Four-wave mixing based widely tunable wavelength conversion using 1-m dispersion-shifted bismuth-oxide photonic crystal fiber

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Abstract: We demonstrate widely tunable wavelength conversion based on four-wave mixing using a dispersion-shifted bismuth-oxide photonic crystal fiber (Bi-PCF). A 1-meter-long Bi-PCF is used as the nonlinear medium for wavelength conversion of a 10 Gb/s non-return-to-zero (NRZ) signal. A 3-dB working range of the converted signal over 35 nm is obtained with around 1-dB power penalty in the bit-error-rate measurements.

OCIS codes: (060.4370) Nonlinear optics, fibers; (190.4380) Nonlinear optics, four-wave mixing

References and links

1. Introduction

The development of highly-nonlinear fibers (HNLF) fabricated by novel glass materials has opened a new window for nonlinear fiber optics owing to its ultra-high nonlinearity and compatible standard single-mode fibers (SMF). Much research effort has been focused on a large variety of nonlinear applications and compact, efficient devices have been demonstrated with fibers fabricated by bismuth-oxide glass [1-3], chalcogenide glass [4, 5], heavy metal-oxide glass [6], etc. Among different kinds of signal processing applications in large capacity communication networks, wavelength conversion plays a major role in providing wavelength flexibility and avoiding wavelength blocking in the wavelength-division-multiplexing (WDM) systems. In particular, four-wave mixing (FWM) is a promising technique for wavelength conversion owing to its ultra-fast response and high transparency to bit rate and modulation format [7]. Previous reports on FWM-based wavelength conversion using conventional silica HNLF [8, 9] or silica photonic crystal fibers (PCF) [10-11] have shown good performances with effectively shortening the required fiber length from kilometers to tens of meters. Recently, report on FWM-based wavelength conversion using highly-nonlinear bismuth-oxide fiber (Bi-NLF) has successfully shortened the required fiber length to even less than 1 meter [12]. However, one major issue of Bi-NLF applications falls on its high material dispersion similar with other non-silica HNLF with novel glass materials, which limits the wavelength working range. In general, HNLF made by different novel glass materials can have extremely high nonlinearity but at the same time suffer from large group velocity dispersion (GVD). In order to obtain wideband FWM for efficient wavelength conversion, the fiber should have high nonlinearity, low dispersion, and short in length [13]. Recent reports show that one effective solution to solve the dispersion problem of Bi-NLF is applying photonic crystal structure to the fibers [14, 15]. In this paper, we experimentally demonstrate a compact, widely tunable wavelength converter using 1 meter of newly developed dispersion-shifted bismuth-oxide photonic crystal fiber (Bi-PCF). By combining its advantages of higher nonlinearity than silica based PCF and adjusted dispersion in the 1550 nm range, a wide working range of 35 nm is obtained. Also, the Bi-PCF is fully spliced to SMF without free space coupling so that the converter can have a stable operation. A power penalty of around 1.2 dB is measured for 10 Gb/s non-return-to-zero (NRZ) signal in the bit-error-rate (BER) measurements.

2. Fiber Design for Wideband Four-Wave Mixing

The wideband FWM wavelength converter comes from the adoption of fiber with high nonlinearity and low dispersion in the 1550 nm range. In particular, maintaining phase matching between the signal and the pump plays important role in generating effective FWM effect. It is difficult to maintain phase matching in a long fiber due to GVD. Previous work shows that the phase mismatch problem even exists in less than 1 meter Bi-NLF with a dispersion value $D$ of -260 ps/nm/km at 1550 nm and limits the tunability [12]. In order to obtain an efficient wideband FWM effect, one ultimate solution is to adopt photonic crystal structure in the Bi-NLF to modify its dispersion characteristics.

