Optical minimum-shift-keying transmitter based on a monolithically integrated quad Mach–Zehnder in-phase and quadrature modulator

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We propose and demonstrate an optical minimum-shift-keying (MSK) transmitter using a single-quad Mach–Zehnder (MZ) in-phase and quadrature modulator, where four sub-Mach–Zehnder modulators are monolithically integrated on a main MZ superstructure. Using the proposed transmitter, a MSK signal at bit rate of B could be successfully generated by orthogonally superposing two low-speed ($B/2$) carrier-suppressed return-to-zero differential phase-shift-keying streams with a relative time offset, $1/B$. MSK signals at bit rate of 20 and 80 Gbits/s were successfully generated using the proposed MSK transmitter. A continuous changed phase trajectory of the obtained MSK was confirmed using a complex spectrum analyzer. The filtering tolerance of the MSK was also characterized using a bandwidth-variable tunable filter.

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Advanced optical multilevel modulation formats, such as differential quadrature phase-shift-keying (DQPSK) and quadrature amplitude modulation (QAM), have been widely investigated to achieve high-spectral-efficiency and to support ultrafast transmission in optical transmission systems. In contrast to multilevel modulation formats, binary modulation formats, such as on–off keying (OOK) and differential binary phase-shift-keying (DPSK), demonstrate their advantages in the simplicity of the transmitter and receiver design. As an alternative binary modulation format, optical minimum-shift-keying (MSK) shows much higher spectral efficiency compared with binary DPSK and comparable efficiency with quadrature DQPSK. Moreover, MSK retains the same receiver sensitivity as binary DPSK [1–4]. Because optical MSK has the advantages of both binary DPSK and quaternary DQPSK, it is becoming one of the preferable binary modulation formats for future high-speed and high-spectral-efficiency optical systems.

So far, several external modulation schemes have been proposed to generate optical MSK using a planar lightwave circuit-based hybrid integrated asymmetric Mach–Zehnder (MZ) modulator [1] or an optical in-phase and quadrature (IQ) modulator [2–4]. However, they may suffer from one or more of the following issues: (i) bit-rate tunability cannot be achieved because a fixed time delay was introduced in the integrated asymmetric modulator [1]; (ii) two cascaded modulators are required to ensure precise continuous phase modulation; and (iii) in the approach using a conventional IQ modulator [3], additional high-speed and sophisticated electronic circuits are required to generate sinusoidal-weighted rf drive signals, and the required modulation bandwidth for the deployed modulator is much higher compared with the case using conventional non-return-to-zero rf drive signals. Here, we propose what we believe to be a novel MSK transmitter using a single quad-MZ IQ modulator [5], where four 40 Gbits/s sub-Mach–Zehnder modulators (MZMs) are monolithically integrated on a main MZ superstructure. Simply by controlling the relative time offset between the two parallel low-speed phase modulations, continuous phase modulation could be easily achieved in the resultant phase pattern to obtain optical MSK. Therefore, by using just one modulator, high-speed binary and spectrally efficient MSK could be effectively generated using low-speed, simple, and more mature electronic and optoelectronic components, without introducing additional complicated high-speed electrical processing to generate sinusoidal-weighted rf drive signals. Besides, as no fixed delay is integrated in the modulator, the proposed MSK transmitter offers bit-rate tunability. Up to an 80 Gbits/s binary MSK was generated using a single modulator and electronics having a bandwidth of less than 40 GHz. To the best of our knowledge, this is the highest bit rate reported to date for optical binary MSK.

The monolithically integrated modulator consists of four sub-MZMs arranged within a MZ superstructure. In each branch, two sub-MZMs are embedded in series. As discussed in [1], an optical MSK at a bit rate of B can be generated by orthogonally superposing two low-speed ($B/2$) carrier-suppressed return-to-zero DPSK (CSRZ-DPSK) streams with a relative 1 bit offset ($1/B$). Two independent CSRZ-DPSK streams are generated in each of the branches, I or Q, using the proposed quad-MZ IQ modulator, as shown in Fig. 1(i). The first sub-MZM in each of the branches, i.e., MZM-1 or MZM-3, is driven by an rf clock with a frequency of one-quarter of the bit rate, $B/4$, and is biased at the transmission null point for CSRZ pulse generation. Note that the generated

