Error-free continuously-tunable delay at 10 Gbit/s in a reconfigurable on-chip delay-line

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Abstract: A coupled-resonator optical waveguide (CROW) consisting of a chain of directly coupled ring-resonators (RRs) fabricated in 4.5%-index-contrast silicon oxynitride technology is employed to control the delay of optical pulses with continuity and over several bit-slots. The moderate deterioration of the signal quality versus the delay is demonstrated by the observation of error-free transmission (BER $< 10^{-9}$) at 10 Gbit/s for fractional delays of up to 3 bits, with fractional losses below 1 dB per bit-delay. The high storage efficiency of the device, exceeding 0.5 bit/RR, enables an easy management of the delay and the reduction of the footprint down to 7 mm^2. The presented reconfiguration scheme is hitless with respect to data transmission, since the CROW delay can be tuned without halting the data flow, while preserving the signal quality.

OCIS codes: (130.3120) Integrated optics devices; (230.4555) Coupled resonators; (200.4490) Optical buffers.

References and links

1. D. Gauthier, "Slow light brings faster communications," Phys. World, 30 December (2005).
2. J. T. Mok and B. J. Eggleton, "Expect more delays," Nature (London) **433,** 811–812 (2005).
3. E. Parra and J. R. Lowell, "Toward applications of slow-light technology," Opt. Photon. News **18,** 41–45 (2007).
4. R. M. Camacho, M. V. Pack, J. C. Howell, A. Schweinsberg, and R. W. Boyd, "Wide-bandwidth, tunable, multiple-pulse-width optical delays using slow light in cesium vapour," Phys. Rev. Lett. **98,** 153601 (2007).
5. Y. Okawachi, M. S. Bigelow, J. E Sharping, Z. Zhu, A. Schweinsberg, D. J. Gauthier, R. W. Boyd, and A. L. Gaeta, "Tunable all-optical delays via Brillouin slow light in an optical fiber," Phys. Rev. Lett. **94,** 153902 (2005).
6. K. Y. Song, M. G. Herrez, and L. Thévenaz, "Long optically controlled delays in optical fibers," Opt. Lett. **30,** 1782-1784 (2005).
7. J. Sharping, Y. Okawachi, and A. Gaeta, "Wide bandwidth slow light using a Raman fiber amplifier," Opt. Lett. **13**, 6092-6098 (2005).
8. B. Zhang, L. -S. Yan, J. -Y. Yang, I. Fazal, A. E. Willner, "A single slow-light element for independent delay control and synchronization on multiple Gb/s data channels," IEEE Photon. Technol. Lett. **19,** 1081 - 1083 (2007).
9. B. Zhang, L. Zhang, L. -S. Yan, I. Fazal, J. -Y. Yang, and A. E. Willner,"Continuously-tunable, bit-rate variable OTDM using broadband SBS slow-light delay line," Opt. Express **15,** 8317-8322 (2007).
10. F. Xia, L. Sekaric, and Y. Vlasov, "Ultracompact optical buffers on a silicon chip," Nat. Photonics **1,** 65-71 (2007).
11. M. Ghulinyan, M. Galli, C. Toninelli, J. Bertolotti, S. Gottardo, F. Marabelli, D. Wiersma, L. Pavesi, and L. Andreani, "Wide-band transmission of non-distorted slow waves in one-dimensional optical superlattices," Appl. Phys. Lett. **88,** 241103 (2006).

#94046 - $15.00 USD Received 18 Mar 2008; revised 28 Apr 2008; accepted 29 Apr 2008; published 23 May 2008