In our experiment, we have adopted a dispersion-shifted Bi-PCF as the nonlinear medium. The inset of Fig. 1 shows the microstructured region of the fiber which is fabricated by the inflating method [15]. Firstly, glass rods are prepared by a conventional melting method and 6 holes are drilled in a rod with encircling the center. A single hole is drilled in the center of another rod as jacketing tube. Then the rod with 6 holes is drawn to proper diameter in order to be inserted into the jacketing tube. The rod together with the jacket is drawn simultaneously
with applying positive pressure on 6 holes and negative pressure on the gap between the rod and the jacket. Through this process 6 holes are expanded and the core diameters can be adjusted by appropriate design of jacketing tube geometry and number of rod-in-tube [15]. By varying the core and hole diameters, the dispersion of the fiber can be shifted. With this structure, we have fabricated a fiber with a mode filed diameter (MFD) of 2.01 μm, and a dispersion value $D$ of -9.9 ps/nm/km at 1550 nm measured by the homodyne interferrometric method (Agilent 81901A). Since there is a trade-off between dispersion-shift and nonlinearity, the fiber has a nonlinear coefficient of around 580 W$^{-1}$km$^{-1}$. Also, the attenuation of the fiber is 1.9 dB/m in the 1550 nm range. Table 1 summarizes the optical parameters of Bi-PCF in our experiment, Bi-NLF in [12] and common silica HNLF. The Bi-PCF segment adopted in the experiment is 1.09 meters in length with both ends spliced to standard single-mode fiber (SMF), yielding a total loss of 11.9 dB. An updated report on Bi-PCF splicing shows that with perfect MFD conversion in the end of collapsed hole region, the fiber can play like the step index Bi-NLF with core diameter of 1.6 μm and MFD of 5.5 μm in which the theoretical splicing loss to SMF can be 1.8 dB/point. [16]. Note that unlike common silica PCF to SMF splicing, there is no intermediate fiber spliced between Bi-PCF and SMF so that there is no extra reflection from the 2 more splicing points.

Table 1. Optical parameters of Bi-PCF, Bi-NLF, and common silica HNLF

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Bi-PCF</th>
<th>Bi-NLF</th>
<th>HNLF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonlinearity (W$^{-1}$km$^{-1}$)</td>
<td>580</td>
<td>1100</td>
<td>15.5</td>
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<tr>
<td>Dispersion @ 1550 nm (ps/nm/km)</td>
<td>-9.9</td>
<td>-260</td>
<td>1.7</td>
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<tr>
<td>Effective area (μm$^2$)</td>
<td>3.17</td>
<td>3.08</td>
<td>11</td>
</tr>
<tr>
<td>Propagation loss (dB/m)</td>
<td>1.9</td>
<td>0.8</td>
<td>0.0016</td>
</tr>
</tbody>
</table>

3. Experiment and Discussion

The experimental setup on tunable wavelength conversion using Bi-PCF is shown in Fig. 1. The input signal is a $2^{31}$-1 bits pseudorandom NRZ signal at 10 Gb/s. The input signal is combined with a wavelength tunable continuous-wave pump laser using a 3-dB coupler.
combined signal is then launched on an erbium-doped fiber amplifier (EDFA) followed by a segment of 1.09 m long (excluding fiber pigtails) dispersion-shifted Bi-PCF. The launched pump power is estimated to be around 22.5 dBm. It is worth noting that there is no stimulated Brillouin scattering (SBS) observed at this pump power level without any (SBS) suppression scheme in the experiment as the estimated SBS threshold is around 31 dBm. This comes from a relatively high SBS threshold with such a short length of fiber with less accumulated Brillouin gain [13]. The amplified pump and signal then undergo FWM effect and generate new wavelength components. Finally, we use a tunable fiber Fabry-Perot filter (FFP) to filter out the converted signal and wavelength conversion is obtained.

Figure 2 shows the spectra obtained after the Bi-PCF at different converted wavelengths. In our experiment the input signal (S) is fixed at 1550.0 nm and different converted wavelengths are obtained by tuning the pump (P) wavelength. Figures 2(a) and 2(b) are the spectra showing the up conversion to 1553.9 and 1563.4 nm, respectively. Figures 2(c) and 2(d) show the output spectra of down conversion to 1544.5 and 1536.7 nm, respectively. Note that the optical signal to noise ratio (OSNR) of the converted signal is maintained over 20 dB over the whole working range.

