Active ring resonators based on GaInAsP/InP

Michael Hamacher*, Ute Troppenz, Helmut Heidrich, Dominik Gerhard Rabus
Heinrich-Hertz-Institut für Nachrichtentechnik Berlin GmbH,
Einsteinufer 37, D-10587 Berlin

ABSTRACT

Compact integrated microring resonators are promising candidates for various applications in optical signal processing and communication such as optical filters, wavelength (de)multiplexers, single mode sources, dispersion compensators and wavelength converters. Active GaInAsP/InP material is particularly suited for the fabrication of "lossless" filter devices as well as novel laser components with outstanding performance. Design, technology as well as transmission / emission mode characteristics for typical applications are sketched and summarized.

Keywords: InP, filters, resonators, optical couplers, micro resonators, MMI

INTRODUCTION

In a future broadband Internet network most of the traffic passing the optical nodes will require wavelength management functions for flexible signal processing and routing and overall capacity increase [1]. Functionalities within an Optical CrossConnect (OCX) such as separation and processing of the incoming headers, separation and transparent transportation, and reassembly of the payloads include wavelength routing and wavelength switching [2], optical demultiplexing [3], and wavelength conversion (cf. [1]). Components for optical signal processing in the wavelength/space domain and time/space domain are becoming a key issue being strongly related to Photonic Integrated Circuits (PICs) based on active ring resonators.

Below a bit rate limit of a few 10 Gb/s the application of resonant devices is coming into focus as the efficiency is increased in resonant structures. In the case of a linear resonator the cavity can be defined by Bragg gratings or highly reflective facet coatings resulting in multiple bi-directional reflections. In the case of rings clockwise and counter-clockwise signals are propagating independently. Multiple rings can be coupled forming novel filter functionalities in analogous to electronics (e.g. box-like filter response). The Free Spectral Range (FSR) of a cavity is determined by the cavity roundtrip period. The increase of the FSR is inversely proportional to the cavity length. As the filter quality and the power enhancement are very sensitive to resonator losses an integrated optical amplification function is indispensable for cascaded ring structures and for highly efficient and high performance devices.

Here we sketch approaches in technology and components of active ring resonators based on GaInAsP/InP and open up perspectives on applications.

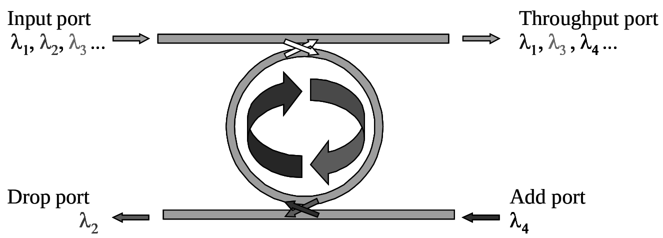
* e-mail: hamacher@hhi.de, phone: ++49 30 31002-408, fax: ++49 30 31002-551

RING RESONATOR APPLICATIONS

A scheme of a ring resonator acting as a "basic" cell is shown in Fig. 1. Depending on the required functionality it consists of one or two straight bus waveguides coupled to a microring cavity in between. The ring acts as an optical reservoir to accumulate the power only at such wavelengths matching the phase condition in resonance for constructive superposition. Ring resonators operate very similar to Fabry-Perot (FP) resonators, however, the interaction occurs in one propagation direction, clockwise or counter-clockwise. In contrast to FP resonators they do not require any additional mirrors or reflecting facets for optical feedback. The amount of light which couples in and out of the ring is determined by couplers whose coupling efficiency affects directly the "reflectivity" of the resonator.

This "basic" cell can roughly be divided into three building blocks: the feeding bus waveguide(s), the coupler(s) and the ring resonator itself.

The main task of the bus waveguides is on the one hand to enable an efficient low loss fiber-chip coupling but also to facilitate a nearly "lossless" and monomodal propagation of the light within the chip. There are in principle two possible waveguide structures, which can be utilized: the buried ridge- and the ridge waveguide. The buried ridge stripe assures both an excellent coupling to an external fiber and possible polarization insensitivity due to a nearly radial symmetrical field distribution. However, the index contrast between the core and the cladding is in general too low to support a sufficiently strong guiding which is essential for realizing sharp curvatures. In the InP material system for ring resonator applications the ridge waveguide architecture is favored despite lower polarization tolerances and more challenging fiber coupling. In a recent work [4] a polarization independent so-called highmesa waveguide has been designed and fabricated. To minimize the fiber/chip coupling losses our integration concept enable the implementation of spot-size converters [5].



