All-optical regenerative NRZ-OOK-to-RZ-BPSK format conversion using silicon waveguides

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We propose a scheme to achieve regenerative format conversion from a distorted non-return-to-zero-on–off-keying (NRZ-OOK) signal to a return-to-zero-binary-phase-shift-keying (RZ-BPSK) signal of high quality in an integrated device. This proposal is achieved by employing an interferometer on a silicon chip with a coupled ring resonator optical waveguide embedded in one arm. In this scheme the amplified NRZ-OOK signal is injected into the converter together with a locally generated return-to-zero (RZ) pulse train at a different wavelength. Owing to the linear and nonlinear effects in the silicon waveguides, the RZ pulse train changes to a clean RZ-BPSK signal after it is cross modulated by the NRZ-OOK signal. To verify the feasibility of our scheme, we simulate the conversion at 10 Gbits/s.

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In the past few years, there has been an increasing interest in all-optical format conversions as future optical networks could employ different modulation formats according to the network scales and applications. In short-reach networks, the use of the non-return-to-zero-on–off-keying (NRZ-OOK) format is considered as a cost-effective solution for its simplicity, while in high-speed long-haul networks, the phase-shift keying (PSK) format has been widely recognized as one of the most promising choices [1–3]. Therefore, to seamlessly interconnect different types of optical networks, all-optical format conversions, especially the NRZ-OOK-to-PSK conversion, may become a critical technology in the network interface.

To date, several schemes have been proposed to achieve the non-return-to-zero (NRZ)-to-PSK conversion [1–6] by employing the Kerr effects presented in high nonlinear fiber, or in semiconductor optical amplifier. All the existing schemes assume that the signal input to the converter is of high quality. However, in practice, the signal to be converted is likely distorted through the transmission when it reaches the edge of the network. Therefore, in this case, the previously proposed methods may not work well if there is no regenerator before the converter.

To reduce the system complexity and size, this Letter proposes a regenerative NRZ-OOK-to-return-to-zero-binary-phase-shift-keying (RZ-BPSK) converter based on a silicon microring structure. This converter is realized by an interferometer with a coupled ring resonator optical waveguide (CROW) embedded in one arm, where a return-to-zero (RZ) pulse-train is cross modulated by the distorted NRZ-OOK signal, resulting in a high-quality RZ-BPSK. This silicon-based converter possesses another advantage in its compatibility with the mature complementary metal-oxide semiconductor fabrication process, which enables high-density integration of our system on a single chip.

Our proposed regenerative NRZ-OOK-to-RZ-BPSK converter is essentially an unbalanced interferometer in Fig. 1. At the input of the interferometer, a low-power RZ pulse train is divided into two branches with a splitting ratio of 2:1. At the upper arm, the RZ pulse train is cross modulated by a degraded NRZ-OOK signal and converted to a high-quality RZ signal. At the interferometer output, the RZ signal is destructively interfered with the RZ pulse train at the lower arm, converting to a desired RZ-BPSK signal. The following illustrates the principle in detail.

As shown in Fig. 1 an N-order CROW is embedded in the upper arm of the interferometer, which consists of a chain of N-coupled microring resonators. These rings have the same radii and are side coupled to two straight waveguides. By properly choosing the coupling coefficients, the CROW can exhibit a boxlike notch around its resonance and will become more boxlike with the increasing of N [7]. In practice, the notch shape is sensitive to the parameters such as the coupling coefficients and the radii. Typically, these perimeters are hard to control during the fabrication. Fortunately, such mismatch can be postcompensated by modifying the radius of the central ring using an e-beam [8].

When a high-power signal is injected into the CROW, the Kerr effect will cause a redshift of the resonance [9], as illustrated in Fig. 2. Such a shift in-

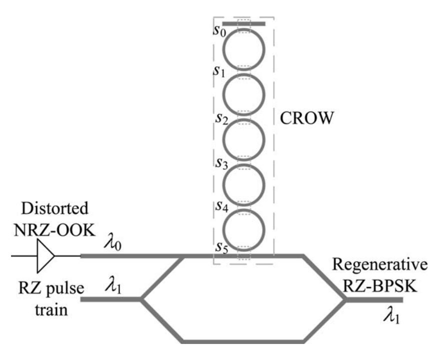

Fig. 1. Regenerative NRZ-OOK to RZ-BPSK format converter.

