Optical Microring Devices for Optical Networks Applications: Investigation, Design and Characterization

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Abstract. In this dissertation, the optical characteristics of active microring resonators are investigated. The result of this thesis is the complete investigation of the SML properties and also the optimization of the key design parameters in order to be used in future microring-based lightwave system applications. In the first part the following are presented: investigation of the influence of various structural parameters, correlation between structural and functional parameters, analytical description of a numerical simulation model based on multimode rate equations. In the second part experimental measurements are presented. These measurements are: characterization of all-active and active-passive integrated devices, examination of different ring radii, investigation of operating regimes and a strong correlation between the coupling efficiency and threshold current density was established. Mode hopping phenomena and phase and intensity noise were investigated. A complete matching of the experimental findings with the theoretical predictions was established. Tuning capabilities of SMLs are also presented for different configurations where an extra broad tuning range of 40nm is recorded. Finally some applications: direct modulation at 7Gb/s and transmission through 100km, wavelength conversion in similar data rates by exploiting cross gain modulation (XGM) and a 10 dB optical amplification at 10Gb/s modulated.

Keywords: Microring resonator waveguiding analysis, semiconductor microring lasers, tunable laser sources, direct modulation and propagation.

1 Dissertation Summary

This dissertation is structured in two parts. The first, deals with microring lasers from a theoretical point of view, whereas in the second part, experimental measurements are demonstrated from actual devices measured on the optical communications laboratory. In more detail, the summary per chapter of this dissertation is as follows.

Beginning with the first chapter of the dissertation, an overview of optical networks is presented. A synopsis of the technological evolution of optical networks is shown, alongside the requirements of second and third generation networks for all optical signal processing. These include standards for devices like laser sources, photoreceivers, optical amplifiers, wavelength converters, filters and logic gates. According to these requirements the desired functionalities of laser sources are

*Dissertation Advisor: Dimitrios Syvridis, Professor described in order to be included in nodes of future generation networks. At the end of the chapter the contribution of the thesis in the realization of fundamental building block of WDM networks is developed.

Microring resonators are ideal devices for developing almost every fundamental block in WDM networks. They are compact and so can be integrated in very large scale. In parallel, they are wavelength selective which in combination with the ability to amplify field due to feedback makes them suitable for a broad range of applications in optical signal processing. Furthermore, the lack of costly mirrors or Bragg gratings in order to achieve optical feedback, simplifies the fabrication procedure and cost and allows them to be monolithically integrated with other structures. Here, a full description of the optical characteristics of active microrings is presented. Microring resonators are nowadays well established as the alternative way for optical resonators in general, alongside Fabry-Perot cavities and Bragg gratings. Specifically, microring lasers are offered as a means to construct sources for future optoelectronic integrated circuits (OEICs) because they combine simple fabrication and small size. Microring laser devices coupled with a straight bus waveguide that delivers light in or out of the device are explored. The study is intended to provide insight on the correlation of structural design parameters like the ring radius, the ring-bus power coupling efficiency and the bus facet residual reflectivity with operational characteristics like threshold current, phase and intensity noise, wavelength tunability and modulation capabilities. The result of this investigation is the synthesis of a general picture about the properties of microring laser diodes and the determination of the optimal design guidelines to be used in OEIC of the future.

In this context, a thorough investigation of microring resonator properties was carried out with special focus on microring lasers. This begins from a design level, passes through the development of numerical modeling and concludes with experimental results not only with characterization but also in practical applications.

The multiple InGaAsP/InP quantum well structures were fabricated at te Fraunhofer Institut in Berlin, Germany using wafer bonding techniques. The purpose of the measurements was to compare theoretical and experimental results and draw useful conclusions about the optimization of the abovementioned devices. Also, actual systems were implemented with performance comparable to existing state of the art applications, which by the time of their publication were considered to be a first. These implementations, which are a main part of this dissertation contribution, highlight a series of novel applications of microrings in WDM building blocks and emphasize on the importance of these structures on the evolution and development of optical networks in general.