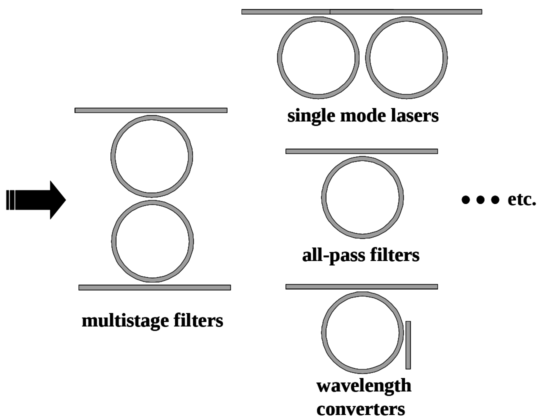


Fig. 1 Left**:** Single microring resonator coupled to two straight bus waveguides: the on-resonance wavelengths λ_2 and λ_4 can be dropped and added, respectively, whilst the off-resonance wavelengths λ_1 and λ_3 rest in the waveguide and can be detected at the throughput port.

Right: Ring resonator architectures for various functionalities

There are mainly two different possibilities to couple light from the bus into the ring and vice versa. Either co-directional couplers or multi-mode interference couplers (MMI) can easily be implemented depending on the required coupling ratio. The first approach uses planar directional couplers of any designed coupling strength. The narrow separation gap of the waveguides is in the order of a few 0.1 microns and requires high performance contact lithography or electron-beam writing for the fabrication. The MMI coupler is favored for 3 dB coupling due to its fabrication tolerance. As matching of the coupling condition is of crucial importance for the filter performance, accurate fabrication of the coupler is essential. The coupling factor has a strong influence on the quality factor of a ring resonator, additionally it influences directly the crosstalk level of the device and must therefore be controlled very precisely. In particular for the fabrication of directional couplers the vertical coupling scheme is advantageous where the critical separation gap can be adjusted accurately by epitaxial growth or other deposition techniques. Another advantage is that the feeding waveguides and the resonator itself can be grown with different material compositions in a single epitaxial growth step. This facilitates the design of novel active/passive ring resonator architectures like modulators [6], microdisk lasers [7] or biosensors [8], but increases the technological effort. In this paper we focus on lateral coupling and standard lithographical techniques.

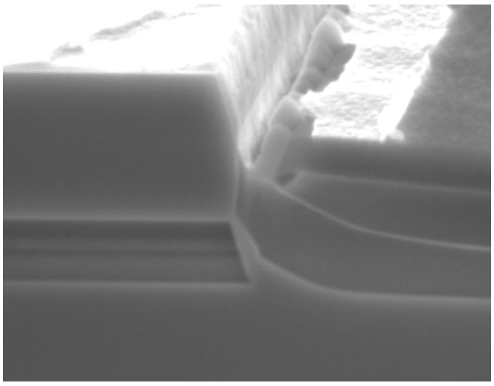


Fig. 2: Micrograph of the laser/waveguide interface fabricated by selective area MOVPE regrowth. SiNx on top of the whole structure assures a sufficient passivation.

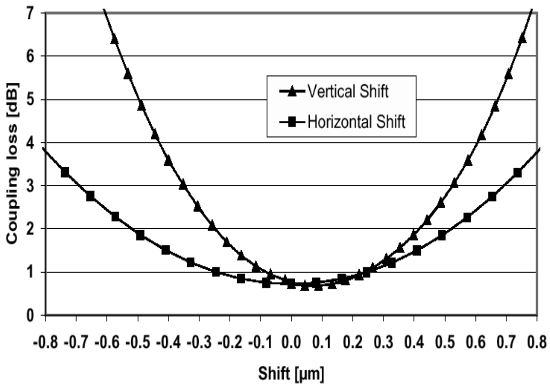


Fig. 3: 2-dim. FDM calculation of the butt coupling losses caused by fabrication tolerances.

The ring itself consists of well confined curvatures of different radii. When the center of an optical field moves more and more into the margin of the waveguide rib, bending losses as well as radiation losses by surface roughness and sidewall imperfections influence the power budget negatively. To reduce the bending loss the index step is asymmetrically increased by deeply etched regions in the outer part of the bends. Different propagation constants for the polarization states TE and TM result in different resonator conditions. The problem of polarization conversion [9] which can occur at the transition between the bus waveguide(s) and the curvatures and within tight bends can be minimized by a proper choice of waveguide geometries and material composition. No polarization conversion has been observed in architectures presented here.

In general the performance of ring resonators is mainly limited by internal losses like radiation losses due to sharp bend radii, scattering losses due to waveguide imperfections and coupling losses due to not ideal coupling. The implementation of semiconductor optical amplifier (SOA) sections in the ring for loss compensation is indispensable for a high performance filter response. Even better device performance is feasible by using active semiconductor laser material for the whole device. These two different types of integrated InP based ring resonators have been fabricated and investigated experimentally.

