Experimental Demonstrations of All-Optical Phase-Multiplexing Using FWM-Based Phase Interleaving in Silica and Bismuth-Oxide HNLFs

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Abstract—We propose an all-optical phase-interleaving technology based on dual-pump four-wave mixing (FWM) in highly nonlinear fiber (HNLF). The proposed all-optical phase-interleaving technology is applied in an all-optical phase-multiplexing scheme to successfully phase-multiplex 2x or 3 × 10-Gb/s DPSK-WDM signals to a 20- or 30-Gb/s DPSK in non-return-to-zero (NRZ) formats. The proposed all-optical phase multiplexing scheme is demonstrated using dual-pump FWM in highly nonlinear silica and bismuth fibers. In contrast with optical time-division multiplexing technology, the proposed all-optical phase-multiplexing technology does not require pulse-carving, thus offering a high spectral-efficiency. Differential precoder for each input tributary is operated independently, and no additional encoder or postcoder is required to recover the original data after demodulation on the receiver side.

Index Terms—All-optical signal processing, four-wave mixing (FWM), multiplexing, phase modulation.

I. INTRODUCTION

All-optical signal processing is a key and promising technology for improving the flexibility and increasing the capacity in the future photonic networks [1]. The limit of electronic devices can be overcome through all-optical signal processing. Therefore, the system design of optical communication systems can be improved by involving all-optical signal processing.

Among various all-optical effects that enable all-optical signal processing, four-wave mixing (FWM) in highly-nonlinear fiber (HNLF) [2], [3] holds great interest because of its ultrafast response, wide tuning-range, and transparency in modulation format and bit rate. It has been widely employed in various applications such as tunable wavelength conversion [4], [5] and multicasting [6], phase conjugation [7], optical reshaping [8], and optical time-division multiplexing (OTDM) demultiplexing [9]. More interestingly, a dual-pump FWM, referred to as nondegenerate FWM, could offer a wide tuning bandwidth with uniform efficiency [5], [6].

As a high-efficient FWM process, optical parametric amplifier (OPA) in HNLF has been recognized as an efficient approach for optical amplification and optical signal processing [10]–[12]. Besides signal amplification offered by the parametric gain, the OPA with one or two pumps [13], [14] has been used in a variety of optical signal processing schemes, such as, optical pulse carving [15], optical switching [16], all-optical sampling [17], optical buffering [18], [19], all-optical regeneration in amplitude [20], [21] and phase [22].

To accommodate the explosive growth of internet and telecommunication traffic in wide-area, metro-area, and local-area networks, different multiplexing techniques, such as wavelength division multiplexing (WDM), OTDM, and polarization multiplexing (POLMUX), have been proposed and employed for traffic grooming [23]–[25]. Recently, there has been increasing attention on phase modulated formats, which are more tolerant to fiber nonlinearities, such as differential phase shift keying (DPSK) [25]–[27], especially suitable for long-haul transmission systems. Thus, like the intensity or polarization multiplexing, it is highly desirable to explore all-optical multiplexing technology that is based on the phase of the optical field.

In this paper, we propose and experimentally demonstrate, for the first time, an all-optical phase interleaving technology for multiplexing of DPSK signals in non-return-to-zero (NRZ) format using FWM in highly nonlinear silica [28] and Bismuth-oxide fibers. The proposed all-optical phase-multiplexing scheme based on phase interleaving is a simple approach to increase the bit rate for DPSK signals without using high-speed electrical multiplexing circuitry. It has a potential to enable very high bit-rate operation at low costs. In addition to increasing the transmission capacity, it offers the following advantages: 1) the scheme requires no pulse-carving for input signals, making it simple to implement in NRZ formats, and offers higher spectral-efficiency compared with OTDM; 2) the phase-multiplexed data can be selectively carried at an arbitrary wavelength; 3) differential precoder for each input tributary is operated independently, without additional logical encoder or decoder.

