Study of Semiconductor Microring Lasers for use in Wavelength Division Multiplexing (WDM) Telecommunication Networks.

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Abstract. In this thesis, the optical characteristics of all-active microring resonators as lasers are studied. The structure of a semiconductor microring laser coupled to a bus waveguide is investigated. The scope of the study is to examine the microring's laser operation and also emphasize the influence of the key design parameters on single mode and/or unidirectional operation, both being of major concern for future microring-based lightwave system applications. An analytic multimode model for the simulation of 1.55 μm InGaAsP-InP microring laser's dynamic properties is presented. Different operation regimes are observed. The boundaries of the operating regimes are investigated with respect to the ring current level, the bus waveguide reflectivity and the ring radius. Moreover the Relative Intensity Noise spectra are studied. In addition an experimental verification of the numerical results is presented. A complete study is performed varying the ring radius and the microring's bias current. Further, the mode hopping phenomena are measured and presented through the time traces spectra and the Relative Intensity Noise spectra. For the first time an alternative method of controlling the bus waveguide facet residual reflectivity by varying the bus waveguide's current is experimentally demonstrated.

Keywords: Semiconductor microring lasers, non-linear gain, multimode operation, mode-hopping, bidirectional operation.

1 Introduction

Semiconductor microring lasers (SMLs) are attractive candidates for optoelectronic integrated circuits (OEICs) as they combine simple fabrication, small footprint, and high spectral purity [1]. Large diameter circular and triangular ring laser devices have been fabricated [2-4], and they have been analyzed by considering a near single longitudinal mode operation. This assumption is valid as long as the side-mode suppression ratio (SMSR) is greater than about 20dB. However, the SMSR is strongly dependent on the specific design and current levels used for each device. In the

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general case a microring laser is expected to operate in multiple longitudinal modes. Longitudinal mode hopping phenomena can dramatically increase the intensity noise of micro-ring lasers and thus limit the performance of a ring-based lightwave system. Thus, a dynamic multimode analysis is a necessity for a complete and accurate characterization of microring lasers.

In the first part of the thesis a multimode model is presented based on the rate equation approximation for the simulation of microring laser's mode dynamics including time traces, optical spectra and RIN spectra. The bus waveguide's residual reflectivity is taken into account in the model, providing an additional optical feedback to the resonant microring cavity, which is the coupling mechanism between the two propagating directions. A complete study is performed varying the microring's current, the bus waveguide's reflectivity and the ring radius. The scope of the theoretical investigation is not only to examine the microring's laser operation, on a general point of view, but also to emphasize the influence of key design parameters on single mode and/or unidirectional operation, both being of major concern for future microring-based lightwave system applications

The second part of this thesis contains the experimental investigation on the modal properties of an all-active 1.55μm-InGaAsP/InP semiconductor microring laser coupled to a bus waveguide. The influence of the ring driving current and the ring radius on the operation of the microring laser is presented. Single or multi mode operation and mode hopping is observed in respect with the ring current level. Additionally the influence of the active bus waveguide biasing, on the modal properties of a microring laser is experimentally demonstrated. All-active devices are advantageous because the reflections generated at the output waveguide chip facets can be controlled with the bus waveguide driving current. The electrical pumping of the bus waveguide controls its absorption coefficient (optical loss) and in consequence the optical power level of the light reflected from the waveguide facet. This is therefore, an indirect way of controlling the effective facet reflectivity. Finally, a comparison between the theoretical and experimental results is made, confirming the accuracy and reliability of the mathematical model.

2 Numerical modeling of Semiconductor Microring Lasers

The electric field inside the ring cavity can be expressed as the summation of all resonant modes,

$$E(t) = \sum_{p,\pm m} E_{p,\pm m}(t) e^{-j(\omega_p t)} \tag{1}$$

where $E_{p,\pm m}$ are the mean-field slowly varying complex amplitudes of the electric field of all modes in the ring cavity, p is the mode number, and ±m corresponds to each propagation direction either clockwise (CW), or counterclockwise (CCW). The variation of the electric field $E_{p,\pm m}$, and the carrier concentration, n, are described for the first time by a set of multimode rate equations,

$$\frac{dE_{p,\pm m}}{dt} = \tfrac{1}{2}(1 + j\alpha)\left[G_{p,\pm m} - \frac{1}{\tau_p}\right]E_{p,\pm m} + \frac{K^{\pm m}}{\tau_p}E_{p,\pm m}(t-\tau_d)e^{-j\omega_p\tau_d} + F_p(t) \quad (2)$$

