Advances in Filters and Delay Lines in Silicon Photonics

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***Abstract*— We report on design, characterization, exploitation and limitations of linear devices realized in Silicon Photonics. Filters and tunable delay lines are tested with picosecond pulses and PolDM DQPSK signals. Potentialities, impairments and critical aspects such as tuning, process tolerances, polarization management and waveguide sidewall roughness are thoroughly investigated and discussed.**

Keywords- silicon photonics; filters; ring resonators; slow wave; delay lines; DQPSK

I. INTRODUCTION

Silicon Photonics technology is rapidly progressing and a large number of elementary building blocks are becoming available for the implementation of devices with complex spectral characteristics. Filters, for example, are key elements in any telecom, datacom, optical interconnect and even sensor applications, with tight spectral and reconfiguration requirements. The high integration scale capability, the fast thermo-optic time response and the low power consumption place the SOI platform in a preferred position for applications where these prerequisites are mandatory.

Here we report the outcome of a long theoretical and experimental investigation on filters in SOI technology realized with Mach-Zehnder, rings, gratings and cascaded resonators. As a convincing demonstration of the capabilities of this technology, we report on an experimental investigation on the tuning delay of a 10 ps Gaussian pulse and on the management of a 100 Gbit/s signal with polarization-division-multiplexing (PolDM) differential quaternary phase shift keying (DQPSK) format. We demonstrate the compatibility of Silicon Photonics with the emerging advanced transmission systems at high bit-rate, provided that several delicate aspects (process tolerances, waveguide sidewall roughness, tuning and trimming) are taken into account.

II. TECHNOLOGY AND DEVICES

Fig. 1 (a) shows a detail of the cross-section of the fabricated waveguides (220 nm thick, 490 nm wide). The fabrication process was optimized by using an HSQ electron-beam-resist based technology in order to obtain very low propagation losses (~1 dB/cm) [1] and an accuracy of better than 0.5 nm on the waveguide dimensions. After the etching process, the residual HSQ is not removed and the waveguide is covered with 0.5-µm-thick SiO_2 layer by PECVD. The fabrication has been carried out at the James Watt Nanofabrication Centre of the University of Glasgow.

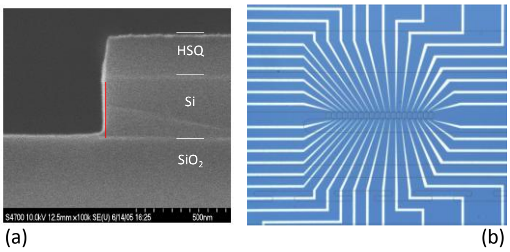

Figure 1. Photographs of (a) the waveguide cross section and (b) a 20-rings reconfigurable CROW.

A large number of circuits and devices have been realized. As an example, Fig. 1 (b) shows a coupled-resonator optical waveguide (CROW) structure, consisting of 20 identical racetrack ring resonators with a radius of 20 µm and a straight coupling section 16 µm long. All the rings have the same shape, while the coupling coefficients are optimized [2] by changing the gap size between the coupler waveguides. A heater consisting of a 50 nm-thick highly resistive metallic layer of nichrome (NiCr) patterned by lift-off to obtain a 0.9 µm wide strip is deposited on each ring, allowing a flexible and full reconfiguration of the devices and, if necessary, a fine tuning of the characteristic.

The choice of the ring dimensions is strongly related to the application and it is the result of a careful compromise between bandwidth, delay and pulse distortion, bend-induced losses, backscatter, sensitivity to technological tolerances, tuning electrical power and overall footprint and minimum number of rings to tune. Fig. 2 shows in solid lines the intensity (a) and group delay (b) spectral characteristic of a 6-rings CROW with a free spectral range FSR = 440 GHz and a -3 dB bandwidth of 100 GHz. The agreement with the theoretical response (dashed lines) demonstrates that the accuracy of the fabrication process guarantees the proper alignment of the ring resonances without the need for an active tuning of the structure. The power consumption required for the shift of an entire FSR is about 23 mW per ring and the time response is 12 µs. The thermal

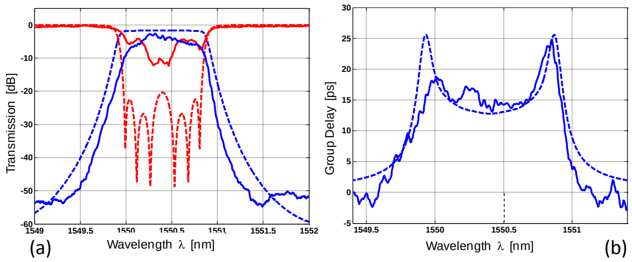

Figure 2. (a) Intensity and (b) group delay spectral characteristic of a 6-rings CROW: comparison between measures (solid) and design (dashed).

crosstalk between adjacent rings is about 1-2 % and is therefore negligible for most of the applications. Further details can be found in [3].

III. IMPAIREMENTS AND ISSUES

When dealing with high index contrast waveguides and especially with high finesse ring resonators and large circuits, several critical issues must be taken into account. Among others, the most detrimental are: uncertainties and tolerances of technological processes, distributed backscatter induced by sidewall roughness [4], structural disorder [5] and undesired polarization coupling and rotation.

