InP-based high index waveguides on GaInAsP/InP for applications in active/ passive ring resonators

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ABSTRACT:

Miniaturization of waveguide circuits is inherently connected with the implementation of highly confined waveguides as one prerequisite for the building of sharp bends and optical microring circuits. Integrated optical ring resonators are promising candidates for compact optical filters and wavelength (de)multiplexers. Their realization in active semiconductor material opens the potential to verify "lossless" filter devices as well as novel laser components with outstanding performance. Since ring resonators do not require facets or gratings for optical feedback they are particularly suited for monolithic integration. Design and technology for device fabrication are summarized. Recent results on transmission and emission mode characteristics of fabricated passive ring resonators as well as gain-included “all-active” resonators in the transmission and emission mode are presented.

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

INTRODUCTION

Following Moore´s predictions in Silicon-microelectronics miniaturization is a more and more pressing issue also in integrated optics. This is valid especially in the application field of photonic communications with hard competition in the emerging market. Here, the evolution of WDM communication systems is generating an exploding demand on **O**ptical **C**ross**C**onnects (**OxC**) including optical space division switch matrices, WDM-(de)multiplexers, switchable **A**dd/**D**rop-**M**ultiplexers (**ADM**) and in particular, a huge amount of laser sources.

Up to now hybrid set-ups are the general solution for complex optoelectronic devices, where e.g. laser- and photodiode-OEICs, fiber based 3 dB-couplers , discretely integrated optical **A**rrayed **W**aveguide **G**ratings (**AWG**), **M**echanical **O**ptical **E**lectronical **M**icro**S**ystems (MOEMS) etc. are implemented. When integrated optics AWG-circuits are used these circuits are based on waveguides with relatively low optical confinement. Otherwise it will not be possible to perform the optical coupling with moderate coupling losses. As a drawback the typical chip area of these devices in the range of some millimeters by some centimeters, is rather large. Consequently, a monolithic integration with laser- or photodiode-OEICs (**O**pto-**E**lectronic **I**ntegrated **C**ircuit) would not have a chance on the market despite their benefits in reliability and compactness.

Progress in integration technology demands a crucial reduction of the waveguide circuit size. This is inherently connected with the implementation of highly confined waveguides in high index material compounds in order to realize sharp bends. E.g. **S**ilicon-**O**n-**I**nsulator (**SOI**) or SiON technologies are used for highly confined passive waveguide circuits. Obviously, quaternary III/V-semiconductor compounds based on GaAs or InP have to be considered for monolithic integration with active OEICs. With the application of high index material and strong optical confinement in waveguiding problems are arising caused by additional scattering losses due to surface roughness, coherent coupling losses and polarization conversion effects in sharp bends. Additionally a precise control of the processing conditions is required since there exists the necessity of realizing sub-micrometer structures with some 10 nanometer accuracy e.g. for the fabrication of directional couplers. Furthermore, new concepts for a low-loss optical interfacing to the fiber world have to be developed.

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Let´s come back to OxC-requirements: One of the key functions is optical filtering for WDM-channel multiplexing and selection of the spectrally spaced channels by a multiple of 25 GHz, e.g. 100 GHz, in the third spectral window of fibers (1.55 µm). A waveguide ring resonator is a novel building block for the realization of compact optical filters. Such components do not require facets or gratings for optical feedback and are thus particularly suited for monolithic integration. Excellent filter devices have been demonstrated as passive glass/polymer- [1], SOI- [2], polymer/SOI- [3], SiON-structures [4] and also on GaAs [5] and GaInAsP/InP [e.g. 6,7]. However, the strong **O**ptical **C**rosstalk **S**uppression (**OCS**) requirement in optical communication (OCS > 20…30 dB) seems to be an unreachable goal for passive devices. This problem can be overcome by integration of loss compensating semiconductor gain sections or by fabrication of so-called all-active ring-resonator structures. Favored components might be optical wavelength filters with well engineered spectral characteristics and dispersion compensators [4].

All-active ring-resonator devices enables the realization of novel optical amplifier and laser components. In a first approximation the microring-laser should have a very low feedback sensitivity since in contrast to the common ridge-waveguide (RW) laser clockwise and counter-clockwise propagating modes are superimposed with itself.

