FWM-based Flexible Wavelength Conversion in Whole C-band Using Realistic HNLF Having Dispersion Slope

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Abstract: Flexible conversion from an arbitrary wavelength to desired wavelength in whole C-band is studied and demonstrated within 1.7dB efficiency variation among all conversion pairs using HNLF having dispersion slope of +0.02ps/nm^2/km and γ of 30/W/km.

OCIS codes: (060,2280) Fiber design and fabrication; (060,4370) Nonlinear optics, fibers

1. Introduction

Four-wave-mixing (FWM)-based parametric processes generated in silica-based highly nonlinear fiber (HNLF) have been actively investigated for optical applications for high-capacity photonic networks [1]. In order to apply the HNLF-based applications to optical signal processings for arbitrary wavelengths including tunable wavelength converters, μs-order tunable delays and reconfigurable add/drop multiplexers, flexible wavelength conversion from an arbitrary wavelength to a desired wavelength over a communication wavelength band is required as schematically shown in Fig. 1. For realization of the flexible wavelength conversion, the pump wavelength (λ_{pump}) should be tuned according both to the signal wavelength (λ_{signal}) and the converted idler wavelength (λ_{idler}) in the case for the degenerated FWM, which is expressed as,

$$\lambda_{pump} = 2(1/\lambda_{signal} + 1/\lambda_{idler})^{-1}. \qquad (1)$$

In order to realize significant wavelength conversion over broad bandwidth, however, the λ_{pump} is usually set around the zero-dispersion wavelength (λ_{ZD}) of HNLF because the phase matching of the wave vectors among lightwaves at the λ_{pump}, λ_{signal} and λ_{idler} are required. For this reason, realization of the flexible wavelength conversion using a standard HNLF having the dispersion slope (Slope) has been believed to be difficult. It has been reported that flexible wavelength conversions using highly nonlinear dispersion-flattened fibers with all-solid composition [2,3] and holey fibers [4]. Such dispersion-flattened fibers, however, have smaller nonlinear coefficients than those of a HNLF having Slope. Moreover, the λ_{ZD} is enormously shifted even with a molecular-scale fluctuation in the core diameter; that is to say, it is desperately difficult to manage the λ_{ZD} in dispersion-flattened fibers.

In this paper, we study flexible wavelength conversions from an arbitrary wavelength to a desired wavelength in the whole C-band using HNLF having the rational dispersion slope of +0.02ps/nm^2/km. It is numerically found that the wavelength conversion in 100 m-long HNLF will be realized within 3dB efficiency variation for all conversion pairs if the λ_{ZD} ranges from 1541 nm to 1553 nm. In the manufacturing viewpoint, this tolerance of the λ_{ZD} is broad enough for realistic HNLF. After this consideration, we actually demonstrate the flexible wavelength conversion in the whole C-band using HNLF with the dispersion slope of +0.02ps/nm^2/km and the γ of 30/W/km.

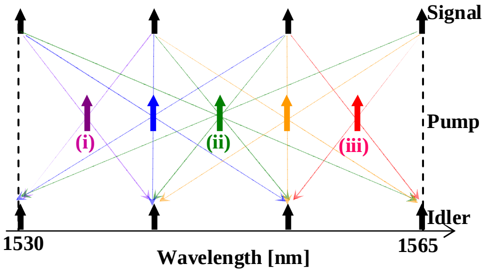
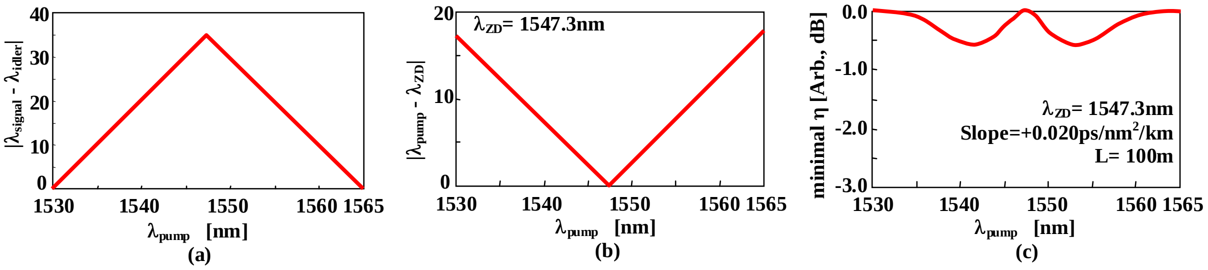


Fig. 1. Flexible wavelength conversion in C-band.

