Optical Network Components Based on Microring Resonators

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ABSTRACT
In the last years much effort has been made to arrive at optical integrated circuits with high complexity and advanced functionality for application in optical networks. For this aim high index contrast structures, like optical microresonators, are employed that allow for a large number of functional elements within a given chip area: VLSI photonics. Experimental results of work performed at MESA+ will be reported including a microresonator-based, ultra-compact reconfigurable optical add-drop multiplexer operating at 40 Gbit/s and fabricated in SiON technology. In addition a discussion will be given of new challenges and possible solutions.

Keywords: integrated optics, optical microresonator, optical communication, silicon-oxynitride technology, VLSI photonics.

1. INTRODUCTION
The application of optical fibers has led to virtually loss-less point to point data links in the core network with practically unlimited bandwidth. In order to reach the ultimate goal, i.e. to provide high speed access to the network to everyone anywhere, one is confronted with two major challenges: optical techniques have to extend from the core network down to the metropolitan and local access network and simultaneously transparency is needed at all hubs and nodes without need of conversion between the optical and electrical domains. Dealing with the access network, where a few or even only a single user share equipment, cost is the major issue, while the demand of transparency in the nodes and hubs results in a high degree of complexity of the devices. In our opinion, the only answer to these challenges will be mass-produced very large scale integrated (VLSI) photonics [1] in close analogy with the electronic VLSI electronic circuits. The individual building blocks in these photonic circuitries, in our case optical microresonators (MRs) [2-3] have to be sufficiently small to eventually enable thousands or more functional elements on a chip area of a few cm². A seemingly trivial hurdle has to be taken to arrive at these small waveguiding structures: light should be transported without losses through bends with a radius of only a few micrometers. This can only be achieved by careful design and working with materials allowing high index contrast structures. In the following we give an overview of our approach to design and realize photonic components with increasing complexity based on optical MRs. The approach follows an evolutionary route that takes aspects of pigtailing and packaging into account together with issues related to low-cost mass production. The preferentially used material system is SiOxNy [4] which can be deposited as high quality transparent layers with a refractive index ranging from 1.45 (SiO2) up to 2 (Si3N4) by Low-Pressure or Plasma-Enhanced Chemical Vapor Deposition (LPCVD and PECVD).

2. THE OPTICAL MICRORESONATOR
An optical MR is an integrated optics structure with optical feedback that can be used, for example, as wavelength filter, optical switch or optical transistor. A MR, see Fig. 1, consists of a waveguide ring (diameter typically 10 – 100 µm) with two adjacent single mode port waveguides, one serving as in- and through-port, the other as add and drop port. The MR is characterized by the free spectral range (FSR), i.e. the wavelength separation between neighboring resonance peaks, and the 3dB bandwidth Δλ_{3dB} of the resonance response at the drop port. A relative measure for the selectivity of the resonator is the finesse \( F = \text{FSR} / \Delta \lambda_{3dB} \). The quality factor \( Q \) is given by \( Q = \lambda / \Delta \lambda_{3dB} \).

There are principally two ways for the positioning of the adjacent waveguides with respect to the resonator: the horizontal or vertical arrangement. The vertical arrangement requires a two-step lithographic process. Here the coupling constants are mainly determined by the thickness and refractive index of the intermediate layer and the relative offsets of the underlying waveguides with respect to the ring. This approach allows for an optimized independent choice for ring and port waveguides. Critical in the vertical arrangement is the alignment of the two lithographic steps, where a precision within 100 nm is needed. In the case of horizontal coupling only a single lithographic step with a single mask is needed. The coupling is mainly determined by the width of the gap between the straight and bent waveguides and demands nanometer precision in the case of high refractive index contrasts. There is reduced design flexibility as core layer and core thickness should be identical.

In a MR, just by changing the wavelength, the effective index or the phase, light can be directed to either the drop or the through port. In this way the device performs as a filter or space switch. Another mode of operation

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can be found by considering a single resonance peak in the drop port where the amplitude and finesse are determined by the roundtrip losses. By enhancing the losses and consequently reducing the Q-factor, light can effectively be switched between the drop- and through-ports. The MR can carry out a large number of optical functions. It can be used as a compact filter with high resolution. For Wavelength Division Multiplexing (WDM) applications a MR with add and drop port serves as an ultra-compact building block for an optical add drop multiplexer (OADM). Switching or modulation of light can be done by changing the phase in the resonator by thermal, mechanical [5] or electro-optical [6] means. Besides for applications in the field of communication, MRs can be used as ultra-compact optical sensors [7].

