Broadband wavelength converter based on four-wave mixing in a highly nonlinear photonic crystal fiber

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We demonstrate a 10 Gbit/s nonreturn-to-zero wavelength converter based on four-wave mixing in a 20 m highly nonlinear photonic crystal fiber. The tunable wavelength conversion bandwidth (3 dB) is about 100 nm. The conversion efficiency is −16 dB when the pump power is 22.5 dBm. Phase modulation was not used to suppress the stimulated Brillouin scattering; thus the linewidth of the converted wavelength remained very narrow. The eye diagrams show that there is no additional noise during wavelength conversion. The measured power penalty at a 10^{-9} bit-error-rate level is about 0.7 dB. © 2005 Optical Society of America

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Wavelength division multiplexing is a promising technique for realizing high-capacity optical networks. In a wave division multiplexed network a wavelength converter is an important component to perform functions such as wavelength routing and switching. It is desirable that the wavelength conversion be tunable over a broad wavelength range and that the linewidth of the converted wave be narrow. Several all-optical wavelength conversion techniques have been demonstrated.[1,2] All-optical wavelength conversion based on four-wave mixing (FWM) in a fiber is attractive owing to the virtually instantaneous response of the Kerr nonlinearity of fused silica and simultaneous multichannel conversion characteristics. Normally the length of the dispersion-shifted fiber used in this application is several kilometers, and the frequency spectrum of the pump source is required to be broadened to increase the threshold of stimulated Brillouin scattering[3,4] (SBS). Using a highly nonlinear conventional fiber[5] can shorten the fiber length to less than 100 m. However, the SBS threshold in a highly nonlinear fiber does not improve much. It is still necessary to broaden the frequency spectrum of the pump source or apply a strain distribution on the fiber to suppress the SBS.[3,4]

Recently the emergence of photonic crystal fibers (PCFs) with low loss and high nonlinearity gives this application another opportunity to perform better. Due to the special structure, highly nonlinear PCFs have special characteristics, such as a large nonlinearity, which is typically 1 or 2 orders of magnitude larger than that of a conventional single-mode fiber; controllable dispersion, which makes a PCF with a small dispersion slope at zero dispersion around 1550 nm available; and adjustable birefringence that is insensitive to the ambient temperature.[6] It is well known that the conversion efficiency of FWM is affected by the nonlinear coefficient, dispersion, birefringence, and the length of fiber. Variation of the zero-dispersion wavelength with temperature in the fiber will decrease the conversion efficiency of FWM.[7] A short length of fiber can decrease the effect caused by the variation of zero-dispersion wavelength and temperature. The high nonlinearity in a PCF should make a short length of fiber practical, the air holes in the PCF should make the fiber relatively temperature insensitive, the small dispersion slope in a PCF should give a large tunable range in FWM, and the high SBS threshold in a PCF should cause the linewidth of the converted wave to be narrow.

FWM in a PCF in the visible wavelength range has already been demonstrated.[8] Wavelength conversion based on FWM in a PCF also has been investigated.[2,9] The widest 3 dB bandwidth of the wavelength converter using PCF[9] is about 40 nm. The length of the PCF in Ref. 9 is 64 m. In this paper we report that a wavelength converter with a larger 3 dB conversion bandwidth (100 nm) is achieved with an even shorter highly nonlinear PCF (20 m). The SBS threshold of the highly nonlinear PCF is as high as 200 mW. Therefore phase modulation is not needed to broaden the spectrum of the pump source to suppress the SBS, and as a result the linewidth of the converted wave is not broadened by the pump source. The fiber power–length product is about 0.004 W km, which is much smaller than the other wavelength converters.

The schematic of our experimental setup is shown in Fig. 1. Both the pump and the signal were derived from tunable lasers, TL1 and TL2. The signal was

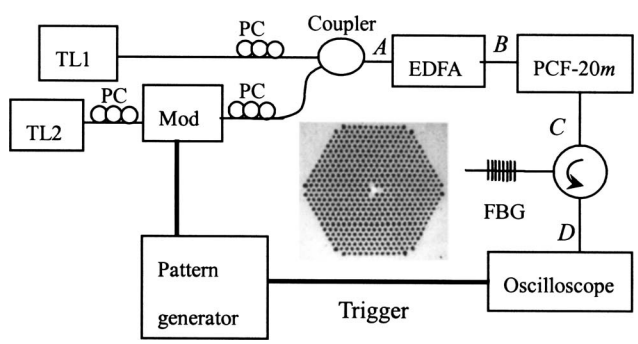

Fig. 1. Schematic of the experimental setup of the wavelength converter.

modulated with a $2^{31}-1$ pseudorandom sequence at a data rate of 10 Gbit/s and then combined with the pump by a coupler. The two beams were then amplified by an erbium-doped fiber amplifier (EDFA) with a maximum saturated output power of 500 mW. Then the two amplified beams are launched into the 20 m highly nonlinear PCF with a zero-dispersion wavelength around 1550 nm. The geometry of the PCF is shown in the inset of Fig. 1. It has a core size of 2.1 ± 0.3 μm and a cladding diameter of 128 ± 5 μm. The total insertion loss of the PCF is less than 1 dB. The nonlinearity coefficient of the PCF used in our experiments is about 30.6 W^{-1} km^{-1} measured by the dual-frequency beat signal method.[10] The modal birefringence (Δn) of the fiber is measured to be 2.2×10^{-5} at 1550 nm with a Sagnac interferometer. The variation of zero-dispersion wavelength due to birefringence[11] will be about 1 nm. The SBS threshold in the PCF is also investigated. We experimentally observed a SBS threshold of ~200 mW as shown in Fig. 2.