The second chapter includes the theoretical background associated with the coupling of light between a bent and a straight waveguide. The influence of basic design aspects to the achievable coupling efficiency is examined which include: the ring radius, waveguide width and lateral displacement. The analysis is focused on the achievement of transversal monomode operation in both active and passive waveguides, since the existence of higher order modes leads to degradation of the performance of these devices by adding an extra loss route. Three methods are proposed and analyze to circumvent this problem. These include: selective excitation of the fundamental mode, selective attenuation of higher order modes and monomode coupling by imposing a positive lateral displacement between the two waveguides.

Furthermore, phenomena related to polarization rotation in curved waveguides are briefly investigated in order to design polarization conversion free devices.

An extensive report on microring resonators and lasers based on microring devices is presented in chapter 3. The equations that describe the light circulation and lead to resonance are analyzed. Also, an overview of up to the date of this dissertation existing microring laser devices is given and at the end the correlation between the design parameters and operational characteristics is theoretically studied. These operational characteristics include phase and intensity noise.

The fourth chapter is dedicated to the analytical development of a complete numerical model for simulating microring lasers coupled with a straight waveguide, based on multimode rate equations. A detailed description of the related equations is demonstrated. The enclosure of linear and non-linear gain terms is analyzed as well as the symmetric and asymmetric ones that lead to the various mode hopping phenomena. Furthermore, the inclusion of external feedback due to residual reflectivity is explained which is practically incorporated as an additional injection term in the rate equations.

The previously described numerical model was used to study the microring laser behavior and the accompanying results are shown in chapter 5. The spectral characteristics of the laser are described and the various operation regimes are identified. These include unidirectional and bidirectional as well as single mode and multimode operation. Moreover, the noise of microring lasers was examined with emphasis on the study of the spectral distribution of relative intensity noise. Both all-active and active-passive devices were simulated for different ring radii and coupling efficiency values, whereas, the tuning properties of microring lasers were theoretically investigated.

In chapter 6, the experimental investigation begins. The fabrication and characterization of various devices is described. At first, results from passive ring structures are shown, which were fabricated for confirmation with theoretical trends and also for parameter extraction like facet reflectivity and waveguide loss. All active devices were also characterized, where both the ring and straight waveguide exhibit gain by injecting current. Also, active-passive integrated devices were characterized in which the bus waveguide is made of passive material in order to minimize the influence of back reflection from the cleaved facets. Characterizations were performed for a variety of ring radii and bus waveguide widths which lead to different coupling efficiency values. The investigation of the different regimes of operation was accomplished through optical and RF spectra, optical time traces and light-current (LI) curves.

Noise phenomena in microring lasers are examined in chapter 7. Initially, mode hopping phenomena are investigated when lasers are operated at the high injection multimode regime. Additionally, the behavior related to intensity fluctuations is studied through time traces, optical and RF spectra as well as relative intensity noise (RIN) measurements. Finally, the phase noise is evaluated by measuring the laser's linewidth where a matching of the experimental findings with theoretically anticipated values is confirmed.

Chapter 8 covers the tuning properties of microring lasers. In 'all-active' microring devices, tuning is achieved through the straight active bus waveguide that controls the phase of the back reflected field by adjusting the injection current. In single ring active-passive devices the same apply with the exception that the bus waveguide is passive, therefore, non-controllable. So, the tuning properties are restricted. In double ring active-passive devices, an extensive tuning range is accomplished through the Vernier mechanism between the two active cavity spectra.

In chapter 9, applications of active microring devices are demonstrated. More specifically, microrings are investigated as directly modulated laser sources with modulation rate capabilities up to 7Gb/s. Also, the propagation of a signal, using a microring laser optically modulated at 5Gb/s, for 100km of single mode fiber (SMF) is shown. Moreover, the usage of active microring lasers as wavelength converters up to 5Gb/s was presented, by exploiting the cross gain modulation (XGM) and as an optical amplifier, capable of amplifying 10Gb/s signals by 10dB.

In the tenth and final chapter, a result and related conclusions summary is presented. Additionally, future works related to the contribution of this dissertation are discussed.

