Compact Wavelength-Selective Switch for Gigabit Filtering in Access Networks

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***Abstract*—A compact [$200 \times 200\ \mu m^2$] wavelength-selective switch based on thermally tunable SiO_2–Si_3N_4 microring resonators has been designed and realized. The switch supports gigabit filtering applications in access networks. Spectral measurements show an ON–OFF ratio of 12 dB and a channel separation of 20 dB. The 10-Gb/s measurements on a single ring show no degradation of the modulated signal and a theoretical bit-error rate $< 10^{-12}$.**

***Index Terms*—Gigabits/second filter, integrated optics, microring resonator (MR), thermally tunable filter.**

I. INTRODUCTION

THE DEPLOYMENT of optical technology in communication networks is shifting more and more toward the customer's premises. Since the costs of the deployment of an access network cannot be shared between large numbers of users, low-cost optical filter techniques are desired. Furthermore, complex integrated functions are needed, since increasing bandwidth demands ask for more data transport and processing in the optical domain. Integrated optical microring resonators (MRs) are viable candidates as building blocks for the optical devices that meet these requirements, since small footprint, complex functions, and mass-production is feasible [1], [2]. This letter describes a small-area MR-based wavelength-selective switch which can be used in high speed and highly integrated structures.

II. MICRORING RESONATOR SWITCH

Integrated optical MRs are known for their compact size and favorable filter shapes [3]–[5]. The wavelength-selective switch described in this letter is based on two MRs, as shown schematically in Fig. 1(a). A typical calculated response of the two-stage switch in ON and OFF state is shown in Fig. 1(b). The first stage selects a certain wavelength band. By tuning the center wavelength of the second stage to overlap the center wavelength of the first stage, the wavelength band is switched to the drop port (ON-state). In the OFF-state, the center wavelength of the second stage does not overlap and the light dropped by the first ring is not used. The individual stages can be made out of higher order filters to increase the ON–OFF ratio as is described in [4], [6]. Simulations show that ON–OFF ratios of 30 dB can be reached with tuning powers of 30 mW when using parallel cascaded stages and a tunability of the center wavelength of 20 pm/mW [7]. The SiO_2–Si_3N_4 MRs are thermally tunable by means of a heater on top of the cladding. Driving the MRs thermally is fast enough for switching applications where submicrosecond responses are sufficient. Switching is possible up to several kilohertz as is described in [8] by optimization of the driving signal. For applications in an access network, the switch is especially useful as it allows us to select just one specific wavelength band and to disregard the others. This is a useful function in passive optical network architectures. The selectivity of the switch can be improved by using two different radii of the rings in the switch. In that case, the Vernier effect accounts for an increase in the total free-spectral range (FSR) up to 36 nm [9]. The switch can be a building block for even more complex structures like an array of switches [10] which can switch different wavelength bands simultaneously.

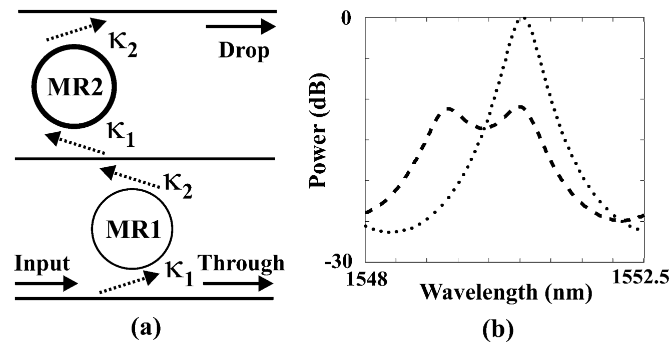

Fig. 1. (a) Schematic drawing of a switch based on two MRs and (b) simulated responses of switch in ON-state (dotted line) and switch in OFF-state (dashed line).

III. DESIGN ISSUES

The main issues in the design of an MR-based switch are related to the ON–OFF ratio, the channel separation, the bandwidth, and the on-chip insertion loss (IL) of the switched channel. The ON–OFF ratio is influenced by the shape of the filter function (steepness) and the thermally induced shift to switch between ON and OFF states. Since the switch is made out of two rings, its response exhibits already an increased steepness in comparison to a single ring. A steeper filter shape also reduces the driving power of the switch since smaller shifts are needed for the same ON–OFF ratio. The channel separation of the switch

Manuscript received August 4, 2004; revised October 1, 2004. This work was supported by the EC funded IST-project NAIS, Next-generation Active Integrated-Optic Subsystems (IST-2000-28018).

