Nonlinear Crosstalk and Compensation in QDPASK Optical Communication Systems

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Abstract—Nonlinear crosstalk in the quaternary differential-phase amplitude-shift-keying (QDPASK) modulation format is analyzed. Significant crosstalk penalty is measured on a QDPASK signal with a 20-Gb/s aggregate capacity for nonlinear phase shifts of 0.17 rad and above. Two different compensation techniques are demonstrated based on either prechirping or postchirping of the optical signal, increasing the nonlinear tolerance by 6.1 and 4.5 dB, respectively.

Index Terms—Fiber-optic communication, multilevel modulation formats, nonlinear compensation, phase modulation.

I. INTRODUCTION

MULTILEVEL modulation formats offer an increased spectral efficiency at a reduced symbol rate. Consequently, they show in general an improved robustness to chromatic dispersion and polarization-mode dispersion. In addition, they offer the opportunity of using lower bandwidth electronics. These are all desirable features for the implementation of higher line rate optical communication systems. Quaternary (four-level) amplitude-shift-keying (QASK) modulation has previously been investigated, but has so far been associated with high power penalty and complicated electronics [1]. Differential quadrature phase-shift-keying, the equivalent of QASK but in the phase domain, has shown promising results [2], [3] but requires complex transmitters and receivers as well as precoding (decoding) of the transmitted (received) data. Recently, a quaternary modulation format combining amplitude-shift keying (ASK) and differential phase-shift keying (DPSK) was proposed and demonstrated for both optical labeling [4], [5] and optical communication with increased spectral efficiency [6], [7]. The principle of the quaternary differential phase amplitude-shift-keying (QDPASK) modulation format is shown in the phasor diagrams of Fig. 1. Amplitude and phase are independently binary coded at half the aggregate bit rate, reducing the complexity of multilevel coding. Thus, the advantage of the QDPASK scheme compared to other multilevel modulation formats is the use of conventional binary drivers, modulators, and receivers while still obtaining a high spectral efficiency and an improved robustness to linear signal impairments.

The QDPASK signal is modulated in a DPSK and an ASK channel, with a finite extinction ratio (ER) for the ASK format. However, due to the different intensity levels in the ASK channel, coupling will take place between phase and amplitude through nonlinear self-phase modulation (SPM). It is, therefore, expected that the DPSK channel will suffer from a nonlinear crosstalk due to the simultaneous ASK modulation, an effect that would be a main issue in any long-haul optical transmission system. In this work, we will quantify the tolerance to nonlinear crosstalk for a simple QDPASK communication system. We will then demonstrate two compensation techniques based on precompensation and postcompensation of the optical signal by adding a phase shift to the DPSK channel synchronized with, and proportional to, the data on the ASK channel.

II. EXPERIMENT

Neglecting the dispersion effect and assuming an equal amount of ones and zeros, the accumulated ASK-induced crosstalk $\Delta\phi_{\text{ASK}}$ may be written as

$$\Delta\phi_{\text{ASK}} = \frac{2\gamma I_{\text{eff}} P_{\text{in}}}{D_f} \frac{\text{ER} - 1}{\text{ER} + 1} \quad (1)$$

where $D_f$ is the pulse duty factor, $I_{\text{eff}}$ is the nonlinear effective length, $P_{\text{in}}$ is the average input power, and $\gamma$ is the nonlinear coefficient. As illustrated in Fig. 2(a), $\Delta\phi_{\text{ASK}}$ represents the difference in accumulated SPM (measured in radians) between the ASK modulated “1s” and “0s.” Fig. 2 also illustrates the principle of our precompensation and postcompensation techniques. By adding a chirp with a sign opposite but a magnitude proportional to that accumulated by SPM, it will be possible to cancel out the amplitude to phase coupling. The chirp could be added to the signal either before or after transmission, i.e., prechirping or postchirping of the optical signal as illustrated in Figs. 2(b) and (c), respectively. For optimum performance, the generated phase difference between a detected ASK “1” and “0” matches $\Delta\phi_{\text{ASK}}$ (1).

The experimental setup is shown in Fig. 3(a). Dashed and dotted lines indicate where the compensation devices for
precompensation and postcompensation were inserted, respectively. The QDPASK transmitter with an aggregate bit rate of 20 Gb/s consists of a continuous-wave distributed feedback laser, a LiNbO$_3$ phase modulator (PM1), and two zero-chirp single-drive Mach–Zehnder modulators (MZ1, MZ2). DPSK data at 10 Gb/s is generated by PM1 where a 1-bit sequence with length $2^7−1$ is modulated by a $\pi$ phase shift between adjacent bits and a “0” is modulated by a zero phase shift. The nonreturn-to-zero-QDPASK signal was converted into a 33% duty-cycle return-to-zero signal by MZ1 biased at maximum transmission and driven by a 5-GHz sinusoidal wave. ASK data is generated through MZ2. The inset oscilloscope trace in Fig. 3(a) shows the measured eye going into the HNLF, the ER was 7 dB. The precompensation device consisted of a PM driven with a 0.9-dB splice loss at the input splice and 0.4-dB/km fiber attenuation. Figs. 3(b) and (c) show the schematic of the precompensation and postcompensation devices, respectively.

The precompensation device consisted of a PM driven with a part of the ASK signal, the strength of the ASK signal being adjusted by a variable electric attenuator. The postcompensation device consisted of a photodetector (PD), monitoring part of the received signal, with the detected signal then being fed to a PM. The strength of the compensating signal was adjusted by a variable optical attenuator in front of the PD. The sign of the PM was opposite to the acquired SPM and the electrical and optical time delay were matched, so that the applied chirp was synchronized with the ASK signal. A polarization controller (not shown in Fig. 3) was placed in front of the postcompensator, manually aligning the polarization of the received signal with the PM. The polarization controller may be replaced by a polarization diversity scheme [8].