In this contribution we focus on recent results on the fabrication of microring resonator components with high index waveguides based on GaInAsP/InP: Passive ring resonators and SOA-integrated ring resonators for optical filter applications, as well as on all-active ring resonators (Section 3) for optical add/drop-multiplexing, dispersion filter applications, single mode ring lasers, comb lasers and functions based on nonlinear effects. The potential of all-optical signal processing operation will be discussed in a final section including issues on innovative functionalities such as all-optical switching, wavelength conversion and novel technologies for the realization of vertical coupling in two optical planes.

RING RESONATOR FILTER STRUCTURES

How should an ideal optical filter device look like? It's frequency response is a flat pass- or stopband with a rectangular box like shape[I] with a maximum roll-off. The extinction ratio (defined as the ratio between transmitted power at resonance wavelengths to that at non-resonant wavelengths) should be higher than 20 dB to achieve high wavelength selectivity and a low optical crosstalk between adjacent channels. The demand for narrow linewidth filters which are suitable for WDM applications require filter structures with high *Q-factors (Q-factor = free spectral range / bandwidth*). Such demands require low losses within the monomode coupled multiring cavities i.e. at highest priority strong guiding of the light in the bent waveguides in particular within the ring cavity.

Especially if sharp curvatures are needed, high contrast waveguides are required to assure monomodal propagation of the light at negligible losses. There are in principle two possible waveguide structures which can be used: the buried ridge- and the ridge waveguide. While the buried ridge stripe meets the demand for good coupling with an external fiber excellently and can be designed nearly polarization insensitive due to its geometry, the index difference between the core and the cladding is too small to support a sufficiently strong guiding in sharp bends. Therefore for InP based architectures the ridge waveguide was selected to be the best candidate for the filter. In general rib waveguides are polarization sensitive. To overcome this problem a polarization diversity architecture can be used. All required devices like polarization rotators and TE/TM splitters have already been developed on InP in the past [8,9]. For a well confined wave the center of the optical field moves more and more into the rib and therefore two problems have to be taken into account: the influence of sidewall roughness and surface imperfections are rising and so the reproducible fabrication of compact codirectional couplers require provoking technological techniques due to narrow separation gaps in the submicron range. One solution is to increase the confinement of the light within the ring. Therefore the index step of the ridge is asymmetrically increased by deeply etched regions only in the outer part of the waveguide bends.

It is well known that the propagation constant differs for the polarization states TE and TM resulting in different resonator conditions. The problem of polarization conversion which can occur at the transition between the curvature

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[I] The shape factor f = 1dB bandwidth / 10 dB bandwidth, e.g.[3], helps to qualify different filter characteristics (i.e f=1 means an ideal box like shape).

and a straight waveguide (i.e. in racetrack resonators) [10] can be minimized by a proper choice of waveguide geometries and material formation. In our case the polarization conversion is negligible. Fig. 1 shows calculated field distributions of an active straight waveguide (a) and a curved asymmetrically deep etched waveguide (b) using the conformal mapping technique[11]. Thereby the curved waveguide is transformed into an equivalent straight waveguide with a transformed index profile as sketched in the corresponding insert. The stronger optical confinement in case of the high index step is clearly shown in part b) of the figure. Our integration concept enables the implementation of spot-size converters to reduce the fibre-chip coupling [12].

