All-optical OOK to 16QAM Modulation Format Conversion Employing Nonlinear Optical Fiber Loop Mirror

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Abstract: We propose a novel all-optical modulation format conversion scheme from on-off-keying to 16 quadrature amplitude modulation using nonlinear optical loop mirror based on parametric amplification and cross-phase modulation in optical fibers.

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1. Introduction

Increase in data capacity and transmission distance is still of great interest and an urgent subject in optical communication systems. Be up against the requirement of large capacity transmission system, a number of multilevel modulation formats have been extensively studied for its high spectral efficiency. While such advanced formats will be used in wide area network (WAN), conventional on-off keying (OOK) format will continue to be used in metro area network (MAN) due to its simplicity and cost effectiveness. Therefore, there will be demands for converting OOK signals to advanced multilevel modulation format signals at the gateway node between MAN and WAN to enhance network interoperability. Recently, all-optical modulation format conversion from OOK to phase shift keying (PSK) and amplitude phase shift keying (APSK) using semiconductor optical amplifier based Mach-Zehnder interferometer (SOA-MZI) [1], or highly nonlinear fiber (HNLF) [2-3] has been proposed. To the authors' knowledge, as far as all-optical OOK to M-QAM conversion is concerned, there has been no report on 16QAM signal, which has been proven to be practically significant [4].

In this paper, we propose a novel all-optical OOK to 16QAM modulation format converter employing nonlinear optical loop mirror (NOLM) based on cross phase modulation (XPM) and parametric amplification in optical fibers. The three-level clearly defined pulse train and 16QAM constellation of simulation results indicates the feasibility of this proposed converter.

2. Scheme of OOK to 16QAM modulation format conversion

The proposed OOK to 16QAM conversion scheme employs two HNLFs for phase and amplitude modulation by the phenomenon of XPM and parametric amplification. Fig.1(a) shows the configuration of the proposed modulation format converter which consists of a NOLM. The probe pulse incident on the NOLM from the 3dB coupler travels through the loop in both directions. The BPFs are used to remove OOK signals and CW pump light. We call the two probe pulses clockwise and counter-clockwise probe pulses. The HNLF1 is employed for phase modulation as shown in Fig.1(b). It can be viewed as an OOK to QPSK modulation format converter. The probe pulse and two

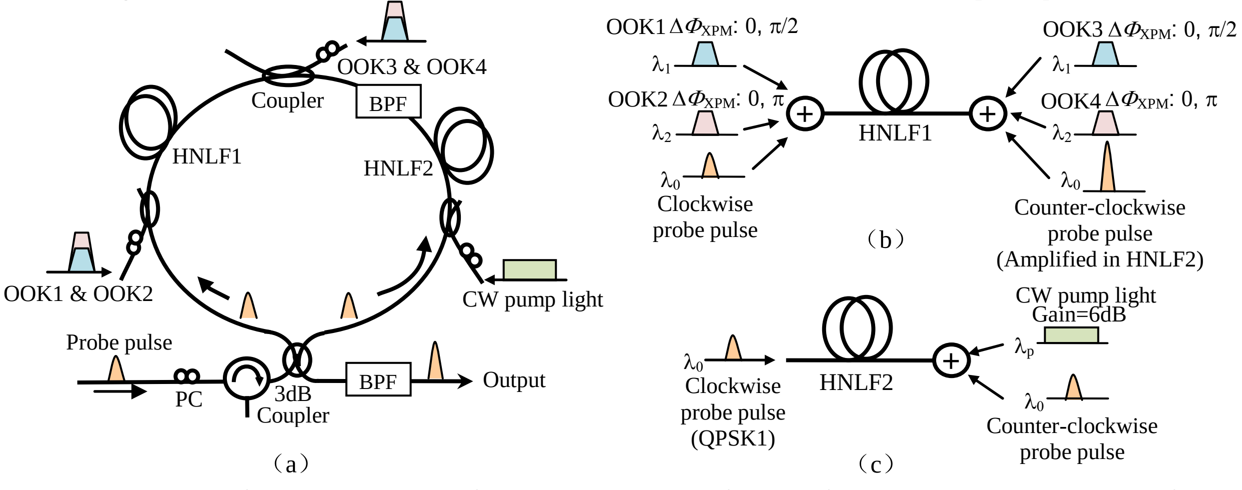


Fig.1. Schematic diagram of the proposed modulation format converter. (a) The configuration of the converter. (b) Schematic diagram of phase modulation in HNLF1. (c) Schematic diagram of amplitude modulation in HNLF2.