We define the conversion efficiency as the ratio of converted signal power to input signal power inside the Bi-PCF, excluding the fiber input and output coupling losses of 4.4 dB and 5.4 dB, respectively. The relation between the conversion efficiency and the converted output wavelength is plotted in Fig. 3. For the case of partially degenerate FWM, when the signal and pump wavelengths are close enough the conversion efficiency $\eta$ can be expressed as [1]:

![Fig. 2. Output four-wave mixing spectra after Bi-PCF showing (a)(b) up conversion and (c)(d) down conversion. S: input signal; P: pump; and C: converted signal.](image-url)
\[ \eta(L) = (\gamma P_{av} L)^2 \]  
where \( L \) is the propagation distance, \( \gamma \) is the nonlinear coefficient, and \( P_{av} \) is the path average pump power:

\[ P_{av} = P \left[ 1 - \exp(-\alpha L) \right] / \alpha L. \]  

with input pump power \( P \) and fiber loss coefficient \( \alpha \). From Eq. (1) the peak conversion efficiency is calculated as -20.9 dB, which is consistent with the experimental results.

With tuning the pump wavelength thus the converted wavelength, a 3-dB working range of the converted signal is observed over 35 nm from 1532 to 1567 nm in our experiment. Consider the case when signal and pump wavelengths are detuned away, the conversion wavelength tunability is limited by the finite phase mismatch \( \Delta k = \beta_2 \Omega^2 \) caused by the fiber GVD, where \( \beta_2 \) is the GVD parameter at the pump wavelength and \( \Omega \) is the optical frequency shift between signal and pump waves. Thus, the conversion range is limited by frequency shift hence phase mismatch as [17]:

\[ \eta(L) = \left( P_{av} L \sin(\Delta k L / 2) \right)^2 / \Delta k L / 2 \]  

Note that the bandwidth of \( \eta \) in Eq. (3) is defined with the case using fixed pump and tuning input signal, which is different from this experiment where the pump wavelength is tuned. In another experiment, we have investigated the fixed pump FWM case using the same segment of Bi-PCF. By Eq. (3) and the experimental results we find that the \( \beta_2 \) value of the fiber is around 23 ps\(^2\)/km at 1550 nm, which is around -18 ps/nm/km when converted to \( D \) value. The measured \( \beta_2 \) value by such method is in the same order of magnetite consistent with that of mentioned in the pervious session. However, due to the very short length of fiber adopted in our experiment, a strictly precise measurement of dispersion parameters is still difficult to obtain. Although the \( \beta_2 \) value of the Bi-PCF is still higher than that of conventional solid-core highly-nonlinear fiber, combining the advantages of high nonlinearity and short fiber length we can still obtain wideband wavelength conversion.

![Fig. 3. Plot of conversion efficiency against converted signal wavelength.](image-url)
In order to investigate the system performance of the wavelength converter, 10 Gb/s BER measurements are performed. The wavelength of input signal is fixed at 1550 nm and the BER of both up and down conversion are measured. Figure 4 plots the output BER against the received optical power of different converted wavelengths. The insert shows the 10 Gb/s eye diagram of the input signal and the 15 nm down-converted signal. The power penalties measured of all converted wavelengths are ranging from 1.2 to 1.4 dB at 10⁻⁹ BER level, which shows that error-free conversion with similar properties can be obtained within the whole wavelength tuning range. The BER performance tends to drop when tuning beyond 15 nm up- or down-conversion and no 10⁻⁹ BER level can be obtained outside the 1532-1567 nm range. The around 1 dB power penalty is believed to be originated from the multi-path reflection between the two splicing points of the fiber, as the refractive index of bismuth-oxide glass can be as high as 2.1 at 1550 nm. Based on such power penalties it is believed that the wavelength converter can work with higher data rate. With the technical improvement of the Bi-PCF splicing as mentioned, both the power penalty and the conversion efficiency can be improved. Previous work on silica PCF shows that the dispersion can be precisely tailor-made with different kinds of core and hole structures. With the compatible bismuth-oxide glass such PCF technologies can be applied and Bi-PCF with different dispersion characteristics can be obtained to fit specific applications.

4. Conclusion

A 1-meter-long dispersion-shifted bismuth-oxide photonic crystal fiber has been adopted to experimentally demonstrate a four-wave mixing based widely tunable wavelength converter. A 3-dB working range up to 35 nm of the converted signal with around -20 dB conversion efficiency over 1532-1567 nm has been achieved. Also, power penalties of around 1 dB with different converted wavelengths are measured in the 10 Gb/s BER measurements. Improvement of the splicing loss and more precise dispersion control of Bi-PCF are foreseeable so that results with lower power penalty, higher conversion efficiency and wider conversion range are expected in the near future.

Acknowledgement

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