12. Y. Akahane, T. Asano, B. S. Song, and S. Noda, "High-Q photonic nanocavity in a two-dimensional photonic crystal," Nature (London) **425,** 944-947 (2003).
13. D. O'Brien, M. D. Settle, T. Karle, A. Michaeli, M. Salib, and T. F. Krauss, "Coupled photonic crystal heterostructure nanocavities," Opt. Express **15,** 1228-1233 (2007).
14. T. Tanabe, M. Notomi, E. Kuramochi, A. Shinya, and H. Taniyama, "Trapping and delaying photons for one nanosecond in an ultrasmall high-Q photonic-crystal nanocavity," Nat. Photonics **1,** 49-52 (2007).
15. B. E. Little, et al., "Very high-order microring resonator filters for WDM applications," IEEE Photon. Technol. Lett. **16,** 2263-2265 (2004).
16. J. K. S. Poon, L. Zhu, G. A. DeRose, and A. Yariv, "Transmission and group delay of microring coupled-resonator optical waveguides," Opt. Lett. **31,** 456-458 (2006).
17. F. Morichetti, A. Melloni, C. Canavesi, F. Persia, M. Martinelli, and M. Sorel, "Tunable Slow-Wave Optical Delay-Lines," in Slow and Fast Light, Technical Digest (CD) (Optical Society of America, 2006), paper MB2.
18. F. Morichetti, A. Melloni, A. Breda, A. Canciamilla, C. Ferrari, and M. Martinelli, "A reconfigurable architecture for continuously variable optical slow-wave delay lines," Opt. Express **15,** 17273-17282 (2007).
19. A. Melloni, R. Costa, P. Monguzzi, and M. Martinelli, "Ring-resonator filters in silicon oxynitride technology for dense wavelength-division multiplexing systems," Opt. Lett. **28,** 1567-1569 (2003).
20. F. Morichetti, R. Costa, G. Cusmai, A. Cabas, M. Feré, M. C. Ubaldi, A. Melloni, and M. Martinelli, "Integrated optical receiver for RZ-DQPSK transmission systems," in Proc. of Optical Fiber Communication Conference **2,** Los Angeles, CA, Feb. 23-27 (2004).
21. C.K. Madsen, M. Cappuzzo, E.J. Laskowski, E. Chen, L. Gomez, A. Griffin, A. Wong-Foy, S. Chandrasekhar, L. Stulz, L. Buhl, "Versatile integrated PMD emulation and compensation elements," IEEE J. Lightwave Technol. **22,** 1041 (2007).
22. A. Melloni, F. Morichetti, and M. Martinelli, "Linear and nonlinear pulse propagation in coupled resonator slow-wave optical structures," Opt. Quantum Electron. **35,** 365-379 (2003).
23. A. Melloni, and F. Morichetti, "Observation of Subluminal and Superluminal Velocity Swinging in Coupled Mode Optical Propagation," Phys. Rev. Lett. **98,** 173902 (2007).
24. B. Zhang, L. Yan, I. Fazal, L. Zhang, A. E. Willner, Z. Zhu, and D. J. Gauthier, "Slow light on Gbit/s differential-phase-shift-keying signals," Opt. Express **15,** 1878-1883 (2007).
25. L. Yi, W. Hu, Y. Su, M. Gao, L. Leng, "Design and system demonstration of a tunable slow-light delay line based on fiber parametric process," IEEE Photon. Technol. Lett. **18**, 2575-2577, (2006).
26. ITU-T Rec. G-872, "Architecture of optical transport networks," Genève, (2005).
27. A. Melloni, F. Morichetti, and C. Ferrari, "1-byte reconfigurable integrated optic delay-line," in Slow and Fast Light, Technical Digest (CD) (Optical Society of America, 2008).
28. B. Little, "VLSI photonics platform," Optical Fiber Communication Conference 2, Atlanta, Georgia, Mar. 23-27, paper ThD1 (2003).
29. F. Morichetti, A. Melloni, M. Martinelli, R. G. Heideman, A. Leinse, D. H. Geuzebroek, and A. Borreman, "Box-Shaped Dielectric Waveguides: A New Concept in Integrated Optics?," J. Lightwave Technol. **25,** 2579-2589 (2007).
30. F. G. Sedgwick, B. Pesala, J. Y. Lin, W. S. Ko, X. Zhao, and C. J. Chang-Hasnain, "THz-bandwidth tunable slow light in semiconductor optical amplifiers," Opt. Express **15,** 747-753 (2007).

1. Introduction

Slow-light technologies are expected to enable all-optical processing in many applicative domains [1, 2]. Among these, telecom applications concerning the control of light speed and delay, like bit and frame synchronization, time-multiplexing and buffering, are forthcoming [3]. However, handling the optical delay can be of real interest provided that (1) the delay is tuned with continuity over a wide range and (2) by means of simple, easily-manageable and cost-effective devices; (3) the increase of insertion losses versus delay is moderate, (4) the quality of the signal is preserved.

Large variable delays have been recently achieved in a variety of optical systems exhibiting slow-light properties, like transparency resonances in atomic vapors [4] and nonlinear scattering processes in optical fibers [5, 6, 7]. For instance, broadband Stimulated Brillouin Scattering (SBS) has been employed to demonstrate the synchronization of three 2.5-Gbit/s data channels [9] and the time-multiplexing of two 2.5 Gbit/s data signals [8] by continuously controlling the delay over about 0.25 bit-lengths. However, because of the nature itself of these slow-light mechanisms, a chip-scale implementation of these approaches seems unpractical. From this point of view, coupled-resonator optical waveguides (CROW) made of ring resonators (RRs)

#94046 - $15.00 USD Received 18 Mar 2008; revised 28 Apr 2008; accepted 29 Apr 2008; published 23 May 2008

are believed one of the most promising slow-light technologies [10]. Compared to other kinds of optical resonators, like Fabry-Pèrot cavities [11] or photonic crystal nanocavities [12, 13, 14], RRs do not need strong refractive-index discontinuities along the propagation direction, thus reducing scattering effects and losses [10, 15, 16, 17].

Regarding losses, a fundamental figure of merit of tunable delay-lines is the fractional loss per bit, expressing how much power gets lost per every bit-delay. Formally, it can be defined as $L_f = I_L T_b / T_d$, where I_L and T_d are the delay-line insertion loss and delay, respectively, and T_b is the pulse width. The ratio T_d / T_b is often referred to as fractional delay. The parameter L_f is intrinsically related to the propagation loss α and can never drop below $L_{f,min} = \alpha c T_b / n_g$ [18], with n_g the effective group index and c the vacuum light speed. The best technology to realize low-loss slow-wave devices is the one minimizing the ratio between the imaginary (α) and the real (n_g) part of the group refractive index. To give a rough estimate, at 10 Gbit/s state-of-the-art silicon buffers exhibit $L_f = 4.5$ dB/bit [10], whereas the expected lower bound for integrated glass technologies ($\alpha < 0.1$ dB/cm) is below $L_{f,min} = 0.2$ dB/bit. This is the main reason why the device reported in this work was fabricated on a glass platform, enabling $L_f < 1$ dB/bit. However, since the fractional loss scales as the inverse of the signal bandwidth, at higher bit-rates semiconductor technologies can become really competitive for delay-line applications.

