Self-Pumping Wavelength Conversion for DPSK Signals and DQPSK Generation Through Four-Wave Mixing in Highly Nonlinear Optical Fiber

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Abstract—A novel scheme is proposed to achieve self-pumping wavelength conversion for two differential phase-shift keying (DPSK) signals at different wavelengths through four-wave mixing (FWM) effect in a highly nonlinear optical fiber. By changing the phase modulation depths to $\pi/2$ for both of the DPSK signals, the two signals can be multiplexed to generate a differential quadrature phase-shift keying signal. The simulations and experimental results demonstrate the feasibility of phase manipulations for phase-shift keying signals through the FWM process.

Index Terms—Differential phase-shift keying (DPSK), differential quadrature phase-shift keying (DQPSK), four-wave mixing (FWM), wavelength conversion.

I. INTRODUCTION

FOUR-WAVE mixing (FWM) has been utilized to realize optical devices such as wavelength converters, optical samplers, optical multiplexers/demultiplexers, etc. For example, an all-optical method was proposed to multiplex two on-off keying (OOK) signals into a single quaternary amplitude shift-keying (ASK-4) signal based on FWM effects [1]. On the other hand, advanced modulation formats such as differential phase-shift keying (DPSK), have greatly improved the performance of transmission systems because of their tolerance to nonlinear effects and effectiveness to achieve higher receiver sensitivities, which relax the optical signal-to-noise ratio requirement and mitigate the nonlinear impairments, relative to conventional OOK systems. For DPSK signals, the phase acts as the carrier of data information instead of the amplitude, and the amplitude of each bit possesses uniform waveform shape. Recently, wavelength conversion experiments for return-to-zero (RZ)-DPSK format were reported using FWM in semiconductor optical amplifiers (SOAs) [2] and in a dispersion-flattened highly nonlinear (HNL) photonic crystal fiber [3], respectively. Furthermore, a three-input all-optical XOR Boolean operation in the phase domain for 20-Gb/s RZ-DPSK signals has been demonstrated using FWM in an SOA [4].

In this letter, a novel phase operation scheme based on FWM effect in a high nonlinearity fiber is proposed to achieve simultaneous self-pumping wavelength conversion for two 10-Gb/s DPSK signals without any additional continuous-wave (CW) pump signals, which is different from the previous wavelength conversion schemes [2]–[4]. This method can also be used to generate a differential quadrature phase-shift keying (DQPSK) signal at a new wavelength by adjusting the phase modulation depths for both of the DPSK signals.

II. THEORY OF PHASE OPERATION BASED ON FWM

When two optical signals copropagate inside a fiber, the degenerate FWM process produces new sidebands due to the fiber nonlinearity [3]–[6]. If the two signals have the same polarization and the power depletions are negligible, the electric field of the wavelength-converted light through the FWM can be expressed as [4], [5]

$$E_{+,-} = kE_{2,1}^2 E_{1,2} \exp \left[ \frac{j(2\omega_{2,1} - \omega_{1,2}) t}{+ (2\varphi_{2,1} - \varphi_{1,2}) + \Delta\varphi} \right]$$

(1)

where $E_{1,2}$, $\omega_{1,2}$, and $\varphi_{i}$ (i ∈ 1, 2) are the electrical field, the angular frequency, and the phase of two input signals, respectively. $k$ is a proportional constant, $\Delta\varphi$ is the accumulated phase shift after transmission, and $E_{+,-}$ are the FWM-generated fields at upper and lower sidebands, respectively.

As DPSK signals show constant envelopes for all the bits, the FWM component at the frequency of $\omega_{+}$ or $\omega_{-}$ also keeps uniform waveform for each bit. The phases $\varphi_{+,-}$ of the sidebands are expressed as

$$\varphi_{+,-} = \varphi_{2,1} - \varphi_{1,2} + \Delta\varphi.$$  

(2)

If the phase shift $\Delta\varphi$ is assumed to be a constant, for the FWM component, the phase differences between adjacent bits $\delta\varphi_{+,-}$ are given by

$$\delta\varphi_{+,-} = \delta\varphi_{2,1} - \delta\varphi_{1,2}$$

(3)

where $\delta\varphi_{i}$ (i ∈ 1, 2) is the respective phase difference between adjacent bits for the corresponding input signal. Equation (3) shows that the FWM can be utilized to manipulate the phase information of the DPSK signals.
III. SIMULATIONS AND EXPERIMENTS

A. System Setup

We perform simulations and experiments to verify the theory, and show the self-pumping wavelength conversion of DPSK signals and the generation of DQPSK format. The schematic is shown in Fig. 1. Two input signals are located at such frequencies: \( f_1 = 192.7 \) THz and \( f_2 = 192.8 \) THz, with the same polarizations. Two phase modulators are used to generate 10-Gb/s DPSK signals with \( 2^{23} - 1 \) pseudo-random bit sequence (PRBS) in the experiment and the phase modulation depth can be adjusted by changing the gain of the electrical-driver amplifier. The FWM medium is a 1-km HNL fiber with the following parameters: attenuation factor \( \alpha = 0.78 \) dB/km, nonlinear coefficient \( \gamma = 10.7 \) (W · km)\(^{-1} \), dispersion \( D = -0.23 \) ps/(nm · km) at 1550 nm, dispersion slope \( S = 0.018 \) ps/(nm\(^2\) · km) at 1550 nm, and the zero-dispersion wavelength \( \lambda_0 = 1562.8 \) nm. The input signal powers into the erbium-doped fiber amplifier (EDFA) are assumed to be \(-3\) dBm and the output powers are 16 dBm. In our simulations, \( 2^{23} - 1 \) PRBS is used as the data pattern, which is limited by the current computation power, and the numerical model for the fiber channel is the same as that in [7], where self-phase modulation, cross-phase modulation, and FWM effects are included for all the channels but Raman crosstalk is ignored.