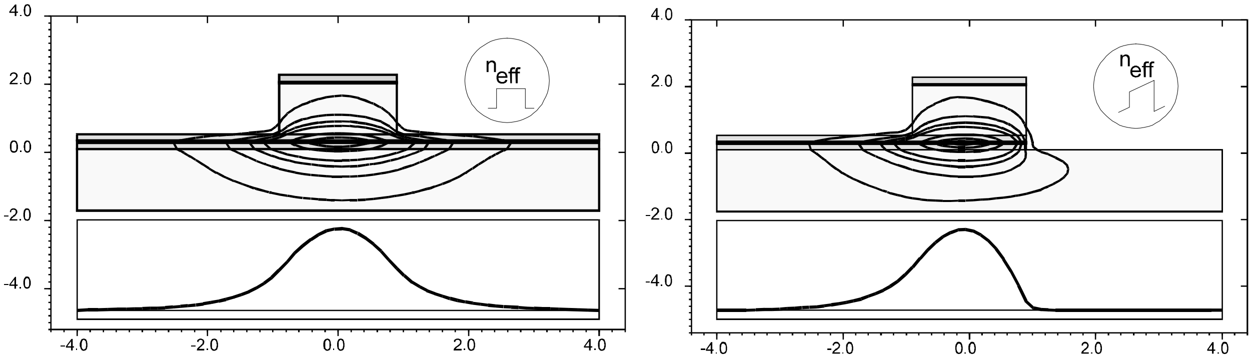

Fig. 1 FDM-calculated field distribution (TE polarization) of a straight (a) and a deeply etched curved waveguide (b), inserts illustrate the effective index profiles, for the curved waveguides conformal mapping of cylindrical to Cartesian coordinates is applied

Three types of integrated InP-based filter structures have been investigated experimentally: passive ring resonators, ring resonators with an integrated SOA (**S**emiconductor **O**ptical **A**mplifier) section for loss compensation and ring resonators based on all-active material. In the latter case the device is segmented into electrically isolated sections to adjust separately the gain or loss level in the ring, the coupler and the straight waveguide.

A generic view of a ring structure is shown in Fig. 2. It consists two "bus" waveguides coupled to a microring cavity in between. The optical reservoir which is a synonym for the resonator i.e. the ring accumulates the power only at selected wavelengths matching the phase conditions in resonance for constructive superposition. Such resonators operate equivalently to Fabry-Perot resonators, however, the superposition is performed in clockwise or counterclockwise direction. The required mirror is formed by a coupler and the "reflectivity" is determined by the amount of light, which couples into the ring defined by the coupling coefficient.

Directional couplers as well as multi-mode interference couplers are acting as optical valves to define the amount of light to be coupled into and out of the ring. This coupling ratio has a strong influence on the Q-factor of the ring resonator and is hence determining the crosstalk level of the filter components. For high Q micro cavities the width and the separation gap of these couplers must be controlled accurately. Using the electron beam writing technique for the definition of the waveguides helps controlling the critical dimensions, but this technique is very cost intensive due to the on-chip definition and the long exposure time. Therefore standard photolithographical techniques have been used. Anavoidable processing tolerances are limiting the device performance (e.g. precise structuring of the directional coupler´s gap, matching the effective index within the ring cavity).

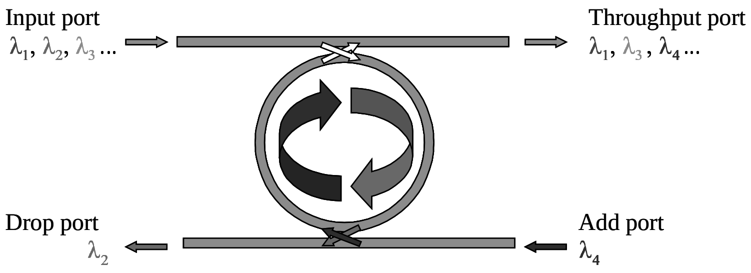

Fig. 2 Single microring resonator coupled to two straight bus waveguides: the on-resonance signals λ_2 and λ_4 can be dropped and added, respectively, whilst the off-resonance signals λ_1 and λ_3 rest in the waveguide and can be detected at the throughput port.

1. Passive Ring Resonators

The ridge waveguide used in the passive ring resonator devices is built of InGaAsP material with a bandgap-wavelength of 1.06 µm. A width of 1.8 µm was chosen for the ridge (fabrication details see footnote [II]) which guarantees monomode operation. 2 x 2 multimode interference couplers are used for splitting ratios of 3 dB as they exibit better tolerances against imperfections within the fabrication process than codirectional couplers. For the design of smaller coupling ratios co-directional couplers are implemented.

Different passive ring architectures as shown in Fig. 3 have been fabricated and analyzed: so called single ring resonators (SRR), where only one ring cavity is used, and also double ring resonators (DRR) consisting of two rings with nominal identical geometry. Depending on what coupling ratio is desired we have used both options for coupling the light from bus waveguides into the ring and vice versa: the implementation of codirectional couplers with gap values of 0.8 and 0.9 µm and MMI type couplers. Typical lengths of all these coupler sections are ranging from 100 to 300 µm. The coupler sections are designed as straight waveguides and hence, since they belong to the cavity, the resonator gets a racetrack shape. For simplicity the general name “ring” is still used in the following.