Apart from losses, the quality of the delayed signal strictly depends on the capability of configuring and managing the delay-line. In a RR-CROW this implies that the resonant frequency of all the RRs must be finely controlled by means of some active tuning mechanisms. In order to ease the tuning procedure, the number N of RRs should be minimized, without preventing continuous delay tunability. This feature is expressed by the storage efficiency $\eta_S = T_d / (T_b N)$, giving the number of bits stored in every RR of the delay-line. A high η_S means that a given delay T_d can be achieved with few resonators, this implying not only a footprint reduction but also remarkable advantages in the delay-line (re)configuration.

Although CROWs have been addressed as ultra-compact optical buffers [10], they still fail satisfying two fundamental requirements. First of all, only the digital control of the CROW delay, by large fractions of the bit length, has been demonstrated, yet requiring additional devices to accomplish an analog delay [18]. Second, the quality of transmission through CROW buffers exhibits unpractically high bit error rates (BERs) (more than 10^{-2} at 10 Gbit/s [10]), which are orders of magnitude above the standard telecom requirements.

In this contribution, we show that a reconfigurable slow-wave delay-line (RSWDL) based on an integrated CROW realized on a silicon oxynitride (SiON) platform enables a flexible control of the delay over several bit-slots, with a moderate deterioration of the signal quality. We demonstrate that, despite the discrete nature of the structure, containing a very small number of resonators (N = 6), a CROW can provide a continuously controllable delay over a large range (from 0 to 320 ps) and with a high accuracy (less than 1 ps). We report also the first demonstration of error free transmission (BER $< 10^{-9}$) through a fully reconfigurable CROW, at bit rates typically used in optical communications. The reconfiguration scheme is simple, robust and hitless, since it can be performed without stopping the data-flow, while preserving the signal quality.

2. Design and fabrication technology

Figure 1 shows a top-view photograph of the presented device. The CROW delay-line is made of 8 directly-coupled RRs fabricated in 4.5% refractive index-contrast silicon oxynitride (SiON) technology. The optical channel waveguide (nominal size 2.2 μm x 2.2 μm) is obtained by reactive ion etching a SiON film, with refractive index n_{SiON} = 1.513, deposited by Plasma Enhanced Chemical Vapour Deposition (PECVD) on a 15-μm-thick thermal silicon dioxide substrate. Before lithographic processes, an annealing treatment at 1100 °C has been conducted

#94046 - $15.00 USD Received 18 Mar 2008; revised 28 Apr 2008; accepted 29 Apr 2008; published 23 May 2008

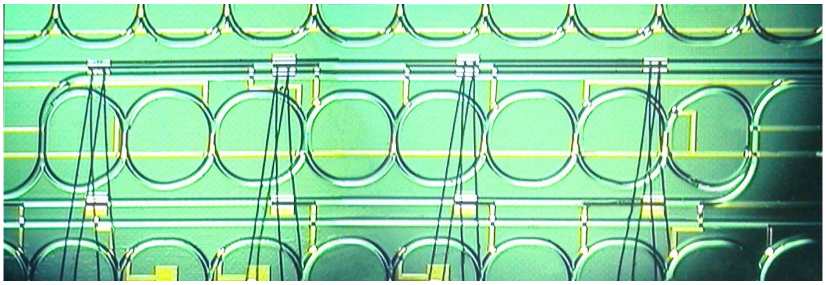

Fig. 1. Top view photograph of a CROW in SiON techology. The bus waveguide coupled with the leftmost RR acts as input/output port, whereas the bus waveguide coupled with the rightmost RR enables monitor operations. The different shape of the first (last) rings realizes the impedance-matching condition (apodization) between the bus waveguide and the coupled-resonator structure. Gold striplines connect every resistor to the contact pads, the latter being wire-bonded to the tuning control unit.

to reduce both material losses and stresses. A 7-μm-thick layer of borophosphosilicate glass (BPSG) is employed as upper-cladding material. The resulting waveguide exhibits 0.35 dB/cm propagation loss at 1550 nm and is suitable for the realization of RRs with up to 100 GHz free spectral range (FSR) [19]. This technology is rather standard and more details are described elsewhere [20].

All the RRs shown in Fig. 1 have the same optical length, with bending radius ρ = 570 μm and FSR = 50 GHz. In order to achieve a maximally flat spectral response and a moderate ripple in the group delay characteristic over the 12.5 GHz-wide passband, the power coupling coefficients were suitably apodized as follows: $K_2 = K_8 = 0.34$, $K_3 = K_7 = 0.19$ and $K_4 = K_5 = K_6 = 0.17$, being K_i the power coupling between the $(i-1)$-th RR and the i-th RR of the CROW. The coupling coefficients between the first (last) RR and the bus waveguide are $K_1 = K_9 = 0.8$. In all the directional couplers the gap is 1.8 μm wide and K_i changes with the coupling region length, as indicated by the different shape of the first (last) RRs in Fig. 1.