$$\frac{dn}{dt} = \frac{I}{eV} - \frac{n}{\tau_s} - \sum G_{p,\pm m}\left|E_{p,\pm m}\right|^2 \quad (3)$$

$$G_{p,\pm m} = A_p - sg(n-n_0)\left|E_{p,\pm m}\right|^2 - \sum_{p,q,\pm m} D_{p(q)}\left|E_{q,\pm m}\right|^2 - \sum_{p\neq q,\pm m} H_{p(q)}\left|E_{q,\pm m}\right|^2 \quad (4)$$

where, G_p is the modal gain, A_p the linear gain coefficient, s is the self gain suppression coefficient and $D_{p(q)}$, $H_{p(q)}$ are the symmetric and asymmetric cross gain suppression coefficients respectively given by the following expressions:

$$A_p = g\left(n - n_0 - b\left(\lambda_p - \lambda_0\right)^2\right) \quad (5)$$

$$H_{p(q)} = \frac{3\lambda_p^2 g^2}{8\pi c}\frac{\alpha\left(n-n_0\right)}{\lambda_q - \lambda_p} \quad (6)$$

$$D_{p(q)} = \frac{4}{3}\frac{s(n-n_0)}{\left(\frac{2\pi c\tau_{in}}{\lambda_p{}^2}\right)^2\left(\lambda_p - \lambda_q\right)^2 + 1} \quad (7)$$

The expression for each mechanism, as well as all the other parameters can be found in [5]. The nonlinear system of equations is solved for equal number of modes propagating in each direction (CW/CCW). The number of supported modes is determined by the gain bandwidth, and the ring's free spectral range, FSR=$\lambda_0$2/ngL. The parameter $K_{\pm m}$ represents the linear coupling, between counter propagating modes of the same frequency, due to reflection on the bus waveguide and τ_d=$L_b$ng/c is the time delay of the reflected light to be coupled back into the ring, In our case, the bus waveguide is considered as a lossless section, g_{net}=0. Assuming that the facets are antireflection (AR) coated with a power reflectivity, $R_{cw/ccw}$, varying from -20dB to -60dB, the resonant characteristics of the bus waveguide are suppressed and therefore are not taken into account in the analysis. This residual reflectivity is taken into account in our model, providing an additional optical feedback to the resonant microring cavity, coupled from one direction to the other. Equations (2)–(9) are numerically integrated to simulate the microring's laser operation. In the computation of laser dynamics, usual Langevin [6] noise sources are used, represented by the terms $F_p(t)$ in Eq. 2.

3 Multimode Dynamics of InGaAsP/InP SMLs

A detailed characterization is performed including calculated optical spectra, time traces and relative intensity noise (RIN) spectra. Different operation regimes are observed, bidirectional multimode with/without alternate oscillations, unidirectional single mode, bidirectional single mode and mode hopping. The boundaries of the above operation regimes are investigated with respect to the current level, bus waveguide reflectivity and ring radius. Varying the current level a transition from multimode to single mode and eventually mode hopping operation is observed. Increasing the bus waveguide reflectivity a transition from unidirectional to bidirectional operation is revealed, while the use of non-equal reflectivities between the two facets, promotes unidirectional operation. Moreover, the ring radius is proved to be a critical parameter for the extent of each operation regime since it directly influences the modal wavelength separation.

3.1 Influence of injection current for low reflectivity values

A detailed characterization of the microring laser is performed for the case of low reflectivity values at various current levels. Specifically, a reflectivity value of $R_{cw}=R_{ccw}=-60dB$, for a radius of r=50μm, is selected. The model predicts a sequence of different operating regimes. At current values in the order of the threshold current a bidirectional operating regime combined with alternate oscillations is observed. When the current is further increased a unidirectional operating regime is observed. Eventually for current values greater than $2.0I_{th}$, a mode-hopping operating regime combined with alternate oscillations occurs. The mode-hopping takes place between longitudinal modes propagating in the same direction. The transition from the stable to the hopping operation regime is also observed through the RIN spectra. The stable multimode and single mode operation regimes exhibit a usual peak at the relaxation frequency, while an enhanced low frequency RIN is depicted at the mode hopping regime. The respective RIN spectra at current values $I=1.0I_{th}$, $I=1.4I_{th}$ and $I=2.3I_{th}$ are illustrated in Fig 1. A broad low frequency peak is depicted at $I=2.3I_{th}$.

