Ultrahigh speed OOK-to-PSK conversion using linear filtering in silicon ring resonators

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A scheme to achieve ultrahigh speed all-optical format conversion from on-off keying (OOK) to phase-shift keying (PSK) by using the linear filtering in the silicon ring resonators is proposed. It is shown that the OOK-to-PSK conversion can be achieved through a linear signal processing. Simulation results are provided for the 160-Gb/s non-return-to-zero (NRZ)-to-PSK and carrier-suppressed (CS) return-to-zero (RZ)-to-(CS)RZPSK conversions.

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In future optical networks, different modulation formats will possibly be selectively employed, depending on the network size and the data rate[1]. In short-reach networks, such as local area networks (LANs) and metropolitan networks (MANs), the use of the on-off keying (OOK) formats is considered as a cost-effective solution for the simplicity. While, in high speed (> 40 Gb/s) wide area networks (WANs), the phase-shift keying (PSK) format has been widely recognized as one of promising choices. As a result, to reduce the complexity in optic-to-electric-to-optic (OEO) conversion at the gateways between MANs and WANs, simple all-optical format conversion from OOK to PSK is desired.

Some schemes have been proposed for the conversions from OOK to PSK formats[1−6]. All of the proposals mainly utilize nonlinear effects presented in either the semiconductor optical amplifiers (SOAs)[1,3−5] or the fibers[2,6]. However, the SOA inherently has a recovery time from its saturation state, which will potentially limit the signal-processing speed and introduce unnecessary chirp into the converted signal[3]. Meanwhile, in the methods based on nonlinear effects in fibers, high optical powers and long fibers are typically necessary. This makes the system power-consuming and bulky.

In this letter, we show that the conversion from OOK to PSK formats can be achieved through a linear signal processing. In our scheme, silicon ring resonators[7,8] are employed as ultrahigh-Q-factor optical filters to precisely remove tones in the optical spectra of the OOK signals. This scheme possesses several remarkable advantages including simplicity, applicability to the ultrahigh speed systems, and facility to integration thanks to the use of silicon ring resonators. Our simulation performed at 160 Gb/s verifies that the non-return-to-zero (NRZ), carrier-suppressed return-to-zero (CSRZ), and RZ can be converted to PSK, CSRZ-PSK, and RZ-PSK, respectively, by using a set of resonators with high Q-factors.

Figure 1 illustrates the relationship between the OOK and PSK formats. An optical NRZ signal changes to a PSK signal after it is subtracted with a continuous-wave (CW) signal having a half amplitude but the same frequency and phase. The “0” bit minus the CW light generates a bit, which has the same amplitude but an inverse phase compared with the CW. On the other hand, the subtraction of the CW from the “1” bit results in a reduction of the amplitude by half without inducing any phase inversion. Consequently, the amplitude of the resulting signal keeps unchanged and the phase alternates between 0 and π. In the frequency domain, this operation is essentially to eliminate the tone at the optical carrier, corresponding to the suppression of fluctuation in the amplitude of the signal. This gives us an idea to achieve the conversion from NRZ to PSK by filtering out the central tone using an ultra-narrow notch filter.

This idea can be further extended to perform the conversion from (CS)RZ to (CS)RZ-PSK. The CSRZ (CSRZ-PSK) and RZ (RZ-PSK) signals can be obtained by carving the NRZ (PSK) waveform with pulse carvers, which correspond to the spectrum-shifting in the frequency domain. For example, the CSRZ carver can be approximately expressed as $\cos\left(\frac{\omega_s}{2}t\right)$, and its Fourier transformation (FT) is

$$\pi\delta\left(-\frac{\omega_{\mathrm{s}}}{2}\right)+\pi\delta\left(\frac{\omega_{\mathrm{s}}}{2}\right), \tag{1}$$

where ω_{s} is the frequency of the NRZ signal. When the NRZ (or PSK) signal is shaped by the carver, its spectrum is scaled and shifted a distance of $\omega_{\mathrm{s}}/2$ towards the left and right sides, which yields the sidebands of the CSRZ (or CSRZ-PSK) signal, respectively. Thus,