2. Flexible wavelength conversion scheme in whole C-band using HNLF having rational dispersion slope

Considering the wavelength conversion within the C-band, both λ_{signal} and λ_{idler} should rage from 1530 to 1565 nm. Therefore, the conversion bandwidth of $|\lambda_{signal} - \lambda_{idler}|$ should be the broader when the λ_{pump} is around the center of the C-band (1547.3 nm) like the case for λ_{pump} at (ii) in Fig. 1, whereas the $|\lambda_{signal} - \lambda_{idler}|$ could be narrower when the λ_{pump} is around the edges of the C-band like the cases for λ_{pump} at (i) and (iii). From (1), required $|\lambda_{signal} - \lambda_{idler}|$ for the flexible conversion is shown in Fig. 2(a) as a function of λ_{pump}. In the FWM process, the conversion efficiency of η, ignoring negligibly small attenuation of HNLF with short length, can be approximately written as

$$\eta \approx \left\{ P_{pump} \cdot \gamma \cdot L \cdot \frac{\sin(\Delta\beta \cdot L/2)}{\Delta\beta \cdot L/2} \right\}^{2}, \qquad (2)$$



Figs. 2. Calculated performances as a function of λ_{pump} required for flexible conversion in C-band; (a) conversion bandwidth, (b) difference between λ_{pump} and λ_{ZD}, (c) minimal efficiency via a λ_{pump} normalized to the maximum among all conversion pairs.

where γ and L are the nonlinear coefficient and length of the fiber respectively. P_{pump} is the launched pump power into the fiber. $\Delta\beta$ is the phase mismatching among related lightwaves. Ignoring higher-order dispersions and phase shift due to P_{pump}, the $\Delta\beta$ can be written as

$$\Delta\beta = -\pi^2 c^2 \lambda_{pump}^{-4} \beta_{2p} (\lambda_{signal} - \lambda_{idler})^2,$$

$$\approx (\pi c \cdot \lambda_{pump}^{-4} \lambda_{ZD}^{2}/2) \cdot Slope \cdot (\lambda_{ZD} - \lambda_{pump}) (\lambda_{signal} - \lambda_{idler})^2, \qquad (3)$$

where c is the vacuum light velocity and β_{2p} is the second-order dispersion at λ_{pump}. From (3), $|\lambda_{signal} - \lambda_{idler}|$ is in proportion to $\{Slope \cdot (\lambda_{ZD} - \lambda_{pump})\}^{-0.5}$. As in Fig 2(a), the $|\lambda_{signal} - \lambda_{idler}|$ should be broad around the λ_{pump} at the center of the C-band; therefore, it would appear that the λ_{ZD} should be around 1547.3 nm for the flexible conversion. In the case that the λ_{ZD} is at 1547.3 nm, $(\lambda_{ZD} - \lambda_{pump})$ is shown in Fig. 2(b) as a function of λ_{pump}. In this case indeed in Figs. 2(a) and (b), it is found that the $(\lambda_{signal} - \lambda_{idler})$ and $(\lambda_{ZD} - \lambda_{pump})$ are complementary to each other.

The other importance to realize flexible conversion is to reduce the Slope as in (3). The lower the dispersion slope, however, the larger the fluctuation in λ_{ZD} becomes. Figure 3 shows the calculated shift of the λ_{ZD} when the core diameter is changed by 0.1% as a function of the Slope. As can be seen, the fluctuation of the λ_{ZD} increases drastically if the Slope is lower than around +0.02 ps/nm^2/km. In addition, with the Slope of +0.02 ps/nm^2/km, we have been realized a HNLF with the highest nonlinear coefficient γ of 30/W/km as a reported silica-based fiber [5], which would be positive as well to enhance the conversion efficiency η. The η fully covering the C-band were calculated, and the minimal η for conversion pairs via each λ_{pump} was determined. The minimal η normalized to the maximum η among all conversions is shown in Fig. 2(c) as a function of the λ_{pump}. Here, the HNLF was assumed to have the Slope of +0.02 ps/nm^2/km, the λ_{ZD} of 1547.3 nm and the length of 100 m. As can be seen, flexible conversion in the whole C-band will be able to realize within the efficiency variation of 0.5 dB. Then, in order to evaluate this flexible conversion is realistic or not, we calculated the efficiency valiance for flexible conversion as a function of the λ_{ZD}, which is shown in Fig. 4 as a curve line. Here, the γ and P_{pump} are assumed to 30/W/km and 50 mW respectively, and phase shift of $-2\gamma P_{pump}$ was considered in (3). It is found from Fig. 4 that the λ_{ZD} can range from 1542 nm to 1552 nm for 3-dB bandwidth. This wide tolerance of λ_{ZD} is corresponding to the core diameter fluctuation of 0.2% from Fig. 3, which is broad enough for the latest HNLF fabrication technology in which the core diameter can be controlled within 0.1% fluctuation [5].

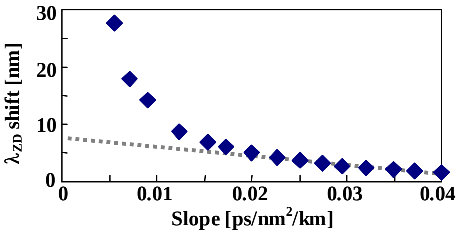


Fig. 3. Calculated λ_{ZD} shift by 0.1% core-diameter change as a function of dispersion slope

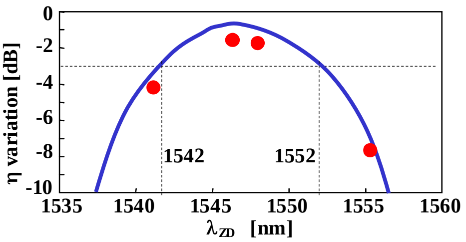


Fig. 4. Efficiency variation for flexible conversion in C-band for λ_{ZD}. Line: calculation, plots: measurements.