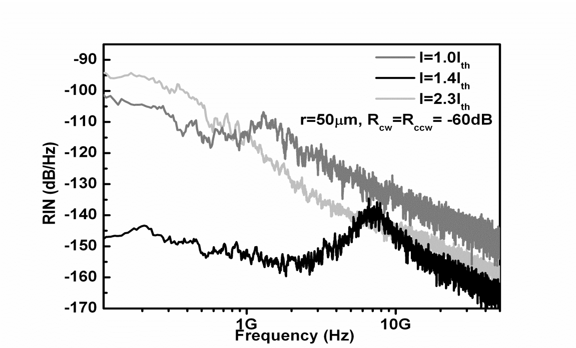

Fig. 1. RIN spectra for $I=1.0\ I_{th}$,$1.4\ I_{th}$ and $2.3I_{th}$ with $R_{cw}=R_{ccw}=-60dB$ for r=50μm.

3.2 Influence of various reflectivity values.

The influence of the residual reflectivity on the microring laser operation regimes is examined. A range of power reflectivity values in the area of -60dB to -20dB, for a radius of r=50μm, is investigated. A detailed mapping of the bus waveguide reflectivity and current level influence on the microring operating regime for ring

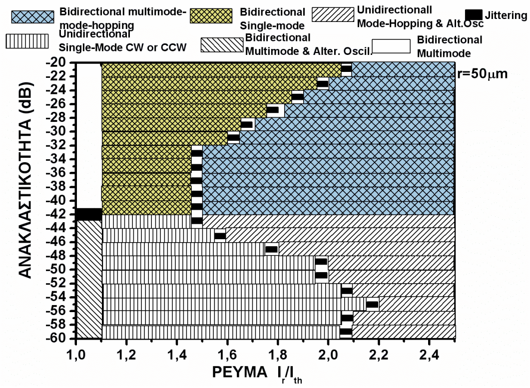

Fig 2 Detailed mapping of the bus reflectivity influence with to the current level for ring radius 50μm

radius 50 μm is illustrated in fig. 2.

Many typical and interesting features are extracted from this figure. Bidirectional multimode operation dominates at low current values approximately up to $1.1I_{th,}$ however the reflectivity value can be a control parameter whether the operation is bidirectional with or without alternate oscillations. Increasing the current value, and for low reflectivity values, approximately up to -42dB, the ring laser operates at a unidirectional single mode operation with an equal probability of either the CW or CCW to lase. When the reflectivity increases, the ring operates at a bidirectional single mode operation. Finally the transition to the mode-hopping operation regime varies accordingly to the reflectivity value and the current level as indicated in fig, 2. The study is extended to the case of non-equal reflectivities for the bus waveguide facets in order to provide the microring laser with the required asymmetrical factors and unidirectional characteristics are observed.

3.3 Influence of various microring radii

A critical parameter for an optimum microring laser performance in terms of unidirectionality and/or single mode operation is the modal wavelength separation. The microring radius directly affects the Free Spectral Range (FSR) of the mode spectrum; smaller radii give larger FSR. Thus, a detailed characterization of the dynamic properties of the microring laser is also performed for different radii. In addition to the mapping presented in fig.2, similar mapping for the operating conditions for r=30μm and r=70μm is also performed. The already mentioned, operation regimes were observed for all three different radii. Smaller radius rings (i.e r=30μm) proved to have an extended unidirectional single mode operation regime, up to current values of approximately $2.2I_{th}$ and for facet reflectivities up to approximately -30dB. It is observed that for bidirectional single mode operation to occur, a 30μm radius ring needs increased reflectivity values, more than -30dB. The mode-hopping regime is reduced and it is present only at higher current values, more than $2.2\text{-}2.3I_{th}$ as a function of the power reflectivity value. At increased ring radii (r=70μm) the single mode regimes either unidirectional or bidirectional are reduced and the mode-hopping regimes either the stable mode-hopping or with alternate oscillations are considerably extended. The detailed mapping of the bus reflectivity influence with respect to the current level for ring radii 70 μm and 30 μm can be found in [4]. The consideration of the above parameters is critical for design of microring lasers with optimum performance for future lightwave system applications.