B. Wavelength Conversion of Two Channels

For conventional DPSK signals, the phase change between adjacent bits, \( \delta \varphi_1 \) or \( \delta \varphi_2 \), is “0” or “π”. Based on (3), the phase difference \( \delta \varphi_{1,2} \) will be the same as \( \delta \varphi_{1,2} \) and the data is preserved after the wavelength conversion, due to the fact that \( 2\delta \varphi_1 \) becomes “0” in either case. From (2), the output signals at \( \omega_+ \) and \( \omega_- \) are conjugates of the input signals at \( \omega_1 \) and \( \omega_2 \), respectively. In this FWM process, one input signal works as the pump and no additional CW pump is needed, thus the scheme is termed as “self-pumping” wavelength conversion.

If the fixed phase term is ignored, the simulated phases of the optical signals at \( \omega_- \) and \( \omega_2 \) are shown in Fig. 2(a). The phase ripples of the signal at \( \omega_- \) are attributed to the chirp on the rise and falling edges of modulated signals. The output signals at \( \omega_+ \) and \( \omega_- \) are filtered by a Gaussian optical filter with a bandwidth of 40 GHz and then are detected by a DPSK balanced receiver. In Fig. 2(b), the eye diagram of the signal at \( \omega_- \) indicates a good eye opening and the amplitude fluctuation only occurs at the bit transitions. Similar results are obtained for the signals at \( \omega_+ \) and \( \omega_3 \).

The simulated (solid line) and measured (dashed line) output signal spectra are provided in Fig. 3. The spectrum profiles at \( \omega_+ \) and \( \omega_- \) remain the same as those of the original DPSK signals, which reveal that the phase information is preserved. As the actual rise and fall times of the electrical data signal in the experiment are longer than those in the simulations, more chirps are introduced into the DPSK signals, making the measured spectra at \( \omega_+ \) and \( \omega_- \) broader than the simulation results. This can be overcome by employing x-cut Mach–Zehnder (MZ) modulators or using RZ pulses for the signals.

We then tried MZ modulators to replace the phase modulators in order to generate the DPSK signal \( (2^{23} - 1 \text{ PRBS}) \) with less chirps in the experiment. The output spectra are shown in Fig. 4. The generated signals have the same spectral width as the original signals. In Fig. 5(a), the bit-error-rate (BER) curves...
and after the FWM, how will also the phase difference between adjacent bits result from different bit (right). will present four-level at the constructive and destructive ports of the DPSK de- and . The simulation results are adjusted to the output signals at “spectral ef- [8], [9] have attracted much attention as they can improve the polarization independence, highly ef- cient in optical communication systems. If the phase modulation depths of the input signals at $\omega_1$ and $\omega_2$ are adjusted to $\pi/2$, for the output signals at $\omega_+\text{ and } \omega_-$, the phase difference between adjacent bits $d_{\phi_{+-}}$ will present four-level distributions as $[0, \pi/2, \pi, 3\pi/2]$. The simulation results are shown in Fig. 6(a). Assuming Boolean values “0” and “1” as “no phase change” and “phase change” between adjacent bits, the output signals at $\omega_+$ and $\omega_-$ can result from different bit combinations. One is (00, 11, 10) and the other is (00, 11, 01, and 10). Therefore, through the FWM process, two DPSK signals with different frequencies can be multiplexed to generate a four-level DQPSK signal at a new frequency.

On the other side, if the phase modulation depths of the signals at $\omega_1$ and $\omega_2$ are adjusted to $\pi/4$ and $\pi$, for the output signal at $\omega_-$, the phase difference between adjacent bits $d_{\phi_-}$ will also present four-levels phase distributions as $[0, \pi/2, \pi, 3\pi/2]$. The scheme of bit combinations is (00, 10, 01, and 11).

The received eye diagrams of the signals at $\omega_2$ and $\omega_-$ are given in Fig. 6(b). The top subplots are the simulation results with a balanced photodetector and the bottom ones are the experimental results using a single photodiode. In Fig. 7, the measured results agree well with the simulations in optical spectra. Discrete spectral components appear close to $\omega_1$ and $\omega_2$, however, they have been suppressed at $\omega_+$ and $\omega_-$ after the FWM, showing that DQPSK signals are generated at $\omega_+$ and $\omega_-$. The FWM in an HNL optical fiber is used to realize self-pumping wavelength conversion for two DPSK signals without any CW pump, and it also can be utilized to multiplex two DPSK signals at different wavelengths into a single DQPSK signal. Furthermore, this scheme is a potential candidate for future phase operation in optical label switching systems.

IV. CONCLUSION

The FWM in an HNL optical fiber is used to realize self-pumping wavelength conversion for two DPSK signals without any CW pump, and it also can be utilized to multiplex two DPSK signals at different wavelengths into a single DQPSK signal. Furthermore, this scheme is a potential candidate for future phase operation in optical label switching systems.

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