Using structures made of more than one ring has several advantages for telecommunication filtering and switching applications. By using several rings for a single function, higher order filters can be realized. By introducing additional feedback paths more desirable filters shapes with flat-top and steep roll-off are obtained. Also the FSR can be extended by using the Vernier effect. By using multiple rings multi-functional complex devices like the reconfigurable OADM (ROADM) described below, can be made.

3. A MR-BASED ROADM

An important component in which the wavelength dependent switching function and small size of MRs can be applied is a ROADM, see Fig. 2 [8]. It consists of a central waveguide (I\textsubscript{in}/I\textsubscript{out}) and four Add/Drop waveguides. These waveguides are spaced at 250 µm to allow for a standard fiber-array connection. A single MR is located at each intersection of central- and add-drop waveguides. The cross-grid waveguide approach [9], in which the two waveguides that couple to the MR cross each others, leads to some crosstalk but is also the
most efficient geometry for the OADM. Each of the four MRs can be thermally tuned by a heater across the FSR of 4.2 nm. The heater is Ω-shaped for high power efficiency. The MRs have a radius of 50 µm, a height of 190 nm and a width of 2.5 µm, giving an $N_{\text{eff}} = 1.517$ (TE @1550 nm). The MRs are vertically coupled to the port waveguides which are 2 µm wide, 140 nm high and have a $N_{\text{eff}} = 1.505$ (TE@1550 nm). Both, the MRs and the port waveguides have been designed for TE operation and are realized in Si$_3$N$_4$ by standard contact lithography.

The pigtailed OADM was measured using a broadband source and an optical spectrum analyzer with a resolution of 0.05 nm. Figure 3 shows the normalized responses measured at $I_{\text{out}}$ when the broadband source was connected to $I_{\text{in}}$ for two distinct configurations which were set by thermally tuning the MRs. In this setup the OADM drops the channels present on $I_{\text{in}}$ to the desired drop ports $\text{IDrop1-IDrop4}$. These dropped channels are visible as dips in the MR through responses in $I_{\text{out}}$. In the "4 single channels" configuration a total heater power of 446 mW was applied to set the MR resonance frequencies on a 100 GHz ITU Grid (spaced at 0.8 nm). The minima of the individual MR through responses are $\approx 12$ dB below the normalized input power level. Thus $\approx 94\%$ of the input power is extracted. A fit of the individual MR responses to a theoretical MR model showed amplitude coupling constants $\kappa_1$ and $\kappa_2$ of 0.56±0.04 and 0.44±0.04 respectively at ring losses of 1.5±0.5 dB/cm. The measured FSR and Finesse were 4.18 nm and 10.3 respectively, giving a FWHM of 0.41 nm (= 51 GHz). The "single combined channel" configuration in Fig. 3a shows how the responses of the individual MRs could also be shifted to overlap each other. This configuration could be set while dissipating only 20 mW due to the fact that the untuned MRs already had nearly overlapping resonance frequencies, showing good fabrication reproducibility. The minimum of the combined through response is 30 dB (>99 % extracted).

In cooperation with the HHI in Berlin high speed measurements on the OADM have been performed [10]. Fig. 4a shows the measured EYE patterns of 40 Gbit/s incoming signal (top) and at the Drop1 port (bottom) while the MR was tuned to the wavelength of the tunable laser. Also Multicasting could be demonstrated by
setting drop 1 and 2 to the wavelength of the input signal, see Fig. 4b. In all cases clean EYE openings could be seen demonstrating error free detection with a slight power penalty of 1 dB. All other ports, both drop and add, showed similar responses.

4. TOWARDS A TUNABLE WDM ROUTER

Arranging MRs in a two-dimensional matrix new extremely compact WDM devices can be realized like a tunable WDM router. Figure 5a shows a possible 4-channel implementation of such a router, which consists of five 4-way OADMs. In this router the WDM input signal $I_{in}$ is first separated into individual wavelength channels ($\lambda_1$,...,$\lambda_4$) by an OADM. Each of these channels is then guided into one of four additional OADMs where they can be added on demand to one of the four output waveguides $I_{out}$. Recently a design has been made for a complete WDM router as depicted in Fig. 5b. For the realization the same SiON technology is used as for the ROADM described above. The 20 MRs have a diameter of 100 µm and are covered by a $\Omega$-shaped heater to allow individual tuning of each of them. The devices are processed, in cooperation with ASML by advanced waferstepper lithography allowing alignment of the sequential masks within 100 nm. The total device area including port waveguides is 2 x 5 mm², see Fig. 6.

