A novel reconfigurable modulator implementation for generating optical eight-ary PSK/QAM signals

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We propose a reconfigurable 8PSK/8QAM modulator implementation by employing two cascaded QPSK modulators with an interferometer in between. With simple control of bias voltage of the interferometer, a flexible switching between 8PSK/8QAM can be achieved. The transmission performance of the generated 8PSK/8QAM signals over different link scenarios is compared via numerical simulations. The results reveal that the proposed implementation has the capability of maximizing transmission distance in the case of dynamic optical network.

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Coherent detection together with high-speed digital signal processing (DSP) technique has enabled advanced optical multilevel modulation formats such as multi-level phase-shift keying (M-PSK) and quadrature amplitude modulation (QAM) to meet the increasing demand on high transmission capacity in optical communication systems[1]. Among existing multi-level formats, quadrature phase shift keying (QPSK) becomes attractive for its high tolerance against fiber nonlinearities and optical signal-to-noise ratio (OSNR) degradation. These characteristics make it become best candidate for 100Gb/s commercial optical networks. In contrast, optical 8-ary phase-shift keying (8PSK)[2] and 8-ary quadrature amplitude modulation (8QAM)[3], carrying three information bits in a single symbol, are promising candidates of next-generation optical transmission systems. As a comparison, 8PSK is attractive for its high tolerance against fiber nonlinearities whereas 8QAM shows superior OSNR efficiency[4]. In the future optical networks, the flexible and adaptive switching between different modulation formats is necessary to meet dynamic optical path scenarios. Therefore, a reconfigurable 8-ary transmitter is desired for agile optical network, and it is very essential to investigate a novel implementation with flexible and digital-to-analog free conversion.

Several transmitter schemes have been reported to generate optical 8PSK/8QAM. In the common scheme, a QPSK modulator is followed by a phase modulator (PM) with a phase deviation of $\pi/4$[5] and the generated constellation diagram is closely dependent on the driving voltage and the frequency response of PM. Meanwhile, the voltage amplitude of the driving signal for PM has to be precisely adjusted to obtain the desired phase deviation[6]. Lu has proposed the R-QPSK and S-QPSK scheme[1,7], in which precise control of both bias voltage and driver signal amplitude are required. Here, we have proposed and successfully demonstrated a switchable 8-ary PSK transmitter using two cascaded QPSK modulators with a delay-line interferometer (DLI) in between. The principle of the scheme for generating 8PSK or 8QAM by simply configuring the applied voltage on the DLI is analyzed. The proposed implementation has the advantage of binary driver signals and no tuning requirements on the amplitude and bias voltage. Finally, the performance of the reconfigurable scheme in dynamic transmission scenarios is investigated in detail via simulation. The simulation results show that the proposed scheme is more flexible and efficient in the case of different transmission links. Compared with the previously proposed 8PSK/8QAM transmitters, our optical 8PSK/8QAM scheme has many advantages, including better tolerance against elctrical-optical (E-O) bandwidth, less generated phase chirp, easy implementation, and flexible format switching.

The proposed 8PSK/8QAM transmitter, which is constructed with a DLI placed between two QPSK modulators, is illustrated in Fig. 1. We use the first DQPSK modulator followed by the DLI, which alters the subsets of DQPSK constellations with $\pi/4$ phase shift between them, to achieve the function of a phase modulator in the conventional D8PSK/8QAM modulator implementation. The other in-phase and

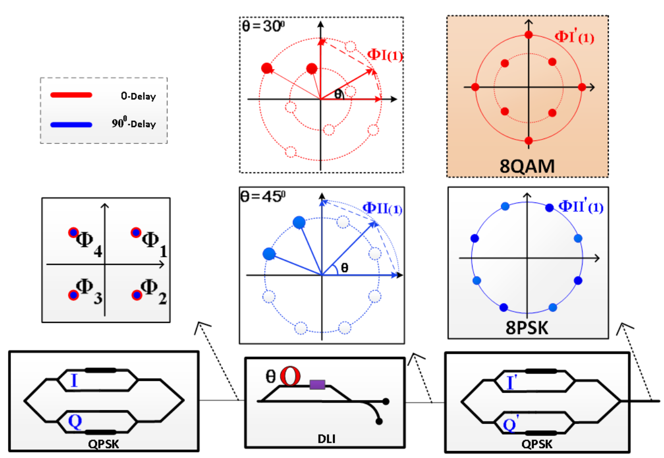

Fig. 1. operation principle of the proposed modulator.