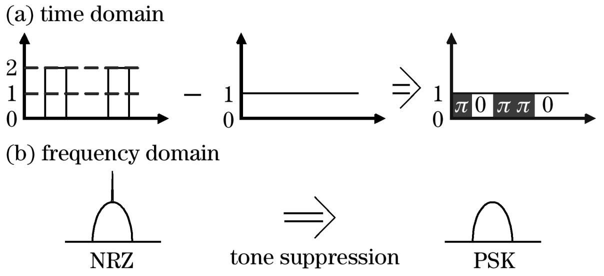

Fig. 1. Illustration of the relationship between the NRZ and PSK formats.

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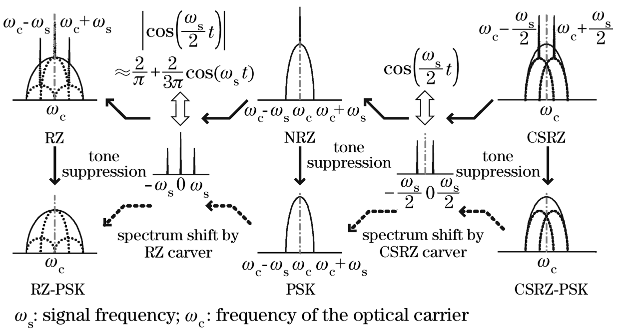


Fig. 2. CSRZ (CSRZ-PSK) and RZ (RZ-PSK) spectra are the shifting results of the NRZ (PSK) spectrum by using the respective carver signals.

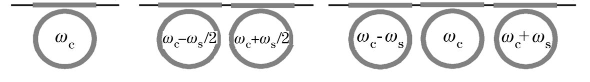
the differences between the CSRZ and CSRZ-PSK signal are the tones in both sidebands. Such relationship is illustrated in Fig. 2. As a result, a CSRZ signal can be converted to a CSRZ-PSK signal if the two tones in both sidebands are suppressed. Similarly, one can perform the RZ-to-RZ-PSK conversion by removing the tones in the RZ spectrum, as plotted in Fig. 2.

Clearly, in our scheme, the optical filter with an ultranarrow bandwidth is indispensable to eliminate the tones of concern without impairing other frequency components. The emerging silicon ring resonator technology makes this scheme feasible. Given the transmission coefficient t, the radius r of the ring, and the attenuation τ of the field per round-trip in the ring, the transfer function of the resonator is given by[7]

$$|H|^2=\frac{t^2-2t\tau\cos\phi+\tau^2}{1-2t\tau\cos\phi+(t\tau)^2}, \tag{2}$$

where $\phi=4\pi^2 r n_{\text{eff}}/\lambda$ is the phase shift per round-trip around the ring, n_{eff} is the effective refractive index of the propagation mode in the ring, λ is the input wavelength. By careful design of these parameters, a ring resonator can act as an optical filter with an ultrahigh Q-factor up to 139000 ± 6000[7] at its resonance wavelengths, which are periodically distributed in the wavelength domain. Usually, the free spectral range (FSR) of a resonator, depending on the length of the ring, is on the order of several nanometers, typically, much wider than the bandwidth of a modulated optical signal. In this letter, we employ the resonator as an ultra-narrow filter to precisely suppress a tone in the OOK spectrum.

According to the above discussion, we present our schematic setups for the OOK-to-PSK conversion in Fig. 3. The number of the resonators in each scheme depends on the number of the tones we have to remove for the conversion. For example, we employ two resonators with different resonance wavelengths in Fig. 3(b), since two tones at different wavelengths in the CSRZ spectrum should be filtered out to obtain the CSRZ-PSK signal.



(a) NRZ to PSK (b) CSRZ to CSRZ-PSK (c) RZ to RZ-PSK

Fig. 3. Schematic setups for the conversions.

Note that, the two resonators for this conversion can be replaced by a signal resonator if there is an ultrahigh-Q-factor resonator with the FSR equal to $\omega_s/2$.