We experimentally demonstrate the all-optical phase multiplexing of independent 2x or 3 × 10-Gb/s DPSK-WDM signals to a 20- or 30-Gb/s DPSK signal, respectively. The experiments based on dual-pump FWM were demonstrated using both highly nonlinear silica and bismuth fibers. Owing to the ultrafast and low dispersion in the silica HNLF, a 40-nm-wide tuning range of the phase-multiplexed signals was achieved by simply tuning the probe’s wavelength, with ∼3-dB variation in FWM efficiency and less than 0.7-dB fluctuation in...
eye-opening Q-factor. On the other hand, to ensure the compactness and tackle the polarization stability issue of fiber-based nonlinear signal-processing devices [29], the all-optical phase multiplexing scheme was also demonstrated using a 2-m-long Bi-HNLF with a nonlinear coefficient of 1100 W⁻¹ km⁻¹. Thanks to its high nonlinearity and relative high stimulated Brillouin scattering (SBS) threshold [30], the utilization of 2-m Bi-HNLF enhances the compactness and stability of the proposed all-optical phase-multiplexer.

With more inputs, the proposed scheme can be extended to phase-multiplex several tributaries to a high-speed DPSK signal. It has a potential to enable interfacing between access/metro networks and long-haul backbone networks as a gateway in future all-optical networks.

This paper is organized as follows. In Sections II and III, the operation principle of all-optical phase multiplexing technology based on the phase interleaving in a dual-pump FWM in nonlinear fiber is explained. The proposed phase multiplexing scheme is experimental demonstrations using the dual-pump FWM in silica HNLF and Bi-HNLF in Sections IV and V, respectively. Finally, a short discussion is presented in Section VI.

II. PHASE PRESERVATION IN DUAL-PUMP FWM

The operation principle of the proposed all-optical phase interleaving technology is based on a nondegenerate FWM process in HNLF. As shown in Fig. 1, in nondegenerate FWM, the phase matching condition is satisfied by placing two pumps (P1 at ω₂₁, P2 at ω₂₂) symmetrically with respect to the zero-dispersion wavelength (ZDW, ω₀) of the fiber. By inputting the two pumps and a probe (ω₃), the nondegenerate FWM process mainly generates three products at ω₁₁₃, ω₂₃₁, and ω₂₃₂, respectively. The corresponding fields, E₁₁₃, E₂₃₂, and E₂₃₁, of the FWM products at ω₁₁₃, ω₂₃₂, and ω₂₃₁ can be expressed as

\[ E_{113} = k(E_1 \cdot E_2) \exp[j(2\omega_1 - \omega_3)t + (2\varphi_1 - \varphi_3)] \tag{1} \]

\[ E_{223} = k(E_1 \cdot E_2) \times \exp[j(\omega_1 + \omega_2 - \omega_3)t + (\varphi_1 + \varphi_2 - \varphi_3)] \tag{2} \]

\[ E_{231} = k(E_2 \cdot E_3) \times \exp[j(\omega_2 + \omega_3 - \omega_1)t + (\varphi_2 + \varphi_3 - \varphi_1)] \tag{3} \]

where ω₁, E₁, and ϕᵢ (i ∈ [1, 2, 3]) are the angular frequency, the corresponding field, and the phase of the pumps and probe, respectively, and k is a coefficient related to the FWM efficiency. Among these three FWM products, we are interested in the two generated products at ω₂₃₁ and ω₂₃₂, as they contain the phase information from the probe and the two pumps. From (2) and (3), it is clear that the phases of the generated FWM components at ω₂₃₂ and ω₂₃₁ satisfy the relations ϕ₂₃₂ = ϕ₁ + ϕ₂ − ϕ₃ and ϕ₂₃₁ = ϕ₂ + ϕ₃ − ϕ₁, respectively. With (0, π) phase modulation of the input probe and the pumps, the phases of the generated FWM products at ω₂₃₂ and ω₂₃₁ can be regarded as the result of a logical XOR operation of three input phases, i.e., ϕ₁₂₃ (or ϕ₂₃₁) = ϕ₁ ⊕ ϕ₂ ⊕ ϕ₃.

By simply tuning input’s wavelength through 1+, 1−, 2+, and 2− bands, the wavelengths of generated FWM products can cover the whole tuning band. Therefore, the phase information of input probe and pumps can be multiplexed and selectively transferred to arbitrary wavelength with a wide-band tuning range regardless of the zero-dispersion wavelength of fiber. Moreover, it is possible to achieve polarization insensitivity operation with orthogonally polarized pumps [5], [6].