The ER of MZ1 was optimized to 7 dB in order to achieve the same receiver sensitivity back-to-back for the ASK and DPSK channels. By examining the complex plane of the E-fields [see Fig. 1(c)], we note that the optimum ER in an ideal QDPASK system, neglecting any signal dependent noise, should be 1/3 in field amplitude or 9.5 dB in intensity. The experimental deviation from the theoretical optimum ER is partly due to the signal dependent noise in the pre-erbium-doped fiber amplifier, as well as the nonideal transmitter and receiver. The receiver sensitivity, measured as input power into the preamplifier at BER = $10^{-6}$, was −29.5 dBm for the DPSK channel and −29.2 dBm for the ASK channel. The receiver sensitivity for the pure DPSK and the pure ASK format (with ER > 20 dB) was −38.5 and −35.5 dBm, respectively. The data was a pseudorandom binary sequence with length $2^7_1−1$. Similar to the work reported by Liu et al. [7], where the same word length was used, we observed pattern dependence in the QDPASK format with a reduced sensitivity at longer word lengths. However, no pattern dependence was observed in the pure DPSK or ASK formats. This indicates that the reduced ER increases the requirements on the low frequency response of the ASK MZ (MZ2). Fig. 4 shows measured power penalties at BER = $10^{-6}$ for the ASK channel, the DPSK uncompensated, precompensated, and postcompensated channels versus $\Delta\phi_{\text{ASK}}$. For the uncompensated DPSK channel, there is a 1-dB crosstalk penalty at $\Delta\phi_{\text{ASK}} = 0.13$ rad, which corresponds to a total accumulated phase shift for the ASK modulated “1s” of 0.17 rad. However, when the postcompensator is turned on, the allowable $\Delta\phi_{\text{ASK}}$ is increased to 0.37 rad for the same penalty, resulting in an increased nonlinear tolerance of 4.5 dB. The precompensator shows an even greater improvement of 6.1 dB. We believe the reduced performance for the postcompensation technique is possibly due to residual nonlinearities in the electric amplifiers and the photodetector feeding the PM. The penalty at large nonlinear phase shifts ($>0.5$ rad) for both the precompensation and postcompensation schemes is probably due to the nonlinear broadening of the optical spectrum. Intuitively, the difference in

The bit-error rate (BER) was measured for both the DPSK and the ASK channel. The transmission link was emulated by 1 km of highly nonlinear fiber (HNLF) with a nonlinear coefficient, $\gamma = 10$ W$^{-1}$km$^{-1}$, a chromatic dispersion at the operating wavelength 1551 nm of $-1$ ps/nm/km, and with a dispersion slope of 0.07 ps/nm/km$^2$. The total span loss was 1.84 dB with a 0.9-dB splice loss at the input splice and 0.4-dB/km fiber attenuation. Figs. 3(b) and (c) show the schematic of the precompensation and postcompensation devices, respectively. The precompensation device consisted of a PM driven with a part of the ASK signal, the strength of the ASK signal being adjusted by a variable electric attenuator. The postcompensation device consisted of a photodetector (PD), monitoring part of the received signal, with the detected signal then being fed to a PM. The strength of the compensating signal was adjusted by a variable optical attenuator in front of the PD. The sign of the PM was opposite to the acquired SPM and the electrical and optical time delay were matched, so that the applied chirp was synchronized with the ASK signal. A polarization controller (not shown in Fig. 3) was placed in front of the postcompensator, manually aligning the polarization of the received signal with the PM. The polarization controller may be replaced by a polarization diversity scheme [8].

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spectral broadening between ASK “1s” and ASK “0s” reduces their spectral overlap, resulting in an eye closure after the DPSK demodulator. The ASK channel performance was not affected by optical nonlinearities within the measured range. Fig. 5(a) shows measured BER curves for the DPSK and ASK channels in a QDPASK system without crosstalk. It also shows the uncompensated channel sensitivity. Two different nonlinear phase shift compensation schemes were proposed based on either ASK synchronized prechirping or postchirping of the signal. Using either of the proposed techniques, an increased nonlinear tolerance of more than 4.5 dB was measured. Similar to dispersion in linear systems, prechirping or postchirping should in an ideal system work equally well for eliminating the nonlinear crosstalk. However, we note that the postcompensation scheme has the additional benefit that it will also reduce nonlinear phase noise caused by a limited optical signal-to-noise ratio [9], [10].

III. CONCLUSION AND DISCUSSION

We have experimentally evaluated the nonlinear tolerance of the QDPASK modulation format. For the 7-dB ER used in our experiment, we measured a significant crosstalk penalty for nonlinear phase shifts of $0.17\pi$ rad and above. It may be noted that the nonlinear crosstalk penalty may be decreased by reducing the amplitude ER at the expense of a decreased ASK channel sensitivity. Two different nonlinear phase shift compensation schemes were proposed based on either ASK synchronized prechirping or postchirping of the signal. Using either of the proposed techniques, an increased nonlinear tolerance of more than 4.5 dB was measured. Similar to dispersion in linear systems, prechirping or postchirping should in an ideal system work equally well for eliminating the nonlinear crosstalk. However, we note that the postcompensation scheme has the additional benefit that it will also reduce nonlinear phase noise caused by a limited optical signal-to-noise ratio [9], [10].

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