The resonant wavelength $\lambda_{r,i}$ $(i = 1, 2, ...N)$ of every i-th RR is independently controlled at few hundreds of microseconds speed by means of chromium heaters deposited on top of the waveguides [21], providing the CROW reconfiguration functionality. Every chromium resistor, realized by standard lift-off process, is 2-mm long, 9-μm wide, 200-nm thick, resulting in a typical measured resistance of about 600 Ω ($\pm$ 10 Ω). The temperature of each RR is controlled by a PC software according to a lookup table, which takes into account the small thermal crosstalk between two adjacent rings. Less than 600 mW are required to shift the resonance of a RR by an entire FSR, corresponding to a waveguide temperature variation of roughly 72 °C. A closed-loop Peltier thermocooler, placed below the optical sample, is employed to stabilize the temperature within ± 0.1°C, corresponding to ± 0.12 GHz frequency shift of the CROW bandwidth.

3. Continuously-tunable delay at 10 Gbit/s

Our scheme for controlling the optical delay of a CROW is based on a gating mechanism across the chain of CROW coupled resonators. The possibility of changing the delay of a CROW by large discrete time-steps (> 100 ps) has been already demonstrated in a recent contribution [18] for signals modulated at 2.5 Gbit/s rates. For clarity's sake, in this section the digital tuning scheme is briefly recalled and its extension to 10 Gbit/s signals is demonstrated. Then we show how the delay induced by a CROW can be controlled by arbitrarily small time-steps

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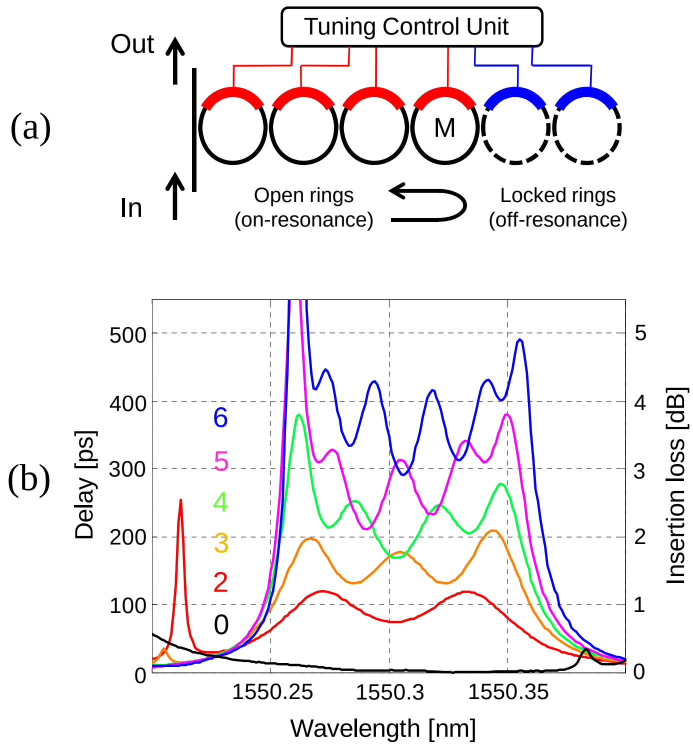

Fig. 2. Discrete tuning of the delay. (a) Schematic of the CROW reflective operation principle. (b) Measured group delay and insertion loss of the CROW for an increasing number of open rings: M = 0 (black line), 2 (red line), 3 (orange line), 4 (green line), 5 (pink line) and 6 (blue line).

(1 ps accuracy), thus providing a continuously tunable delay without the need for additional devices.

Figure 2(a) shows a schematic of the tunable CROW working principle. The management of the RRs' resonant frequencies is achieved by a PC based tuning control unit. Let us define B the CROW bandwidth and $\Delta\lambda_i = \lambda_{r,i} - \lambda_s$ the wavelength detuning between the resonant wavelength of the i-th RR of the CROW and the signal carrier λ_s. The i-th RR is *locked* when resonating away from the signal carrier, that is if $|\Delta\lambda_i| \simeq$ FSR/2. If all the RRs of the CROW are locked, the incoming signal cannot access the CROW and is directly transferred to the *Out* port with no appreciable delay. By acting on the waveguide heaters, the resonant frequencies of the first M resonators, hereinafter referred to as *open rings*, can be set to λ_s ($\Delta\lambda_1$=...=$\Delta\lambda_M = 0$). Therefore, the signal can propagate across all the open RRs and is back-reflected at the first $(M+1)$ off-resonance locked RR, acting as a mirror. The double-transit propagation inside the CROW provides a delay $T_d = 2M/\pi B$, which can be digitally controlled with a minimum time-step equal to the double transit delay $T_r = 2/(\pi B)$ across every open RR [18].

Figure 2(b) shows the measured group delay and the insertion loss of the SiON CROW of Fig. 1 with bandwidth B = 12.5 GHz, finesse $F = \mathrm{FSR}/B = 4$ and slowing factor 2.6 (for the definition of the slowing factor see [22]). The group delay characterization was performed with a phase-sensitive low-coherent technique [23]. By opening an increasing number of RRs (M = 0, 2, 3, 4, 5, 6), the delay increases almost uniformly over the passing band, each RR providing T_r = 50 ps additional delay. The bandwidth is not narrowed neither widened by the tuning process.