III. ALL-OPTICAL PHASE INTERLEAVING

Phase interleaving is an effective technology to generate a high-speed DPSK signal by cascading several low-speed and independent phase modulators. We have successfully demonstrated an 80-Gb/s DPSK transmitter using two cascaded 40-Gb/s DPSK modulators in [31]. Because of the phase preservation feature in dual-pump FWM, it is possible to achieve an all-optical phase interleaving based on dual-pump FWM, and apply it in all-optical phase-multiplexing to phase-multiplex low-speed DPSK-WDM tributaries to a high-speed DPSK signal in an all-optical manner.

The operation principle of all-optical phase interleaving is illustrated in Fig. 2. Here, we assume that the bit period of the probe and pumps is T. With a relative time offset, T/3, among the input probe and two pumps, the resultant phase-modulation speed of the FWM products at ω₂₃₂ and ω₂₃₁, ϕ₄ = ϕ₁₂₃ = ϕ₂₃₁, is increased to 3/T. Therefore, without using pulse-carving, three low-speed input DPSK tributaries carried at

![Fig. 1. Principle of the proposed all-optical phase-interleaving technology based on dual-pump FWM. (P1: input DPSK-1, P2: input DPSK-2, Probe: input DPSK-3).](image)

![Fig. 2. Phase patterns of input and output signals in the proposed all-optical phase interleaving scheme based on dual-pump FWM.](image)
different wavelengths are successfully phase-multiplexed into a high-speed DPSK signal with a bit rate increased by a factor of 3. The resultant phase patterns, shown as (d) in Fig. 2, in time slots \(3i\) and \(3i-1\), \(\phi_{4}^{3i}\) and \(\phi_{4}^{3i-1}\), are given by

\[
\phi_{4}^{3i} = \phi_{4}^{3i-1} + \phi_{1}^{3i} + \phi_{2}^{3i-1}
\]

\[
\phi_{4}^{3i-1} = \phi_{4}^{3i-1} + \phi_{1}^{3i-1} + \phi_{2}^{3i-1}
\]

After a Mach–Zehnder delay interferometer (MZDI) with \(T/3\) relative delay, the demodulated data in time slot \(3i\) is given by

\[
\phi_{4}^{3i} = \phi_{4}^{3i-1} + \phi_{1}^{3i} + \phi_{2}^{3i-1}
\]

which corresponds to the original data applied in phase modulation of P2 at \(\omega_2\). Therefore, it indicates that, for the phase-multiplexed FWM products, after the phase demodulation, the obtained data is a simple multiplexing of three input tributaries in the time domain with increased capacity. Although the resultant phase pattern is the result of a logical XOR operation among three input tributaries, the differential precoder for each input tributary is independently operated at the transmitter side. On the other hand, the phase-multiplexed data at the two generated FWM products can be independently recovered to the original data by simply using an electrical or optical demultiplexer after demodulation. No additional logical encoder or decoder is required.

IV. EXPERIMENT DEMONSTRATION OF ALL-OPTICAL PHASE-MULTIPLEXING IN SILICA HNLF

Fig. 3 shows the experimental setup. Light beams from tunable lasers at 1544.1 nm and 1554.1 nm were employed as the two pumps (P1 and P2), while light from another tunable laser was employed as a tunable probe for FWM. Here, to easily adjust the wavelength of inputs, external cavity lasers were employed. However, conventional DFB lasers can also be used for DPSK signals [32]. After phase modulation by 10-Gb/s \(2^{15}-1\) PRBS data streams and power amplification individually, P1, P2, and the probe were combined by couplers and fed to a 500-m length of silica HNLF with launched powers of 16.3, 16, and 13.2 dBm, respectively. The silica HNLF (SEI, Japan) has a ZDW of 1549.1 nm, dispersion slope of 0.02 ps/nm²/km, low \(\beta_4(2 \times 10^{-50} \text{ s}^5/\text{m})\), uniform ZDW distribution (\(\lambda_0 \pm 0.1\) nm), and high nonlinear coefficient \(\gamma \) of 30 W⁻¹km⁻¹ [33]. It ensures a wideband tunable operation with constant efficiency and uniform performance by using the HNLF with low fourth-order dispersion and low fluctuation of \(\lambda_0\). The measured SBS threshold of the HNLF was around 16 dBm. The SBS could be suppressed due to the phase modulation in the pumps. After the HNLF, the generated FWM product was filtered out by a 1-nm tunable filter and was demodulated by a set of MZDI and a following balanced photo-detector, which has a 3-dB bandwidth of around 22 GHz. Then the demodulated data was fed into an electrical 1:4 demultiplexer. To simplify the configuration, in the experiment, the clock for demultiplexer was directly from the synchronizer at the transmitter side without performing the clock recovery. The obtained 20- or 30-Gb/s phase-multiplexed DPSK signal was demultiplexed to three channels through the electrical demultiplexer by tuning the delay of applied 10-GHz RF clock. We scanned the delay of RF clock until error-free was achieved for any particular channel. Then, the other channels could be demultiplexed by simply tuning the delay with relative offset of around 33 ps for 30-Gb/s, or 50ps for 20-Gb/s phase-multiplexed DPSK signals.