2 Results and Discussion

All results related to waveguide design for achieving monomode transversal behavior are summarized in [1-5]. All-active devices and numerical modeling related applications are described in [7-10]. Previous studies of vertically coupled microring lasers using a wafer-bonded transfer substrate have defined the bus waveguide prior to inverting the wafer. However technological challenges derived from the complexity of processing active components has lead to an inversion in the design. The laser structures are defined on the first face, prior to wafer bonding. The complete epitaxial structure is grown, the laser waveguides are defined and the p-type metal is deposited prior to wafer bonding to the transfer wafer. The substrate is removed by etching prior to the formation of bus waveguides and the opening of via holes to the p-metal at the transfer wafer. This results in a buried active microring waveguide structure, with the additional advantage that the laser is well protected during wafer dicing process. A standard laser epitaxial growth process now becomes feasible prior to wafer bonding. The buried microring structure is clad by low index benzo-cyclo-butene (BCB) material applied during the wafer-bonding process, where the high index difference ensures a good modal confinement within the waveguide.

The passive bus waveguides are formed on top of the active microring structure. Both p and n contacts are implemented on the top surface of the fabricated device. The width of both the passive bus waveguide and active microring are 1.8 μm. The active region of the microring laser comprises of six GaInAs quantum wells, with a band gap of Q_{ring}=1.55 μm, the InGaAsP bus waveguide has a band gap of Q_{bus}=1.44 μm, and a thickness of 0.35 μm. In order to minimize undesired reflections resulting from cleaving a 7° tilt is implemented on both ends of the bus waveguide. Detailed descriptions of the wafer bonding fabrication process can be found on [11-13].

2.1 Back to back measurements

Ring devices with ring radii ranging from 40 μm to 80 μm are analyzed. A copper submount is used to place the chips and temperature at 20°C is maintained throughout all measurements. A 50Ω terminated Ground Signal Ground (GSG) probe head is used for biasing and modulation and the optical output is coupled out using tapered fibers. Single mode emission is of crucial importance for the quality of high data rate operation. In figure 1, an L-I curve is shown along with an emission spectrum for bias current 41.28 mA and modulation depth 1 V_{pp} where single mode operation with side mode suppression ratio (SMSR) above 30dB is observed.

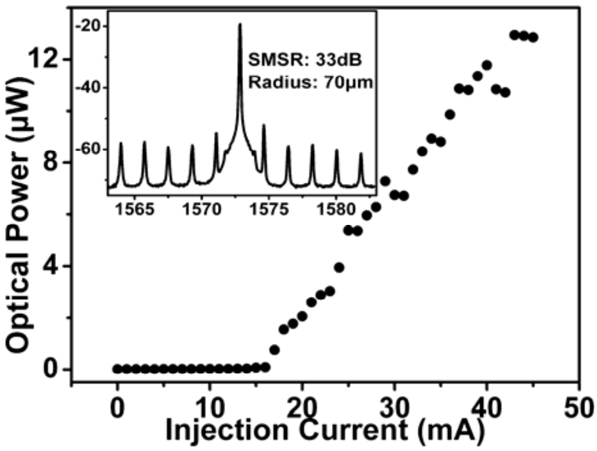

Fig. 1. L-I curve for a microring laser with radius 70 μm. The inset shows a single mode spectrum with SMSR approx. 33 dB for modulation bias at 41.28mA.

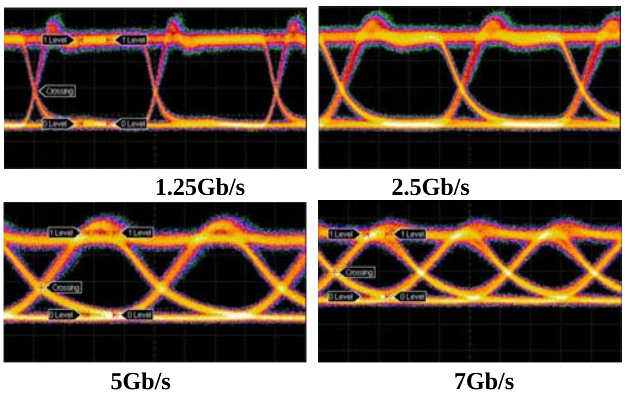

Fig. 2. Eye diagrams of ring laser modulated at 1.25, 2.5, 5 and 7 Gb/s with ER 7.6, 8.2, 8.2, and 5.8dB respectively in back to back configuration.