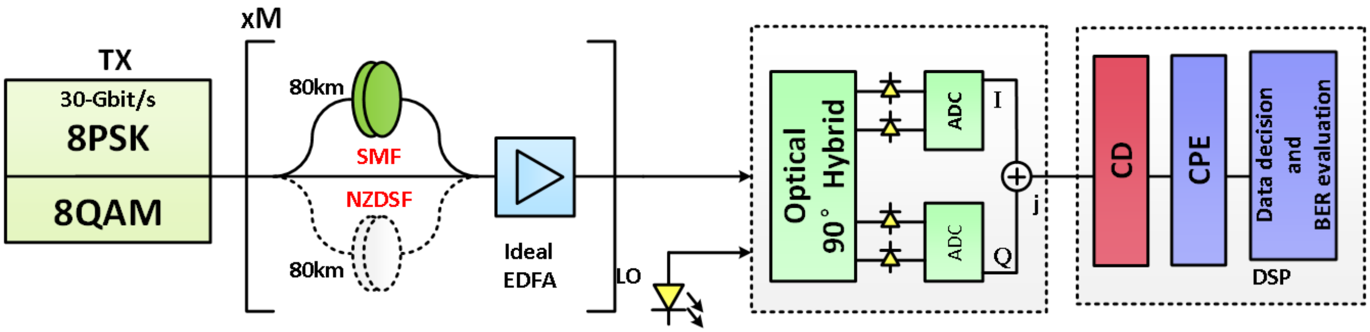

Fig. 2. Schematic of the simulation system.

quadrature (IQ) modulator is configured as a standard QPSK transmitter, serving the same function as the DQPSK modulator in conventional implementation. The left diagram of Fig. 1 shows the DQPSK constellation $\{\Phi i = (i-1)\ \pi/2 + \pi/4, I = 1 \ldots 4\}$. The two successive output symbols are ensured to have a differential phase of either zero or $\pi/2$ by choosing the appropriate driving signals {I Q}[8].

The DLI offers a $\pi/4$ or $\pi/6$ phase offset in the interference between the two symbols. In the DLI part, if we apply the $\pi/4$ driving voltage (The middle diagram of Fig. 1), then we can get D8PSK (the right diagram of Fig. 1). In the similar way, D8QAM (the right diagram of Fig. 1) can be achieved with the driving voltage of $\pi/6$ ΦI and ΦII represent the output phase after DLI, which serve as the input of the second QPSK modulator. At the output end, two DQPSK constellations are gotten respectively: ΦI' (i) and ΦII' (i), having $\pi/4$ phase shift between each other. Based on the differential detection and Gray-code mapping, the logical relations of pre-coding are found as[8]

$$
\begin{aligned}
& d_{i\text{-}1} = I'_{i-2}\overline{I'_{i-1}} + \overline{I'_{i-2}}I'_{i-1} + Q'_{i-2}\overline{Q'_{i-1}} + \overline{Q'_{i-2}}Q'_{i-1}, \\
& s = \left(ab + \bar{a}\bar{b}\right)c + \left(a\bar{b} + \bar{a}b\right)\bar{c}, \\
& I'_i = \overline{Q'_{i-1}}\,\overline{d'_{i-1}}s + I'_{i-1}d_{i-1}s + \overline{Q'_{i-1}}d_{i-1}\bar{s} + I'_{i-1}\overline{d_{i-1}}\bar{s}, \\
& Q_i = Q'_{i-1}\overline{d_{i-1}}\bar{s} + I'_{i-1}d_{i-1}\bar{s} + Q'_{i-1}d_{i-1}s + I'_{i-1}\overline{d_{i-1}}s, \\
& I_i = \overline{d_{i-1}}\left[a\left(ib + \bar{q}\bar{b}\right) + \bar{a}\left(\bar{i}\bar{b} + qb\right)\right] \\
& \qquad + d_{i-1}\left[c\left(ia + \bar{i}\bar{a}\right) + \bar{c}\left(qb + \bar{q}\bar{b}\right)\right], \\
& Q_i = \overline{d_{i-1}}\left[a\left(qb + i\bar{b}\right) + \bar{a}\left(\bar{q}\bar{b} + \bar{i}b\right)\right] \\
& \qquad + d_{i-1}\left[c\left(qa + \overline{qa}\right) + \bar{c}\left(\bar{i}b + i\bar{b}\right)\right].
\end{aligned}
\tag{1}
$$

In equation (1), I'_i, Q'_i, I_i, and Qi stand for the coded symbol of the electrical encoder. To obtain the output bits in time slot i, both the original symbol a, b, c and the output bits in time slot i-1 are inserted. These formulas are proved by numerical simulations.

In Fig. 2, the schematic of the simulation system is shown. The transmitter and the fiber link are simulated via the commercial VPI software, and the receiver side is simulated by Matlab. At the transmitter side, the 8-PSK/8QAM signal is generated by the proposed modulator and the transmitted data signal is a 2^{16} de Bruijn sequence. The transmission loop is investigated for two different configurations. The first kind of implication loop consists of 80-km standard single mode fiber (SSMF) and an erbium doped fibre amplifier (EDFA), which is used for compensation of fiber loss. For the second kind of loop, the standard single mode fiber (SSMF) is replaced by Non-Zero Dispersion Shifted Fiber (NZDSF). In both sections, optical filters are used to remove out-of-band ASE noise of the EDFAs. At the receiver side, the signal is mixed with the light of a local oscillator (LO) in a 90° hybrid. The captured data is then processed offline by DSP, including chronic dispersion compensation, oversampling, carrier-phase estimation[9], etc. I and Q components are finally recovered for constellation reconstruction and bit error rate (BER) estimation.

