Monolithic modulator and demodulator of differential quadrature phase-shift keying signals based on silicon microrings

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Silicon microring resonators are proposed to achieve ultrasmall differential quadrature phase-shift keying modulators and demodulators operated at 20 Gb/s, which may require a dramatically reduced chip size. The modulators are characterized in terms of the carrier transit time and misalignment of the driving signals, while the demodulation performance is analyzed in terms of the bandwidth and frequency detuning of the demodulator. A bit-error rate of $<10^{-9}$ is achieved using all microring-based devices in the back-to-back case.

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Advanced data formats have become quite important within the optical communications community. As compared with on–off keying, phase-shift keying provides enhanced receiver sensitivity and tolerance to fiber nonlinearities [1]. Quadrature phase-shift keying (QPSK) is spectrally efficient and tolerant to chromatic dispersion, and its differential versions, differential phase-shift keying (DPSK) and differential quadrature phase-shift keying (DQPSK), carry information via the phase difference of adjacent symbols but don't require a local oscillator in the receiver. Typically, a Mach–Zehnder modulator (MZM) is used for DPSK modulation, while a delay-line interferometer (DLI) works as a demodulator. Transmitters and receivers for DQPSK are more than twice as complex [1]. DQPSK is generated using a pair of MZMs and a 90° phase shifter, all nested in an interferometric structure. The DQPSK demodulator has two DLIs that are phase shifted relative to each other. All the structures tend to be fairly complex and large. Recently, novel modulators and demodulators of DQPSK signals have been demonstrated [2,3], and a laudable goal would be to explore how to design smaller DQPSK modulators and demodulators.

Microring modulators and filters have attracted much attention, especially for silicon platforms [4–9]. We reported a technique of using ring resonators to design a DPSK modulator and demodulator [10,11], which potentially requires a smaller chip area and might ease fabrication into arrays. In this Letter, we propose and analyze the operation of microring resonators for the modulation and demodulation of 20 Gb/s nonreturn-to-zero (NRZ) DQPSK. The proposed structures might be fabricated within small chip size, which enables a densely integrated transceiver for advanced modulation formats. Using a DQPSK data format enables one to generate signals at a doubled bit rate by a relatively low-speed silicon modulator in chip-scale interconnection [12].

As illustrated in the inset of Fig. 1(a), an overcoupled microring modulator is used to modulate DPSK signals [10]. The cw laser source experiences a phase shift of π across the resonance, as the resonance peak is shifted. DQPSK signal can be modulated using a single interferometric structure as shown in Fig. 1(a), in which two microring modulators generate two DPSKs independently, while a ring filter with a bandwidth of 60 GHz acts as a phase

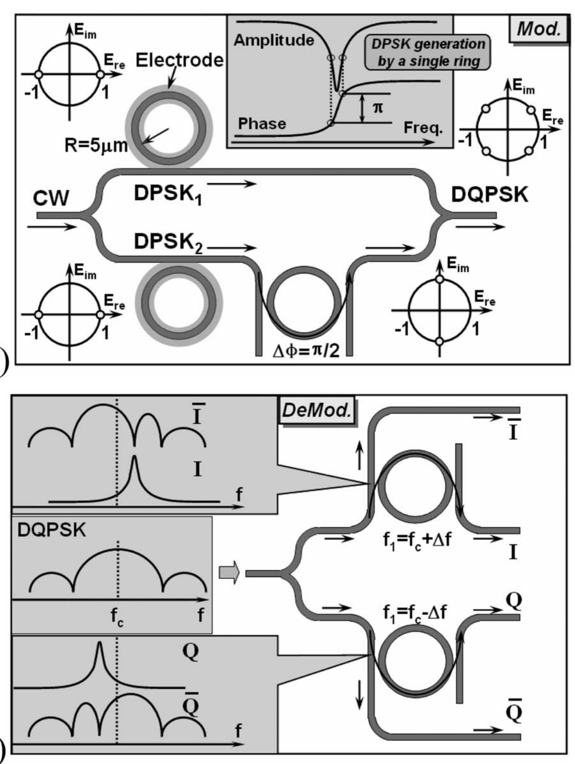

Fig. 1. Microring-based DQPSK (a) modulator and (b) demodulator.