The resonance frequencies of a (passive) filter is determined by phase-matching conditions of the superimposed ring cavity modes. The overall cavity length including the coupler lengths defines the free spectral range (channel spacing). Small derivations from the designed optical length due to process tolerances can be corrected very easily by thermal effect by the implementation of Pt-resistors which are placed on top of the waveguides in the ring and the couplers (see Fig. 3).

The ring resonators were characterized using a tapered standard singlemode fiber for launching the light from an external cavity laser. All measurements were performed in TE polarization. A simple ring resonator architecture and simultaneously the base cell for all fabricated ring resonator devices is a single ring resonator (SSR) as shown in Fig. 3a

The cavity roundtrip length was designed to get an FSR channel spacing of 50 GHz. A radius of 200 µm was chosen with straight waveguide section in between for easy coupler integration. The presence of radiation losses in the bends degrades the transmission characteristics of such devices. To reduce losses due to leakage deeply etched sections as shown in Fig. 3c) are implemented which increase the effective index step in the curvatures. Fig. 4a) shows the filter characteristic of this device exhibiting an on-off ratio of 21 dB. An FSR of 49 GHz was obtained which is in good

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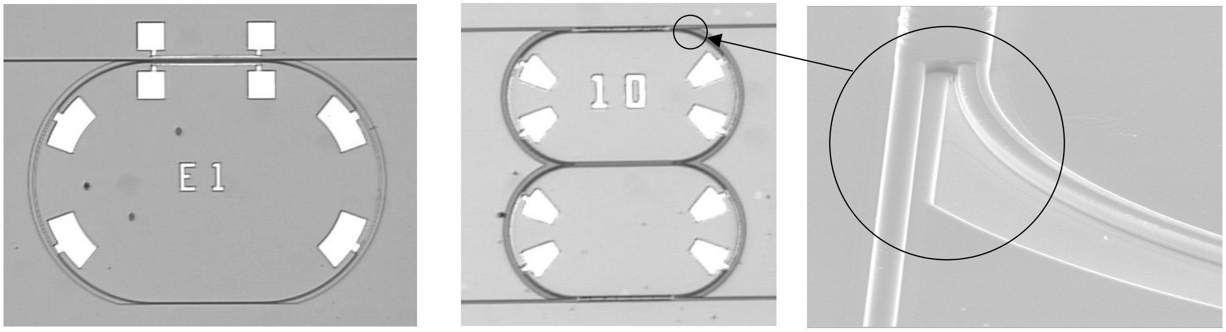
[II] Fabrication and technology: On an iron-doped semi-insulating InP substrate a 0.38 µm thick thick InGaAsP:Fe layer with a material bandgap equivalent wavelength of 1.06 µm, a 20 nm thick InP:Fe etch-stop layer and a 0.84 µm thick InGaAsP:Fe layer (λ_g = 1.06 µm) are grown by metal organic vapor phase epitaxy (MOVPE). Standard lithographical exposure is used to define the 1.8 µm wide waveguides. 0.84 mm thick rib waveguides are formed by using CH_4/H_2 reactive ion etching technique. In order to reduce the formation of polymers which influences sidewall roughness and surface imperfections during the etching process a small portion of oxygen is added.