5. CHALLENGES

For the successful realization of the WDM router and other complex MR-based devices special effort has to be devoted to the following technological issues:

(i) reduction of waveguide losses in the ring as well as in the port waveguides, 
(ii) reduction of stray light in the chip,
(iii) definition of nanometer-scaled structures on different levels, 
(iv) reduction of reflections and improved fiber-chip coupling.

Ad (i): reduction of waveguide losses in the ring as well as in the port waveguides

It is obvious that in a device with increasing number of functional elements any non-function related losses have to be avoided. Our target is to reach losses in slab waveguides for all relevant indices in the order of 0.1 dB/cm. The second source of losses is scattering at layer inhomogeneities, voids and especially at interfaces. It is a characteristic of the PECVD SiON technology that these imperfections can be observed if the deposition is done on structured surfaces, e.g. as cladding- or intermediate layer above waveguides. In addition, etching waveguide and resonator profiles by the commonly used Reactive Ion Etching (RIE) process, results in sidewall roughness with an amplitude in the order of ten nanometers. Optimizing of the deposition and etching process will be necessary. In addition, new approaches like surface tension induced smoothening (STIS) should be explored in order to obtain perfectly smooth surfaces and reduction of voids.

Ad (ii): reduction of stray light in the chip

A special point of attention in the highly compact structures is the reduction of stray light within the optical chip. Stray light, i.e. light that does not belong to the desired waveguide modes, can be generated at scatter centers or imperfect structures. This light can be transferred to modes in neighboring channels resulting in unwanted cross-talk. The measures of i) will reduce part of the stray light, but there are also inherent sources of scattering. Looking at Figs. 2 or 5 one encounters for a two-level design a large number of waveguide crossings that besides losses of approximately 0.2 dB cause scattering of light. Careful design may improve this, but the
best solution will be to avoid crossings completely by using a three-level approach [11]. If resonators and east-west as well as north-south waveguides are all fabricated in different layers any undesired interference can be avoided. Reduction of stray light can also be obtained by incorporating absorbing layers (in practice thin metal films) at a safe distance (~10 µm) from the waveguides.

**Figure 6.** Mask lay-out of 5WDM routers (for details see Fig. 5b) and a number of test structures currently being processed by the authors; the area on the wafer is 1 x 1 cm².

Ad (iii): nanometer-scaled structures defined on different levels
High precision is needed not only in order to perform lithography steps with nanometer-scale critical dimensions, but also to align the different waveguiding layers with accuracy better than 100 nm. As can be seen in Fig. 5, critical alignment is needed in the x- as well as in the y- direction. This alignment accuracy can only be obtained with modern wafersteppers, as developed for the IC-technology. Direct e-beam writing is not a practical alternative, as relatively large areas of tens of mm² have to be written and, more important, a route to low-cost mass production should be explored. In order to show the potential of current LSI photonics technology, a 1x1 cm² area of a recent 4-level mask design is shown in Fig. 6. It shows 5 complete WDM routers and a large number of test structures.

Ad (iv): reduction of reflections and improved fiber-chip coupling
An additional aspect that influences the device performance is the occurrence of transitions in the waveguide mode profile. These transitions not only cause losses and stray-light by scattering, but also give rise to reflections that result in additional cross-talk. The solution for this problem is to work with adiabatic transitions...
where any abrupt changes of the mode profile are avoided. By detailed simulation optimized transition structures can be found that require nanometer-scale precision in the couple section of the ring and port waveguides. More severe problems arise at the fiber-chip coupling. The fiber mode, even with small core fibers still with a diameter of \( \sim 4 \mu m \), has to be adiabatically transformed to the much smaller planar waveguide modes. Horizontal tapering in combination with sophisticated nanostructuring should result in fiber-chip losses below 1 dB/facet.

6. CONCLUSIONS

With the foregoing the basic principles and the potential of optical MRs for application in optical networks have been shown. It is, of course, still too early to speak about VLSI photonics, but MRs can be considered as promising candidates for the basic building blocks needed in optical circuitry. Much work has still to be done but the progress in the field demonstrates that the potential of micro- and nanophotonics is gradually being exploited resulting in complex, mass-produced and low-cost optical circuits.

The examples presented in this paper have mostly been taken from work carried out at the IOMS group of MESA’ of the University of Twente, often in collaboration with others.

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