1. FABRICATION AND TECHNOLOGY

The fabrication of “SOA-ring resonator” type and the “all-active ring resonator” type devices is based on the following fabrication process, which is derived from a standard ridge waveguide laser process.

In the case of an all-active fabrication process, the bus waveguide(s) as well as the resonator structure(s) and the coupler(s) consist of active waveguide material which was epitaxially grown on an InP:Sn substrate. The epitaxial layer structure from top to bottom is as follows : p^+-InGaAs (0.2 µm), InP (1.3 µm), 6 quantum wells (λ_g = 1.29 µm), n^+-InGaAsP (λ_g = 1.15 µm; thickness = 0.2 µm). To assure a monomodal propagation of the light the width of the waveguide was designed between 1.8 µm and 2.1 µm. The waveguides are formed using reactive dry etching technologies in a CH_4/H_2 plasma. In order to reduce the formation of polymer which influences sidewall roughness and surface imperfections during the etching process a small portion of oxygen is added. For fabrication of co-directional couplers with separation gaps of 0.8 µm and lower the corresponding high aspect ratios (aspect ratio = etch depth/separation gap) have to be taken into account. This results in different etching depths in the gap region and in the outer parts and hence, influences the coupling ratio and is exploited to realize shorter coupling lengths. To reduce radiation losses due to leakage deeply etched sections down to the n-contact layer are implemented in the curvatures to increase the effective index step. The p- and the n-contacts are formed using both sputtering and evaporation techniques, a SiNx passivation layer is deposited and bondpads are applied on top of its surface. The p-contacts are reinforced by anodic gold metalization for a preferably low electrical resistance to assure a uniform driving current over the whole waveguide area. The device is cleaved and both facets are antireflection coated to minimize parasitic resonances.

In the case of an "SOA integrated ring resonator" the above mentioned fabrication process is modified after forming the SOA islands: in a further epitaxial growth step using the selective area MOVPE regrowth, the waveguide layers consisting of a semi insulating GaInAsP slab (height: 0.38 µm) and a semi insulating GaInAsP rib (height: 0.84 µm) both with a material bandgap equivalent wavelength of 1.06 µm are grown in a single run (cf. Fig. 2). In the following the laserstripe and the waveguide are etched down simultaneously by a self defining process for optimum lateral alignment. Butt coupling losses of 2 dB for each butt-joint have been measured. Certainly these losses must be compensated by the SOA, therefore the length of the amplifier section must be chosen sufficiently large. Further processing steps are comparable to the "all-active ring resonator".

2. ACTIVE OPTICAL FILTERS

Active loss compensation in ring resonators can be performed, as mentioned above, in two different ways: One approach is using an integrated SOA section, the other is based of all-active material.

WAVELENGTH FILTERS WITH INTEGRATED SOA SECTIONS

SOA sections have been implemented in the ring of each ring independently. Due to the trade-off between miniaturization and the required SOA length, the ring circumference and so the free spectral range is limited. Furthermore the quality of the epitaxial interface between the SOA section and the passive waveguide bends depends strongly on the proper height adjustment of the multiple epitaxial layers. Calculations using the 2-dimensional finite difference method have been made to estimate the expected losses at the butt-joint as shown in Fig. 3. A typical interface for well accrued waveguide layers are shown in a micrograph in Fig. 2. Experimentally the butt-joint losses have been determined using passive straight waveguides with integrated SOAs of different lengths. Measured butt-coupling losses of only 2 dB/interface indicate the quality and a smooth transition between the laser stack and the waveguide in agreement with the theoretical estimate.

Increasing demands for filter applications like improved out-of-band rejection and steeper roll-off lead to modified architectures like multiple ring structures where the rings can be arranged serially or in parallel. Exemplarily a device operating as an add/drop (de) multiplexer is depicted in Fig. 4 using two cascaded rings. Two 3 dB MMI couplers in the feeding waveguides (length = 150 µm, width = 6 µm) and a codirectional coupler (length = 150 µm, gap = 1 µm, power coupling = 0.05) in between the rings power the two ring resonators, both with a radius of 347 µm, and 500 µm long amplifier sections. The overall cavity length was designed for an FSR of 25 GHz. Additional Pt-resistors have been implemented within the ring on top of the waveguides. Due to a local heating effect by applying a voltage on each pair of Pt-heaters the effective index can slightly be changed for tuning the optical length in a particular resonator to a specific wavelength and/or to match the resonances in multiple coupled ring resonators.