Further, it must be kept in mind that an error of one nanometer on an SOI waveguide cross-section dimension typically produces a shift of one nanometer of the spectral response. Hence, trimming or tuning procedures are of prime importance to finely control the device characteristic. Thermo-optic control is a viable technique to perform fast and low power circuit tuning and reconfiguration, with the advantage that thermal crosstalk between adjacent waveguides in an SOI material platform is much lower than in glass-based devices and can be made negligible with a proper design.

IV. APPLICATIONS AT 100 GBIT/S

As a first example we investigated the tunable delay induced by a 20-rings reconfigurable CROW with a 10 ps Gaussian input pulse, the spectrum of which fits completely within the structure bandwidth. The tuning scheme is shown in Fig. 3 (a) and it is a folded CROW with each ring that can be individually tuned to change the delay [6]. The input pulse and the delayed output pulses are shown in Fig. 3 (b) when the resonance of 4, 8 and 12 rings are tuned to match the signal bandwidth. At resonance the double-transit induced-delay per ring is 7.3 ps but a suitable detuning of the last ring allows for a fine control of the delay within a fraction of a picosecond [6]. Delays up to 88 ps, corresponding to more than 1 byte, have been achieved with 12 open rings and an acceptable pulse broadening and a moderate intersymbol interference. After a delay of 8 bits the pulse FWHM is 11 ps and the extinction ratio is reduced to 7 dB, still an acceptable value for low-penalty transmission. Clearly, the relative delay on longer pulses is shorter because of the narrower spectrum of the signal. The fractional insertion loss is 0.8 dB/bit (or 0.6 dB/ring) up to 6 delayed bits, after which the pulse intensity reduces because of the broadening induced by chromatic dispersion.

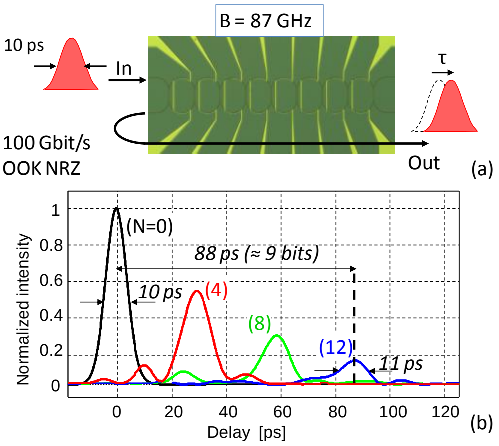

Figure 3. Sketch of the reflective tunable CROW delay line. b) Delays of a 10 ps gaussian pulse achieved by aligning the resonances of 4, 8 and 12 rings.

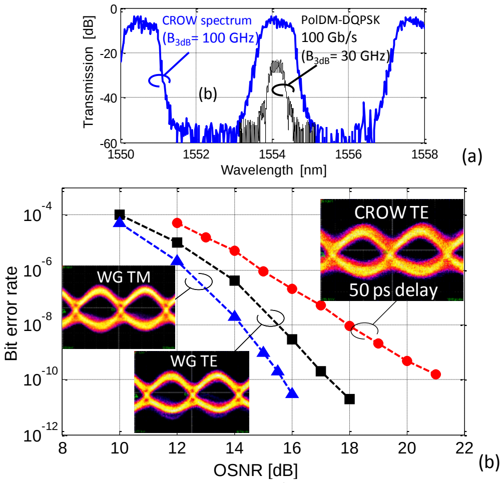

Figure 4. (a) Transmission spectrum of the 6-rings SOI CROW shown in Fig. 2 and spectrum of the 100 Gbit/s RZ-PolDM-DQPSK signal; (b) BER measurements after propagation through 1-cm-long SOI nanowire (TE and TM polarization) and through the CROW with 50 ps delay (TE only).

The synchronization of two 50 Gbit/s DQPSK modulated signals to form a 100Gbit/s PolDM one is the most advanced demonstration of the potential of this device. The two data streams were independently generated, combined and sent to the CROW input with the same optical power. One of the two polarizations is then aligned with the TE CROW passband and delayed with respect to the other one [7], to achieving the time-interleaving condition.

Figure 4 (a) shows the transmission spectrum at the Drop port of the CROW for a TE polarized input light. The 30-GHz-wide spectrum (evaluated at 3 dB attenuation) of the 100 Gbit/s PolDM-DQPSK signal is entirely contained within the (TE) CROW passband and the impact of chromatic dispersion and filtering is very limited. Figure 4 (b) shows that error-free propagation (BER < 10^{-9}) through the CROW is achieved with less than 3 dB OSNR penalty with respect to propagation in the straight waveguide. This penalty, which is mainly due to non optimal alignment of the rings' resonances, is expected to be largely reduced by a proper tuning of the device. At this wavelength the TM-polarized channel is not coupled to the CROW, propagates in the 1-cm-long bus line only and outcouples from the through port of the device, showing the same BER performance as the straight waveguide.

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