Eye patterns as well as Bit Error Rate (BER) measurements are carried out using various pseudo random bit sequence (PRBS) data streams for Non Return to Zero

(NRZ) pulses. Well opened eye diagrams are shown in figure 2, for 1.25, 2.5, 5 and 7 Gb/s bit rates for a 70 μm radius microring laser with extinction ratios (ER) 7.6, 8.2, 8.2 and 5.8 dB respectively. Modulation at 10Gb/s was also performed but with a poor extinction ratio of 3.7dB. Back to back BER measurements are in accordance with the eye diagrams showing error free (BER$<10^{-12}$) operation up to 7 Gb/s where as for higher data rates BER increases significantly (e.g. 10^{-6} for 8 Gb/s).

2.2 Transmission experiment

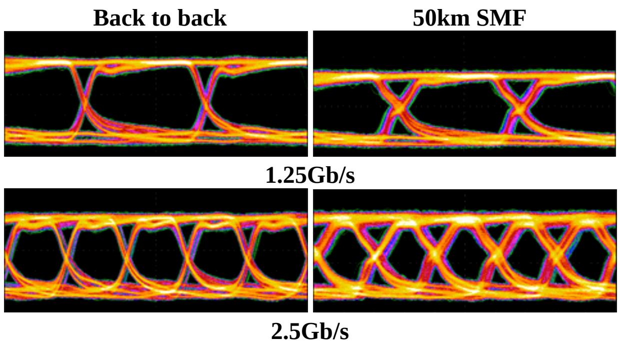

Fig. 3. Eye diagrams for a ring laser modulated at 1.25 Gb/s and 2.5 Gb/s in back to back configuration (left) and after 50 km propagation (right) in a SMF.

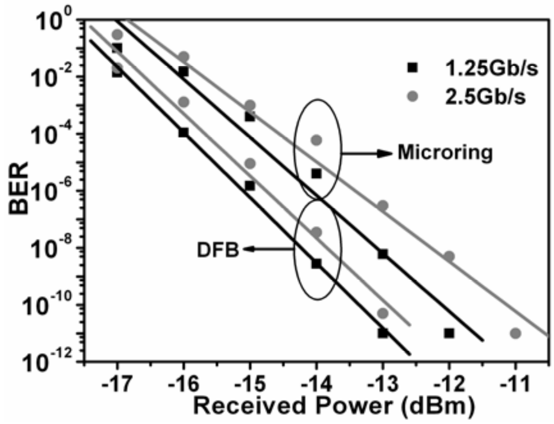

Fig. 4. BER measurements at 1.25 Gb/s and 2.5 Gb/s (50 km), for the microring and a DFB laser with the same ER.

A transmission experiment is also carried out using the microring lasers as data modulated sources for the first time to date. The signal from a 70 μm radius microring is amplified by an EDFA, filtered and launched into a 50 km single mode fiber. Error free transmission at 1.25 and 2.5 Gb/s is reported without dispersion compensation.

ER remains stable at 7.5dB for 1.25 Gb/s and reduces from 8 dB to 7.2 dB at 2.5 Gb/s and the corresponding eye diagrams are shown in figure 3.

A comparison with an edge emitting laser is made showing that microrings have comparable performance as shown in figure 4. In order to achieve a good extinction ratio a modulation depth in the order of 1V is needed which corresponds to a 5mA injection current span. Over this current span, a microring under CW operation hops through several cavity modes. Although the same mode oscillates at both ‘1’ and ‘0’ states, during the bit transitions, energy is transferred at different wavelengths resulting in a chirp like emission effect which is detrimental for the transmission properties of a directly modulated microring laser.

