160-Gb/s NRZ-to-PSK Conversion using Linear Filtering in Silicon Ring Resonators

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Abstract: This paper proposes a scheme to achieve high-speed all-optical non-return-to-zero to phase-shift keying (NRZ-to-PSK) conversion by using the linear filtering in the silicon ring resonators. Simulation results are provided to verify the feasibility.

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1. Introduction

In future optical networks, different modulation formats might be selectively employed, depending on the network size and the data rate [1]. In short-reach networks, the use of the NRZ format is considered as a convenient and cost-effective solution, while in high speed (> 40 Gb/s) backbone, PSK formats have been widely recognized as one of the promising choices. To reduce the complexity in optical-electric-optical (OEO) conversion at the gateways between different types of networks, simple all-optical format conversion from NRZ to PSK is desired.

Some schemes have been proposed for the conversions from NRZ to PSK formats [1-6], which all utilized nonlinear effects 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 potentially limits the signal-processing speed and introduces 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 paper, for the first time to the best of our knowledge, we show that the conversion from NRZ to PSK format can be achieved through a linear signal processing by an ultra-high-Q silicon ring resonators [7]. Compared with previous proposal, this scheme has the advantages including simplicity, low power consumption, applicability to the ultrahigh speed systems, and facility to integration thanks to the use of silicon ring resonators.

2. Principle and scheme

Fig. 1 illustrates the relationship between the NRZ and PSK formats. An optical NRZ signal changes to a PSK signal after it is subtracted with a continuous-wave (CW) signal having the same frequency and phase but a half amplitude. The "0" symbol 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 essentially eliminates 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.

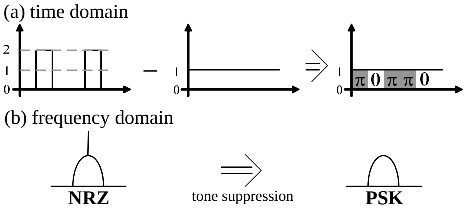

Fig. 1. Illustration of the relationship between the NRZ and PSK formats: (a) time domain and (b) spectrum domain.

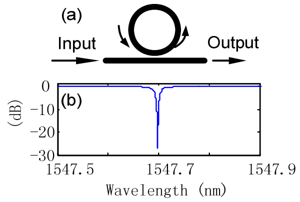

Fig. 2. (a) Structure of a microring resonator;(b) Linear filtering of the microring resonator

Clearly, in our scheme, the optical filter with an ultra-narrow bandwidth is indispensable to eliminate the tones of concern without impairing other frequency components. The emerging silicon ring resonator technology makes this scheme feasible. Fig. 2(a) shows the structure of a microring resonator, fabricated on silicon-on-insulator wafer. The microring is side coupled to the straight waveguide with an air gap between the straight waveguide and the microring. Given the transmission coefficient t, the radius of the ring r, and the attenuation of the field per round-trip in the ring τ, the transfer function of the resonator is expressed by [7]:

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

where $\phi = 4\pi^2 r n_{eff}/\lambda$ is the phase shift per round-trip around the ring, n_{eff} is the effective index of refraction of the propagation mode in the ring, and 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.

3. Simulation results and discussions

This section evaluates the performance for the NRZ-to-PSK conversion using the resonator with a similar design to that in [7], which has a ~25-dB attenuation at 1547.7 nm and a 3-dB bandwidth $\Delta\lambda_{3dB} < 0.012$ nm, as shown in Fig. 2(b). The optical carrier is modulated by a 160-Gb/s pseudo-random binary sequence (PRBS) with a length of 2^7-1.Fig. 3(a) and (e) display the waveform and spectrum of the input NRZ signal, respectively. After passing through the resonator, the central tone of the input signal is suppressed and thus converted to a PSK signal, as shown in Fig. 3(b), (c) and (f). An abrupt inversion in phase between the "0" and "1" bit is observed in Fig. 3(c). The phase of "0"s is π while that of "1"s is 0, consistent with our analysis in Section II. Fig. 3(b) and (d) give the waveform and the eye diagram of the output PSK signal, with a negligible residual amplitude fluctuation. However, the fluctuation will be more visible when the notch depth of the microring resonator becomes shallower. We investigate the ratio of the average amplitudes of "1"s to "0"s (P1/P0) as a function of notch depth in Fig.4, which clearly shows that the P1/P0 improves with the increasing of the notch depth. According to our results, the amplitude fluctuation could be negligible when the notch depth of the filter is larger than 20 dB. We also analyze the effect of the 3-dB bandwidth on the quality of the converted PSK signal. Maintaining the notch depth at 25 dB, Fig. 5 shows that the increased 3-dB bandwidth does not affect the signal quality significantly, but makes the pattern-dependent amplitude fluctuation more remarkable. This is due to the fact that the group velocity dispersion vanishes at the resonance and the third order dispersion plays an important role, making the pulse no longer symmetric.

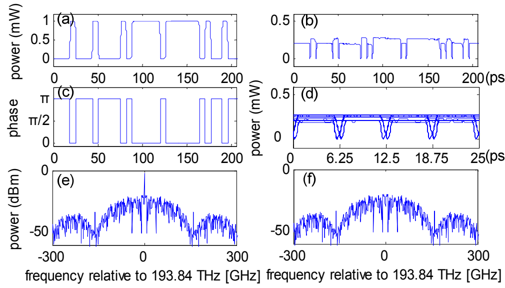

Fig. 3. 160-Gb/s format conversion from NRZ to PSK: (a), (e) waveform and spectrum of the input NRZ signal; (b), (c), (d), and (f) are the waveform, phase, eye diagram, and spectrum of the output PSK signal, respectively.

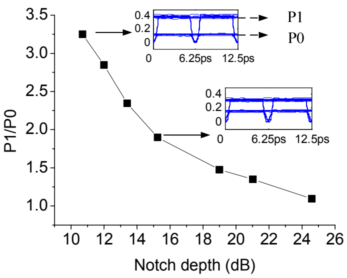

Fig. 4 Ratio of the average amplitudes of "1"s to "0"s (P1/P0) vs. notch depth with the same 3-dB bandwidth.

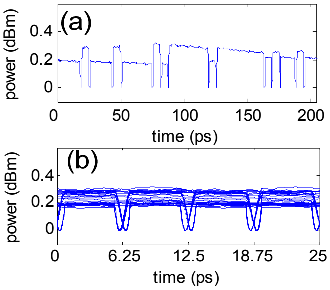

Fig. 5 (a) Waveform and (b) eye diagram of the output PSK with a 25-dB notch depth and 0.03 nm 3-dB bandwidth.

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4. References

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