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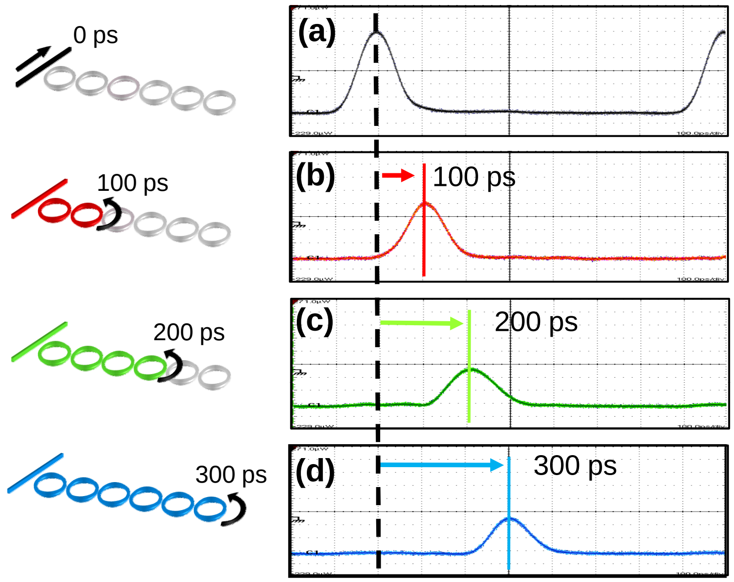

Fig. 3. Time-domain measurements of the digitally tunable delay of the CROW. The probe pulses come from a 10-Gbit/s NRZ optical data-stream with carrier λ_s = 1550.31 nm. The reference trace (a) refers to propagation in the bus waveguide only, when all the RRs are locked. Fractional delays of 1 bit (b), 2 bits (c) and 3 bits (d) with negligible pulse distortion are obtained when 2, 4 and 6 RRs are opened, respectively. The time traces are reported in the same time (horizontal) and intensity (vertical) scale.

The in-band delay ripple is due to tolerance-induced non-optimal impedance matching of the CROW, which makes the incoming signal not perfectly coupled to the CROW. Nonetheless, time-domain measurements demonstrate that, at 10 Gbit/s, these spectral oscillations do not introduce a significant pulse distortion, since they are averaged on the signal spectrum. Some off-band spikes, which are due to cavity effects in the locked RRs, can be observed at the sides of the spectral response. If needed, such resonances can be conveniently shifted in a suitable frequency region away from the CROW passband. More than 300 ps delay can be achieved with 6 RRs at the expenses of only I_L = 3 dB insertion loss. The attenuation derives from 0.2 dB RR round-trip loss, where 0.15 dB is the waveguide propagation loss and the excess 0.05 dB include directional couplers' loss and bending loss.

Pulse delay was measured in time-domain by acquiring the traces of 100-ps-long gaussian pulses, with optical carrier $\lambda_s = 1550.31$ nm, transmitted through the structure working at different delay configurations. As shown in Fig. 3, when all the RRs are locked (M = 0), the pulse propagates along the bus waveguide only and experiences the minimum reference delay reported in trace (a). Traces (b) to (d) show the output pulses for an increasing number of open RRs. After 300 ps (3 bit-delay) the pulse envelope it is still well preserved both in intensity and shape. This demonstrates that transmission is not significantly affected by the moderate ripple in the spectra of Fig. 2, which is averaged over the 10 GHz signal bandwidth. Referring to the figures of merits defined in Sec. 1, at 10 Gbit/s the CROW delay-line exhibits a storage efficiency η_S = 0.5 bits/RR, with only L_f = 1 dB/bit fractional loss. Note that this loss value is close to the theoretical lower-bound $L_{f,min} = 0.7$ dB/bit imposed by the SiON waveguide propagation loss.

Actually, the discrete number of RRs does not prevent the CROW from providing a con-

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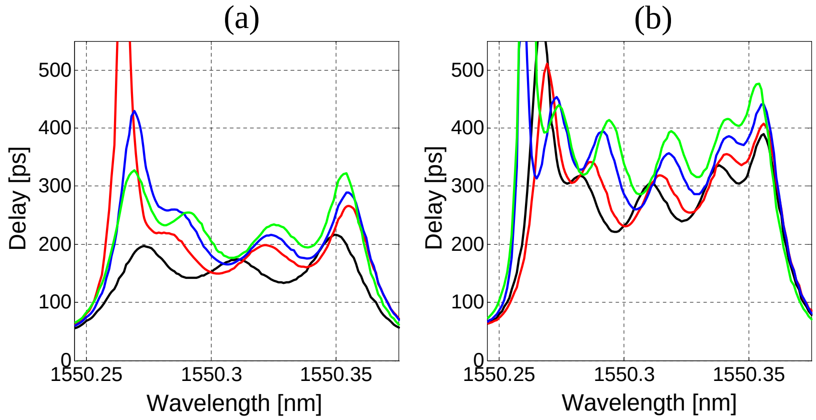

Fig. 4. Frequency-domain characterization of the analog tuning of the CROW delay. (a) Measured group delay of the CROW when the first three RRs are opened and the fourth RR is drawn towards λ_s: $\Delta\lambda_4 = -200$ pm (black line), $\Delta\lambda_4 = -28$ pm (red line), $\Delta\lambda_4 = -12$ pm (blue line) and $\Delta\lambda_4 = 0$ pm (green line); (b) Measured group delay of the CROW when the first five RRs are opened and the sixth RR is drawn towards λ_s: $\Delta\lambda_6 = -200$ pm (black line) $\Delta\lambda_6 = -54$ pm (red line), $\Delta\lambda_6 = -28$ pm (blue line) and $\Delta\lambda_6 = 0$ pm (green line).