2.3 Wavelength Conversion

Next the usage of microring laser (MRL) as a wavelength conversion system is show. The MRL was biased above threshold and emitted at a wavelength λ_o, in single mode operation. Although MRLs are multimode devices in nature, they have proven to provide enhanced spectral purity characteristics due to the absence of spatial hole burning effects. In our case the MRL has a side mode suppression ratio (SMSR) as high as 35 dB without any wavelength selection mechanism.

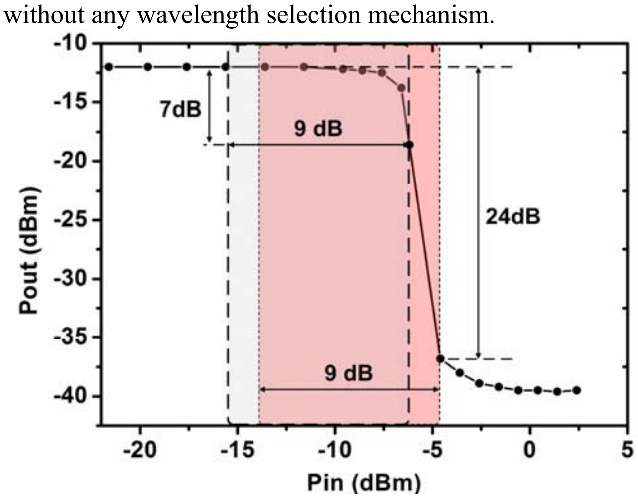

Fig. 5. Output power at 1539 nm against input at 1525 nm. The highlighted areas correspond to an input signal with extinction ratio ER = 9 dB. The darker area has sufficient logical ‘1’ power to switch off the main mode whilst the other suppresses the main mode to produce an output signal with ER = 7dB.

An intensity modulated (IM) signal at a wavelength λ_i was injected into the laser and caused a modulation of the carrier density in the gain section resulting in IM of the output signal at λ_o. Thereby, the information on the incoming signal at λ_i was transferred to the lasing wavelength λo. In figure 5, the output power at λ_o = 1539 nm is plotted against input power at λ_i = 1525 nm. A complete switch-off of the mode at λ_o is obtained, for input power exceeding -5dBm, which would theoretically lead to an extinction ratio (ER) of 24 dB.

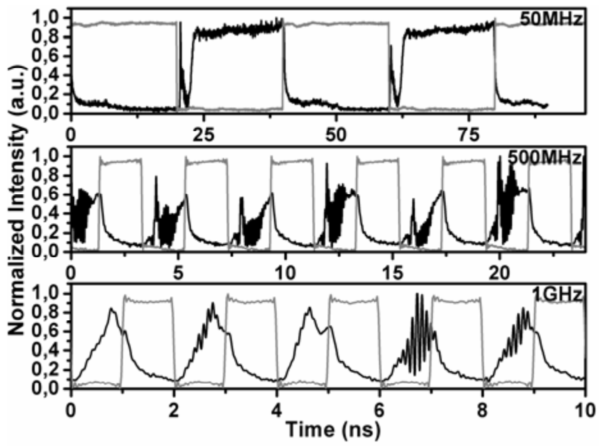

Fig. 6. Transient response (black line) for a clock input signal (gray line) that causes complete mode switching at frequencies: 50 MHz, 500 MHz and 1 GHz (top to bottom).

However, the transient response in this dynamic range is significantly limited by the required switching time of the laser modes which is in the nanosecond order. To better demonstrate this, the transient response of wavelength conversion for a clock input signal with frequencies of 50 MHz, 500 MHz and 1 GHz is shown in figure 6.