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Digital Object Identifier 10.1109/LPT.2004.839451

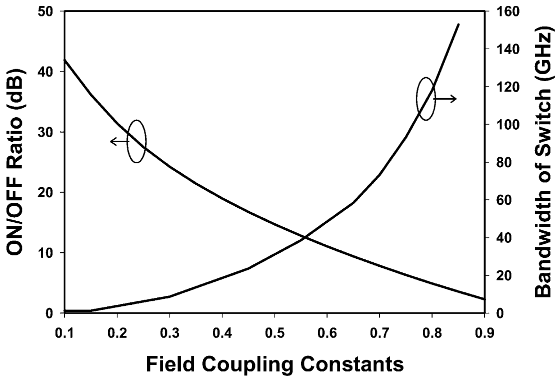

Fig. 2. Effect of coupling constants on the ON–OFF ratio of the switch and the 3-dB bandwidth of the switch. Both the coupling constants are assumed equal, ring losses of 5 dB/cm and a radius of 50 μm.

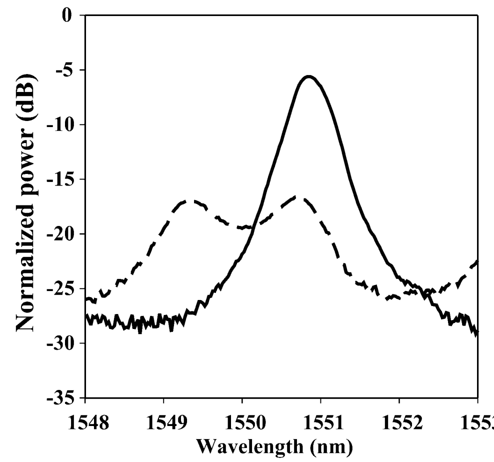

Fig. 3. Measured response of switch. Solid line: ON-state. Dashed line: OFF-state.

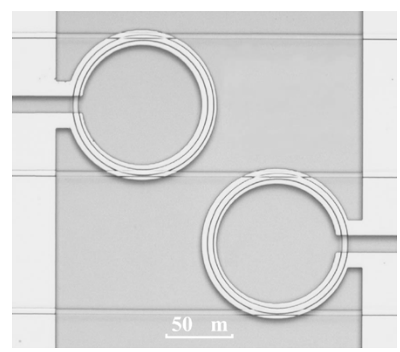

Fig. 4. Microscope photograph of a realized switch based on two MRs.

is determined by the finesse of the device, defined by the ratio between the FSR and the 3-dB bandwidth. The bandwidth and IL are determined by the losses inside the individual rings and the coupling constants κ_1 and κ_2, i.e., the fraction of the field that is coupled from the waveguide to the ring and vice versa. In order to have as much power as possible in the drop port, the losses must be low and the coupling constants of the two coupling regions must be matched to the losses in the ring [6]. The highest extinction ratio (difference between power in drop port and power in through port) can be reached when the individual rings are designed to be critically coupled, as described in [11]. The microrings of the described switch have a radius of 50 μm. The effective refractive index of the ring is matched to that of the waveguide underneath the ring. By setting the thickness of the separation layer and the horizontal distance between the ring and waveguide, the coupling constant is controlled. To ensure a certain 3-dB bandwidth, the coupling constants of the ring are determined according to Fig. 2. For a 3-dB bandwidth of the switch of 50 GHz and a loss of 5 dB/cm in the rings, the coupling constants should be chosen around 0.6. To obtain the desired coupling constants, a commercial three-dimensional beam propagation method simulation program[1] was used to determine the corresponding lateral and vertical distances between ring and port waveguides. Fig. 2 also shows that the ON–OFF ratio will, in this case, be around 12 dB. To improve this ratio with the current parameters, the bandwidth must decrease. For the current device, optimization of the bandwidth is chosen over optimization of the ON–OFF ratio.

IV. Spectral Measurements

An MR-based switch has been realized in SiO_2–Si_3N_4 technology [12], [13]. The switch was made out of two MRs which are vertically coupled to the port waveguides. The port and ring waveguide dimensions are 2×0.140 μm and 2.5×0.180 μm, respectively. The vertical separation between port and waveguide is 1 μm. Omega-shaped chromium heaters were applied on top of the device. The measured spectral responses of the switch in both the ON and OFF states are shown in Fig. 3. The responses are normalized to the measured power in the through port of the device while OFF-resonance and give, consequently, the on-chip IL in the drop port. The measurements are in close correspondence with the simulated response in Fig. 1(b). The switch has a measured ON–OFF ratio of 12 dB and a channel separation better than 20 dB. The on-chip IL in the drop port of the switch is around 6 dB. The device was switched between ON and OFF using 225 mW of electrical power. This implies a shift in center wavelength of 6.5 pm/mW. Also, single rings with the same specification have been characterized. The measured responses were fitted to analytical models to extract the loss in the ring and the coupling constants. The loss inside the ring was found to be about 5 dB/cm, corresponding to 0.16 dB/round-trip. The measured field coupling constants of 0.6 are in good agreement with the designed values. The propagation losses inside the straight waveguides are lower than 1 dB/cm. The on-chip IL in the drop port of a single ring is about 3 dB which is in accordance with the 6-dB IL in the switch. The rings in the switch show high drop efficiency even after being dropped by two rings. The fit to the measured response shows that the coupling constants for the two coupling regions for both rings are almost identical, which explains the high drop efficiency. Fig. 4 shows a photograph of a realized switch. The two omega-shaped heaters on top of the two rings and the port waveguides are clearly visible. The size of the switch itself is about 200×200 μm^2 excluding the pads to wire the heaters.