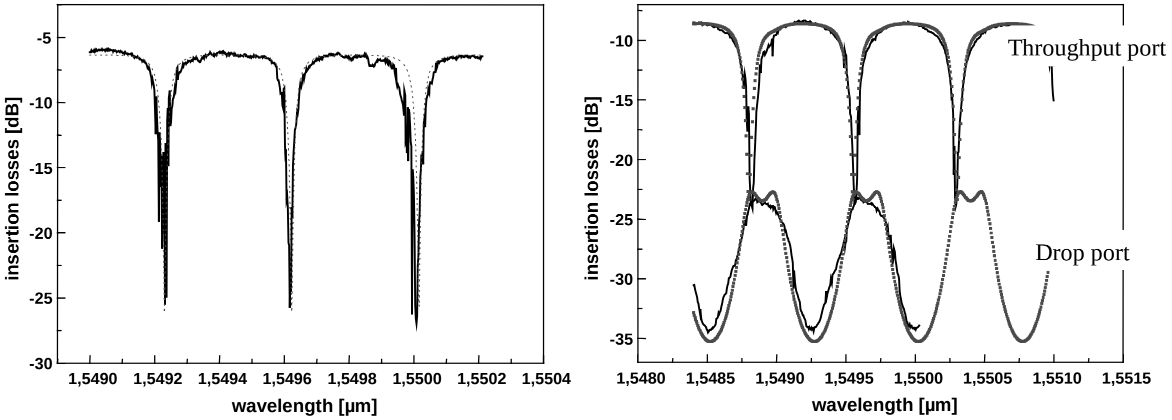
agreement with the designed value. The quality of a ring is often defined by the finesse which is given by finesse F (F = FSR/ FWHM{FWHM= **F**ull **W**idth at **H**alf **M**aximum}). Here the finesse was measured to be 9.34.

Increasing demands for filter applications like improved out-of-band rejection and/or steeper roll-off lead to modified architectures as shown in Fig. 3b) where two rings are cascaded. This devices operates as an add/drop (de)multiplexer for a designed FSR. The double ring resonator (DRR) incorporates two rings with a radius of 100 µm which are coupled to the bus waveguides by using 3dB-MMI couplers with a length of 150 µm at the input and the output port. A 150 µm long codirectional coupler with a very small coupling ratio of 0.06 and a separation gap of 1 µm was located in between the rings to transfer light between the rings. The orbit length of the cavity was designed for an FSR of 100 GHz. In comparison to the SRR the response shape could be successfully broadened to a FWHM of 0.32 nm and a corresponding finesse of 2.3. The ghost peaks in the simulated curve of the drop port demonstrate that the resonance frequency in both rings is mismatched. To solve this problem a voltage at the Pt-resistors of the second ring was applied. Due to this local heating effect the effective index in the lower ring increases slightly and improves the on/off ratio by 3 dB. Tuning to a specific wavelength can be performed after frequency matching in such a way, that each Pt-heater in both rings is activated. Of course the driving voltage is different due to the previous frequency matching but has to be increased by the same amount so as to shift to the desired wavelength.



a) Single Ring Resonator (SRR) b) Double Ring Resonator (DRR) c) Deep etched section in the ring curvature

Fig. 3 Passive single and double ring resonator architectures with Pt-resistors for in-situ wavelength tuning.



a) Single Ring Resonator b) Double Ring Resonator

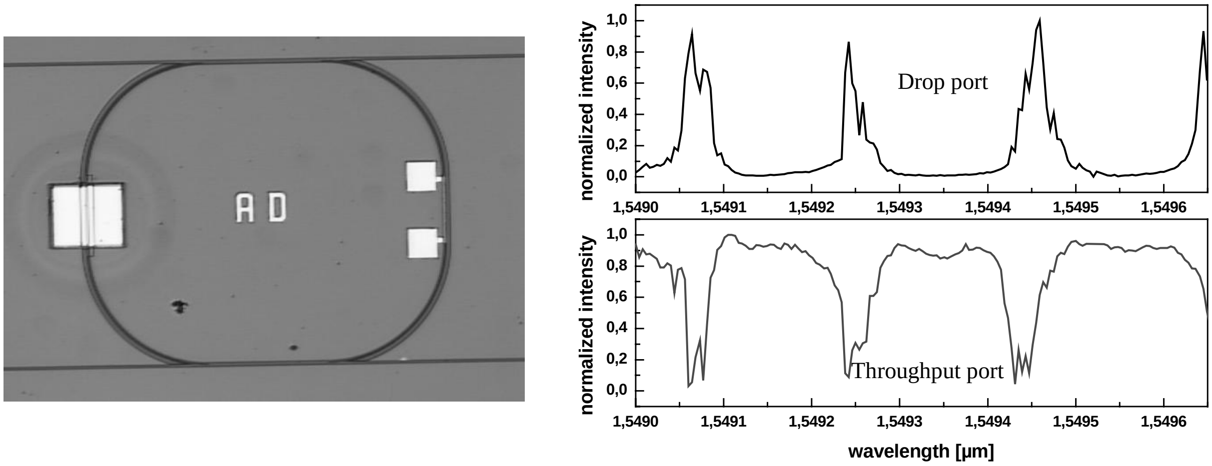
Fig. 4 Filter characteristics of a SRR (a) and a DRR (b) exhibiting a channel spacing of 49 GHz and 93 GHz, respectively**.** Simulation (dotted curves) and measurements are in good agreement.

