Analysis of smooth phase modulation formats compared with conventional QPSK and BPSK using coherent detection

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Novel optical offset quadrature phase shift keying (OQPSK) and improved minimum-shift keying (MSK) modulation schemes to smooth optical phase hopping for high speed fiber optics transmission are proposed. Simulations have been done among the MSK, OQPSK, quadrature phase shift keying (QPSK), and binary phase-shift keying (BPSK) modulation formats at 40 Gb/s over 100-km transmission link using coherent detection. Simulation results present good performances to elevate chromatic dispersion tolerance and reduce the influence of nonlinear effects by adopting the smooth phase modulation formats. Inter-symbol interference decreases for the fast side-lobe property and tight spectrum as a result of avoding the π phase shift and reducing envelop fluctuation.

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In 2002, Bell Laboratory reported 40-Gb/s wavelength-division multiplexing (WDM) transmission over 4000 km with return-to-zero differential phase shift keying (RZ-DPSK) format[1], which attracted more attentions on phase modulation since its robustness against nonlinear impairments and 3-dB optical signal-to-noise ratio (OSNR) improvement (with balanced detector)[2]. Differential quadrature phase shift keying (DQPSK) was proposed to increase spectral efficiency, optimize dispersion management, and reduce polarization mode dispersion (PMD) distortion[3,4]. Since then, practical high speed optical transmission systems are based on phase modulation technology such as polarization-multiplexing (PolMux) quadrature phase shift keying QPSK[5,6], staggered DPSK (SDPSK)[7,8]. However, conventional binary phase shift keying (BPSK) and QPSK have π or $\pi/2$ phase shift, resulting in more information energy transferring to side-lobes, which may cause inter-symbol and inter-channel interferences. Therefore, we expect to smooth the phase shift to obtain low side-lobe and constant envelop.

Obviously, minimum-shift keying (MSK) modulation just meets our requirement. It exhibits the properties of constant amplitude and continuous phase in the bit slot and between the consecutive bits. The optical MSK transmitter structure has been proposed in Refs. [9,10]. But it hardly generates sine and cosine optical seeding sources because of the nonlinear properties of the Mach-Zehnder modulator (MZM) with clock signal driving. We suggest using triangle wave signal to drive the MZM. Nevertheless, MSK modulation raises the setup complexity and instability. Therefore, we propose a novel offset QPSK (OQPSK) modulation scheme to improve π phase shift hopping based on the QPSK transmitter with a slight modification. Meanwhile, only one Mach-Zehnder delay interferometer (MZDI) is needed to demodulate OQPSK signal.

In this letter, we focus on the comparison between traditional phase modulation (BPSK and QPSK) and smooth phase modulation (OQPSK and MSK). We deploy coherent detection rather than delay interference scheme so as to precisely evaluate fiber transmission impairments considering the inter-symbol association. Numerical simulation results show improvements in dispersion and nonlinear tolerance, and more robustness for tight optical filtering with smooth phase modulation.

OQPSK is considered as a kind of improved QPSK from the view point of phase shift hopping. Phase shift $\Delta\Phi$ for QPSK format can be 0, $\pm\pi/2$, and π. To improve the phase shift fluctuation, we firstly propose optical OQPSK, for which $\Delta\Phi$ can only be 0 and $\pm\pi/2$, avoiding π phase shift. We consider the phase hopping under control as a simple and smart scheme to smooth phase changing without adding much cost based on QPSK transmission system. OQPSK setup is shown in Fig. 1. The quadrature-phase (Q) arm is delayed by half of the single line bit period (T), so that the time points of phase hopping of in-phase (I) arm and Q arm are staggered. In that way, the π phase shift will not happen for the combined optical signal, while the bit rate of the optical signal is doubled compared with QPSK. Same as DSPK, the OQPSK signal is easily demodulated by using one current MZDI receiver.

The MSK transmitter is similar to the scheme in Ref. [9]. We use triangle wave signal to drive the first MZM instead of sine wave clock to realize the linear phase changing track, as shown in Fig. 1.