tinuously controllable analog delay. The idea shown here is to exploit the fine tuning of the last open RR in order to produce an arbitrarily small variation of the overall CROW delay. To demonstrate the feasibility and the robustness of the analog tuning scheme, we can start from an arbitrary CROW configuration. Let us assume that the first three RRs are opened ($\Delta\lambda_i = 0$, with $i = 1,2,3$), while all the subsequent RRs are locked ($\Delta\lambda_i = -\mathrm{FSR}/2 = -0.2$ nm, with $i = 4,5,6$). As shown in Fig. 4(a) this configuration provides an average delay of 150 ps (black line) in the neighborhood of $\lambda_s = 1550.31$ nm. When the fourth RR is progressively opened by making $\lambda_{r,4}$ approach λ_s, an arbitrary delay comprised between 0 and T_r = 50 ps is added. For example, Fig. 4(a) shows the change of the CROW delay when $\Delta\lambda_4 = -28$ pm (red line), $\Delta\lambda_4 = -12$ pm (blue line) and $\Delta\lambda_4 = 0$ pm (green line). The average group delay around λ_s progressively rises and, even though a small asymmetry is induced in the group delay characteristic, this does not cause a significant distortion of the transmitted signal. Figure 5(a) shows the measured eye-diagrams of a 10-Gbit/s NRZ optical signal (2^{31}-1 Pseudo-Random Bit Sequence) transmitted through the CROW working at the four configurations of Fig. 4(a). The time-shift of the eye diagrams achieved by partially detuning the forth RR are 150 ps at $\Delta\lambda_4 = -200$ pm (a_1), 167 ps at $\Delta\lambda_4 = -28$ pm (a_2), 186 ps at $\Delta\lambda_4 = -12$ pm (a_3) and 198 ps at $\Delta\lambda_4 = 0$ pm (a_4). Likewise, Fig. 4(b) shows the frequency-domain delay when the first five RRs are opened and the sixth RR is partially detuned. As shown in Fig. 5(b), the delay is controlled from 260 ps to 318 ps without affecting the quality of the signal. The eye-diagram opening demonstrates that the analog tuning implies no appreciable signal degradation, even though the last open RR does not resonate at λ_s. The comparison between the simulated (solid line) and the measured (squares) delay of the CROW versus $\Delta\lambda_4$ and $\Delta\lambda_6$ is reported in Figs. 5(c) and 5(d), respectively.

To give a better insight into the mechanism of the analog tuning of the CROW delay, Fig. 6 shows in a movie the evolution of the simulated frequency-domain delay when an increasing number of RRs are sequentially brought to resonance. The time-shift of the measured eye-diagram of a 10 Gbit/s NRZ optical signal (2^{31}-1 PRBS) transmitted through the CROW is shown in the animation of Fig. 7.

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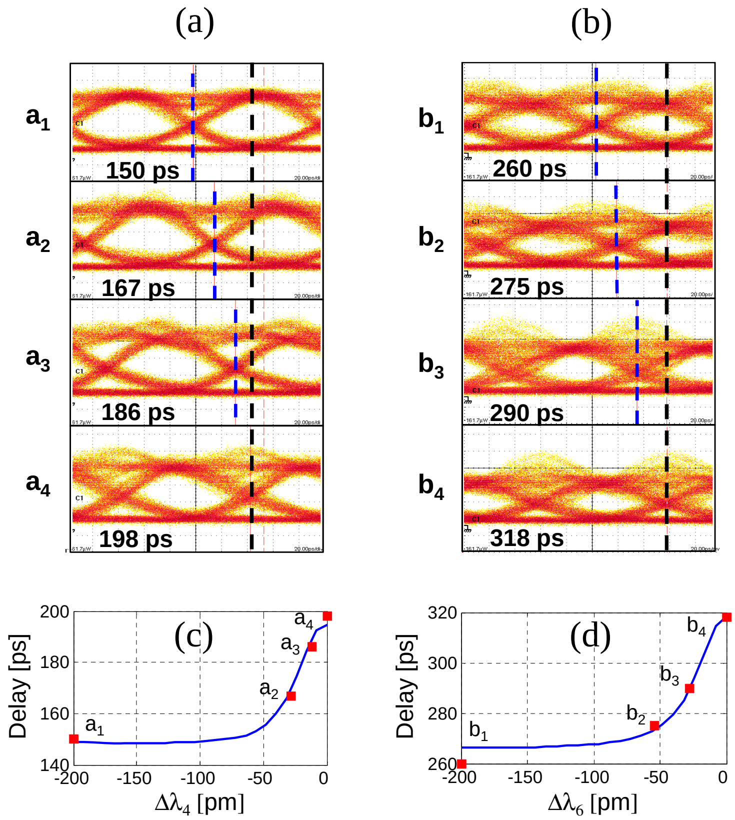

Fig. 5. Time-domain characterization of the analog tuning of the CROW delay. Measured eye-diagrams of a 10 Gbit/s NRZ optical signal (2^{31}-1 PRBS) transmitted through the CROW when the delay configurations of Fig. 4 are assumed. (a) When only the first three RRs are opened, the fine tuning of the fourth RR provides a delay of (a_1) 150 ps at $\Delta\lambda_4 = -200$ pm, (a_2) 167 ps at $\Delta\lambda_4 = -28$ pm, (a_3) 186 ps at $\Delta\lambda_4 = -12$ pm and (a_4) 198 ps at $\Delta\lambda_4 = 0$ pm. (b) When the first five RRs are opened, the fine tuning of the fourth RR provides a delay of (b_1) 260 ps at $\Delta\lambda_6 = -200$ pm, (b_2) 275 ps at $\Delta\lambda_6 = -54$ pm, (b_3) 290 ps at $\Delta\lambda_6 = -28$ pm and (b_4) 318 ps at $\Delta\lambda_6 = 0$ pm. The simulated delay of the CROW versus the detuning of the fourth (c) and the sixth (d) RR is also reported. The measured delays of (a) and (b) are marked by the squares in (c) and (d), respectively.