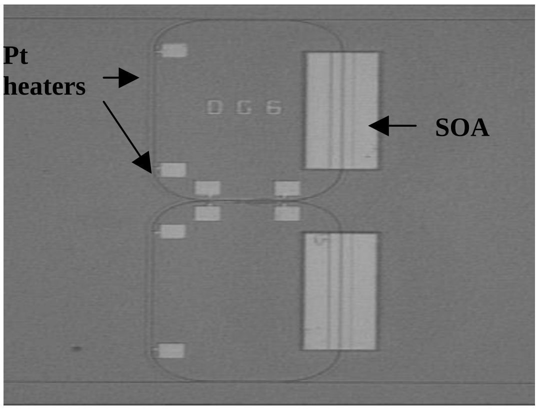


Fig. 4: Photograph of a double ring resonator with integrated SOAs and Pt heaters for fine tuning.

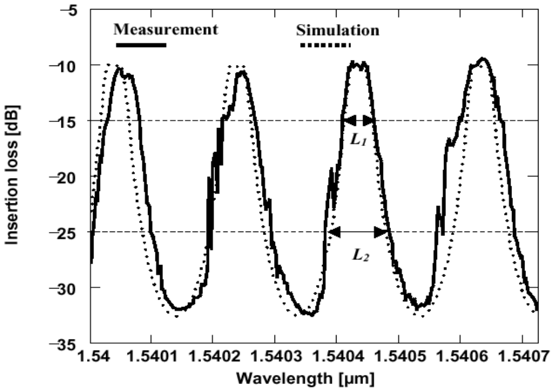


Fig. 5: Corresponding response for the drop port of Fig. 4 with an FSR of 25 GHz and an on/off ratio of 22 dB.

Fig. 5 shows the corresponding transmission characteristic for the drop port with an on/off ratio of 22 dB. Simulation and measurement are in good accordance. The designed and measured shape factor (bandwidth @ - 5 dB / bandwidth @-15 dB) for this architecture is 0.5, the full width at half maximum (FWHM) was measured to be 0.04 nm. The quality of a ring is often defined by the finesse F (= FSR/FWHM) which was calculated to be 5.

To set the operating point for the SOA it has to be taken into account that, for a typical filter application as shown here, the task of the amplifier section is only to compensate the losses of the device i.e. the amplitude factor α_0 ($\alpha_0 = \exp(-g*L/2)$ with g = power loss/gain coefficient, L = ring circumference) which describes the power budget in the device, is slightly less than 1. If the SOA is switched off it acts as an optical baffle. For this application each SOA driving current was set to 50 mA.

"ALL-ACTIVE" ALL-PASS FILTERS / DISPERSION COMPENSATORS

Optical delay lines, all pass filters or infinite impulse response filters can be used in wavelength division multiplexed (WDM) applications for dispersion compensation and in optical time division multiplexing (OTDM) applications for synchronization purposes. In contrast to other dispersion compensating techniques like dispersion compensating fibers, Mach-Zehnder configurations or Bragg gratings, ring resonators as shown in Fig. 6 allow to generate time delays by tuning the group velocity dispersion in an effective way by resonance enhancement of the feedback path [10,11].

The group delay depends on the circumference length and on the coupler properties, which influence the cavity photon lifetime. By using SOA-integrated or all-active ring resonators, "lossless" all-pass filters can be designed with a unity magnitude response. In this case, the amplitude factor α_0 equals 1. Recent papers [cf. ref. 10,12] have shown a significant improvement in dispersion compensation by cascading multiple single ring filters. Additionally, by using phase shifters in each filter stage, the overall phase response can be designed to any desired shape.
We have investigated the delay time introduced by our active ring filters as a function of wavelength. By using an external cavity laser combined with an optical modulator a 1 GHz sinusoidal probe signal was generated. The time delay caused by the ring resonator was measured with respect to a reference signal via a fast external photodiode and a digitizing time scope.

Experimental results obtained for a 50 GHz active ring resonator as shown in Fig. 6 are depicted in Fig. 7. The delay time rises up to approximately 80 ps at the resonance wavelengths. Close to the resonance wavelengths a dispersion slope of ±280 ps/nm was obtained within a bandwidth of 5 GHz.

Fig. 6 : "all-active" ring resonator for phase compensation with a bend radius of 250 µm

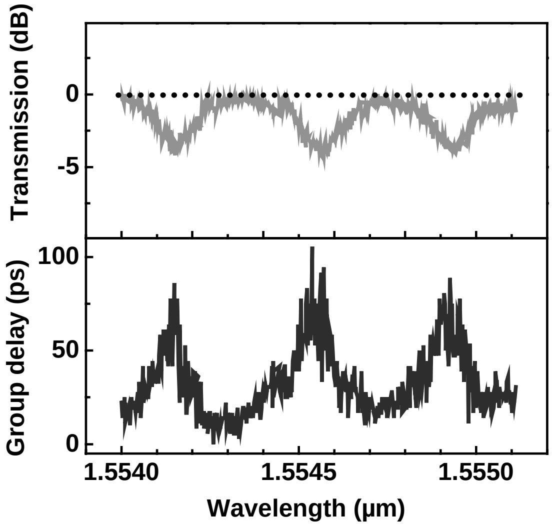


Fig. 7: Response of the transmitted signal (cf. Fig. 6) and the corresponding group delay which was measured to be up to 80 ps. The dashed curve shows the ideal all-pass filter spectrum.

