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Improving the Performance of Optical Phase Conjugator using a Mid-way Filter

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Abstract

We propose a novel optical phase conjugator with a mid-way filter to prevent nonlinear products being shifted into the signal band. The simulated signal $Q_{\max}$ improved by 1.1 dB in an 800-km 557.5-Gbp/s 16-QAM CO-OFDM system.

I. INTRODUCTION

Recently, Mid-Span Spectral Inversion (MSSI) using optical phase conjugation (OPC) at the center of a link has been studied for nonlinearity compensation of CO-OFDM systems [1,2]. Previously, we experimentally demonstrated an improvement in the nonlinear threshold by 4.8 dB for a 10×80-km 604.7-Gb/s 16-QAM CO-OFDM super channel using MSSI [3]. However, the performance at the optimum signal power improved by only 0.2 dB. This was because OPC itself introduces noise-like nonlinearity products into the signal band [3].

In this paper, we present a novel two-part MSSI module, with a mid-way filter to remove the XPM components of nonlinearity before they are wavelength-shifted to fall upon the output signal band. Numerical simulations using the split-step Fourier method (SSFM) show that two-part MSSI improves the back-to-back Q performance by almost 3 dB; this leads to a performance improvement of about 1.1 dB in a 10×80-km 16-QAM 557.5-Gb/s CO-OFDM super channel.

II. OPTICAL PHASE CONJUGATION WITH A MID-WAY FILTER

Figure 1(a) shows the block diagram of a system using MSSI near the middle of the link. The detailed block diagram of the two-part MSSI module with a mid-way filter has been shown in Fig. 1(b). We split a conventional MSSI module into two parts, each having the $\chi^{(3)}$ nonlinear element half the length that of a conventional module. The output of the first half of the OPC module is passed through a band-stop filter (response as inset (*i*)) to remove the pump and the XPM products; but the input signal, OPC signal and, obviously, any unwanted components that fall within these bands are allowed to pass (inset (*ii*)). The filtered signal then enters into the second half of the OPC module, which reinserts a pump that must have the same frequency and phase as the first pump; thus, practically, it should be from the same source. The combined signal then propagates along the second HNLF2, then through a BPF and an output EDFA. Inset (*iii*) shows the spectrum at the output of the HNLF2, showing newly generated XPM and the unwanted XPM-OPC. The output of HNLF2 is then filtered to remove the original signal and the pump and leave the OPC signal (inset (*iv*)), which then enters into a CO-OFDM receiver in a back-to-back configuration.

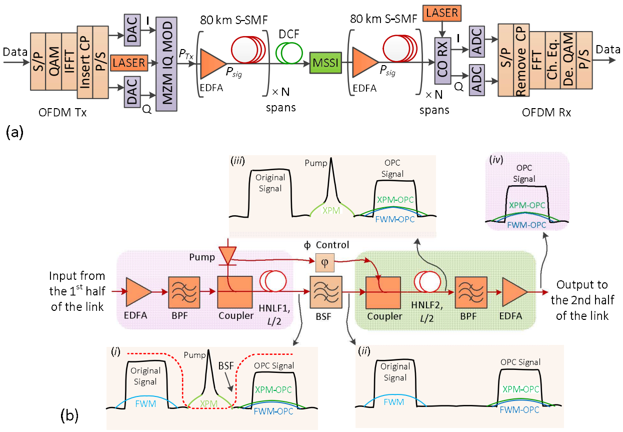

Fig. 1. (a): System schematic; (b): (*i*) Block diagram of the MSSI module with a mid-way filter; (*ii*) Spectrum after the first half of OPC; spectrum after the BSF; (*iii*) Spectrum after the second half of OPC; (*iv*) Spectrum at the output of the MSSI module.

In a short HNLF with insignificant dispersion, nonlinear products grow coherently along the length of the HNLF, so the OPC signal has a power proportional to length-squared [4]; however, the power of the two-stage mixing product, XPM-OPC, is proportional to 4th-power of the length [5,6] as shown in Eqs. (1) and (2):

$$P_{OPC} = (\gamma L)^2 P_{pump}^2 P_{sig} \tag{1}$$

$$P_{XPM-OPC} = 2.667 (\gamma L)^4 P_{pump}^2 P_{sig}^3 \tag{2}$$

Therefore, filtering-out XPM after half the length means that the two-stage XPM-OPC process starts all over again in the second half, and hence its total power due to the first and the second half is lower than the value it would be without the filter. The wanted OPC signal is not removed by the mid-stage filter so its power is proportional to the total length squared. Note that the XPM-OPC and the signal from both halves of the system add coherently.