The sensitivity of the delay versus the RR detuning is maximum at $\Delta\lambda_i \simeq 0$ (about 1.25 ps/pm) and decreases for higher $\Delta\lambda_i$. The ultimate limit to delay resolution is not imposed by the CROW architecture, but by the physical mechanism inducing the effective index change of the RRs' waveguides. In the case of thermal activation, 1 ps resolution delay can be achieved by controlling the temperature of the heaters within 0.1 $^\circ$C. We expect that this analog tuning scheme does not hold only for RRs architectures but can be generalized to CROWs realized in alternative optical technologies.

4. System performance

System performances were evaluated by means of BER measurements in a 10 Gbit/s system test-bed in back-to-back conditions. The optical signal-to-noise ratio (OSNR) at the receiver

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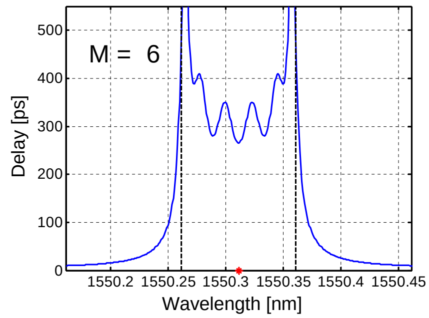

Fig. 6. Movie of the simulated group delay of the CROW during the analog tuning of the delay. M is the number of RRs set to resonance, while the $M+1$-th RR is driven from off-resonance ($\Delta\lambda_{M+1} = \mathrm{FSR}/2 = 0.4$ nm) to on-resonance ($\Delta\lambda_{M+1} = 0$) condition. The red asterisk indicates the frequency position of the $M+1$-th RR of the CROW. The vertical dashed lines show the bandwidth of the CROW. Multimedia file (MPEG, 4 MB).

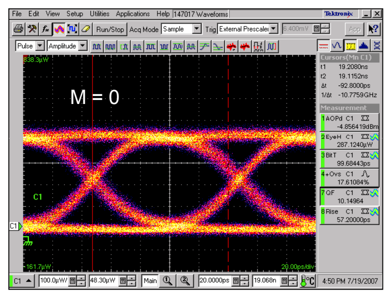

Fig. 7. Movie of the measured eye-diagram of a 10 Gbit/s NRZ optical signal (2^{31}-1 PRBS) transmitted through the CROW for several configuration of the delay. M is the number of RRs set to resonance, while the $M+1$-th RR is driven from off-resonance ($\Delta\lambda_{M+1} = \mathrm{FSR}/2 = 0.4$ nm) to on-resonance ($\Delta\lambda_{M+1} = 0$) condition. From $M = 3$ to $M = 6$ shorter delay steps (about 10 ps/frame) are reported, showing in time-domain the analog tuning of the delay. Multimedia file (MPEG, 3 MB)

was controlled by employing an Amplified Spontaneous Emission (ASE) noise source, followed by a variable optical attenuator, adding an arbitrary noise level to the signal. The OSNR was then measured on a bandwidth of 0.5 nm centered at the signal carrier frequency. At the pre-amplified receiver the signal was filtered by an optical filter with 3-dB bandwidth of 0.2 nm and the optical power at the photodetector was kept constant at -14 dBm for all the reported measurements. The receiver sensitivity is -18 dBm and its electric bandwidth is 30 GHz.

Figure 8 shows the BER curves of an intensity modulated 10-Gbit/s NRZ optical signal (2^{31}-1 PRBS) versus the optical signal to noise ratio (OSNR) measured at the receiver. The pink line provides the back-to-back BER measurement of the transmission setup in the absence of the CROW. The blue line gives the reference BER, measured when all the RRs of the CROW are locked and the signal propagates in the bus waveguide only. No OSNR penalties are observed due to fiber-to-waveguide coupling and propagation in the bus waveguide. As the CROW delay increases, the BER performance slightly degrades, but error-free operation (BER $< 10^{-9}$) is reached for any measured delay between 0 and 3 bits. The OSNR penalty, evaluated at the error-free point, is less than 1.5 dB for 150 ps delay (green line), less than 2.5 dB for 200

#94046 - $15.00 USD Received 18 Mar 2008; revised 28 Apr 2008; accepted 29 Apr 2008; published 23 May 2008

