Four-wave mixing based 10-Gb/s tunable wavelength conversion in dispersion-flattened microstructure fibers

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All-optical wavelength conversion of 10-Gb/s signal based on four-wave mixing is experimentally demonstrated in a 30-m-long dispersion-flattened microstructure fiber with small positive dispersion. For an average pump power of 26 dBm, the conversion efficiency was around −19.5 dB with the fluctuation less than ±1.4 dB, covering a conversion bandwidth of 20 nm. The eye diagram of the converted signal shows good eye opening.

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All-optical wavelength conversion is considered to be a crucial technique in future high-speed dense wavelength-division-multiplexed (DWDM) network[1]. Among various wavelength conversion techniques, the use of the four-wave mixing (FWM) in nonlinear optical fibers would be one of the easiest and the most flexible approaches because of its simple configuration and transparency to both bit rate and modulation format[2]. The relatively low nonlinearity presented by the dispersion-shifted fiber (DSF) requires the use of long length[3]. As a consequence it is difficult to control and stabilize the conversion device. Also, the necessity of placing the pump at or near the zero-dispersion wavelength of the fiber to ensure phase matching may limit the flexibility of the optical networks.

Microstructure fibers (MFs) are currently a topic of high interest because of their unusual optical properties which cannot be realized in conventional optical fibers[4]. MFs have central region of pure silica surrounded by a lattice of air-holes in the cladding running along the fiber length, and they offer design flexibility in controlling the mode propagation properties by changing the size and pattern of the air holes[5−7]. The design freedom offered by the MF technology makes highly nonlinear MF very suitable for wavelength conversion where the fiber parameters should be tailored to satisfy specific demands, namely a flat dispersion profile and a high nonlinearity. The low dispersion values of MF make it satisfy the quasi-phase matching condition over a wide wavelength range. FWM-based wavelength conversion has been demonstrated utilizing MF[8−10], showing promising applications in DWDM networks.

In this letter, we report the wavelength conversion of 10-Gb/s signal using FWM in a dispersion-flattened MF with low positive dispersion values. We show a conversion efficiency of −19.5 dB for an average pump power of 26 dBm and a conversion bandwidth of 20 nm. The quality of the converted signal is monitored by eye diagrams.

The schematic of our experimental setup is shown in Fig. 1. The signal beam at a fixed wavelength of 1550.05 nm was modulated with a $2^{15}-1$ pseudorandom data sequence at a data rate of 10 Gb/s and then combined with the pump beam using a 3-dB coupler. The two beams were then amplified using a high power erbium-doped fiber amplifier (EDFA) with an average saturated power of 26 dBm.

The fiber used in this experiment is a 30-m-long commercial available dispersion-flattened high nonlinear MF from Crytal-Fibre A/S (NL-1550-POS-1). The MF has a nonlinear parameter of 11 $\mathrm{W}^{-1}\cdot\mathrm{km}^{-1}$ at 1550 nm and a small positive dispersion of $0.5-1.5$ ps/(km·nm) over the range of $1480-1620$ nm, as shown in Fig. 2. Also, the MF is spliced to standard single-mode fiber pigtails, leading to a total loss of 2 dB from connector to connector.

The states of polarization of both the signal and the

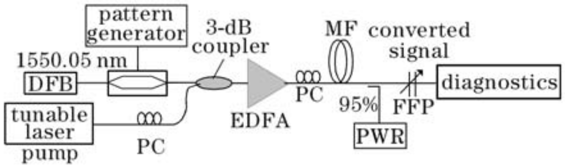

Fig. 1. Schematic of the experimental setup. DFB: distributed feedback laser; PC: polarization controller; PWR: optical power meter; FFP: fiber Fabry-Perot filter.

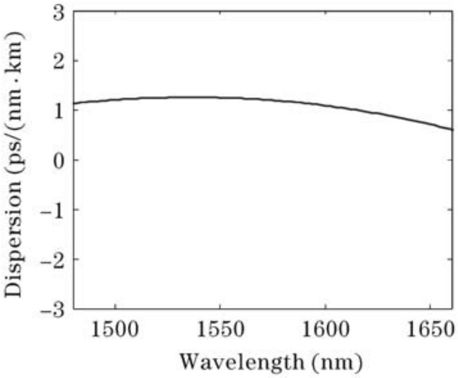

Fig. 2. Dispersion curve of the MF used in experiment.

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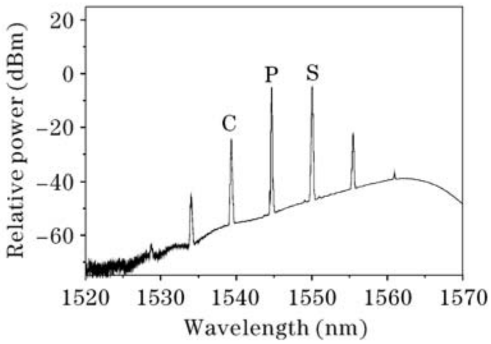

Fig. 3. Measured output spectrum from the FWM-based wavelength converter. C: converted signal; P: pump wave; S: signal wave.

pump beams were optimized to ensure the highest conversion efficiency. Furthermore, the differential group delay (DGD) of the MF was measured to be 4 ps using the Sagnac interference method, corresponding to a birefringence of $\Delta n = 4 \times 10^{-5}$. At the fiber output, the converted signal was filtered out using a tunable fiber Fabry-Perot filter with the 3-dB bandwidth of 0.8 nm. The output was investigated using an optical spectrum analyzer of 0.01-nm resolution and a 20-GHz photodetector together with a digital sampling oscilloscope.