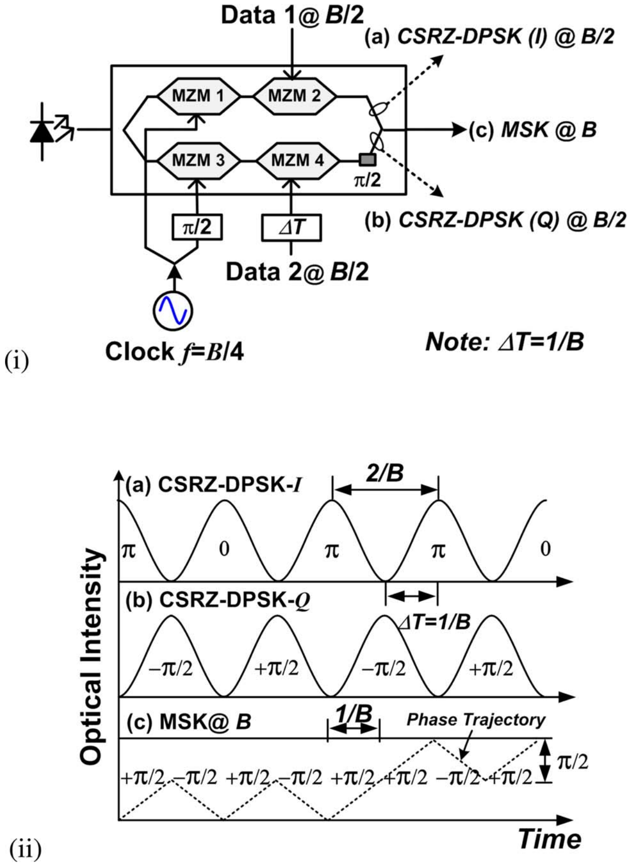

Fig. 1. (Color online) (i) Operation principle of the proposed optical MSK transmitter. (ii) Illustration of intensity and phase (dotted line) pattern in the quad-MZ IQ modulator.

CSRZ pulses in these two sub-MZMs are 90° out of phase. Two data streams, data 1 and data 2, at bit rate $B/2$ are employed to drive the followed sub-MZM (MZM-2 or MZM-4) in each branch for DPSK modulations with a relative 1 bit time offset ($1/B$) between them. The relative phase difference between the two branches can be changed by tuning the dc bias of the main MZ superstructure. As shown in Fig. 1(ii), two independent CSRZ-DPSK streams at bit rate $B/2$ are finally multiplexed with a 1 bit time offset and a $\pi/2$ phase difference, thus generating an optical MSK at bit rate B. The upper or lower sideband (USB or LSB) of the generated MSK can be alternatively generated according to the sign of the relative phase difference between the two CSRZ-DPSK streams. Using the proposed IQ superstructure modulator, continuous phase change and constant amplitude can be inherently achieved, which results in a compact spectrum and effectively suppresses undesired sideband components in comparison to conventional DPSK.

In the fabricated quad-MZ IQ modulator, four 40 Gbits/s sub-MZMs were integrated on a MZ superstructure using a $LiNbO_3$ integration platform. Each sub-MZM had a traveling wave electrode to apply rf and dc for modulation. The measured 3 dB optical bandwidth and V_π of each sub-MZM were 36 GHz and 6 V, respectively. The fiber-to-fiber insertion loss of the modulator was around 6 dB. The monolithically integration offers a good long-term stability for the MSK transmitter.

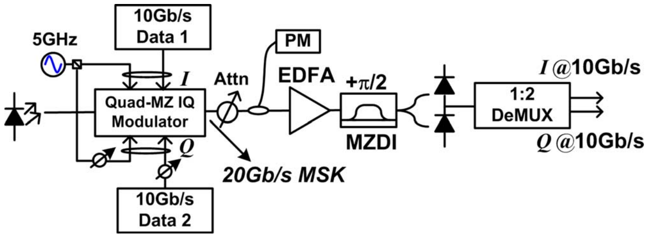

Fig. 2. (Color online) Experimental setup for 20 Gbits/s MSK generation.