If phase modulations were performed at two pumps and the probe was left un-modulated, the obtained phase-multiplexed DPSK signals at the two FWM products were with bit rate of 20-Gb/s, and the multiplexed phase was from the two pumps. As shown in Fig. 4, with phase modulation at only one of the two pumps, after the MZDI of 50 ps, demodulated patterns were shown in Fig. 4(a) or (b). Around 50-ps time offset was observed between the patterns (a) and (b). With both of pumps phase-modulated, after the phase demodulation, the obtained pattern (c) was a simple multiplexed data stream of (a) and (b) in time domain. This verifies that, in the proposed phase-multiplexing scheme, input tributaries are phase-multiplexed independently, and after phase demodulation, no additional encoder or decoder is required to separate and recover the original input data.

With an input of probe at 1546 nm, as shown in Fig. 5, two FWM products at \(\omega_{123}\) and \(\omega_{231}\), encoded as 30-Gb/s DPSK
signals, were generated at 1552.2 and 1556 nm with FWM efficiencies of $-13.7$ and $-13.5$ dB, respectively. Here, we define FWM efficiency as the ratio of the power of the FWM product to that of the input probe. Fig. 6 shows the zoomed-in spectra of the FWM product at 1552.2 nm with one, two and three enabled phase modulations in the input probe and two pumps, corresponding to the obtained phase modulations with 10-, 20-, and 30-Gb/s, respectively. For the obtained 10-, 20-, and 30-Gb/s DPSK signals in the FWM product at 1552.2 nm, the 15-dB spectrum bandwidths are measured as 0.19, 0.37, and 0.44 nm, respectively. This indicates the effectiveness of phase-multiplexing effect in the FWM process. The input phase modulations in two pumps and probe are effectively transferred and multiplexed to the phase of generated FWM products.

As shown in Fig. 7, BER performance of the obtained 20- and 30-Gb/s DPSK output signals at 1556 nm in the scheme using silica HNLF. The measured receiver sensitivities for the three demultiplexed 10-Gb/s channels (CH1, CH2, and CH3) were $-27.3$, $-27.6$, and $-27$ dBm, corresponding to the original input data carried on P1, P2, and the probe, respectively. The measured eye diagrams of input 10-Gb/s tributaries and phase-multiplexed 20- and 30-Gb/s DPSK signals are shown in Fig. 8. Ideally, power penalties of around 3 and 4.8 dB are expected for the multiplexed 20- and 30-Gb/s DPSK signals, respectively, compared with those of three 10-Gb/s tributaries. The observed additional 1- and 2.2-dB penalties for the obtained 20- and 30-Gb/s DPSK signals can be attributed to the FWM-induced additional distortion, the crosstalk between the adjacent channels, and the limited frequency response of the phase modulators employed, especially for the 30-Gb/s case. Better performance could be expected by using dual-drive Mach–Zehnder modulators, instead of phase modulators for the input DPSK streams, especially for the case with long data pattern.

To evaluate the wideband operation of the proposed scheme, FWM efficiency and eye-opening $Q_{eye}$-factor [34] of the generated FWM product at $\omega_{23}$ were measured when sweeping the probe’s wavelength from 1530 to 1570 nm. The tuning range of probe was limited by the available bandwidth of employed EDFA. Around 3-dB FWM-efficiency fluctuation and less than 0.7-dB variation in $Q_{eye}$-factor were observed when the probe was tuned over a 40-nm band, as shown in Fig. 9. As mentioned, this is attributed to the dual-pump configuration, as well as the low fourth-order dispersion and uniform dispersion profile of
the employed HNLF. A wider tuning range is expected with wideband EDFAs.

