A variable delay integrated receiver for differential phase-shift keying optical transmission systems

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***Abstract*— An integrated variable delay receiver for DPSK optical transmission systems is presented. The device is realized in silicon-on-insulator technology and can be used to detect DPSK signals at any bit-rates between 10 and 15 Gbit/s.**

Keywords- differential phase-shift keying, interferometer, optical receiver, tunable delay-lines, silicon photonics

I. Introduction

Differential phase-shift keying (DPSK) optical transmission systems offer several advantages over traditional on-off keying (OOK) systems in terms of tolerance to fiber chromatic dispersion and nonlinearities. Direct-detection of DPSK signals requires the conversion of phase modulation to intensity modulation, which is usually performed by means of a delay interferometer with a fixed delay equal to the inverse of the signal bit rate (e.g. 100 ps delay at 10 Gbit/s). However, it has been demonstrated that the detection of signals affected by bandwidth-narrowing due to concatenated filters [2] or by chromatic dispersion [3] may be improved if the delay at the receiver deviates from the one-symbol delay. Furthermore, receivers capable of demodulating signals at variable bit-rates would better fulfill the requirements of optical communication systems, which are evolving towards higher flexibility and dynamic bandwidth allocation.

For these reasons, in the last years variable delay DPSK receivers have been attracting an increasing interest. Several solutions have been recently proposed in free-space [4] and optical fiber [5] technology. While offering large delay tunability and good optical performance, these devices are bulky and expensive. An integrated solution for an interferometer with adaptive delay has been realized by using cascaded Mach-Zehnder interferometers (MZI) [6], yet this device only provides a discrete switching between three delays.

In this contribution we introduce and experimentally demonstrate an integrated variable delay receiver for DPSK optical communication systems. The variable delay is attained by means of a coupled resonator optical waveguide (CROW) coupled to one arm of a conventional asymmetric MZI. The device is realized in silicon-on-insulator technology and can be used to detect DPSK signals at any bit rates between 10 and 15 Gbit/s.

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II. Design

According to the schematic of Fig. 1(a), the proposed device consists of an integrated unbalanced MZI with a continuously tunable delay line coupled to the delay arm. The delay line is realized by using a CROW in a reflective configuration [7] and is used to modify the mutual delay between the two arms of the MZI, and hence the FSR of the receiver. The maximum attainable free spectral range $FSR_{max} = c/(n_g\,\Delta L_{MZI})$, where c is the vacuum light speed and n_g the waveguide group index, is given by the MZI delay ΔL_{MZI} when the CROW is out of resonance. The FSR of the device can be reduced by setting to resonance an increasing number of resonators, each resonator providing a delay comprised between 0 (off-resonance condition) and $T_{max} = 2/(\pi B)$, where B is the CROW bandwidth [7]. In Fig. 1 the case of a 2-ring structure is considered, but more resonators can be cascaded to increase the delay tunability. Partial detuning of the last ring is exploited to produce any intermediate delay between 0 and

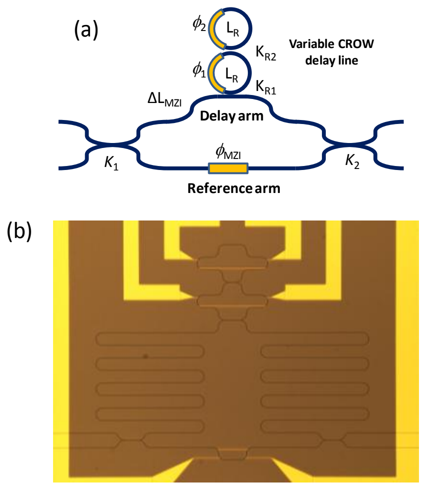

Figure 1. (a) Schematic of the integrated variable bit-rate DPSK receiver and (b) optical microscope photograph of the fabricated device.

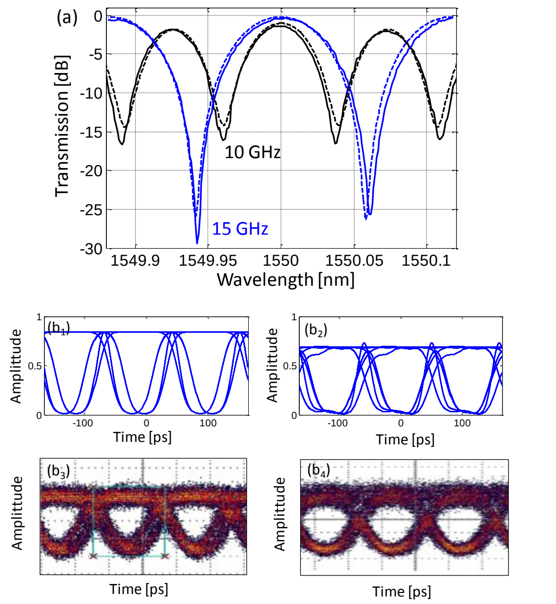

Figure 2. (a) Simulated (dashed) and measured (solid) transmission of the tunable delay MZI for FSR = 15 GHz (blue) and 10 GHz (black). (b) Simulated (b_1, b_2) and measured (b_3, b_4) eye-diagram of a 10 Gbit/s binary DPSK signal detected by the variable delay MZI with a FSR of (b_1, b_3) 15 GHz and (b_2, b_4)10 GHz.