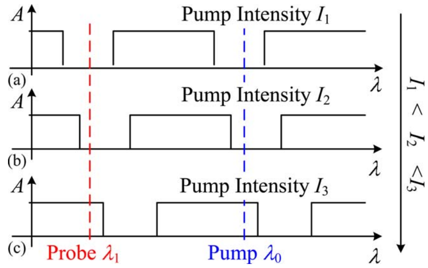

Fig. 2. (Color online) Resonance redshift with the increasing of input pump power, where the pump intensity is (a) zero, (b) small, and (c) sufficiently high, respectively.

creases with the increasing of the signal intensity. Based on this effect, the upper arm of the interferometer can be used to perform the regenerative NRZ-OOK-to-RZ-OOK format conversion, which has been achieved in our previous work [10]. Figure 1 shows that a degraded NRZ-OOK signal after amplification is fed to the upper arm. The NRZ-OOK signal and the RZ pulse train are located at two resonant wavelengths λ_0 and λ_1, respectively. When the input NRZ-OOK signal is a bit "0," though there are small fluctuations, the pump power is sufficiently weak such that it can induce only a small shift of the resonance. In this case, the RZ signal lies in the bottom of the notch and has no output at λ_1 thanks to the boxlike filtering effect of the CROW at the resonance, as illustrated in Figs. 2(a) and 2(b). When the input NRZ-OOK signal is a bit "1," regardless of the distortion, the power at λ_0 becomes high enough and the resonance of the CROW shifts significantly. As a result, the probe signal in λ_1 is completely off resonance. In this case, the output intensity of the RZ pulse is maximized, as illustrated in Fig. 2(c). Consequently, one can obtain a high-quality RZ signal after the CROW at the upper arm.

At the output of the interferometer, the clean RZ signal at the upper arm destructively interferes with the RZ pulse train at the lower arm, which has a half amplitude. As illustrated in Fig. 3, the 0 bits of the RZ signal minus the RZ pulse train generate the pulses with the same shape but inverse phase compared with the RZ pulse train, while the subtraction of the RZ pulse train from the RZ pulse carrying information 1 results in a reduction of the amplitude by half but no phase change. As a result, one can obtain a signal exhibiting RZ pulse shape with the same amplitude but a phase difference between bits 0 and 1, which is clearly a RZ-BPSK signal.

In our simulation, the CROW we employed contains five identical rings. Each ring has a cross section of 450 nm×250 nm and a radius of about 16.5 μm. The effective index of nanoscale silicon waveguides is $n=2.7$. Suppose that the linear loss coefficient $\alpha=-200$ dB/m, which has been achieved in [11]. By setting the cross-coupling coefficients $s_0=s_5=0.32$, $s_1=s_4=0.04$, $s_2=s_3=0.03$, the CROW exhibits a 0.2 nm boxlike notch at its resonant wavelengths as plotted in Fig. 4(a). Figure 4(b) illustrates the sensitivity of the boxlike notch shape to the fabrication imperfection, where the notch shape is remarkably distorted when the perimeter of the third ring is 0.05 μm larger than that of other rings. However, such mismatching can be postcompensated [8]; therefore we assume in our simulations that the CROW can been fabricated as desired. We set the pump light at 1548 nm, and the probe light at the neighboring resonance wavelength at 1539.45 nm. The probe light is phase modulated by the pump light owing to the Kerr effect. Typically, for silicon waveguides, the nonlinear index $n_2\approx 7.9\times 10^{-18}$ m^2/W and the two-photon absorption (TPA) coefficient $\beta_{\mathrm{TPA}}=4.5\times 10^{-12}$ m/W around 1550 nm [12]. Note that the free carrier generated during the TPA process will not only increase the optical loss but also cause a change in the refractive index opposite to the Kerr effect [13]. However, a reverse biased diode structure [14] can be used to sweep out the carriers and thus largely alleviate the effects induced by the free carriers. To date, the free-carrier lifetime can be reduced to ~15 ps by applying a reverse bias voltage of ~25 V [15] to a diode structure.

Figures 4(b) and 4(c) show the transfer functions in power and phase of the format conversion system. It is observed that if the input power is less than 0.04 W or larger than 0.35 W, the powers of the output signals are the same, while their phases have a difference of about π. To explain the choice of a fifth-order CROW used in the converter, we make a comparison about the transfer function between the third-order CROW and fifth-order CROW, which have the same 3 dB bandwidth. It is observed in Fig. 4 that their power transfer functions are quite different, though both cases have similar phase characteristics. It is obvious that the third-order CROW cannot suppress the noise in bit 0, while the fifth-order

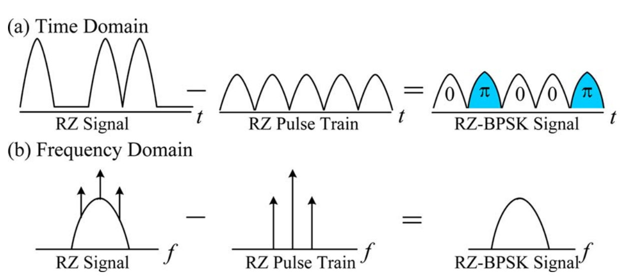

Fig. 3. (Color online) Illustration of the RZ to RZ-BPSK conversion: (a) time and (b) frequency domains.