A schematic of the experimental setup for 20 Gbits/s MSK is shown in Fig. 2. CW light from a distributed feedback (DFB) laser was fed to the quad-MZ IQ modulator for MSK generation. Two 90° out-of-phase sinusoidal clocks at a frequency of 5 GHz were employed to drive the first two sub-MZMs in the quad-MZ IQ modulator for CSRZ pulse carving. Phase modulation was achieved in the followed sub-MZM in each of the branches (I or Q) using two decorrelated 10 Gbits/s pseudorandom binary sequence (PRBS) data streams. After the quad-MZ IQ modulator, two 10 Gbits/s CSRZ-DPSKs were recombined through quadrature addition in the optical field, successfully generating a 20 Gbits/s optical MSK. At the receiver side, only one MZ delay interferometer (MZDI), in conjunction with a balanced detector, was employed for detection, which is same as the conventional DPSK. The MZDI was configured with a 1 bit delay and a $\pi/2$ phase shift between the arms. After detection, an electronic demultiplexer was used to separate the I and Q channels. Thanks to the properties of PRBS sequences, an electrical differential encoder was not required in the experiment demonstrations.

The measured spectra of the 10 Gbits/s DPSK, 10 Gbits/s CSRZ-DPSK, and 20 Gbits/s MSK are shown in Fig. 3(i). The main lobe of the obtained 20 Gbits/s MSK has a bandwidth of around 0.2 nm, which is similar to that of the 10 Gbits/s CSRZ-DPSK, and slightly larger than 20 GHz. For a 20 Gbits/s DQPSK, an around 20 GHz wide main lobe is expected [5]. This indicates that MSK offers a high-spectral-efficiency compared with conventional DPSK, and a comparable spectral efficiency with DQPSK at the same bit rate. To investigate the phase variation in the generated MSK, a complex spectrum analyzer (AP2441B, APEX) was used to measure the MSK

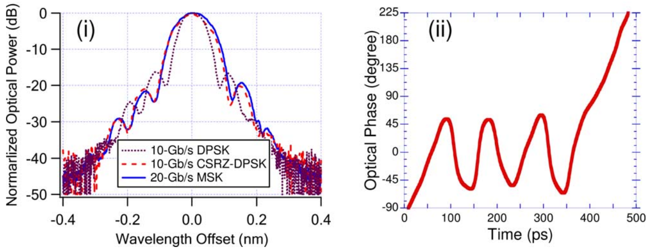

Fig. 3. (Color online) (i) Measured optical spectrum of a 20 Gbits/s MSK, a 10 Gbits/s DPSK, and a 10 Gbits/s CSRZ-DPSK and (ii) measured optical phase trajectory using a complex spectrum analyzer.

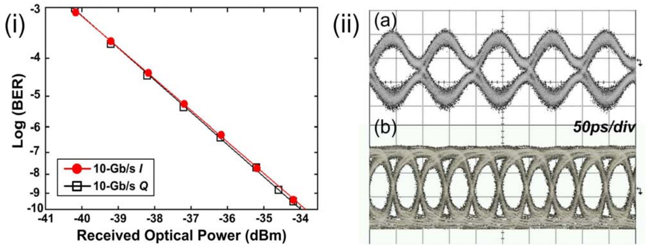

Fig. 4. (Color online) (i) BER curves of a 20 Gbits/s MSK after demultiplexing and the (ii) detected eye diagrams of a 10 Gbits/s CSRZ-DPSK and a 20 Gbits/s MSK.

phase trajectory. As shown in Fig. 3(ii), the optical phase continuously changed without phase jumps, especially at the transient periods between two adjacent bits. Also, the phase change showed a good linearity within the bit period. The linear and continuous phase trajectory resulted in a compact spectrum of MSK, specially the narrowed sidelobes.

The bit-error rate (BER) of the generated MSK was measured after being demultiplexed into two 10 Gbits/s data streams (*I* and *Q*). As shown in Fig. 4(i), a receiver sensitivity of around –34.5 dBm was observed at a BER of 10^{-9} for the generated MSK, which is similar to that of the DPSK signal at the same bit rate. Compared with the result shown in [4], a similar sensitivity was obtained considering a 3 dB difference between 10 and 20 Gbits/s MSK systems. Less than 0.2 dB sensitivity difference was observed for the *I* and *Q* channels. The eye diagrams of the detected 10 Gbits/s CSRZ-DPSK and 20 Gbits/s MSK are shown in Fig. 4(ii). The 10 Gbits/s CSRZ-DPSK was generated by driving only one branch of the quad-MZ IQ modulator.