This result agrees well with the simulated impulse response for a ring filter element including a co-directional coupler with a power coupling ratio of 0.6.

A remaining amplitude modulation of 3 dB in the transmission characteristic of Fig. 7 indicates that the internal ring losses are not completely compensated. Due to an insufficiently antireflection coated facet no further increase of ring current for loss compensation was feasible. In addition, a slight increase of the injected currents switch the device to the amplifying mode which has to be suppressed for this further application.

3. SINGLE MODE RING LASERS

Ring lasers are attractive as compact light sources in photonic integrated circuits since neither cleaved facets nor gratings are required for optical feedback [13,14,15]. Depending on the chosen ring driving current "all-active" ring resonators allow to switch the functionality of the device from filter mode ($\alpha_0 < 1$) to emission mode ($\alpha_0 > 1$) very easily.

An investigated device is shown in Fig. 8 consisting of two coupled ring resonators, both with a radius of 50 µm. The rings, the couplers and the bus-waveguides can be driven independently by separate electrical contacts. Very similar to a Fabry-Perot laser each ring generates an individual slightly shifted comb like laser spectrum with respect to the driving current. Wavelength tuning to specific single mode emission is achieved using the Vernier effect. Fig. 9 shows a measured single mode spectrum. This structure reveals a high side mode suppression ratio of > 40 dB and a maximum output power level of 6.5 mW per facet (@250 mA) was obtained.

To assure monomode operation with a single ring resonator small radii are essential. Due to the large FSR only one longitudinal mode can propagates near the gain maximum. But this may influence the achievable output power level. Due to the independence of the clockwise and counter-clockwise propagating ring modes a high insensitivity against external reflections is expected.

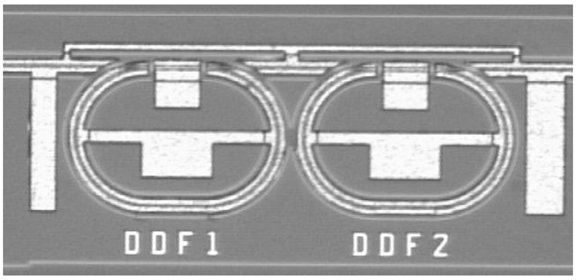


Fig. 8: Micrograph of a double ring resonator as single mode laser

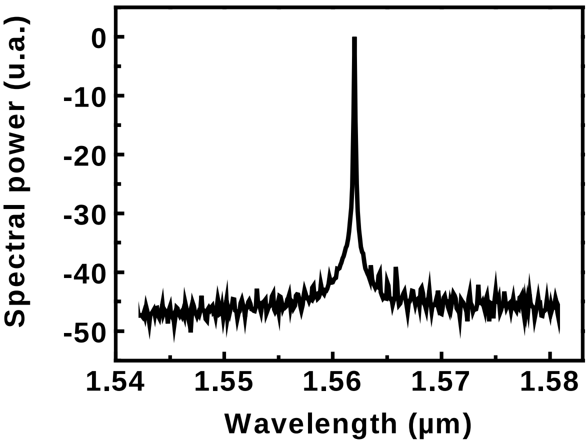


Fig. 9: Corresponding single mode spectrum with a side mode suppression ratio of 40 dB and an output power of 6.5 mW /facet.

An alternative approach for the fabrication of tunable single-mode lasers by using a combination of Fabry-Perot cavities has been proposed [16,17]. The passive ring resonators providing a Fabry-Perot cavity are coupling only radiation at resonance wavelength into SOA elements. SOAs without current injection are used as absorbers in the unused "blind arms" of the structure. Control of the single-mode emission was performed using the Vernier effect by tuning the optical length of the ring resonators with respect to each other. An improvement in linewidth and in frequency chirp is simulated.

4. WAVELENGTH CONVERTERS

Using the four-wave mixing (FWM) effect, active ring resonators enable efficient wavelength conversion for all optical communication systems. Based on GaAs or InP they are combining both, the advantages of a high nonlinear susceptibility and the high linear gain. In contrast to other active resonant structures like DFB lasers or SOAs, ring resonators may enhance both, the optical power of the signal wave at frequency ω_s and that of the conjugated wave at ω_c. Maximum conversion efficiency is achieved, when ω_s and ω_c fit the resonance wavelength of the ring. No stop band has to be taken into account, but of course, operating in the "non-resonant mode" the component will have a reduced conversion efficiency. The internal optical field enhancement and the FSR can simply be designed by the circumference and the power coupling ratio between ring and bus-waveguides in the ring resonator structure.