T_{max} [7]. No significant signal distortion occurs at any delay provided that the CROW group delay is constant versus wavelength across the signal spectrum. This condition is achieved if B is at least twice as large as the desired FSR of the receiver. Moreover the coupling coefficients K_{Ri} of the resonators are optimized to achieve a ripple-free amplitude and delay response of the CROW [8].

III. Fabrication and Experimental Results

The proposed device was fabricated on a silicon on insulator (SOI) platform [9]. The optical waveguide core is 220 nm thick, 480 nm wide and is covered with 1 µm-thick oxide layer (n_g = 4.2 for TE polarization). As shown in the photograph of Fig. 1(b), metallic heaters were deposited onto the waveguides to thermally adjust the round trip phase ϕ_1 and ϕ_2 of the rings and the phase ϕ_{MZI} of the reference arm. The MZI unbalance is ΔL_{MZI} = 4736 μm. The rings of the CROW have length L_r = 473 μm, and the coupling coefficient K_{R1} and K_{R2} are 0.64 and 0.2, respectively. The resulting CROW bandwidth is B = 37 GHz, corresponding to T_{max} = 17 ps.

The simulated (dashed lines) and measured (solid lines) frequency domain response of the device is shown in Fig. 2(a) for a TE polarized input light. When both rings are set off-resonance (blue curves), the device exhibits the maximum FSR_{max} = 15 GHz, corresponding to a time delay of 66 ps between the two MZI arms, and an extinction ratio ER > 25 dB. By setting both rings to resonance, a 34 ps delay is added and the FSR reduces to 10 GHz (black curves). Note that the device insertion loss increases by only 1 dB between the maximum and the minimum FSR condition. Optimized power coupling coefficients, K_1 = 0.6 and K_2 = 0.5, were used to compensate for the delay-dependent loss in the CROW and to guarantee ER > 15 dB at any intermediate FSR. The maximum electric power consumption required to feed the heaters is about 30 mW even in the worst case (phase shift of π for each ring and for the MZI's reference arm).

The variable delay MZI was employed to receive a 10 Gbit/s binary DPSK signal transmitted at a wavelength of 1550 nm. Fig. 2(b) shows the simulated (b_1, b_2) and measured (b_3, b_4) eye-diagrams of the intensity modulated signal at the output of the variable delay MZI when the FSR of the receiver is set to 15 GHz (b_1, b_3) and 10 GHz (b_2, b_4), respectively. When the symbol rate does not match the FSR of the receiver, the eye-diagram is triangularly shaped because of strong intersymbol interference (ISI), causing an evident splitting of the signal transitions. The optimum 100-ps delay achieved by setting both rings on resonance improves the quality of the received signal, widening the eye aperture and narrowing the signal transitions. This result demonstrates the suitability of a MZI loaded with a reflective CROW delay line to detect DPSK signals with no evident signal distortions. A deeper investigation on the system performance of the device with signals at higher bit-rates and high power is currently being performed.

IV. Conclusion

To summarize, we have presented the first integrated DPSK receiver with a continuously tunable delay. The functionality of the device, which has been realized on an SOI platform, has been demonstrated on a 10 Gbit/s binary DPSK signal, but can be extended to generic DPSK systems with more complex data symbol constellations. A variable delay between 66 ps and 100 ps has been achieved, enabling the use of the receiver to demodulate signals at bit-rates between 10 and 15 Gbit/s.

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References

[1] G. Bosco and P. Poggiolini, “On the joint effect of receiver impairments on direct-detection DQPSK systems,” J. Lightwave Technol., vol. 24, pp. 1323-1333, 2006.

[2] B. Mikkelsen, C. Rasmussen, P. Mamyshev, and F. Liu, “Partial DPSK with excellent filter tolerance and OSNR sensitivity,” Electron. Lett., vol. 42, pp. 1363-1364, 2006.

[3] Y. K. Lizé et al., “Free spectral range optimization of return-to-zero differential phase shift keyed demodulation in the presence of chromatic dispersion,” Opt. Express, vol. 15, pp. 6817-6822, 2007.

[4] J. Li, K. Worms, R. Maestle, D. Hillerkuss, W. Freude, and J. Leuthold, "Free-space optical delay interferometer with tunable delay and phase," Opt. Express, vol. 19, pp. 11654-11666, Jun. 2011.

[5] Y. Dai and C. Shu, "Bit-rate variable DPSK demodulation based on cascaded four-wave mixing," Opt. Express, vol. 19, pp. 2952-2958,2011.

[6] Y. Nasu, K. Hattori, T. Saida, Y. Hashizume, and Y. Sakamaki, "Silica-based adaptive-delay DPSK demodulator with a cascaded Mach-Zehnder interferometer configuration," European Conference on Optical Communications (ECOC), We.8.E.5, Torino, Italy, 2010.

[7] F. Morichetti, A. Melloni, C. Ferrari, and M. Martinelli, "Error-free continuously-tunable delay at 10 Gbit/s in a reconfigurable on-chip delay-line," Opt. Express, vol. 16, pp. 8395-8405, May 2008.

[8] A. Melloni and M. Martinelli, "Synthesis of Direct-Coupled-Resonators Bandpass Filters for WDM Systems," J. Lightwave Technol., vol. 20, pp. 296, 2002.

[9] A. Canciamilla et al., “Silicon coupled-ring resonator structures for slow light applications: potential, impairments and ultimate limits,” Journal of Optics, vol. 12, pp. 104008, 2010.