4 Experimental investigation of the modal properties of SMLs

In this part, a simple structure of an all-active microring laser coupled to a bus waveguide is examined. The devices studied experimentally were multi quantum-well InGaAsP(λg=1.55μm)/InP microring lasers derived from a standard ridge waveguide laser process. The investigated single stage laser device is shown in fig. 3 and

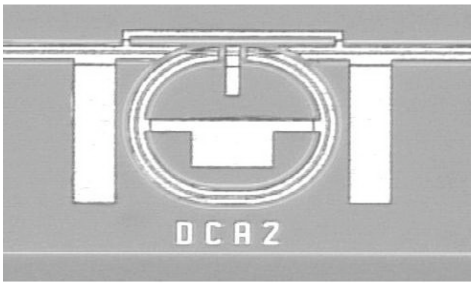

Fig. 3 Planar view of the microring laser

includes a microring coupled to a bus waveguide using directional coupler. The epitaxial layer structure from top to bottom is as follows: p+-InGaAs (0.25 μm), InP (1.5 μm), GaInAsP (0.18μm, p-waveguide), 6 quantum wells (λg = 1.55 μm), n+-GaInAsP (thickness = 0.25 μm, n-contact), on InP:Sn substrate All-active devices are advantageous because the reflections generated at the output waveguide chip facets can be controlled with the bus waveguide driving current. This is an indirect way of controlling the effective facet reflectivity. In this study the influence of the active bus waveguide biasing, on the modal properties of a microring laser is for the first time experimentally demonstrated. The influence of the ring driving current and the ring radius on the operation of the microring laser is also examined. The experimental setup for the measurements under dynamic operation is shown in fig. 4.

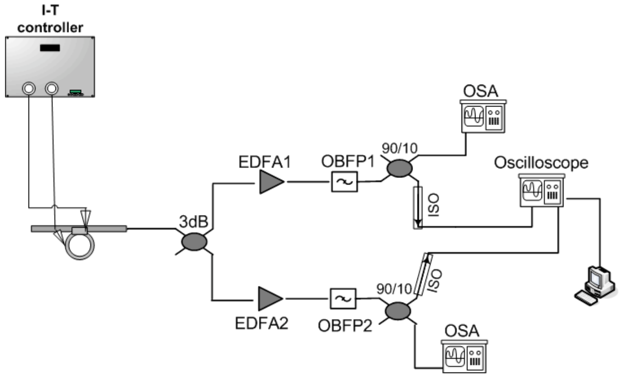

Fig. 4 The experimental setup used for the dynamic measurements of the SMLs. EDFA: erbium-doped fiber amplifier, BPF: band-pass filter, OI: optical isolator.

A detailed characterization of a multimode microring laser was performed for the case of low effective reflectivity of the bus waveguide facet and for ring radius r=540μm. In order to achieve low reflectivity values the driving current of the bus waveguide was kept at a current density lower than the transparency value, causing moderate absorption losses outside the ring and minimizing the back reflections from the chip facets. The driving current for the bus waveguide I_b was kept at I_b = 0 mA. Two different operation regimes were revealed. At ring current values in the order of the threshold current, bidirectional operation was observed. At greater ring current values and up to $1.6I_{th,}$ unidirectional operation was observed being either clockwise (CW) or counterclockwise (CCW), depending on the ring current. At greater ring

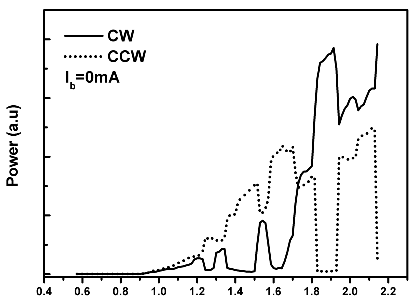

Fig. 5 PI curves for the CW/CCW propagating directions with I_b=0 mA. Ring radius r=270μm

current the single longitudinal mode operation was no longer present but a transition to a stable multimode operation or with mode hopping phenomena was observed. In order to investigate the ring radius influence on the microring laser performance, similar measurements for a ring radius equal to 270μm were also made. It was evident that at low reflectivity values, unidirectional operation also occurred. It was very interesting to observe that the microring laser exhibited an extended unidirectional and single longitudinal mode operation up to ring current values $Ir=2.2I_{th}$. Typical P-I curve for the above conditions, is illustrated in fig. 5. Detailed results can be found in [7]