OOK signals, as control pulses, are synchronously launched into the HNLF1. The probe pulse is modulated in its phase due to XPM induced by the control pulses. The phase change of the probe pulse due to XPM ($\Delta\Phi_{XPM}$) is described by

$$\Delta\Phi_{XPM} = 2\gamma\, L_{eff}\, (P_1+P_2) \tag{1}$$

Where γ $[1/(m \bullet W)]$ is nonlinear coefficient, L_{eff} $[m]$ is the effective interaction length of the HNLF1. P_i $[W]$ are peak powers of OOK1 and OOK2, respectively. Eq.(1) shows that the phase change of the probe pulse is proportional to the peak powers of two OOK signals acting as control pulses. So by properly adjusting the peak powers of two control pulses, $\Delta\Phi_{XPM}$ can be set to 0, $\pi/2$, π or $3\pi/2$. The probe pulse can achieve 4-level phase change after it transmits through the HNLF1. Namely, an OOK to QPSK modulation format conversion is bilaterally realized in HNLF1. The QPSK1 and QPSK2 are generated after the clockwise and counter-clockwise probe pulse experience 4-level phase change in HNLF1, respectively.

Nevertheless, the amplitude of QPSK2 should be doubled compared to QPSK1, in order to achieve amplitude modulation in 16QAM signal. The amplitude modulation is realized in HNLN2 as shown in Fig.1(c). The CW light and the probe pulse are transmitted together and parametric gain can be achieved effectively by designing the wavelengths of probe and CW light. The launched power of CW light should be adjusted to induce 6dB parametric gain to the probe pulse. The CW light will induce the same phase shift by XPM to clockwise and counter-clockwise probe pulses, but only induce parametric gain to the counter-clockwise probe pulse in HNLF2, since that phase matching cannot be achieved between anti-directionally propagating pulses. Also, utilizing one HNLF to accomplish both phase and amplitude modulation is possible by entering the OOK signals and CW pump light into the same HNLF, which guarantees cost effectiveness. However, the four-wave mixing and walk-off between control and probe pulses will induce power difference and unstable phase modulation, so the parameters of HNLFs, wavelengths and peak powers of control and probe pulses should be carefully designed.

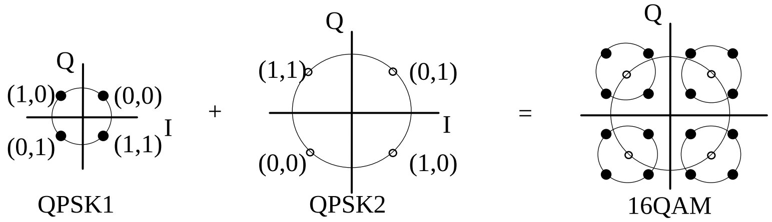


Fig.2. The 16-QAM constellation can be represented as the combination (product) of two QPSK constellations. (The amplitude of QPSK2 is doubled compared to QPSK1.)

To explain the principle of the converter, in Fig.2, we represent the 16QAM constellations as the combination of two QPSK constellations. Each point of the original constellation is obtained as the product of a point from the first constellation (QPSK1) and a point from the second constellation (QPSK2). Namely, 16QAM is generated by the superposition of these two QPSK signals. The converted 16QAM signals can be recovered by coherent receivers.

3. Numerical simulation:

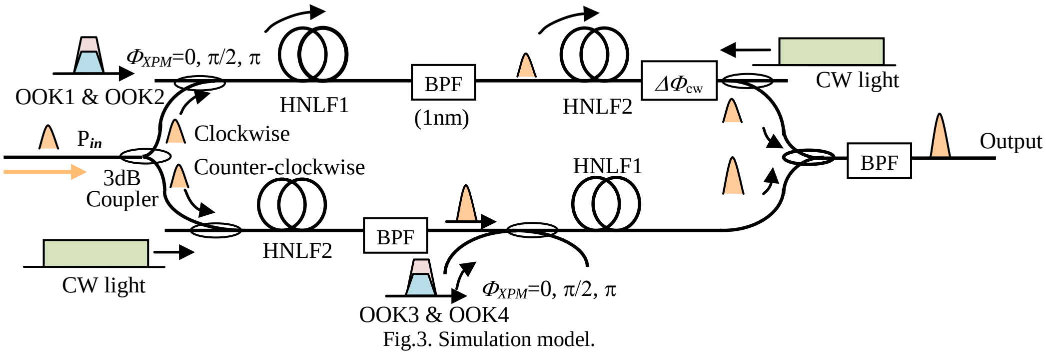


Fig.3. Simulation model.