We assessed the wavelength conversion performance in the spectral domain. The output spectrum is shown in Fig. 3. A strong FWM wavelength-converted signal was observed at 1539.4 nm with the input signal and the pump beams at 1550.05 and 1544.7 nm, respectively. Both second- and third-order idler beams were also observable. The optical signal-to-noise ratio (SNR) of the converted signal is found to be better than 30 dB in a 0.1-nm resolution bandwidth.

The conversion efficiency of wavelength converter is defined as the ratio of output wavelength-converted signal power to the input signal power. The output power can be written as[11]

$$P_{\mathrm{FWM}} = (\gamma P_{\mathrm{p}} L_{\mathrm{eff}})^2 \cdot P_{\mathrm{s}} \exp(-\alpha L) \cdot \eta, \qquad (1)$$

where P_{p} and P_{s} are the input powers of the pump and signal waves, respectively, L is the fiber length, and α is the attenuation coefficient. L_{eff} is the effective interaction length given as

$$L_{\mathrm{eff}} = (1 - \mathrm{e}^{-\alpha L})/\alpha. \qquad (2)$$

η is the FWM efficiency, which can be expressed as

$$\eta = \frac{\alpha^2}{\alpha^2 + \Delta\beta^2}\left(1 + 4\frac{\mathrm{e}^{-\alpha L}}{(1 - \mathrm{e}^{-\alpha L})^2}\sin^2\left(\Delta\beta\frac{L}{2}\right)\right), \qquad (3)$$

$\Delta\beta$ is the propagation constant difference written as $\Delta\beta = \beta_{\mathrm{FWM}} + \beta_{\mathrm{s}} - 2\beta_{\mathrm{p}}$. β indicates the propagation constant. The propagation constant difference, also called phase-matching factor, generally depends on fiber dispersion and wavelength separation. The solid line in Fig. 4 is the theoretical simulation curve for the fiber used in experiment when the average pump power is 26 dBm. The measured conversion efficiency is also shown in Fig. 4. It is clearly seen that the conversion efficiency is around −19.5 dB with the fluctuation less than ±1.4 dB, covering a tunable bandwidth of about 20 nm. The experimental results agree well with the theoretical curve.

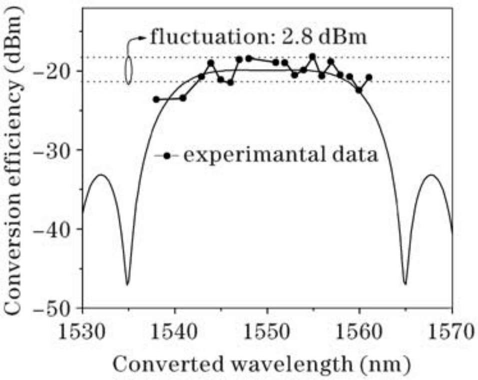

Fig. 4. Conversion efficiency versus converted wavelength when the average pump power is 26 dBm. The solid line is the theoretical simulation result.

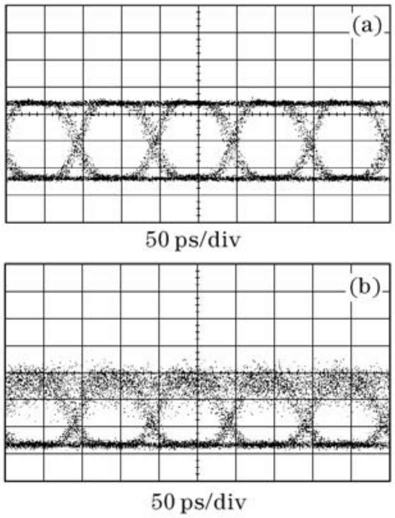

Fig. 5. Eye diagrams of (a) original 10-Gb/s signal at 1550.05 nm and (b) the converted signal at 1540 nm.

For the eye diagrams, a 20-GHz bandwidth photodiode was used in conjunction with a digital sampling oscilloscope with a 20-GHz electrical sampling module. Figures 5(a) and (b) show the eye diagrams of the 10-Gb/s non-return-to-zero (NRZ) input signal (back-to-back) at 1550.05 nm and wavelength-converted output signal at 1540 nm. A good eye diagram of the converted signal is obtained. A small amount of timing jitter and intensity noise is observed from the eye diagrams. We believe that the intensity noise can be attributed to modulation instability, since the MF used in this experiment lies in anomalous dispersion regime. The eye diagrams of converted signal at different wavelengths were also measured. There is no obvious difference when the wavelength of the converted signal is in conversion bandwidth.

MFs can be fabricated to have unusual dispersion and nonlinearity characteristics by altering the size and arrangement of the surrounding air holes. We have experimentally demonstrated a tunable wavelength converter using FWM in a dispersion-flattened nonlinear MF with small positive dispersion. A tuning range up to 20 nm of the converted signal with −19.5-dB conversion efficiency and good flatness over $1541-1561$ nm has been achieved. The results show that a highly nonlinear and dispersion flattened MF with lower (even slightly positive) dispersion is promising for wide-band wavelength conversion applications in all-optical networks. The researches on FWM-based wavelength conversion in dispersion-flattened MF with different dispersion values are in progress.

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