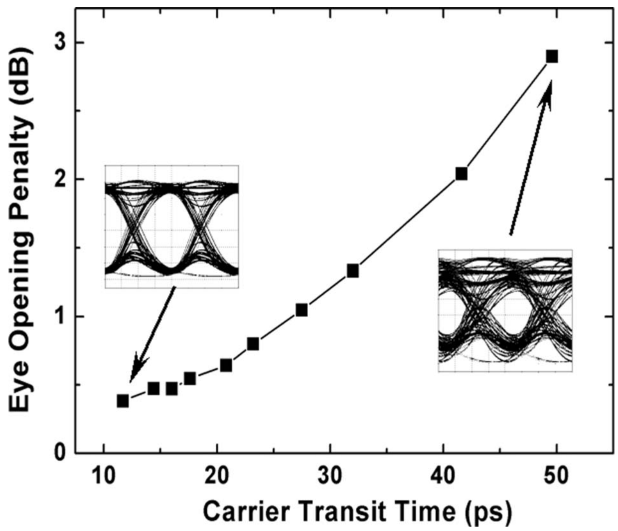

Fig. 2. EOP of the DQPSK signal increases with transit time from 12 to 50 ps.

shifter to induce a phase shift of $\pi/2$ in the lower arm. The DQPSK is obtained from a Y-type power combiner with very low loss [13]. If a dc electrode is added to one arm to enable thermal tuning of the waveguide, the microring-based phase shifter might be replaced by simply making the lower arm longer so that the propagation of optical wave accumulates extra $\pi/2$ phase shift. The demodulation of DQPSK signals can be achieved using two double-waveguide microring filters, each with a frequency offset Δf from signal carrier, as shown in Fig. 1(b). The two band-pass ports of the filters obtain I and Q signals, while the two notch ports produce inverted I and Q signals. Similar to the microring-based DPSK demodulation [10], the filtering effect enables the extraction of I and Q data and their inverted versions from the DQPSK spectrum. The silicon microring modulator is modeled as a metal-oxide-semiconductor capacitor in the electrical domain [4,5]. An ideal 10 Gb/s NRZ drive voltage is sent through a five-pole Bessel filter, with drive pulses that have rise and fall times of $\sim$10 ps [10]. Carrier density is simulated as a charging process following the applied voltage [5]. The carrier transit time is set from 12 to 50 ps [4,7]. The real part of the refractive index, calculated from the carrier density, results in a resonance peak shift, while the imaginary part induces dynamic variation of cavity Q factor. The three rings have a radius of 5 μm and cavity Q of 3000. Dynamics equations [8] are numerically solved to simulate the signal modulation, in which photon lifetime of the resonators is considered.

The microring-based DQPSK modulator is characterized with a variable transit time, with a DLI as a demodulator to isolate the modulation effects. A phase shift of π is obtained with a driving voltage of 8.7 V. A large transit time leads to data pattern dependence, which means that a single '1' pulse and consecutive '1' pulse have unequal peak power in the generated signal. With increased transit time from 12 to 50 ps, the eye diagram of the demodulated DQPSK signal becomes closed. Figure 2 shows eye-opening penalty (EOP) induced by replacing a MZM with the microring-based modulator. EOP can be $<$1 dB for a transit time of $<$25 ps.

EOP varies with time misalignment between I and Q data, with a transit time of 16 ps. As compared with no misalignment, the EOP can be $<$0.5 dB with a time misalignment of up to 25 ps and then increases quickly with the walk-off between I and Q. The MZM-based DQPSK generation also suffers from the misalignment. EOP is compared for the two types of modulators. Figure 3 shows that the microring modulator has higher EOP than a MZM by $<$0.5 dB.

To evaluate the microring DQPSK demodulator, a MZM-based modulator is used. The two microring filters have the same cavity Q of 22,000 and a radius of 5 μm. Conventionally, a DQPSK demodulator consists of two DLIs, with $\pm\pi/4$ phase shift respectively, and thus the DLIs have the frequency offsets of $\pm 1/8$ symbol rate from the signal carrier. We obtain an optimal frequency offset for the microring-based demodulation. In Fig. 4, the EOP decreases as the

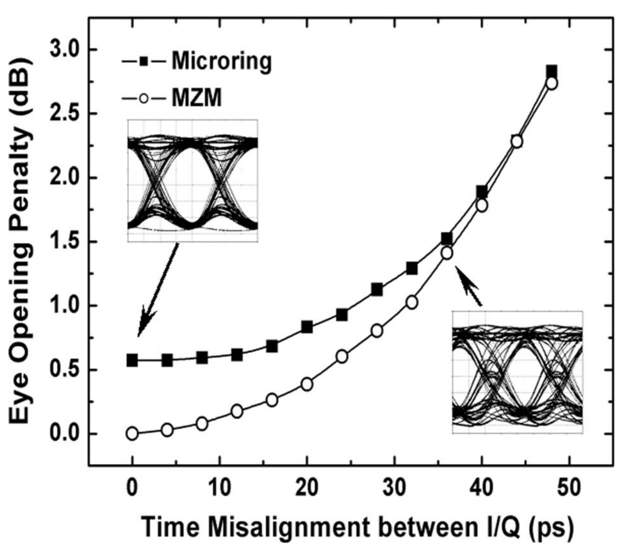

Fig. 3. EOP as a function of time misalignment between I/Q data streams.