In a recent work [18] a passive GaAs microring resonator was used to demonstrate wavelength conversion by four wave mixing with an improved conversion efficiency compared to a straight waveguide. The increase in efficiency was attributed to the increase of interaction length and the enhancement of optical power inside the cavity. However, substantial optical propagation losses still limited the overall performance.

A further improved conversion efficiency is expected for ring resonators built as an "all-active" ring resonator. We investigated an active ring resonator architecture as shown in Fig. 10 with a ring radius of 182 µm including two 160 µm long MMI couplers to couple the light from the straight bus waveguide into the ring an vice versa. Analog to FWM in DFB lasers [19,20], the ring cavity itself can be used as the pump signal source. A proper choice of the driving currents provides a sufficient side-mode-suppression ratio of greater than 35 dB. The device was tested with an external cavity laser (ECL) acting as a cw-signal source. The result of this experiment with a cw-output power of +2 dBm measured in the feeding fiber is shown in Fig. 11. From the output power a conversion efficiency of - 5dB is derived. Taking into account that the input signal will be increased due to the high power enhancement of the active

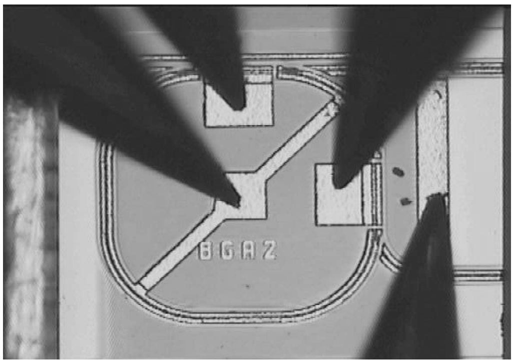


Fig. 10: Micrograph of a single ring resonator as a wavelength converter with two MMI couplers in between the ring cavity.

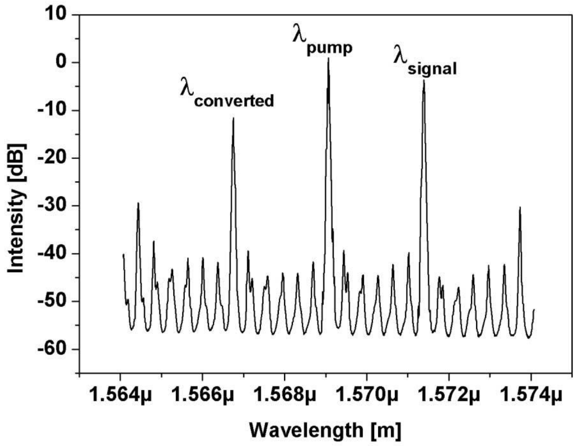


Fig. 11: Optical cw-spectrum measured at the throughput port exhibiting a conversion efficiency of -5 dB (relation of the intensities in the feeding fibers).

ring structure, the conversion efficiency can be corrected by a factor of +8 dB. This results in an “effective” conversion efficiency of +3dB. We investigated the influence of different input power levels on the conversion efficiency which is shown in Fig. 12. Efficiencies of up to +5 dB could be derived for input power levels lower than 0 dBm.

Instead of selecting a single mode laser spectrum by small ring radii and/or a proper choice of driving currents as mentioned above, it is also feasible to get a mode selection by injection locking. If the frequency of the master laser (in the test set-up a second ECL, amplified by an erbium-doped fiber amplifier) is close enough to the ring resonator’s free-running frequency and the signal amplitude is large enough, the device is locked to the master frequency over a certain bandwidth. This approach may be favored for practical use in a real system in order to realize a well controlled resonator of specified FSR for FWM and to control the pump signal by injection locking in a separate device (master laser).

To demonstrate the FWM capabilities of the device an all optical cw-channel switching experiment was performed using a structure as shown in Fig. 13. In this experiment cw-signal at ω_S was kept fixed at a ring resonance wavelength of 1567.9 nm. For maximum conversion efficiency the the injection locked pump wavelength ω_P was chosen to fit the ring resonances. When the detuning is changed stepwise by multiples of the FSR the conjugated signals at $\omega_C = 2\omega_P - \omega_S$ fit the ring resonances too. In this way the conversion efficiency can be kept at a maximum level over a detuning range of certain FSRs, which could be verified in the experiment. Due to a high coupling factor of 0.7, the enhancement effect of the ring is limited and a conversion efficiency of approximately –20 dB was obtained.