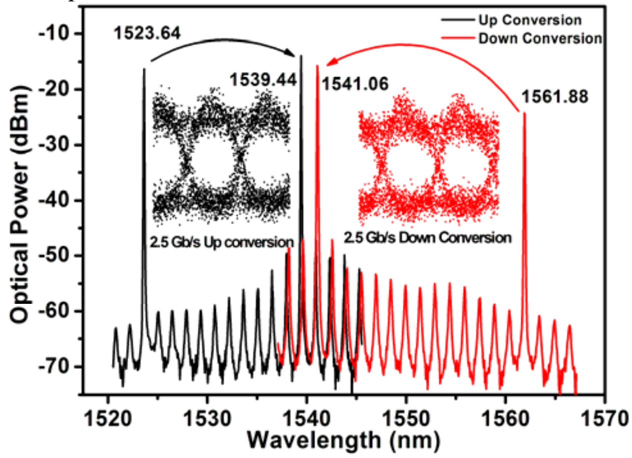

Fig. 7. Wavelength up and down conversion at 2.5 Gb/s. Spectra and eye diagrams with ER approx. 4 dB and high Q factor equal to 9.

The input optical power (P_{in} in figure 5) in these cases (varying approx. between -14 dBm and -5 dBm, as indicated in figure 5) is adequate to cause complete off-switching of the laser mode hence a high ER is measured. In this case the transient response of the output signal is affected by relaxation oscillations and mode competition phenomena occurring during the mode switch-on process. It is evident from the three time-traces that the switching time is in the nanosecond order which means that high ER, that comes with complete mode switching, cannot be achieved for high data rate applications in the Giga scale without severe distortion.

Nevertheless, wavelength conversion up to 5 Gb/s is possible by not switching off the laser mode completely, though at the expense of lower ER. In this case, the response bandwidth is limited by the gain dynamics associated with the carrier lifetime of the laser [9]. A 2.5 Gb/s modulated input signal at 1537 nm with 9 dB ER (input optical power P_{in} varying between -16 dBm and -7 dBm, as shown in figure 5) is up-converted to one of three successive laser modes (λ_1 = 1539.34, λ_2 = 1540.74, λ_3 = 1542.22 nm). The MRL supports mainly these three modes, attainable by adjusting the current injected in the device. Although this limits the output tunability of the conversion process, various methods that utilize MRLs can be used in future implementations to greatly extend the achievable wavelength coverage. Each of these modes is achievable by properly adjusting the injection current in a repeatable and systematic manner. Nevertheless, each mode is stable within a range of 1 mA having SMSR greater than 30 dB. The switching time required to tune the MRL between modes is measured to be below 1 μs which is well suited for λ-conversion applications.

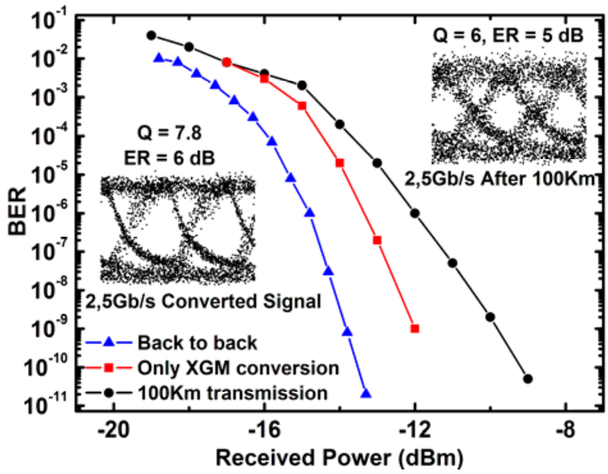

Fig. 8. BER measurements at 2.5 Gb/s for back-to-back, wavelength converted and propagated signal. The corresponding eye diagrams show an ER degradation from 6 to 5 dB and Q factor from 7.8 to 5. The input and output wavelengths in figure 8 are 1552.82 and 1541.06nm respectively.

On the other hand, input tunability is only limited by the gain bandwidth of the device which is approximately 40 nm. The input signal can be tuned to coincide with any MRL mode and the converted output resides at either one of the three laser modes depending on the injection current. Although the output wavelength tuning with injection current will slightly move the resonance peaks of the input wavelength as well, this can be addressed with proper adjustment of the temperature. In figure 7, the input tunability is shown, where successful up- and down-conversion is depicted from the output spectra and eye diagrams. The shown input values 1523.64 and 1561.88 are close to the extreme cases chosen for input tunability showing complete C-band wavelength coverage.

