0) 40 245 5197 e-mail: s.beri@tue.nl*
**G.Verschaffelt[2], P.Tassin[2], J. Danckaert[2]**
*2: Department of Applied Physics and Photonics,Vrije Universiteit Brussel, ,Pleinlaan 2, B-1050, Brussel, Belgium*

*We spectrally investigated the regimes of operation of multi-mode semiconductor ring lasers. We report here on an InAs/InGaAsP/InP quantum dot ring laser. The field emitted by both sides of the device is detected with either a power meter or a 6GHz resolution multi-wavelength meter. We present here the mode-resolved PI-curves for different values of the bias current, the dominant wavelength and the side-mode-suppression ratio. Opposite to single mode devices, whose dynamics is determined by the coupling of two counter-rotating waves which compete for a common gain, we observed a nontrivial partitioning of power between the two directions and the different longitudinal modes.*

## Introduction

Semiconductor ring lasers (SRL) are recently receiving great attention in the technical and scientific communities due to their possible application as optical memories [1]. A ring laser which can operate in either clockwise (CW) or counterclockwise (CCW) direction represents an ideal two-state system to store bits of information in an optical way. A deep understanding of the dynamical regimes of a SRL is therefore crucial in order to fully exploit the device at its full potential.

In a recent work [2], the different regimes of operation of a SRL have been experimentally investigated for a multi-quantum well single-longitudinal-mode device. Bidirectional and unidirectional regimes have been reported as well as periodic oscillations between two different counter-propagating directions. The presence of these different dynamical regimes has been explained as a result of the competition of linear coupling terms induced by the reflections introduced by the presence of an optical coupler as well as scattering by defects, with the nonlinear coupling terms induced by gain saturation effects such as spectral-hole-burning, dynamical spatial-hole-burning or carrier-heating. According to the relative magnitude of linear and nonlinear coupling, the output power is partitioned between the two counter-rotating directions.

On the other hand, when a multimode ring laser is considered, the situation becomes more complicated due to the increase in the number of degrees of freedom and the presence of more nonlinear coupling terms linking the different lasing modes in the ring cavity.

In this paper we focused on the investigation of multimode semiconductor ring laser which are fabricated in quantum dot material. The large bandwidth of the quantum dot gain support contemporary operation in many longitudinal modes. We will spectrally resolve the individual modes and we will report on the different regimes of power partitioning between the different longitudinal modes.

## The device

The QD laser structure was grown at COBRA on n-type InP (100) substrates by metal–organic vapor-phase epitaxy (MOVPE). The gain section consists of five layers of InAs QD layers separated by a 40-nm-thick Q1.25 InGaAsP layer, which are in the centre of a 500nm Q1.25 waveguide core. Bottom and top claddings of the laser structure are 500-nm n-InP buffer and 1.5µm p-InP completed by a compositionally graded 75-nm p-InGaAsP contact layer. The surface density of the dots is approximately 3E10 cm-2 and the gain bandwidth is approximately 80nm **Error! Reference source not found.**.

The ring is 2mm long, which results in a FSR of approximately 40GHz; the optical power is coupled out of the ring by a directional coupler to a straight waveguide which can be independently biased. The waveguide reached the side of the chip under a 7 degrees angle in order to minimize the reflections. In addition to that, an anti-reflection coating has been applied to both facets [4].

For sake of clarity, in what follows we will refer to modes as solutions of the Maxwell equations for the unbiased ring cavity. Each mode can be defined univocally by the number of nodes in its longitudinal profile. During laser operations, the changes in the device temperature as well as the changes in the refractive index induce changes in the oscillating frequency of each of the mode; however, we will refer to a mode-hopping only when the longitudinal mode changes.

## Measurement results

*A. Mode resolved time PI-curves*

The chip was mounted on a copper mount and temperature-stabilized at 14°C with a 0.1°C accuracy using a Peltier element. The output waveguide was pumped at 7mA which corresponds to transparency. The output powers from both sides of the device were coupled out to a lensed fibre and measured simultaneously with a HP dual port power-meter at different values of the bias current on the ring. The corresponding PI curves are shown in Fig.1(left).

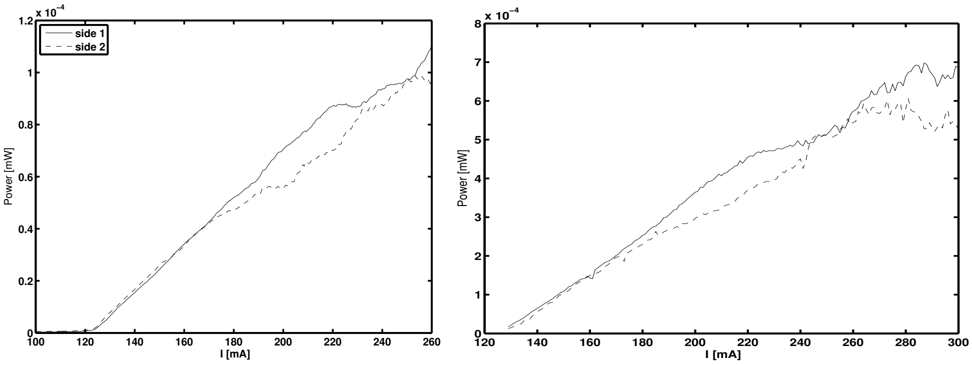

*Figure 1: (Left) PI curves for the two counter-rotating directions as measured with a dual port power meter. (Right) PI curves obtained by integration of the spectrally resolved curves.*