III. SIMULATION RESULTS

The OFDM signal was generated using MATLAB, using a 1024-point inverse fast Fourier transform (IFFT). 920

subcarriers were modulated with 16-QAM and 32-point cyclic prefix (CP) was inserted. The analogue link was simulated using VPItransmissionMaker v8.7. A 160 Gsamples/s DAC was simulated to give a total bit rate of 557.5 Gb/s, with an optical bandwidth of 139.39 GHz.

The transmission link comprises 10×80-km spans of standard single-mode fiber (S-SMF) with 0.2 dB/km loss, nonlinearity coefficient, γ, of 1.32 $W^{-1}.km^{-1}$ and dispersion coefficient, CD, of 16 ps/nm/km. Erbium doped fiber amplifiers (EDFA), with a 6-dB noise figure, are used to set the launch power into each S-SMF span. The OPC module was placed after the fifth S-SMF span. A 60-km DCF was used to improve nonlinearity compensation [7]. The HNLF had a γ 11.5 $W^{-1}.km^{-1}$, CD of -0.05 ps/nm/km, attenuation of 0.97 dB/km and a total length of 1000 m. Pump powers of 10 dBm were used in both parts of HNLF.

At the receiver, a coherent OFDM receiver feeds a digital processor to: remove the CP, perform a Fourier transform to separate the subcarriers, equalize the phases of the subcarriers and demodulate the subcarriers to recover the data in each subcarrier.

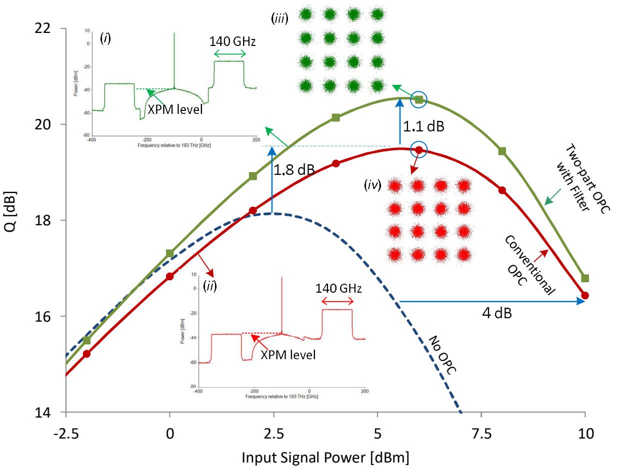

Fig. 2. Signal quality, Q, versus input power for an 800-km transmission system using conventional and two-part MSSI: *(i)* Output spectrum with a two-part MSSI; *(ii)* Output spectrum with conventional MSSI; *(iii)* Constellation diagram with two-part MSSI at optimum input power; and *(iv)* Constellation diagram with conventional MSSI at optimum input power.

Figure 2 shows the comparison of transmission performance between systems with conventional MSSI (●) and with two-part MSSI (🟩). Results without MSSI are also shown (--) to show the benefit of using OPC. Conventional MSSI increases the peak Q_{max} by 1.8 dB and the nonlinear threshold (NLT) by 4.0 dB, relative to the system without MSSI. Our two-part MSSI module provides an additional 1.1 dB of improvement of Q_{max} at the optimal signal power. Two-part MSSI (🟩) does not has the same optimum input signal power as conventional MSSI (●). This is because both systems are affected by the same link impairments; the improvement from the two-part MSSI module is due to its improved back-to-back performance.

Table 1 shows the performance improvement with the two-stage MSSI versus transmission system length at 557.5Gb/s. It shows that improvement of more than 0.5 dB is maintained over a distance of up to 1600km. For longer transmission, increased amount of accumulated ASE along the spans reduces the improvement.

TABLE I
IMPROVEMENT OF Q_{MAX} VERSUS TRANSMISSION DISTANCE

Transmission distance [km]	Q_{max} Conventional OPC [dB]	Q_{max} Two-part OPC [dB]	Improvement [dB]
Back-to-back	24.39	27.24	2.84
480	20.47	22.00	1.52
800	19.46	20.51	1.05
1600	17.38	17.95	0.57

IV. CONCLUSION

We have proposed a novel method of optical phase conjugation to reduce its back-to-back performance penalty by adding mid-stage filtering. Nearly 3 dB improvement in back-to-back performance has been achieved. This leads to a system improvement of about 1.1 dB with a 140-GHz OFDM super channel carrying 16-QAM 557.5-Gb/s data for a transmission distance of 800km.

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