In this section, the all-optical phase multiplexing scheme has been successfully demonstrated using FWM effect in a piece of silica HNLF with ultralow and flat dispersion, which makes it possible to achieve an error-free operation and a wide tunable range with uniform signal performances. To further enhance the compactness and stability of the proposed all-optical phase multiplexer, in the following section, an experimental demonstration using FWM in a barely 2-m-long Bi-HNLF will be presented. The stability performance of the compact all-optical multiplexing scheme using Bi-HNLF, as well as the limitation from the point of pump power requirement and operating bandwidth will be described.

V. EXPERIMENTAL DEMONSTRATION OF ALL-OPTICAL PHASE MULTIPLEXING IN A BI-HNLF

To experimentally demonstrate the proposed all-optical phase multiplexing using Bi-HNLF, an experimental setup similar to the one shown in Fig. 3 was used. Continuous wave light from tunable lasers at 1544 nm and 1547.3 nm were employed as the two pumps (P1 and P2), while light from another tunable laser at 1543 nm was employed as a probe for FWM. After phase modulation by 10-Gb/s 2\(^{15}\) − 1 PRBS data streams and power amplification individually, P1, P2, and the probe were combined by couplers and launched into a 2-m length of Bi-HNLF with launched powers of 24, 24, and 13 dBm, respectively. Note that the launched power quoted here was measured before the input patch cord of the fiber. The estimated power coupled into the Bi-HNLF should be around 1.5-dB lower than the quoted value. The nonlinear coefficient \(\gamma\) of the used Bi-HNLF (Asahi Glass, Japan) in the experiment was measured to be around 1100 W\(^{-1}\) km\(^{-1}\). The fiber propagation loss at 1550 nm was 2 db/m. Both of the ends of the Bi-HNLF were spliced to SMFs using high NA fibers with the input and output splicing losses of 1.5 and 1.8 dB, respectively. The group velocity dispersion was measured to be $-320\, \text{ps/nm/km}$ at 1550 nm. The SBS threshold was estimated as around 28.4 dBm [29]. After the Bi-HNLF, the generated FWM components were filtered out by a 1-nm optical tunable filter, and demodulated by a following MZDI. Then the detected signal was demultiplexed into 10-Gb/s data streams for BER measurement.

With an input of probe at 1543 nm, as shown in Fig. 10, two FWM components at \(\omega_{231}\) and \(\omega_{123}\) encoded as 30-Gb/s DPSK signals, were generated at 1546.3 and 1548.2 nm with FWM efficiencies of $-11.3\, \text{dB}$ and $-11.7\, \text{dB}$, respectively. It is clear that the spectra of generated FWM components at \(\omega_{231}\) and \(\omega_{123}\) are wider compared with those of input pumps and probe, which is because of the phase multiplexing in these FWM components.

BER performance of the obtained 20- and 30-Gb/s DPSK signals at 1546.3 nm was evaluated, as shown in Fig. 11, after being demultiplexed to 10-Gb/s data using an electrical demultiplexer. Receiver sensitivity at BER of $10^{-9}$ of input three 10-Gb/s DPSK tributaries, i.e., P1, P2 and probe, were measured as $-34.5$, $-34.75$, and $-34.25\, \text{dBm}$, respectively. With phase modulations at the two pumps only, a 20-Gb/s DPSK was obtained and the measured receiver sensitivities, after being demultiplexed to two channels (CH1 and CH2), were $-30.5$ and $-30\, \text{dBm}$. Three input tributaries were phase-multiplexed to a 30-Gb/s DPSK when the two pumps and the probe were all phase-modulated at 10 Gb/s. The measured receiver sensitivities for the three demultiplexed 10-Gb/s channels (CH1, CH2, and CH3) were $-26$, $-25$, and $-24\, \text{dBm}$, corresponding to the original input data carried on P1, P2, and the probe, respectively. The measured eye diagrams are shown in Fig. 12. As we discussed in the above section, compared with those of three input 10-Gb/s tributaries, additional 1.3 and 4.7 dB penalties were

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**Fig. 8.** Eye diagrams of input (a) P1, (b) P2, (c) probe, and obtained (d) 20- (e) 30-Gb/s DPSK signals at 1556 nm in the scheme using silica HNLF.