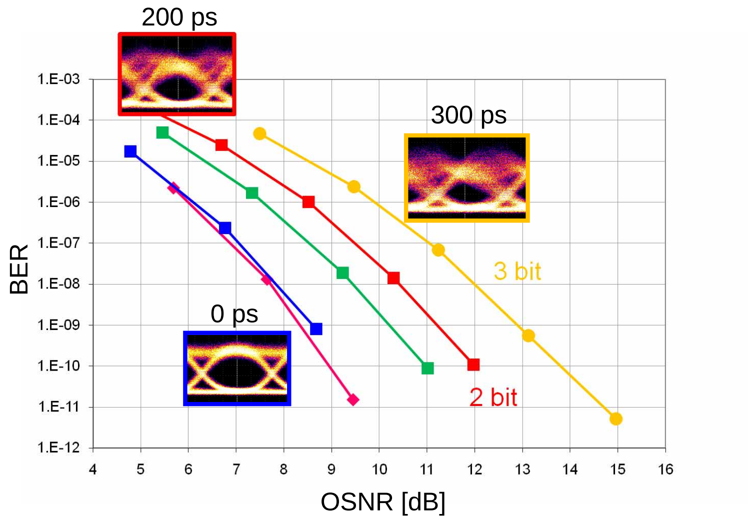

Fig. 8. Bit error rate measurements versus the OSNR at the receiver of an intensity modulated NRZ 10 Gbit/s signal transmitted through the CROW: back-to-back measurement in pink line, 0 ps delay ($M = 0$) in blue, 150 ps delay ($M = 3$) in green, 200 ps delay ($M = 4$) in red and 300 ps delay ($M = 6$) in yellow. The eye-diagrams acquired at error-free operation for 0, 2 and 3 bit delay are shown in the insets of the figure.

ps delay (red line) and about 4 dB for 300 ps delay (yellow line), giving an average OSNR penalty of about 1.3 dB/bit. The eye-diagrams acquired at error-free operation for 0, 2 and 3 bit delay are shown in the insets of the figure. In all the BER measurements reported in the figure the data signal is tuned around the center of the CROW pass band with a wavelength tolerance, imposed by the experimental setup, of ± 5 pm. No significant variation of the signal quality was observed within this wavelength window. The wavelength tolerance window can be expanded by increasing the bandwidth of the device, at the expenses of the storage efficiency η_s.

Since error-free operation is guaranteed for any intermediate delay, the CROW can be reconfigured without halting the data flow, or, in other words, the control of the delay is hitless. This is strictly true only if the tuning mechanism is much slower than the bit time-width, as happens in the case of thermal activation.

Finally, we emphasize that the reported results significantly outperform the state-of-the-art performance reached by slow light delay-lines using nonlinear scattering methods in optical fibers. Error free propagation of a 10.7-Gb/s NRZ-DPSK signal delayed by using a SBS-based delay line was recently demonstrated, yet with 9.5 dB power penalty at a delay of 42 ps (about 22 dB/bit) [24]. Fiber-optic parametric process, expected to enable slow-light propagation at much larger bandwidths than SBS, was employed to delay 10-Gbit/s NRZ data packets by 15 ps with 0.6 dB sensitivity penalty ($>$ 7 dB/bit) [25].

5. Conclusion

Our results demonstrate that handling, delaying and buffering light on chip is not only an attractive field of scientific exploration, but it is readily exploitable in optical communications. For instance, the continuous control of 1-byte delay is already sufficient to guarantee the synchronization required by the emerging Optical Transport Network (OTN) protocol [26], where one byte of tolerance is counted to map the unsynchronized Sonet-SDH carriers into the OTN frame. The possibility of extending the storage efficiency and the tunability range of a CROW

#94046 - $15.00 USD Received 18 Mar 2008; revised 28 Apr 2008; accepted 29 Apr 2008; published 23 May 2008

to an entire byte-slot has been recently observed experimentally [27] and a future contribution is in preparation.

A final remark concerns the use of a CROW with large RRs, a choice that could sound in counter-trend with respect to the general perspectives of integrated optics, moving towards a higher and higher integration scale. Our choice is aimed to maximize the CROW storage efficiency without implying strong technological challenges. The storage efficiency, which can be also expressed as $\eta_s = 2B_s/(\pi B)$, increases when the CROW (B) and the signal (B_s) bandwidths approach. At 10 Gbit/s, the presented SiON CROW based on large RRs (FSR = 50 GHz) requires a very low finesse ($F = 4$) to reach $\eta_s > 0.5$. A low finesse not only reduces the sensitivity to fabrication imperfection, but also eases the configuration and the management of the CROW. At the same bit-rate, silicon microrings, with typical radii < 10 μm and FSRs of several THz [10], need a much higher finesse $F > 100$ to achieve a comparable storage efficiency. To date, this requirement, together with all the challenging technological implications of the silicon platform, still prevents silicon CROWs from providing acceptable system performance.

Low-loss higher-index-contrast glass technologies (Hydex 0.15 dB/cm [28], TripleX 0.05 dB/cm [29]) are expected to extend the bandwidth of CROW tunable delay-lines up to 100 Gbit/s data-streams, while keeping system performances comparable to those of the presented SiON device. Semiconductor platforms are more likely to become leading technologies at much higher bit-rates ($>$ 100 Gbit/s), where very large bandwidths and lower absolute delays are required, or when a very-large scale of integration has to be accomplished, as for optical interconnects. In this context, where glass technologies sound inadequate, slow-light in semiconductor optical amplifiers [30] and silicon CROW [10, 13] are expected to become competitive approaches.

5.1. Acknowledgements

This work was partially supported by the European Project SPLASH (6th FP). The authors are grateful to R. Siano (CoreCom) for help with BER measurements, to A. Breda and A. Canciamilla for the group delay measurements and to Pirelli Labs for the circuit fabrication.

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