We evaluate the performance for the OOK-to-PSK conversion through simulations. The signal wavelength is tuned at ~ 1547.69 nm. The optical carrier is modulated by a 160-Gb/s pseudo-random binary sequence (PRBS) with a length of 2^7-1. Typically, the ring resonator shows polarization sensitivity, which, however, can be eliminated by varying certain design parameters such as internal pressure[9], etch depth, and waveguide width[10,11]. Therefore, to simplify the simulation, we assume that the ring resonator employed is polarization-insensitive.

We use the resonator with a similar performance to that in Ref. [7] to filter out the tone at the optical carrier for this conversion. The transfer function of the resonator is provided in Fig. 4(a), which shows that the resonator has a ~ 26 dB attenuation at 1547.7 nm and a 3-dB bandwidth $\Delta\lambda_{3\text{dB}}<0.012$ nm. Figures 4(b) and (d) display the waveform and spectrum of the input NRZ signal, respectively. After passing through the resonators, the input NRZ signal is converted to a PSK signal with a certain residual modulation in the amplitude, which is verified by the results in Figs. 4(g)—(k). The residual amplitude modulation in Fig. 4(g) can be further reduced if a resonator with a higher Q-factor is available. An abrupt inversion in phase between the "0" and "1" bit is observed in Fig. 4(h). The phase of "0"s is π while that of "1"s is 0, which agree with our analysis in Section II. Compared with the NRZ spectrum in Fig. 4(d), the tone at the optical carrier has been removed in Fig. 4(i). Figures 4(j) and (k) give the eye diagrams for the waveform and phase of the output PSK signal, respectively.

As discussed above, one needs to remove the tones in the two sidebands to achieve the format conversion from CSRZ to CSRZ-PSK. As the signal wavelength is at

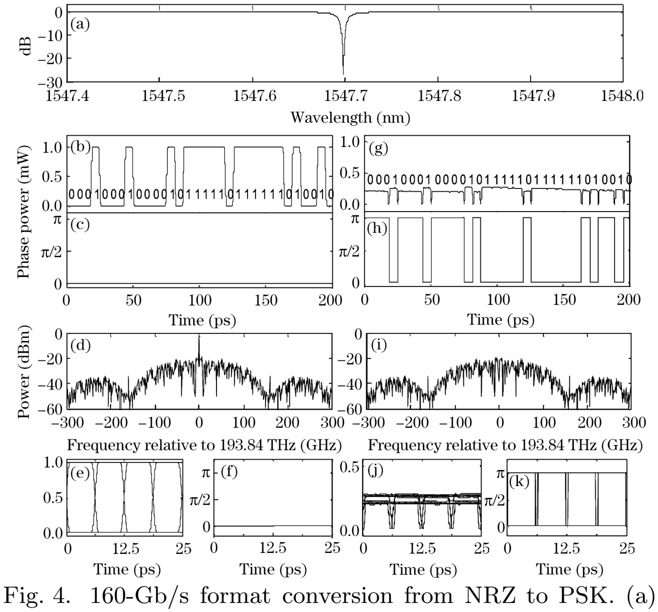


Fig. 4. 160-Gb/s format conversion from NRZ to PSK. (a) Transfer function of the employed resonator; (b) waveform, (c) phase, (d) spectrum, (e) waveform eye-diagram, (f) phase eye-diagram of the input NRZ signal; (g)—(k) are the counterparts of the output PSK signal.

1547.69 nm, the resonance wavelengths should be 1547.05 and 1548.33 nm. In the simulation, we assume that all the resonators have the same transmission characteristics as those used for the NRZ-to-PSK conversion, except their resonance wavelengths. The transfer functions of the employed resonators are given in Figs. 5(a) and (b).