Next results are presented from a transmission experiment of 100 km with SMF at 2.5 Gb/s. In figure 8, the BER measurement and eye diagrams before and after transmission are demonstrated showing low power penalty of 2 dB, for an error-free conversion process. The power penalty after propagation of about 3 dB is reasonably low which indicates that the wavelength converter is suitable for metro and access applications. There is a tradeoff between high ER and Q-factor depending on the input power. This flexibility allows for a higher ER (6 dB) at the cost of Q-factor (7.8) when it comes to propagating the converted signal, assuming always ER of 9 dB for the input signal. In the insets of figure 8, the resulting eye diagrams after wavelength conversion and after the 100 km propagation in SMF are shown. The input and output wavelengths in figure 8 are 1552.82 and 1541.06nm respectively.

3 Conclusions

The modulation properties of vertically coupled microring lasers have been presented [14-15] showing successful -error free- operation up to 7 Gb/s and the potential to operate up to 10 Gb/s. A transmission experiment was also carried out showing error free transmission at 1.25 and 2.5 Gb/s over 50 km of single mode fibre without dispersion compensation proving for the first time the possibility of microring lasers serving as sources in communications systems such as access and metro optical networks.

Wavelength conversion using self pumped cross gain modulation in a microring laser vertically coupled to a passive waveguide was also presented [16]. Successful conversion at 2.5 Gb/s along with a 100 km transmission was demonstrated. Tunable conversion from almost any wavelength of the gain bandwidth to any of the three supported modes of the laser was shown. Future implementations that can accomplish tunable output, i.e. double ring lasers, could greatly enhance the tunability of the conversion process, hence providing a cost effective integrated solution for metro and access optical networks.

More results published or pending publication in other applications other than those shown here can be found in [17-20].

References

1. D. Alexandropoulos, A. Kapsalis, D. Syvridis, "Suppression of higher order modes in vertically coupled micro-ring resonators," Microwave and Optical Technology Letters Vol. 49, No. 12, pp. 2963-2968, (2007)
2. M. Kusko, A. Kapsalis, C. Kusko, D. Alexandropoulos, D. Cristea and D. Syvridis, "Design of single-mode vertically coupled microring resonators", J. Opt. A: Pure Appl. Opt. 10 (2008)
3. M. Kusko, D. Alexandropoulos, C. W. Tee, A. Kapsalis, D. Cristea, D. Syvridis, C. Kusko, "Numerical analysis of microring resonator obtained by wafer-bonding technology", Proceedings of the SPIE, Volume 5956, pp. 349-360 (2005)
4. D. Alexandropoulos, A. Kapsalis, D. Syvridis, U. Troppenz, M. Hamacher H. Heidrich, "Design considerations for spatial monomode operation of InP-based passive vertically

coupled microring resonators", Proceedings of the 5th International Conference on Numerical Simulation of Optoelectronic Devices, NUSOD '05, pp. 119- 120 (2005)