We deploy an ideal coherent detection with a monochromatic local laser to receive these phase modulation signals, because it seems like a probe which reflects the

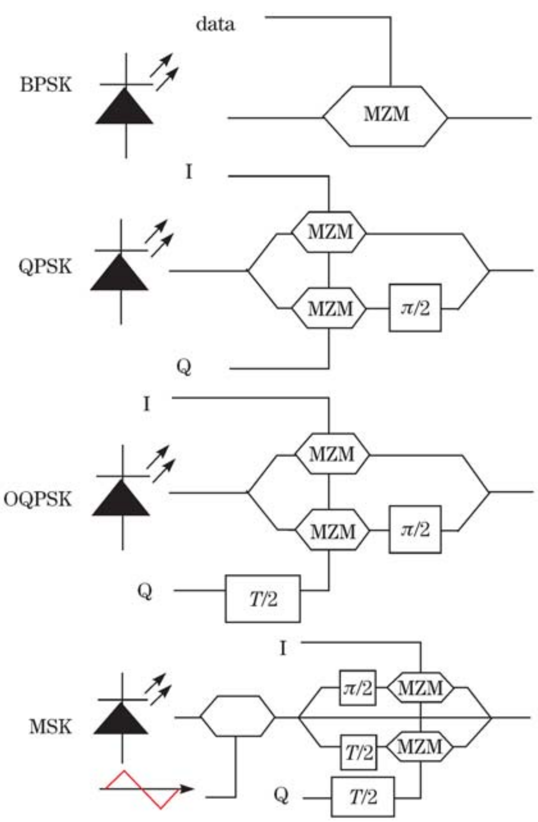

Fig. 1. Transmitter configuration.

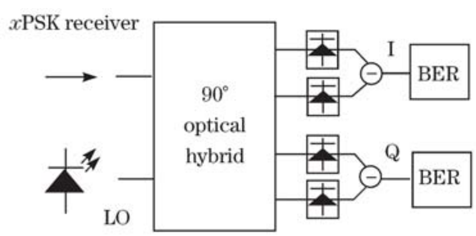

Fig. 2. Coherent detection configuration. BER: bit error rate; LO: local oscillator; xPSK: BPSK, QPSK, OQPSK, and MSK.

fiber transmission impairments to help evaluate the performances independently. The scheme is shown in Fig. 2, 90° optical hybrid is used to obtain I and Q information.

Simulations have been done among MSK, OQPSK, QPSK, and BPSK modulation formats based on VPI Transmission Maker. We measure the transmission performances of these four phase modulation schemes at 40 Gb/s over 100-km standard single mode fiber (SSMF) span with complete dispersion compensation by using dispersion compensating fiber (DCF). The transmission optical fiber parameters are shown in Table 1. The linewidth of the laser is set to 100 kHz.

The optical spectra of these phase modulation formats are shown in Fig. 3. OQPSK and QPSK have the same spectral envelop. Although the OQPSK prohibits the π phase hopping, it doubles the phase hopping rate. However, the OQPSK can maintain the same spectral occupancy while conventional QPSK has distortion to the desired signal after high power nonlinear amplifiers.

Table 1. Transmission Optical Fiber Parameters

Fiber Parameters	SMF	DCF
Length (km)	100	17.8
Attenuation (dB/km)	0.2	0.6
Dispersion (ps/(nm·km))	16	-90
Dispersion Slope ((ps/(nm^2·km))	0.08	-0.21
Nonlinear Coefficient (W^{-1}·km^{-1})	2.6	4
Core Area (μm^2)	84.9	314.2

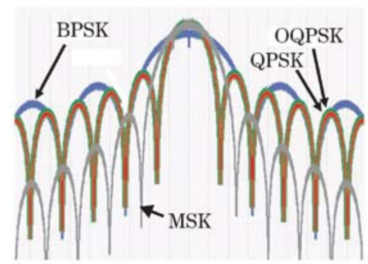

Fig. 3. Optical spectra of phase modulation formats.

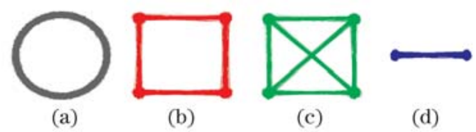

Fig. 4. Phase trace constellation. (a) MSK, (b) OQPSK, (c) QPSK, and (d) BPSK.

The main-lobe of the MSK is broader than those of OQPSK and QPSK, but it has the fastest side-lobe. The spectrum of BPSK broadens fast, resulting in the limitation for high capacity transmission.

We sample the signal phase to draw the trace of phase changing. The phase trace constellation is shown in Fig. 4. The trace of MSK is a uniform circle, and the traces of OQPSK and QPSK are squares, whereas a cross in QPSK indicates the π phase hopping. BPSK has only two phase states.

The bit error rate (BER) values versus the filtering bandwidth of optical filters after the transmitter are shown in Fig. 5. Generally, the narrower optical spectrum displays more tolerance to tight optical filtering distortion. MSK format has very fast side-lobe decay to enhance the resistance to high-order filtering fading. It can be more robust against inter-channel interference effect arising from the tight optical filter, especially for the WDM system. The performance against tight optical filtering of OQPSK format is a little better than that of QPSK since they have similar spectral envelops.