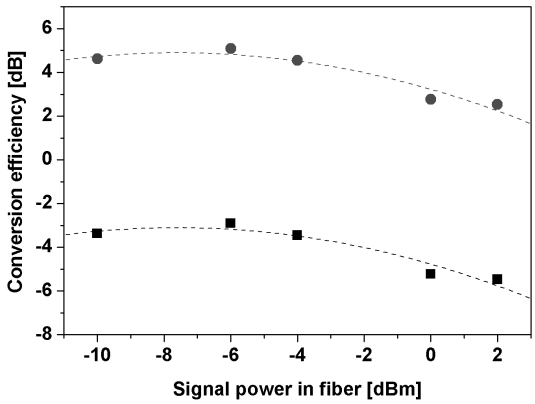


Fig. 12: Influence of the signal power level on the conversion efficiency with (circles) and without (squares) correction of signal amplification factor

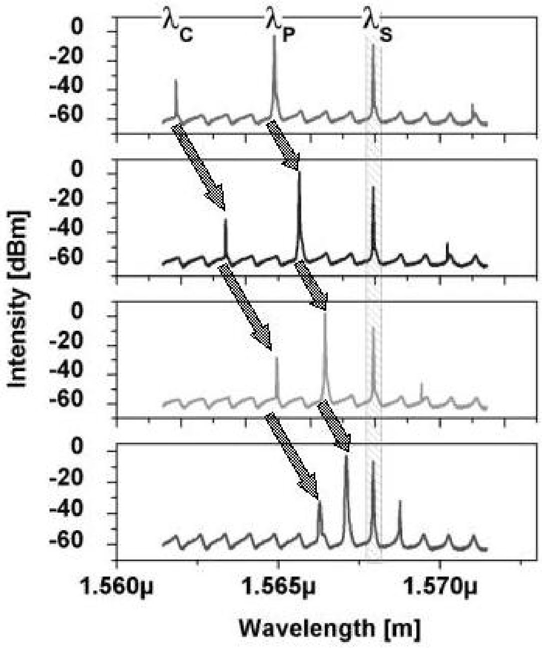


Fig. 13: All optical channel switching experiment in cw-operation using injection locking. The signal wavelength is fixed and the pump wavelength routes the conjugated signal.

CONCLUSION

Today's networks are dominated by the traffic and the data demands of Web surfers and big companies. Therefore, the huge increase of the Internet community is one of the main driving factors for the realization of a broadband Internet with its ultimate goal of a dynamic, flexible and widely transparent network topology. On the physical layer optical signal processing in the wavelength/space domain and time/space domain is becoming a key issue being strongly related to multifunctional Photonic Integrated Circuits (PICs) based on active ring resonators.

In this contribution we focused on approaches in technology and first components of active ring resonators based on GaInAsP/InP. As the filter quality and resonance enhancement is very sensitive to the resonator losses an integrated optical amplification function is indispensable for cascaded ring structures and for high efficiency and high performance devices. The implementation of an optical amplifier functionality can be realized by integration of semiconductor optical amplifier sections within the individual ring resonators or by using "all-active" material in the whole structure. First results were given on single and multiple ring filters as well as add/drop multiplexers, fine tuning of the filter response by integrated Pt-heaters, filter and comb laser response of all-active ring resonators with multi-segmented electrodes for individual current injection into the feeding waveguide, coupler, and ring sections. Furthermore the versatility of active ring resonators could be demonstrated in "lossless" all-pass filters for dispersion compensation, effective single mode lasers and, using the high nonlinear susceptibility and the high linear gain in this material for wavelength conversion by four-wave mixing.

The broad spectrum of functionalities of ring resonators will produce a new generation of innovative components for application in optical communication as well as in spectroscopes and sensors.

ACKNOWLEDGEMENTS

Part of the work was performed within a project: "Innovative Laser and Filter Components Based on GaInAsP/InP Ring Oscillators 01 BC 925", of the national KomLaser-program funded by the Ministry for Education, Science and Technology (BMBF) of the Federal Republic of Germany and within the project “Realization of high order optical filters using multiple coupled microring resonators with incorporated SOA-sections” funded by the Deutsche Forschungsgemeinschaft (DFG).
The authors would like to thank all people involved in the subject .