3. Demonstration of flexible wavelength conversion

According to above discussion, we actually measured the η using 100m long HNLFs having the Slope of +0.02 ps/nm^2/km and γ of 30/W/km. In the measurement setup, a pump light from a tunable CW-laser was amplified by an EDFA to be P_{pump} of 50 mW and was launched into HNLF, along with a signal with 1 mW from another tunable CW-laser. Polarization controllers were used to adjust polarization states of the pump and signal lightwaves. Generated idler light was measured with an optical spectrum analyzer. The λ_{signal} was scanned over the whole C-band from 1530 to 1565 nm, and the λ_{pump} was tuned so λ_{idler} converted from the λ_{signal} as to fully cover the C-band.

Calculated (lines) and measured (plots) η in HNLFs with λ_{ZD} of (a) 1546.4 nm and (b) 1541.2 nm for the λ_{signal} of 1550 nm and 1565 nm normalized to the maximum η are shown in Figs. 5 as a function of the λ_{idler}. Being in good agreement with the numerical discussion and the calculation, wavelength conversions measured in HNLF with λ_{ZD} of 1546.4 nm, around the center wavelength of C-band, have small efficiency variation about 1 dB; on the other hand, conversions in the HNLF with λ_{ZD} of 1541.2 nm have much larger efficiency variation of 4 dB. In order to validate flexible conversion in HNLF with λ_{ZD} of 1546.4 nm, the η for conversion pairs within the whole C-band were measured, in which the λ_{signal} was set to 1530, 1532, ... , 1564 and 1565 nm while the λ_{pump} for each λ_{signal} was tuned so the λ_{idler} to be a wavelength covering the C-band. Measured η are plotted in Fig. 6 as a function of λ_{idler}, and it is found that the variation for all the η is within 1.7 dB.

In the same way, the η in HNLFs with the λ_{ZD} of 1541.2, 1548.0 and 1555.4 nm were measured. The evaluated variations of the η in the HNLFs fully covering the C-band are within 4.2, 1.6 and 7.7 dB respectively, which are shown in Fig. 4 as plots. The measured and calculated results are in good agreement with each other, although the measurements exhibit larger variation than the calculation by about 1 dB because of the effects from polarization states fluctuation, measurement errors and the like. As a conclusion, it can be safely said that the flexible wavelength conversion fully covering the C-band has been successfully realized with HNLF having the rational Slope of +0.02 ps/nm^2/km and the high γ of 30/W/km within a realistic tolerance of HNLF manufacturing.

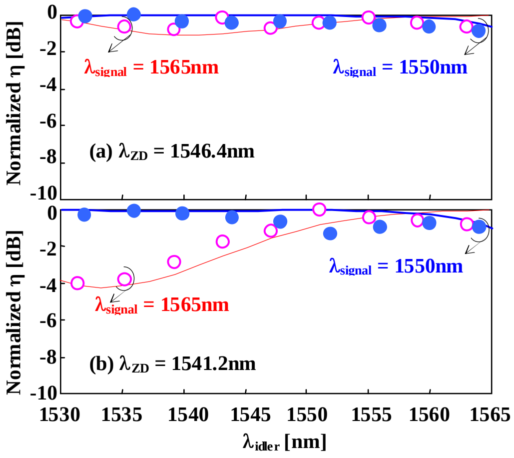


Fig. 5. Normalized conversion efficiency, lines: calculations, plots: measurements.

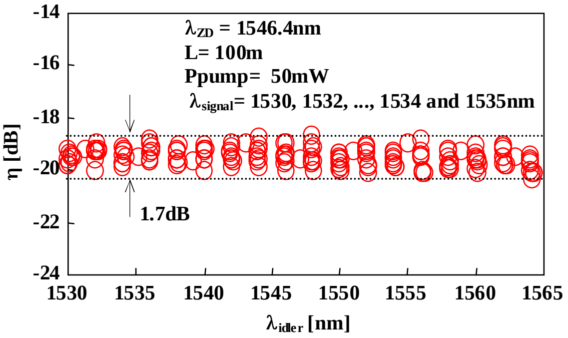


Fig. 6. Conversion efficiency fully covering the C-band.

4. Summary

The flexible conversion from an arbitrary wavelength to a desired wavelength using HNLF having Slope has been believed to be difficult. After numerical consideration, however, we have clarified that the flexible wavelength conversion in the whole C-band can be realized with HNLF having rational Slope of +0.02ps/nm^2/km. Within manufacturable tolerance of λ_{ZD}, we have actually fabricated HNLF and demonstrated the flexible wavelength conversion with the efficiency variation less than 3 dB. Results that the λ_{ZD} should be around the center of the C-band may be the same as an intuitive idea; however, this report would give the first quantitative discussion in our best knowledge. This flexible wavelength conversion using realistic HNLFs will be promising for practical all optical processings for arbitrary wavelengths, we believe.

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