Chromatic dispersion (CD), nonlinear effects, and PMD are important factors to evaluate transmission performances. Predictably, compared with QPSK, OQPSK, MSK, and BPSK formats have bad PMD tolerance because of the two-fold optical symbol rate, although the specific simulation results are not given.

The power penalty is measured when residual dispersion exists. Figure 6 shows that OQPSK and QPSK formats have better dispersion tolerance with less than 1-dB power penalty when the residual dispersion is 60 ps/nm. However, the performance of MSK format shows

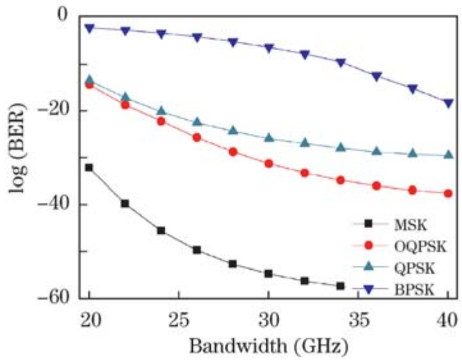

Fig. 5. BER versus filtering bandwidth.

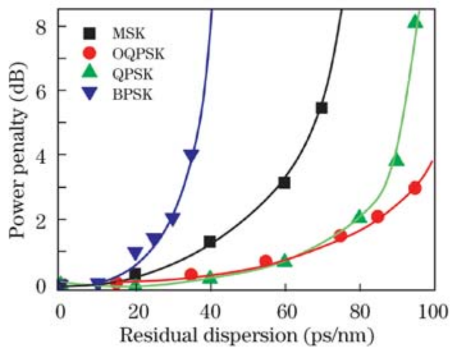

Fig. 6. Power penalty versus residual dispersion.

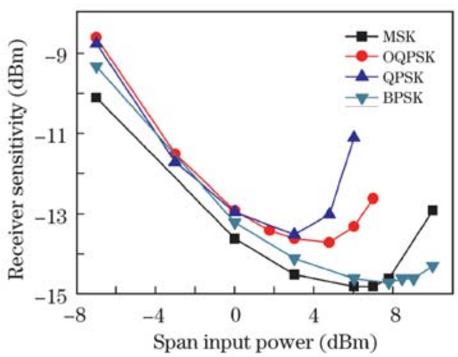

Fig. 7. Sensitivity versus launched optical power.

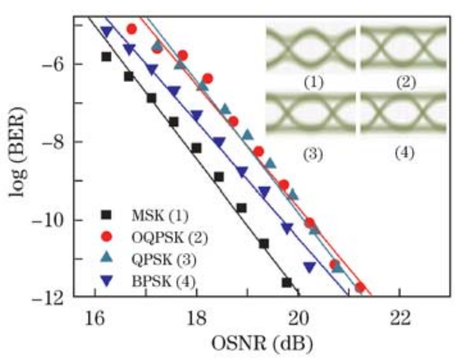

Fig. 8. BER versus OSNR.

unexpected decline when the dispersion increases in spite of narrow optical spectrum. The reason may concern the detection of MSK signal. As mentioned above, the phase trace of the MSK is a circle, which causes the inconstant power level for the demodulated signal bits. The eye closes quickly when the dispersion accumulates. The result is similar to the dispersion tolerance between non-return-to-zero (NRZ) and RZ. For the BPSK formats, the perfect dispersion compensation management is needed to eliminate dispersion impairment for the long haul transmission.

The nonlinear effect impacts are observed by varying the launch power into the fiber (Fig. 7). MSK format has around 1-dB advantage of sensitivity over the other formats below 0 dBm. When the power is above 0 dBm, the nonlinear effects will severely induce signal degradation. 2-dB launched power is improved for the OQPSK format compared with QPSK since the OQPSK has a quasi-constant envelop. The MSK and BPSK formats with constant envelop exhibit more robust against nonlinear effects. The phase smoothing methods offer nonlinear effects tolerance improvement, which means longer transmission distance can be achieved.

The BER curves versus OSNR are shown in Fig. 8 with eye diagram insets. OQPSK and QPSK formats have similar OSNR performance. There is about 0.5-dB OSNR improvement for the BPSK format because a lower extinction ratio (ER) of demodulated OQPSK and QPSK signal. For the same reason, the MSK can achieve the biggest ER, meanwhile its narrow bandwidth decreases the amplified spontaneous emission (ASE) noise interference. Therefore, the required OSNR declines by about 1 dB.

In conclusion, we propose adopting smooth phase modulation formats such as the novel OQPSK format and the recent MSK format to improve fiber transmission performance for the future high speed and high capacity systems. Decreasing phase hopping can restrain side-lobe to improve dispersion and nonlinear tolerance, and reduce inter-symbol interference.

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