[1]"Olympios Integrated Optics Software," C2V, Enschede, The Netherlands.

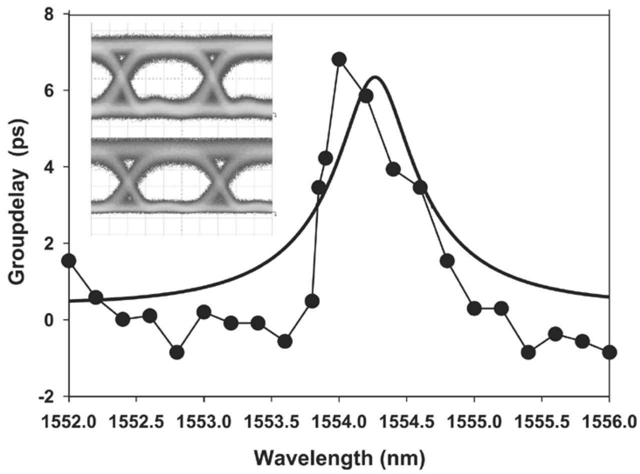

Fig. 5. Measured and simulated group delay of a single ring. Also shown are the eye diagrams of 10-Gb/s NRZ signals of modulator output (top) and after being filtered by an MR (bottom).

V. Gigabit/s Measurements

Measurements on single rings with similar dimensions were performed with a $LiNbO_3$ Mach–Zehnder modulator driven by a 10-Gb/s pseudorandom binary sequence generator to see the influence of the filter on the modulated nonreturn-to-zero (NRZ) signal. The group delay of the ring was measured by using the phase-shift method [14]. At resonance, the measured relative group delay is 7 ps, as is shown in Fig. 5. The measured 10-Gb/s modulation signal with a bit length of 100 ps is shown in the inlay of Fig. 5 where the eye responses are shown. The top eye diagram is obtained directly after the modulator, the bottom one after being filtered by the ring. The ring does not degrade the modulated signal significantly as could be expected since the bandwidth was designed to be 50 GHz and the maximum group delay difference is much smaller than the duration of a single bit. The measured Q factor of the eye diagram of the filtered signal as defined in [15] is about 7.5, leading to a theoretical bit-error rate of $< 10^{-12}$. The power penalty due to the ring is 3 dB, since only the IL is of influence given this bit rate. The proposed switch is made out of two microrings. Therefore, the group delay of the switch is twice the amount of the single ring. In the two-ring device, where the rings are arranged in a serial configuration, the 3-dB bandwidth is reduced by approximately $\sqrt{2}$. For a 10-Gb/s modulation signal, the enhanced group delay and reduced 3-dB bandwidth are still acceptable. The IL of the switch is also twice the IL of a single ring, as can be seen in Fig. 3. This means that the eye opening and the Q factor will decrease. For a switch, it is important to reduce the IL of the individual rings as much as possible.

VI. Discussion and Conclusion

A compact wavelength-selective switch based on two SiO_2–Si_3N_4 microrings has been designed and realized. Measurements show an ON–OFF ratio of 12 dB and a channel separation of 20 dB. The measurements are in close correspondence with the calculated responses. Based on measurements of a single MR which shows a filtered 10-Gb/s NRZ modulated signal without degradation, the switch can be considered to be suited for gigabit filtering applications in access networks. The measurements show the capability of using multiple rings to get a certain functionality. To improve the specifications of the switch, even more rings can be used, either as higher order filter stages or as clean-up rings, as described in [16]. By using polarization diversity, the polarization dependency of the device can be solved. To increase the ON–OFF ration and lower the power consumption while keeping first-order stages, the ring radii have to decrease by a factor of two.

Acknowledgment

The authors would like to thank B. Peeters and J. Fells from Nortel Network, Harlow, U.K. for their support with the gigabits/s measurements.

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