To comprehensively investigate the filtering tolerance of the generated MSK, after the MSK transmitter, an optical bandwidth-variable tunable filter (BVF-100, Alnair Laboratories) was used to filter the generated 20 Gbits/s MSK signal. The filter has a flat-top response with a sharp roll-off at the filter edges. Figure 5(i) shows the measured optical spectra of the filtered signal using a bandwidth-variable optical filter with a bandwidth varied from 15 to 27 GHz. As shown in Fig. 5(ii), the receiver sensitivities were measured with different bandwidths. Only around 0.6 dB power penalty was observed for the filtered 20 Gbits/s optical MSK when the bandwidth is reduced to around 21 GHz. It indicates that optical MSK offers high tolerance against strong filtering compared with DPSK signal [6]. The measured eye diagrams with filter bandwidth of around 21 GHz was shown in the inset of Fig. 5(ii).

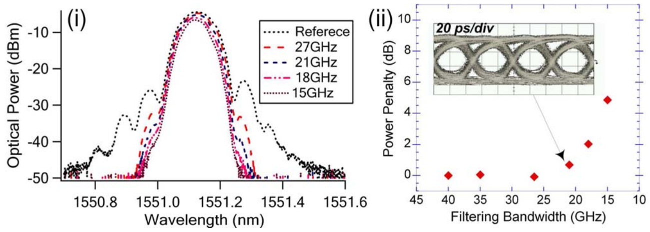

Fig. 5. (Color online) (i) Filtered optical spectra using a bandwidth-variable tunable filter with different bandwidths, (ii) and the power penalty of a filtered 20 Gbits/s MSK with different bandwidths. Inset: detected eye diagrams of a 20 Gbits/s MSK with filtering bandwidth of around 21 GHz.

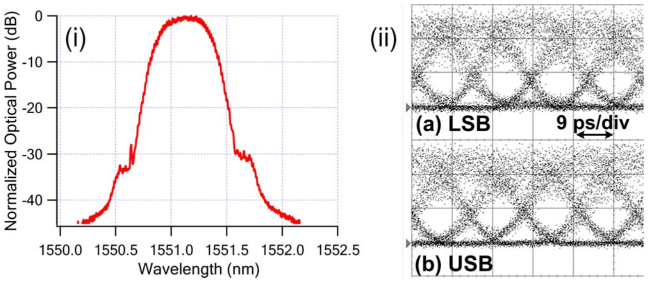

Fig. 6. (Color online) (i) Measured optical spectrum of an 80 Gbits/s MSK, and (ii) the detected 80 Gbits/s eye diagrams after filtering (a) LSB and (b) USB.

An 80 Gbits/s optical MSK was also generated using the proposed MSK transmitter. To generate an 80 Gbits/s MSK, two 90° out-of-phase 20 GHz rf clocks were used for CSRZ pulse carving, whereas two independent 40 Gbits/s PRBSs were employed for DPSK modulations in the quad-MZ IQ modulator. The obtained spectrum for 80 Gbits/s MSK is shown in Fig. 6(i) with an obtained 20 dB bandwidth of around 0.8 nm. Owing to the lack of a balanced 80 GHz MZDI, after filtering out the USB and LSB of the 80 Gbits/s MSK using a single-ended 80 GHz MZDI, the demodulated 80 Gbits/s data were monitored by an ultrafast optical sampling oscilloscope. The corresponding detected eye diagrams after filtering out the LSB and USB components of the 80 Gbits/s MSK are shown in Fig. 6(ii).

In this Letter, we have experimentally demonstrated an optical MSK transmitter using a single quad-MZ IQ modulator, where four sub-MZMs were monolithically integrated on a main MZ superstructure. MSK signals at bit rate of 20 and 80 Gbits/s were successfully generated using the proposed MSK transmitter. A continuous changed phase trajectory of the obtained MSK was confirmed using a complex spectrum analyzer. The filtering tolerance of the MSK was also characterized using a bandwidth-variable tunable filter.

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