We measured the conversion efficiency by changing the wavelength of the pump while the wavelength of the signal was fixed. During the measurements, the pump power, as measured by the optical spectrum analyzer (OSA), was around 22.5 dBm, and the signal power was around 0 dBm. No stimulated Brillouin backscattering is observed when the pump power is as high as 22.5 dBm. The maximum power of the converted wavelength was obtained by adjusting the polarization controller for each measurement. The conversion efficiency was calculated as a ratio of the power of the converted wavelength to that of the signal. The conversion efficiency spectrum obtained from the experiment is shown in Fig. 3.

It can be seen that the wavelength of the converted signal can be varied from 1520 to 1620 nm by adjusting the pump wavelength accordingly. The maximum conversion efficiency is about −16 dB. The conversion efficiency drops by 3 dB from its maximum value within 100 m, which is from 1520 to 1620 nm. Therefore the 3 dB tunable bandwidth is about 100 nm.

The bandwidth and efficiency of the FWM-based wavelength converter depend on the nonlinearity-assisted phase matching of the propagation vector and the nonlinearity-induced parametric gain. Consider the phase-matching parameter κ in FWM,[8,12]

$$\kappa = 2\gamma P_0 + \Delta\beta, \tag{1}$$

where $\Delta\beta=\beta_s+\beta_i-2\beta_p$ is the linear phase mismatch. β_s, β_i, and β_p are the propagation constants of the co-

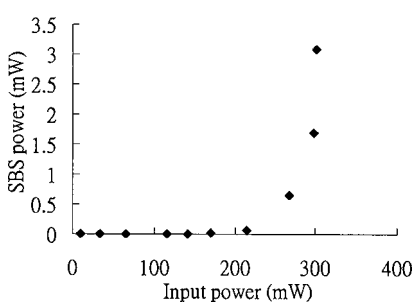

Fig. 2. SBS (backward) versus the launched power.

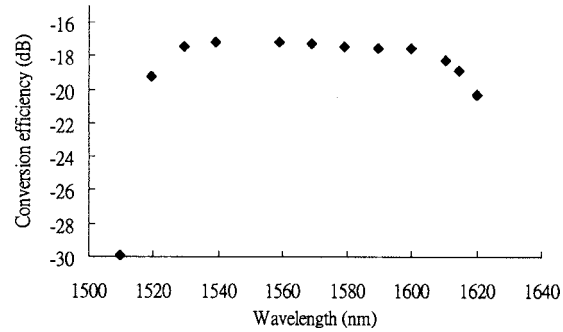

Fig. 3. Conversion efficiency versus converted wavelength.

propagating signal, idler, and pump, respectively. γ is the nonlinearity coefficient of the fiber, and P_0 is the pump power.

In our experiment the pump wavelength is varied near the zero-dispersion wavelength in order to obtain a tunable converted wavelength while the signal wavelength is fixed. $\Delta\beta$ can be written approximately as[1,12,13]

$$\Delta\beta = [\lambda_0{}^4/(2\pi c)^2]S_0(\omega_p - \omega_0)\Delta\omega^2, \tag{2}$$

where ω_p is the pump angular frequency, ω_0 is the zero-dispersion angular frequency, and $\Delta\omega=\omega_s-\omega_p$ is the frequency detuning of the signal from the pump. $S_0=\partial D/\partial\lambda$ is the dispersion slope of the fiber, and D is the chromatic dispersion near the zero-dispersion wavelength λ_0. c is the velocity of light in vacuum. The parametric gain coefficient of the FWM is given by[1]

$$g = [(\gamma P_0)^2 - (\kappa/2)^2]^{1/2} \tag{3}$$

and represents real gain over a conversion bandwidth corresponding to $-4\gamma P_0<\Delta\beta<0$, which is obtained from Eqs. (1) and (3) and which can be expressed, by using Eq. (2), as

$$-4\gamma P_0 < \frac{\lambda_0{}^4}{(2\pi c)^2}S_0(\omega_p - \omega_0)\Delta\omega^2 < 0. \tag{4}$$