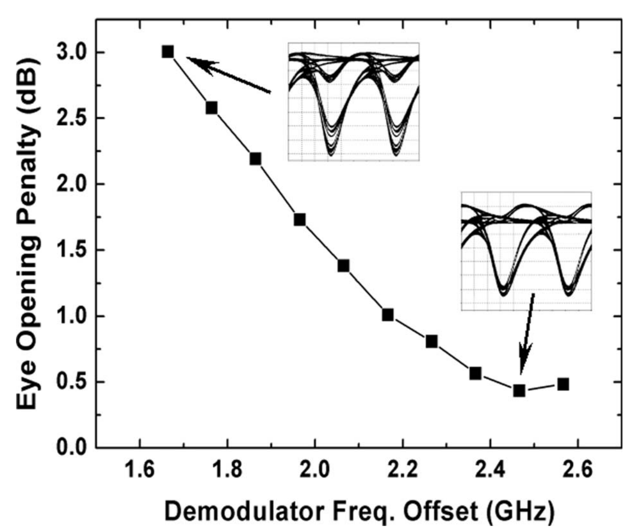

Fig. 4. EOP of using the microring-based demodulator drops with demodulator frequency offset.

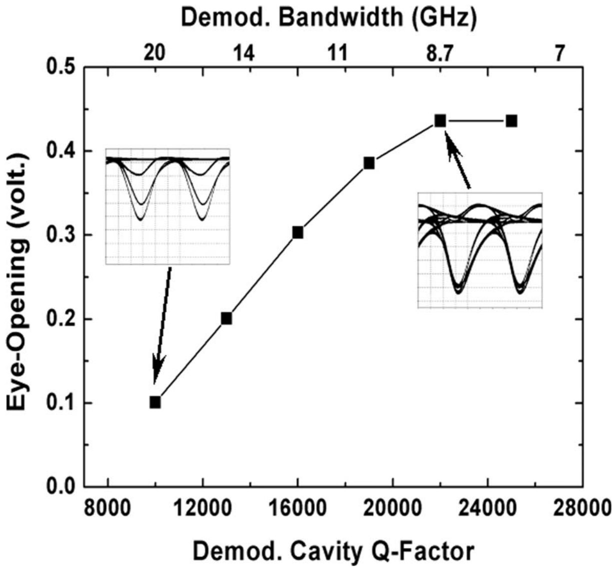

Fig. 5. EOP is improved with a demodulator bandwidth of 8.7 GHz.

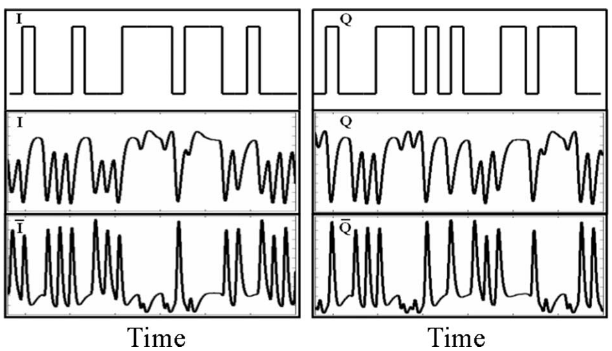

Fig. 6. Original logic pattern, demodulated I/Q data, and their inverted versions.

frequency offset increases to 2.45 GHz, ~1/4 symbol rate. Eye diagrams illustrate that, with a small frequency offset, I and Q data are not separated well, and tracks in the eye-diagram split. This is because, unlike a DLI that has a cosine-square filter response, the microring filters are Lorentzian shaped. EOP is changed with demodulator bandwidth, as cavity Q of the microring filters varies from 10,000 to 25,000. In Fig. 5, an optimal demodulator bandwidth is around 8.7 GHz, corresponding to a cavity Q of 22,000, for 20 Gb/s DQPSK. The eye diagram of the demodulated signal becomes closed for a large filter bandwidth, since inverted I/Q data are mostly notched out and an integral part of the signal power remains in I/Q.

The I and Q channels are demodulated correctly, as shown in Fig. 6, where the demodulated signals are compared with original logic data that are precoded and modulated onto a cw carrier. In I/Q signals, there are some spikes at consecutive '0' time slots, but they are not sampled and would not affect signal detection. Polarization-insensitive performance could be achieved for microring filters [14,15]. Coupling loss might be reduced to ~3.6 dB [16].

Employing microring structures as both the modulator and the demodulator, we examine overall performance of a DQPSK link. The transit time is set to be 11 ps, and the Q factors in the modulator and demodulator are chosen to be 3000 and 22000, respectively. Receiver sensitivity is −25 dBm. A bit-error rate of $<10^{-9}$ is achieved in an all-microring configuration in the back-to-back case, with a 3 dB power penalty compared with a conventional (MZM+DLI) scheme.

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