The influence of the bus waveguide facet residual reflectivity on the operating regimes of the microring laser was also investigated. The electrical pumping of the bus waveguide controls its absorption coefficient (optical loss) and in consequence the optical power level of the light reflected from the waveguide facet. This is therefore, an indirect way of controlling the effective facet reflectivity. The measurements were repeated for both the devices and the experimental outcomes were the same for both the ring lasers. A transition from the unidirectional regime observed for the case of I_b=0mA, to the bidirectional regime was observed. All-active microring lasers may give the opportunity to overcome impairments that are mainly due to fabrication procedures, such as accurate control of the chip facets reflectivity. The most substantial benefits of the present investigation were that the real time observation and the accurate control of the spectral characteristics of the microring laser become feasible by only manipulating the main functional characteristics of the device such as the ring and the bus waveguide driving current

4.1 Experimental demonstration of Mode-Hopping phenomena in SRLs

Future lightwave systems based on microrings will be critically affected by the relative intensity noise (RIN) of the microring laser source. Moreover, competition phenomena between longitudinal modes, due to nonlinearities, can dramatically

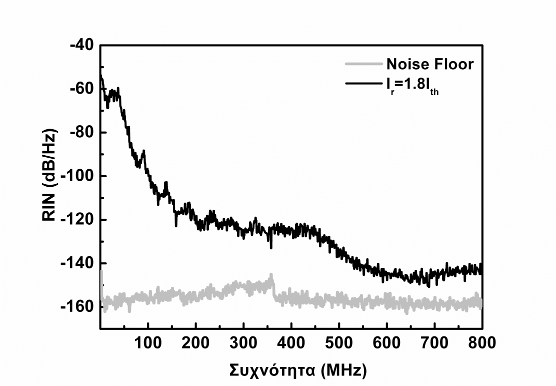

Fig. 6 The measured RIN spectra, for $Ir=1.8I_{th}$ as a high injection level. A significant low-frequency RIN enhancement is depicted.

increase the RIN of microring lasers and thus limit the performance of a ring-based application. Mode hopping phenomena were measured and presented through the time traces spectra and the Relative Intensity Noise spectra. At ring injection levels that multimode operation took place an asymmetric multimode-like spectrum appeared. As the temperature of the microring laser sample was fixed, the asymmetric spectral profile emerging at high injection levels can be attributed to cross gain suppression. The measured RIN spectrum is presented in fig. 6. A significant enhancement of the low-frequency RIN is depicted, combined with a peak in the frequency range between 50-150 MHz. The mode hopping phenomenon was also observed through the time traces spectra. A two-channeled Oscilloscope was used to monitor the intensity of two adjacent longitudinal modes propagating in the same direction. The energy

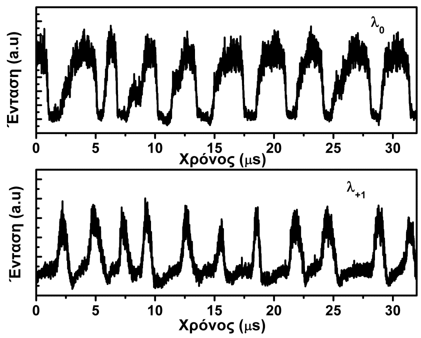

Fig. 7 Time traces for two adjacent longitudinal modes. Energy exchangeability is present.

exchange was recorded and is illustrated in fig. 7.

In the last part of the thesis, a detailed comparison between the theoretical and the experimental results is presented. Both revealed the different operation regimes that take place in a SML. Both showed that the ring radius proved to be a critical parameter for the extent of each operation regime since it directly influences the modal wavelength separation. Smaller radius rings proved to have extended single mode operation either unidirectional or bidirectional, while larger radius rings promoted mode-hopping phenomena. From the theoretical results it was confirmed that low reflectivity values, favored the unidirectional operation while higher values of reflectivity seem to promote bidirectional operation. The experimental results showed that low bus waveguide driving current which corresponds to low reflectivity values of the bus waveguide facets, favor unidirectional operation while higher values of reflectivity seem to promote bidirectional operation. The validity of the multimode model was ascertained.

5 Conclusions

A detailed theoretical investigation of the multimode dynamics of InGaAsP/InP Semiconductor Microring Lasers was carried out. The ring radius, the waveguide facet reflectivity and the ring biasing are critical parameters determining the performance of the laser. It was concluded that smaller radius rings can provide better spectral characteristics than the larger radius rings as far as the single mode operation, the side mode suppression ratio and the noise characteristics is concerned. The aforementioned theoretical results are confirmed by experimental measurements. An alternative way of controlling the effective facet reflectivity is proposed for the first time in this thesis giving the opportunity to overcome impairments that are mainly due to fabrication procedures. Also the experimental results confirmed that the multimode model that was employed is a reliable model to describe active and passive microring devices.

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