From inequality (4) we see that the difference between the signal and the pump frequencies, which determines the bandwidth, is inversely proportional to the slope of the dispersion curve S_0 at the zero-dispersion wavelength. Therefore, the smaller S_0 is, the wider the frequency range at which we can get efficient wavelength conversion. To investigate the dispersion of the PCF we observed the modulation instability by using a high power pump. The result shows that the wavelength difference between the sideband and the pump is almost constant (4.62 nm) when the pump wavelength is tuned from 1530 to 1560 nm (The tuning range of the pump source is limited by the bandwidth of the erbium-doped fiber amplifier). This indicates that the dispersion slope of the PCF in use is very small, estimated to be 0.0004 ps/(nm^2 km). The dispersion slope is much smaller than that for the conventional dispersion shifted fiber, which is about 0.07 ps/(nm^2 km). In Ref. 8 the bandwidth of the wavelength converter based

on a PCF is only 10 nm because the dispersion slope of their PCF is too large [approximately −0.6 ps/(nm^2 km)] compared with that of ours. In Ref. 9 the dispersion slope of their fiber is about 0.001 ps/nm^2 km, so they find the bandwidth of the wavelength converter to be about 40 nm, which is smaller than ours (100 nm).

After the PCF, a fiber Bragg grating (FBG) is used to filter out the converted wavelength and suppress the input pump and signal. The optical spectra are monitored by an optical spectrum analyzer at points A, B, C, and D with a 15 dB attenuator placed before the optical spectrum analyzer.

The two optical spectra observed at points C and D are shown in Fig. 4. The wavelengths of the signal and the pump are 1572.2 and 1549.8 nm, respectively, giving a wavelength difference of 22.4 nm. A strong FWM converted wavelength is clearly evident at 1528.3 nm at point C. A FBG and the circulator serve as a bandpass filter with a central wavelength of 1528.3 nm to filter the converted wavelength. Therefore, at point D, the converted wavelength is about 12 dB higher than the pump power, which is suppressed by more than 42 dB, showing that the setup in Fig. 1 is an efficient wavelength converter.

In order to analyze whether the data stream is affected by the wavelength conversion, we also have observed the eye diagram of the wavelength converted signal in the range of 1500 to 1600 nm. Figure 5 shows one example of the eye diagrams for both 10 Gb/s nonreturn-to zero (NRZ) input signal [Fig. 5(a)], which is obtained at point A but with TL1 turned off, and the converted signal at 1528.3 nm [Fig. 5(b)], which is obtained at point D. The eye diagram of the converted signal is almost as clear as the eye diagram of the signal. It implies that almost no additional noise is added during the wavelength conversion process. Figure 6 shows the measured bit error ratio (BER). We obtained a power penalty of 0.7 dB relative to that of the original input signal at the 10^{-9} BER level.

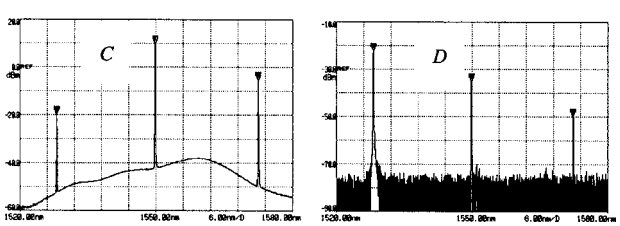

Fig. 4. Optical spectra at points C and D.

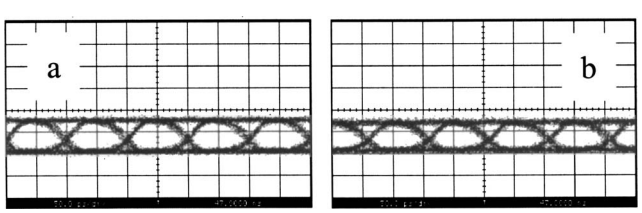

Fig. 5. Eye diagram for wavelength conversion of 10 Gb/s NRZ signal at a wavelength of 1528.3 nm. a, For original signal; b, for converted signal.

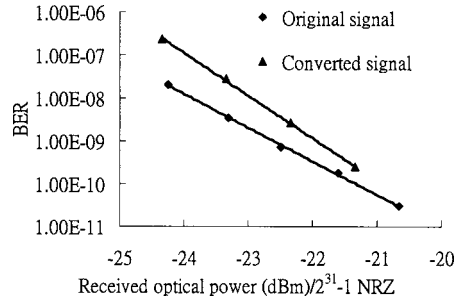

Fig. 6. Measured BER versus received optical power for wavelength conversion of a 10 Gb/s NRZ signal.

In conclusion, we have demonstrated a broadband tunable wavelength converter based on FWM in a short, highly nonlinear PCF. Our results show that wavelength conversion can be achieved in a PCF even with low pump power and a short length of fiber. The fiber–power length product is as small as 0.004 W km. The 3 dB tunable range of the new generated signal is about 100 nm. The conversion efficiency is −16 dB, which is same as that in Ref. 9, but our conversion bandwidth is much larger. In the experimental setup, no phase modulation is used to suppress the SBS. So the linewidth of the converted wave is as narrow as the signal. The eye diagram shows that almost no additional noise is added during the wavelength conversion process. A power penalty of 0.7 dB at a BER of 10^{-9} is obtained, confirming the wavelength converter's good performance.

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