By adjusting the OSNR of the signal at the coherent receiver, the BER of 30-Gb/s optical 8PSK

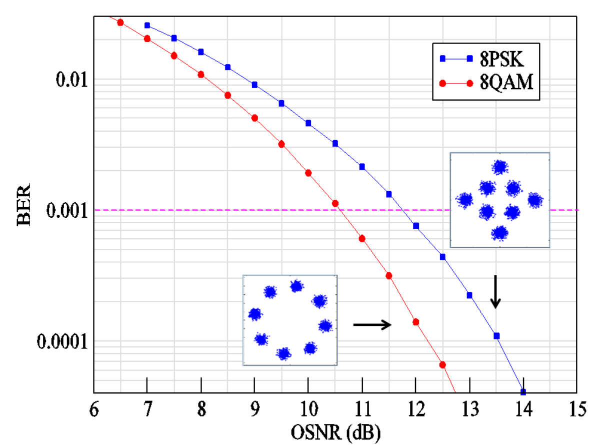

Fig. 3. Simulated BER of 30Gb/s 8PSK and 8QAM.

Table 1. Fiber Parameter

	GVD	Length	α	Aeff
	(ps/nm.km)	(km)	(dB/km)	(μm)
NZDSF	3	100	0.239	53
SSMF	16	100	0.222	78

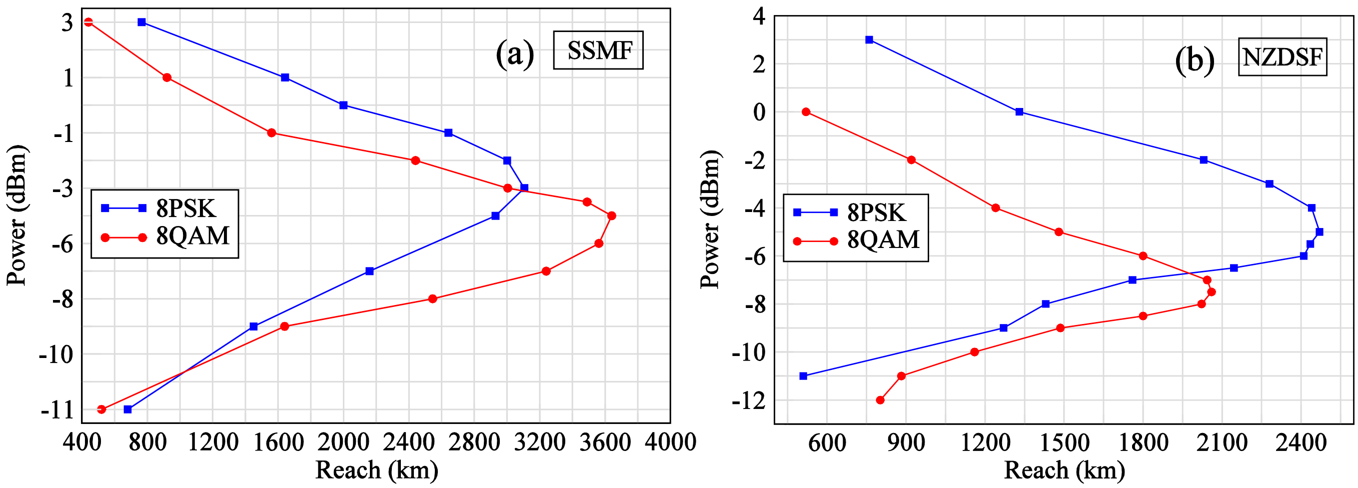

Fig. 4. Achievable transmission distance for 30Gb D8PSK and 8QAM using (a) Single mode fiber and (b) NZDSF.

is evaluated using offline processing. Around 43,000 symbols are used for BER counting. Compared with the theoretical value, to get the BER of 1E-3, extra OSNR of 0.56 dB and 0.7dB are required for 8PSK and 8QAM, respectively. We can also see from the Fig. 3 that 8QAM has the ASE tolerance 1.2 dB better than 8PSK.

In Fig. 4(a) and (b), we compare the transmission results with different configurations of the transmission link of the two modulator implementations by generating 30 Gb/s D8PSK and D8QAM signals. It can be seen in Fig. 4(a) that D8PSK has a better transmission performance than 8PSK (about 500 km) whereas in Fig. 4(b), D8QAM performs better (about 400 km). Based on the results of comparison in Figs. 4(a) and (b), the proper selection of the modulation format between 8PSK/8QAM regarding specific fiber links can optimize the network efficiency greatly. Therefore, the reconfigurable modulation format is more flexible and applicable, which makes it promising in future optical fiber communication.

In summary, we propose a reconfigurable scheme for generating optical 8PSK and 8QAM by cascading two commercial QPSK modulators and a DLI. The format switching is achieved by simply tuning the applied voltage on the DLI. The scheme requires no exact control on driving signal amplitude and modulator bias. The simulation results of the generated signals over dynamic transmission scenarios are investigated in details. It is confirmed that the whole network transmission efficiency can be improved by properly configuring the reconfigurable modulator regarding different transmission fiber links.

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