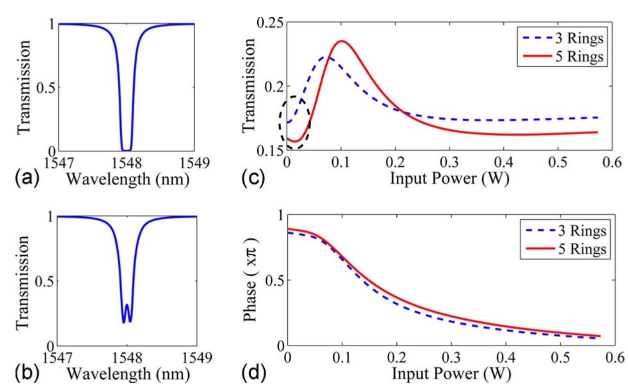

Fig. 4. (Color online) Linear filtering effect of CROW (a) without and (b) with considering the fabrication imprecation; (c) intensity and (d) phase nonlinear transfer functions of the conversion system.

CROW can. This is contributed to the fact that, at the resonance, the notch of the fifth-order CROW has a flatter bottom than that of the third-order case [7]. One can expect that the converter with a seventh-order CROW will have a flatter curve than that with a fifth-order CROW, when the input power is less than 0.04 W.

To verify the feasibility of the proposed scheme, we simulate the process of the regenerative format conversion using the finite-difference method introduced in [9]. We generate a 10 Gbits/s NRZ-OOK signal using a 2^7-1 pseudorandom binary sequence pattern, and transmit it over a standard single-mode fiber without dispersion compensation. The eye diagrams of the NRZ-OOK signals after 30 km transmissions are presented in Fig. 5(a). After amplification, the NRZ-OOK (pump) signal with a peak power of 0.38 W is injected to the upper arm of the interferometer. At the same time, the RZ pulse train (probe) with a FWHM of 25 ps is synchronized with the NRZ-OOK signal and fed into the interferometer. The polarization of both pump and probe lights are set to the TE-like mode. As expected, both the fluctuations in bits 0 and 1 are significantly suppressed, and a clear RZ signal is obtained at λ_1, as shown in Fig. 5(b). Note that the RZ pulse train passing through the upper arm will suffer more optical loss induced by the CROW than that traveling along the lower arm. To compensate such unbalanced optical loss, the power splitter coefficient of the upper and lower arms of the interferometer is set to be 1:0.38. Figures 5(c) and 5(d) show the power and phase eye diagrams of the signal at the output port of the interferometer, respectively, where the RZ signal destructively interferes with the RZ pulse at the lower arm. As seen from the figures, the signal has a RZ shape in the temporal waveform, while its phase changes between 0 and π, which indicates that the signal obtained is a RZ-BPSK signal. In practice, a postdecoding stage would be employed to ensure the correct reception of the data. Note that Fig. 5(d) also shows that there exists a certain noise in the phase 0, which is attributed to the fact that the phase transfer function [see Fig. 4(d)] is still slightly gradient even though the input NRZ-OOK power is higher than 0.35 W. To estimate the regenerative effect of the conversion system, we compare the Q factors of the initial NRZ-OOK signal and the demodulated RZ-BPSK, which are about 2.8 and 16.8, respectively. Therefore, a Q-factor improvement of 15.56 dB after the regenerative format conversion is obtained.

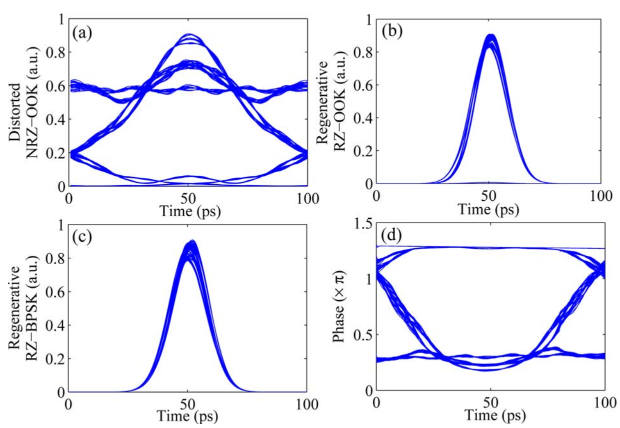

Fig. 5. (Color online) 10 Gbits/s regenerative conversion: (a) initial distorted NRZ signal, (b) RZ signal obtained at the upper arm of the converter, (c) power and (d) phase eye diagram of the output RZ-BPSK signal.

To perform the regenerative format conversion at a higher speed, a higher pump power is indispensable to shift the resonance of the CROW with a wider bandwidth, which leads to a larger power consumption. Also, the carrier removal based on reverse biased diode structure will be limited if the pump intensity exceeds a threshold [15]. In this case, the carrier lifetime is long, and the relevant effects (e.g., free-carrier absorption) are evident, which impose limitations on the data rate of our scheme.

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