2. Resonators with integrated SOA sections

In general the performance of passive ring resonator structures is mainly limited by the internal losses including radiation losses due to sharp bending radii, scattering losses due to waveguide imperfections, and coupling losses due to a not ideal coupling. Now, additional semiconductor optical amplifier (SOA) sections are implemented in the ring to compensate the losses in each ring separately. However this step requires additional technological effort as described in the footnote.[III]

Fig. 5a) shows exemplary a single ring resonator with the integrated SOA section on the left hand side and an auxiliary Pt-heater on the right hand side for a channel spacing of 25 GHz. Of course, the SOA section can be implemented in more complicated ring architectures like cascaded rings whenever required. To compensate the internal losses of the ring including the butt coupling losses between SOA and waveguide the SOA length must be chosen sufficiently. The length of the active section was 400 µm, the ring radius 360 µm and the length and the gap of the codirectional couplers amount to 200 µm and 0.9 µm, respectively. If the amplifier section is switched off it acts as an optical baffle and no signal can be obtained at the drop port. In case the SOA operated at 90 mA an expected high on/off ratio of 26 dB and 19 dB for the drop port and the throughput port, respectively, was obtained, as shown in Fig. 5b). Using a theoretical simulation model for parameter extraction butt coupling losses of 2.9 dB were determined.

The finesse and the free spectral range were measured to be 13.3 and 24.9 GHz, respectively, indicating the high quality of the cavity matching perfectly the designed channel spacing.



a) b)

Fig. 5 Photograph of a single ring resonator for a channel spacing of 25 GHz with integrated SOA section (a) showing typical transmission characteristics for the throughput and the drop port (b).

[III] Fabrication and technology: In addition to the fabrication of passive rings as described in footnote II a standard ridge waveguide laser was grown on InP:Sn substrate. The layer sequence 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 (0.2 µm). After forming the laser islands using wet and dry etching technologies the whole passive waveguide layer stack was grown in a single run using selective area MOVPE growth technique. In the following the laser stripe (width = 2.2 µm) and the passive waveguides (width = 1.8 µm) were etched down simultaneously by a self defining process. This minimizes the inevitable butt coupling losses which were measured to be 2.5 –3 dB for each butt-joint.

3. Resonators based on “all-active” material

As shown in the previous section optical amplification is indispensable to "repair" the power budget and to increase the performance of ring resonator devices significatly. Even better device performance can be obtained if the complete structure is made of active waveguides. The technological challenges[IV] are very similar to a simple ridge waveguide laser with the exception, that design and fabrication of active codirectional and/or multimode interference couplers are more sophisticated. As the balance point of the laser waveguide is defined by the location of the multi quantum wells it is indispensable to deeply etch the laser stripe down to the n-contact layer to increase the effective index in the curvature. This enables the light to follow even sharp bending radii down to 30 µm without important losses. Fig. 7 shows as an example a single ring resonator with a radius of 117 µm. A codirectional coupler with a length of 40 µm and a separation gap of 0.8 µm is used to launch the light into the ring cavity. To increase the functionality of the device it is electrically separated into three parts: Straight waveguides on the left and the right hand side of the ring, the coupler and the ring cavity. This enables high flexibility as each part can be driven individually. Device features include filter response, flip flop operation to single mode and comb laser spectra laser emission.