**Fig. 9.** FWM efficiency and \(Q_{\text{mod}}\)-factor variation of FWM product at \(\omega_{233}\) when probe was tuned from 1530 to 1570 nm in the experiment using silica HNLF.

**Fig. 10.** Measured optical spectrum for the all-optical phase multiplexing from $3 \times$ 10-Gb/s DPSK-WDM to a 30-Gb/s DPSK signal in the scheme using Bi-HNLF.
observed for the obtained 20- and 30-Gb/s DPSK signals, respectively. In addition to the distortion sources we mentioned above, the phase mismatch due to the relative large dispersion in Bi-HNLF results in the OSNR degradation of the generated FWM components. Better performance could be expected if a dispersion-shifted photonic crystal Bi-HNLF is employed.

The tunable range of the proposed all-optical phase multiplexing scheme based on FWM in a Bi-HNLF was also investigated by tuning the wavelength of the input probe from 1541 to 1551 nm. The corresponding FWM efficiency of FWM product \(\omega_{2\omega_1}\) during the tuning of probe wavelength were measured and showed in Fig. 13. The 3-dB bandwidth of the FWM efficiency is around 7 nm, which is related to the spacing of the two pump signals.

We have experimentally demonstrated an all-optical phase multiplexing scheme using FWM-based phase interleaving technology in a short piece of Bi-HNLF. Owing to the extremely high nonlinearity and high SBS threshold of Bi-HNLF, an error-free operation of all-optical phase multiplexing from 2x and 3 \times 10-Gb/s DPSK-WDM to 20- and 30-Gb/s DPSK has been successfully achieved despite the use of only 2-m length of fiber. The utilization of the short Bi-HNLF improves the stability and compactness of the proposed all-optical phase-multiplexer.

VI. SUMMARY

We have proposed and experimentally demonstrated the proposed all-optical phase multiplexing scheme based on the all-optical phase interleaving technology by using dual-pump FWM in silica-HNLF as well as Bi-HNLF. Error-free operations were achieved in both of the experiment demonstrations. The performance of these two schemes based on silica-HNLF and Bi-HNLF is compared and summarized in Table I. In the experiment using silica-HNLF, the phase matching condition is automatically satisfied by placing two pumps symmetrically with respect to the zero-dispersion wavelength of the fiber. In this case, with higher pump power, the FWM efficiency can be further improved due to the parametric gain. As the focus of this work is on the phase multiplexing, to avoid additional noise introduced by the parametric amplification and SBS, here, only around 16 dBm power was applied for each of the pumps. Further improvement in efficiency and performance could be expected by using high power pumps due to the associated parametric gain. Experiment using silica-HNLF also offers wide wavelength tuning range with flat efficiency and uniform signal performance because of its ultralow and flat dispersion. In the case with Bi-HNLF, however, the phase matching condition form FWM was not properly satisfied due to large normal dispersion, which necessitated about an 8-dB higher pump power. Conversion efficiency, similar to that using HNL silica fiber, was achieved by reducing the spacing between the pumps in the experiment using Bi-HNLF, and, the utilization of the short Bi-HNLF improves the stability and compactness of the proposed all-optical phase-multiplexer. However, due to the relative large dispersion of the employed Bi-HNLF, a relative large power penalty and narrow tuning range were obtained. A further improvement in performance could be expected by employing low-loss bismuth based photonic crystal fibers that are properly engineered to offer both large nonlinearity and small chromatic dispersion.

In this paper, 2 or 3 \times 10-Gb/s DPSK-WDM signals were experimentally demonstrated to be phase-multiplexed to a 20- or 30-Gb/s DPSK signal in NRZ formats, respectively. The proposed multiplexing scheme is simply achieved based on the
The phase of optical fields in NRZ formats. It requires no pulse-carving or additional logical encoders for the input tributaries.

ACKNOWLEDGMENT

The authors would like to thank Dr. T. Hasegawa of Asahi Glass Co., Ltd., for helpful discussion.

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