REFERENCES:

1. K. Oguchi, M. Jinno, S. Norimatsu and T. Kitagawa, "Future fully wavelength furnished optical network and supporting technologies", SPIE vol. 3491, pp. 639-644.
2. S. Diez, R. Ludwig, H.G. Weber, "All-optical switch for TDM and WDM/TDM systems demonstrated in a 640 Gbit/s demultiplexing experiment", Electron. Lett., vol. 34, 803-805 ,1998.
3. W. Pieper, E. Jahn, M. Eiselt, R. Ludwig, R. Schnabel, A. Ehrhardt, H.J. Ehrke, and H.G. Weber, *System applications for all-optical semiconductor switching devices*, (Springer-Verlag London, 1997, ISBN 3-540-76143-8), Photonic Networks, 473-487.
4. S.-H. Jeong, H.Ch. Kim, T. Mizumoto, J. Wiedmann, S. Arai, M. Takenaka, and Y. Nakano, "Polarization-Independent All-Optical Switching in a Nonlinear GaInAsP-InP Highmesa Waveguide with a Vertically Etched Bragg Reflector", IEEE J. Quantum Electron., vol. 38, pp. 706-716 ,2002.
5. H. Heidrich and C.M. Weinert, “Integrated optical field transformer for adiabatic monomode field transformation**”**, German patent application, Appl. No. 101 23 137.7(30-04-2001).
6. I.-L. Gheorma and R. M. Osgood, "Fundamental Limitations of Optical Resonator Based High-Speed EO Modulators," IEEE Photon. Technol. Lett., vol. 14, no. 6, pp. 795-797, 2002.
7. K. Djordjev, Sang-Jun Choi, Seung-June Choi, and P.D. Dapkus, ”Active Semiconductor Microdisk Devices”, IEEE J. Lightwave Technol., vol. 20, no. 1, pp. 105-113, 2002
8. R. W. Boyd and J. E. Heebner, “Sensitive disk resonator photonic biosensor,” *Appl. Opt.*, vol. 40, no. 31, pp. 5742-5747, 2001.
9. C. van Dam, L.H. Spiekman, F.P.G.M. van Ham, F.H. Groen, J.J.G.M. van der Tol, I. Moerman, W.W. Pascher, M. Hamacher, H. Heidrich, C.M. Weinert, and M.K. Smit, “Novel Compact Polarisation Converters Based on Ultra Short Bends**”**, IEEE Photon. Technol. Lett., vol. 8, no. 10, pp. 1346-1348, 1996.
10. F. Horst, C. Berendsen, R. Beyeler, G.-L. Bona, R. Germann, H. W. M. Salemink, D. Wiesmann, “Tunable Ring Resonator Dispersion Compensators Realized in High-Refractive-Index Contrast SiON Technology**”**, Proceed. 26^{th} Europ. Conf. Opt. Commun., ECOC´2000, Munich (D), Postdeadline paper
11. G. Lenz and C. Madsen, “General optical all-pass filter structures for dispersion control in WDM systems”, IEEE J. Lightwave Technol., vol. 17, pp.1248, 1999.
12. C.K. Madsen, G. Lenz, A.J. Bruce, and M.A. Capuzzo, “Multistage dispersion compensator using ring resonators”, Opt. Lett., vol. 24, pp.1555, 1999.
13. L.A. Coldren. “Monolithic tunable diode lasers”, IEEE J. Select. Topics Quantum Electron., vol. 6, pp. 988-999, 2000.
14. B. Liu, A. Shakouri and J.E. Bowers, “Passive Microring-Resonator-Coupled Lasers”, Appl. Phys. Lett., vol. 79 pp. 3561-3563, 2001.
15. S. Park, S. Kim, L. Wang, and S. Ho, “Single-Mode Lasing Operation Using a Microring Resonator as a Wavelength Selector”, IEEE J. Quantum Electron., vol. 38, no. 3, pp.270-273, 2002
16. B.Liu, A. Shakouri, J.E. Bowers,”Passive microring-resonator-coupled lasers”, Appl. Phys. Lett., vol. 79, pp. 3561-3563, 2001.
17. IST project: http://www.ist-optimist.org/pdf/networks/pres_ecoc2002/NEWTON_ECOC2002.pdf
18. P. Absil, J.V. Hryniewicz, B.E. Little, P.S. Cho, R.A. Wilson, L.G. Joneckis, and P.-T. Ho, “Wavelength Conversion in GaAs Micro-ring Resonators**”,** Optics Letters, vol . 25, pp. 554 – 556, 2000.

19. T. Simoyama, H. Kuwatsuka, B.E. Little, M. Matsuda, Y. Kotaki, and H. Ishikawa, "High-Efficiency Wavelength Conversion Using FWHM in an SOA Integrated DFB Laser", IEEE Photon. Technol. Lett., vol. 12, no. 1, pp. 31-33, 2000.
20. B.E. Little, H. Kuwatsuka, and H. Ishikawa, "Nondegenerate Four-Wave Mixing Efficiencies in DFB Laser Wavelength Converters", IEEE Photon. Technol. Lett., vol. 10, no. 4, pp. 519-521, 1998.