We calculate the waveform and the I-Q diagram of the converted 16QAM signal at the output of NOLM with the symbol rate of 10GS/s by using split-step Fourier method including the 3rd order dispersion in HNLF [5].

The simulation model is shown in Fig.3. To simplify the simulation, we separate the clockwise path and counter-clockwise path as using a Mach-Zehnder interferometer model. $\Delta\Phi_{cw}$ is a calculated phase shift of clockwise probe pulse due to XPM from counter propagate CW light. The wavelengths and peak powers of control pulses of OOK1, OOK2, OOK3 and OOK4, which used to induce 0, $\pi/2$ or π phase shift to probe pulse by XPM, probe pulses and

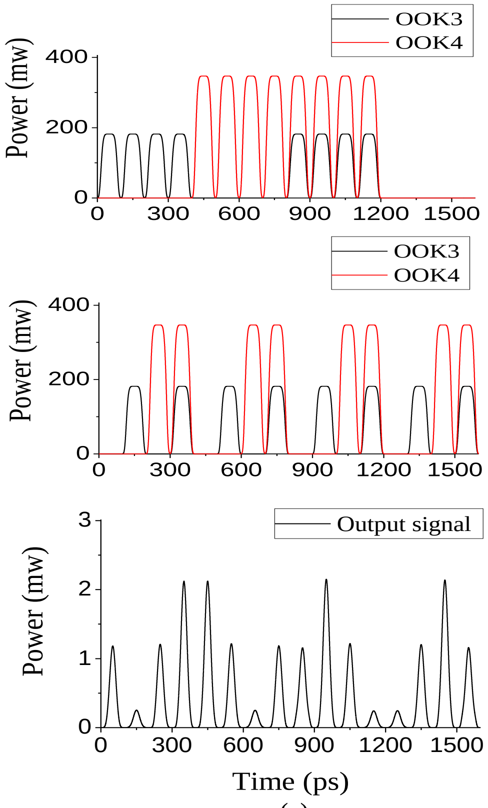
CW pump light that we designed are summarized in Table1. The parameters of HNLF1 and HNLF2 are shown in Table2. Here, we ignore the loss of the BPFs and couplers for coupling OOK signals, CW pump light and probe pulses.

Table1. Parameters of control, probe pulses and CW pump light

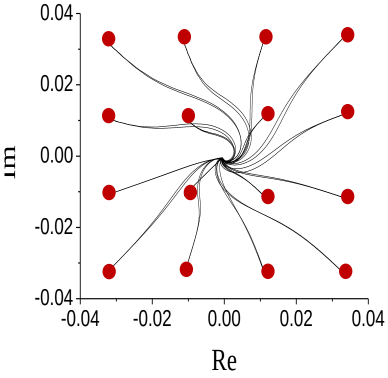
	λ (nm)	*P* (dBm)
OOK1,OOK3	1551.2	22.6
OOK2,OOK4	1536.5	25.4
Probe pulse	1545	0.0
CW pump light	1569.5	24.52

Table2. Parameters of HNLF1 and HNLF2 at the wavelength of 1570nm.

	HNLF1	HNLF2
D[ps/nm/km]	0.08343	0.04646
S[ps/nm^2 /km]	0.02035	0.02047
Loss(dB/km)	0.426	0.411
γ (1/W/km)	12.0	12.0
L(km)	0.406	0.403



(a)



(b)

Fig.4. Waveforms and IQ diagram. (a) The waveforms of four input OOK signals and the output signal. (b) IQ diagram of the output signal.

The simulation results are shown in Fig.4. Fig. 4(a) shows the waveforms of four input OOK signals, such that all possible patterns of M symbols are accounted for, and the output of this OOK to 16QAM modulation format converter. A clear three level pulse train can be observed. The small fluctuation of the pulse peaks is caused by imperfect phase and amplitude modulation to QPSK1 and QPSK2. Fig.4.(b) depicts the modulated 16QAM constellation observed at the output of the proposed converter. These simulation results confirm that OOK to 16QAM modulation format con-version at the symbol rate of 10 GS/s can be realized by the proposed scheme.

3. Conclusion

We have proposed an all-optical OOK to 16QAM modulation format conversion scheme using NOLM. It is noteworthy that this technique will enable to realize a transparent gateway between WAN and MAN for beyond 100Gb/s signal because cross-phase modulation and optical parametric gain in optical fibers used are ultrafast phenomena in the regime of picoseconds.

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