Fig. 7 “All active” ringresonator

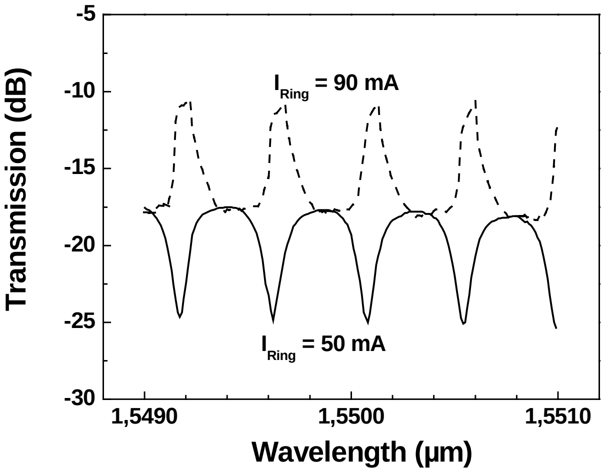


Fig. 6 Filter characteristics for a ringresonator as shown in Fig. **7** for different ring driving currents: Below the threshold current (I=50mA) the ring operates as an optical amplifier and exhibits a typical transmission spectrum. At values above threshold (i.e. I=90 mA) the ring acts as a laser. This can be seen in a flipped transmission curve.

SUMMARY AND PERSPECTIVES

The exponential growth rate of the Internet traffic accelerates the development of a broadband Internet network with a dynamic, flexible and widely transparent network topology including also mobile access links. The network engineers need more components than available today in quantity, performance and functionality. The miniaturization is a key issue also for monolithically integrated optoelectronic and photonic ICs, and here especially for components based on InGaAsP/InP as the chip area is the dominating cost driving factor.

[IV] Fabrication and technology: The fabrication and the layer stack is comparable to the laser as decribed in footnote III in the SOA section. When the codirectional couplers are formed by dry etching it has to be taken into account that the etch depth due to an increased aspect ratio (aspect ratio = etch depth/separation gap) is slightly different in between the waveguides and in the outer parts. This mainly influences the coupling ratio. To supply a strict monomodal propagation of the light the width of the laser stripe was designed to be 1.8 µm.

Today the "outsourcing" of passive waveguide networks (which would cover most of the IC area) from InP based photonic ICs into Si-based **P**hotonic **L**ightwave **C**ircuits (PLC) or **O**ptical **B**oards (OB) is favored. Planar hybrid solutions will be in near and medium term a powerful and flexible solution to overcome the components bottleneck in the implementation of broadband photonic networks. Recent approaches on high index material with strongly confined waveguides makes monolithic integration a powerful as well as economic solution.

Here, we focused on devices on the high index material InGaAsP/InP with strongly confined waveguides for fabrication of low loss bent waveguides. Following the strategy to learn from passive devices then improve their performance by semiconductor optical amplifier (SOA) integration and to extend the functionality in all-active structures. We summarized results on microring resonator devices: passive 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 resonator with multi-segmented electrodes for individual current injection in the feeding waveguide, coupler, and ring sections.

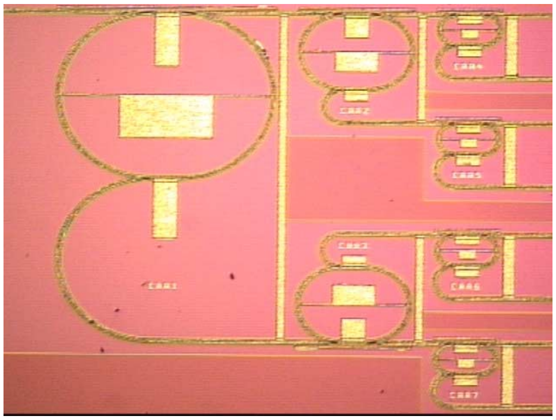


Fig. 8: WDM interleaver based on microring resonators
(FSR: 25 GHz/ 50 GHz/ 100 GHz)

Ongoing investigations will focus on the switching conditions by proper choice of the injection currents of the different sections. Another domain of these resonator devices are optical filters for dynamic dispersion compensation in order to improve the network flexibility [4,13,14] Compact WDM (de)multiplexers are in progress by cascading rings of different FSR forming interleavers in the wavelength domain (cf. Fig. 8). Finally, the resonator effect promises high nonlinear efficiencies e.g. for wavelength conversion by using the four wave mixing effect [15]. 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 spectroscopy and sensors.

ACKNOWLEDGEMENTS

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