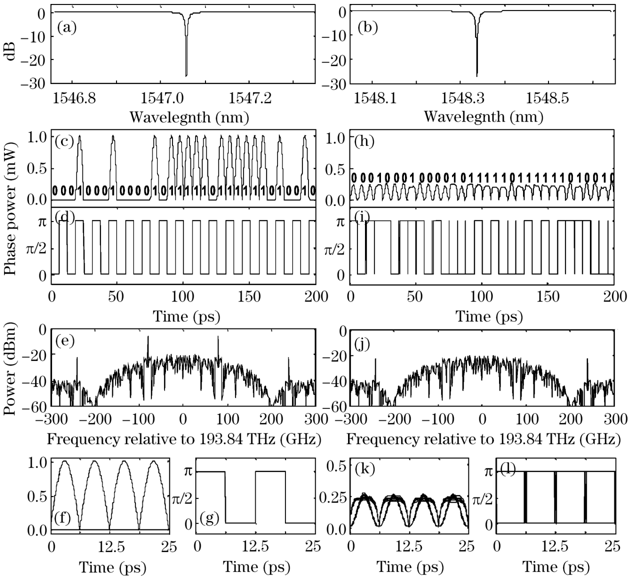


Fig. 5. 160-Gb/s format conversion from CSRZ to CSRZ-PSK. (a) Transfer function of the resonator for the left side-tone and (b) for the right side-tone; (c) waveform, (d) phase, (e) spectrum, (f) waveform eye-diagram, (g) phase eye-diagram of the input signal; (h)—(l) are the counterparts of the output CSRZ-PSK signal.

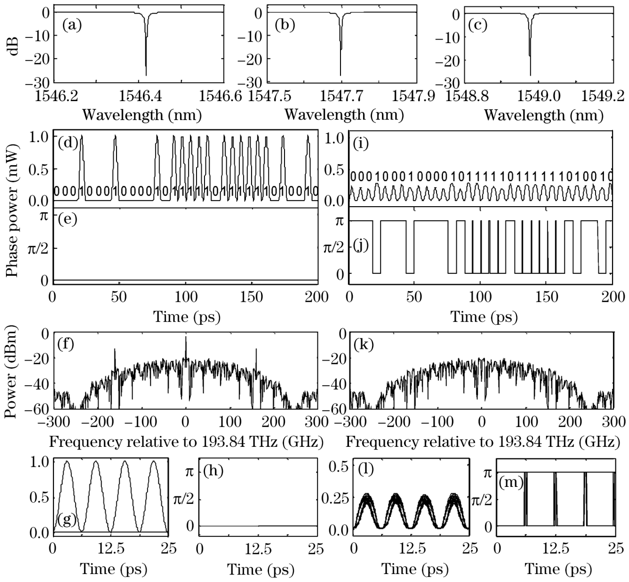


Fig. 6. 160-Gb/s format conversion from RZ to RZ-PSK. (a) Transfer function of the resonator for the left side-tone, (b) for the central tone, and (c) for the right side-tone; (d) waveform, (e) phase, (f) spectrum, (g) waveform eye diagram, (h) phase eye-diagram of the input RZ signal; (i)—(m) are the counterparts of the output RZ-PSK signal.

The input CSRZ signal is plotted in Figs. 5(c)—(g). The resulting CSRZ-PSK signal is shown in Figs. 5(h)—(l). It can be seen that, compared with the phase of the input signal, all the “0”s of the output signal have a phase inversion of π, while all the “1”s keep their phase unchanged, which finally composes the phase sequence of the CSRZ-PSK signal. The eye diagrams in Figs. 5(k) and (l) verify the feasibility of the conversion.

For the conversion from RZ to RZ-PSK, we use three resonators. As shown in Figs. 6(a)—(c), the resonance wavelengths of the ring resonators are 1546.41, 1547.69, and 1548.97 nm, respectively. They are employed to remove the central tone and the tones within both sidebands, as plotted in Fig. 6(f). In the simulation, the input RZ signal has a duty cycle of 50%. The output RZ-PSK signal is given in Figs. 6(i)—(m), which confirms the efficiency of the conversion.

In this letter, we show that the OOK-to-PSK conversion can be achieved by using a set of silicon ring resonators to perform linear filtering. Our simulations verify the feasibility of conversions from NRZ to PSK, CSRZ to CSRZ-PSK, and RZ to RZ-PSK at 160 Gb/s.

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