5. M. Kusko, A. Kapsalis, C. Kusko, D. Alexandropoulus, D. Cristea, D. Syvridis, "Design of single-mode vertically coupled microring resonators," 2nd European Optical Society Topical Meeting:" OPTICAL MICROSYSTEMS ", 30 Sept. – 3 Oct. 2007, Capri (Napoli), Italia, post dead-line paper
6. I. Stamataki, S. Mikroulis, A. Kapsalis, D. Syvridis, "Investigation on the Multimode Dynamics of InGaAsP/InP Microring Lasers", IEEE Journal of Quant. Electronics, vol. 42, no. 12, pp. 1266-1273(2006)
7. A. Kapsalis, I. Stamataki, S. Mikroulis, D. Syvridis, M. Hamacher, "Widely Tunable All-Active Micro-Ring Lasers", IEEE Phot. Techn. Lett., vol. 18, no. 24, pp. 2641-2643 (2006)
8. I. Stamataki, A. Kapsalis, S. Mikroulis, D. Syvridis, M. Hamacher, U. Troppenz and H. Heidrich, "Modal properties of all-active InGaAsP/InP microring lasers", Optics Communications, Volume 282, Issue 12, p. 2388-2393 (2009)
9. A. Kapsalis, D. Alexandropoulos, S. Mikroulis, H. Simos, I. Stamataki, and D. Syvridis, M. Hamacher, U. Troppenz, and H. Heidrich, "Spectral properties of all-active InP-based microring resonator devices", Proceedings of the SPIE, Volume 6115, pp. 386-394 (2006)
10. A. Kapsalis, I. Stamataki, D. Syvridis, M. Hamacher, "Widely Tunable All-Active Micro-Ring Lasers through Phase Shifted Controlled Feedback", We 3.52 ECOC 2006
11. M. Hamacher, U. Troppenz, H. Heidrich, V. Dragoi, A. Kapsalis, D. Syvridis, C.W. Tee, K.A. Williams, M. Alexe, M. Kusko, D. Cristea, "Vertically coupled microring laser devices based on InP using BCB waferbonding," CLEO-Europe IQEC 2007, 17-22 June 2007, Munich, Germany
12. M. Hamacher, H. Heidrich, U. Troppenz, D. Syvridis, D. Alexandropoulos, S. Mikroulis, A. Kapsalis, C.W. Tee, K.A. Williams, V. Dragoi, M. Alexe, D. Cristea, M. Kusko, "Waferbonded Active/Passive Vertically Coupled Microring Lasers," SPIE Photonics West - LASER 2008, January 19-24, 2008, San Jose, California, USA, paper no. 6896-27
13. M. Hamacher, U. Troppenz, H. Heidrich, V. Dragoi, A. Kapsalis, D. Syvridis, C.W. Tee, K.A. Williams, M. Alexe, M. Kusko, D. Cristea, "Vertically Coupled and Waferbonded μRing Resonators on InP," European Semiconductor Laser Workshop 2007, 14 – 15 Sept. 2007, Berlin, Germany
14. A. Kapsalis, U. Troppenz, M. Hamacher, H. Heidrich and D. Syvridis, "7Gb/s Direct Modulation of Vertically Coupled Microring Lasers," OFC 2008, 24-28 February 2008, San Diego, California, USA
15. D. Syvridis, H. Simos, S. Mikroulis, and A. Kapsalis, "Microring-based devices for telecommunication applications," Proceedings of the SPIE, Vol. 7211, (2009)
16. A. Kapsalis, H. Simos, D. Syvridis, M. Hamacher, H. Heidrich, "Tunable Wavelength Conversion using Cross Gain Modulation in a Vertically Coupled Microring Laser," IEEE Phot. Techn. Lett., vol. 21, no. 21, pp. 1618-1620 (2009)
17. A. Kapsalis, D. Syvridis, M. Hamacher, H. Heidrich, "Broadly Tunable Laser using Double-Rings Vertically Coupled to a Passive Waveguide", IEEE Journal of Quantum Electron., vol. 46, no. 3, pp. 306-312 (2010)
18. A. Kapsalis, C. Mesaritakis, D. Syvridis, "Design and Experimental Evaluation of Active-Passive Integrated Microring Lasers", ESWL Lauzanne (2011)
19. A. Kapsalis, I. Stamataki, C. Mesaritakis, D. Syvridis, M. Hamacher, H. Heidrich, "Design and Experimental Evaluation of Active-Passive Integrated Microring Lasers: Threshold Current and Spectral Characteristics", submitted for publication to IEEE Journal of Quantum Electron. (2011)
20. A. Kapsalis, I. Stamataki, C. Mesaritakis, D. Syvridis, M. Hamacher, H. Heidrich, "Design and Experimental Evaluation of Active-Passive Integrated Microring Lasers: Noise Properies", submitted for publication to IEEE Journal of Quantum Electron. Semiconductor Optoelectronic Devices special issue (2011)