Opposite to the case of a single mode device, the multimode laser does not achieve unidirectional operation. However, at a current of about 170mA, a symmetry breaking appears which leads to different power rotating in the two directions. Nevertheless, a complete suppression of one of the rotating direction is not achieved and the suppression ratio between the two directions remains small. Such behavior is not observed in single mode devices. A further increase of the bias current eventually results in a decrease of the suppression ratio which becomes very low at approximately 240mA. In order to investigate the relation between the multimode operation of the laser and the lack of unidirectional emission, both outputs are measured with an Ando AQ6141 multi-wavelength meter with 6GHz resolution. In this way the spectral position of the individual longitudinal modes can be obtained for each value of the bias current on the ring. By linearly fitting the spectral position of the modes, we worked out mode resolved PI curves such as those shown in Fig.2 for different longitudinal modes.

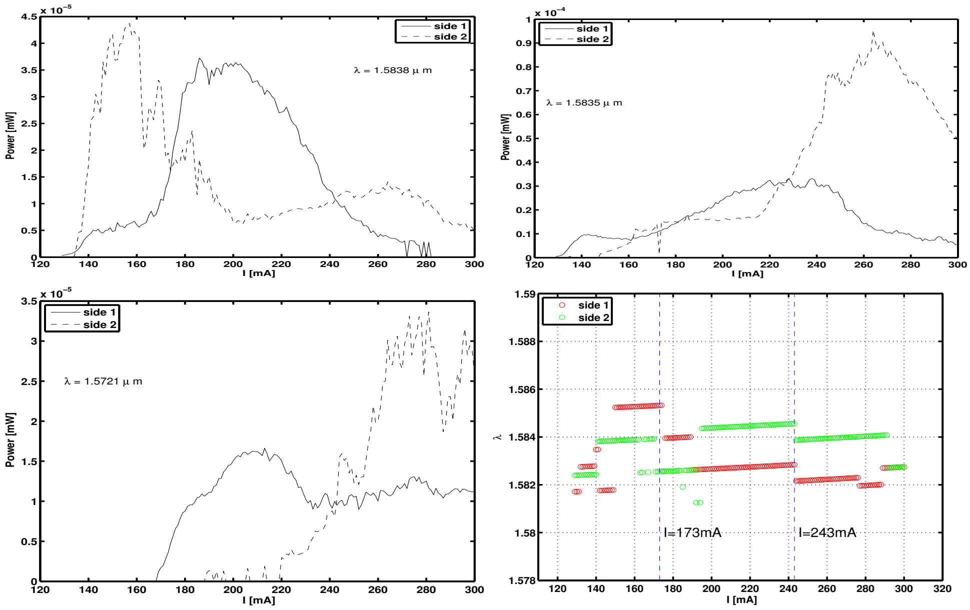

*Figure 2: Mode resolved PI curves for different longitudinal modes for both emission directions. On the bottom right we show the dominant wavelength obtained from the mode resolved PI curves.*

It is apparent that the suppression between the two counter-rotating directions is much larger in the mode-resolved PI curves than in the total (wavelength integrated) output.
A spectrally integrated PI curve is shown in Fig.2 (bottom-right) and it is consistent with the PI-curves measured with the HP meter in Fig.1.

### *B. Dominant mode*

Once the mode resolved PI curves have been worked out as described in the previous sections, the dominant wavelength can be identified on both sides of the ring as a function of the bias current. The results are shown in Fig.2
It is clear from Fig.2 that the power peaks at different wavelengths at the two sides of the ring, and that a certain number of dominant-mode hoppings take place during the operation of the device.
Both directions tend to undergo a dominant mode hop for the same values of the bias current. Such mode hoppings are related to qualitative changes in the PI-curves. For instance, the hop at 173mA is related to the PI curves separating in Fig.1 and the hop at

243mA is related with the PI-curves getting close together.

## Discussion and Conclusions

In this contribution we investigated the different regimes of operation of a semiconductor ring laser focusing in particular on mode resolved properties. A fitting method has been used to work out individual modes out of spectral measurements.

Opposite to the case of single mode devices, we observed a weak suppression of the counter-rotating direction and a low-side mode suppression ratio. These two properties are related. In a single mode device, the power can be partitioned only between two counter-rotating modes. The ratio 1:2 between self and cross gain suppression, therefore drives the system towards unidirectional regime as soon as the power is large enough to make the nonlinear terms non-negligible.

On the other hand, the large, flat gain-bandwidth of quantum dot material allows for many different longitudinal modes oscillating at the same. Therefore, there are several modes that compete for the semiconductor gain and that are nonlinearly coupled.

The large suppression ratio shown by the curves in Fig.2 is due to the 1:2 ratio of self and cross gain suppression for the same mode rotating in two different directions.

On the other hand, the saturation of the side modes (mediated by spectral-hole-burning or spatial-hole-burning) is symmetric for the two counter-rotating directions, and a strong field rotating in a certain direction cannot suppress rotations on the opposite one.

## References

[1] M. T. Hill *et al*, Nature 432, 206 (2004)
[2] M. Sorel, *et al*, IEEE J. Quantum. Electr. 39, 1187- 1195 (2003)
[3] R. Nötzel *et al*, *Jpn. J. Appl. Phys*. 45, p. 6544 (2006)
[4] Y.Barbarin *et al*, Phot. Tech. Lett. 18, 2644 (2006)