Demonstration of intermodal four-wave mixing by femtosecond pulses centered at 1550 nm in an air-silica photonic crystal fiber

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***Abstract*—In this paper, we demonstrated experimentally the intermodal four-wave mixing effect by launching femtosecond pulses centered at 1550 nm into deeply normal dispersion region in the fundamental guided-mode of an air-silica photonic crystal fiber with two zero dispersion wavelengths. When intermodal phase-matching condition is satisfied, the energy of the pump waves at 1550 nm in the fundamental guided-mode is converted to the anti-Stokes waves around 1258 nm and Stokes waves around 2018 nm both in the second-order guided-mode. When femtosecond pulses at input average power P_{av} of 90 mW are propagated inside 22 cm long photonic crystal fiber, the conversion efficiency η_{as} and η_s of the anti-Stokes and Stokes waves generated are 8.5 and 6.8%, respectively. We also observed that the influences of the fiber bending and walk-off effect between the fundamental and second-order guided-modes on intermodal four-wave mixing-based frequency conversion process are very small.**

***Index Terms*—Photonic crystal fiber, intermodal four-wave mixing, anti-Stokes waves, Stokes waves**

I. Introduction

FOUR-wave mixing (FWM) facilitates energy coupling between the involved optical waves propagated at different frequencies and modes, in which two pump photons are converted to one up-shifted signal (anti-Stokes) photon and to one down-shifted idler (Stokes) photon. Most previous studies on FWM in optical fibers and photonic crystal fibers (PCFs) [1]-[4], including non-degenerate and degenerate cases, are intramodal, i.e. the anti-Stokes and Stokes waves are generated within the same guided-mode as the pump wave [5]-[10]. In intramodal FWM processes, the phase-matching condition requires the wavelengths of the pump pulses to be located near the zero dispersion wavelengths (ZDWs) of the guided-modes of optical fibers or PCFs, so it is difficult to achieve a reasonable balance between the fiber design and the choice of the pump lasers. In addition, when the pump pulses are injected close to the ZDWs, supercontinuum (SC) generation [11]-[15] would greatly limit the energy conversion process and severely contaminate the output optical spectra of generated anti-Stokes and Stokes waves. In contrast, the intermodal FWM processes can occur between different guided-modes, because the phase-matching condition does not depend on the ZDWs of optical fibers or PCFs. Thus, for intermodal FWM processes, even if the pump pulses in the fundamental guided-mode are launched at the wavelengths far away from the ZDWs of optical fibers or PCFs, the anti-Stokes and Stokes waves can still be generated through the intermodal phase-matching condition between the fundamental and higher-order guided-modes.

Since it was firstly observed in an optical fiber by Stolen et al. in 1974 [16], the intermodal FWM effect, which is considered as a frequency conversion process at the initial stage of the intricate nonlinear dynamics during SC generation, has been studied theoretically and experimentally in optical fibers [17]-[19] and PCFs [20]-[25] when the pump short pulses are operated at wavelengths of 532, 800, and 1064 nm. Compared with those wavelengths, the pump wavelength at 1550 nm is located in the lowest loss transmission window of the silica optical fibers, where the laser and optical communication techniques are mature. Thus, by the intermodal FWM effect, the energy conversion of the laser pulses at 1550 nm into other near-infrared wavelengths, which are not covered by the available mode-locked lasers, could provide the desired light sources for all-wave-bands optical communication and near-infrared photonics and spectroscopy. Recently, we have preliminarily reported the intermodal FWM-based frequency conversion of femtosecond pulses at 1550 nm [26].

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In this paper, based on the previous work [26], the intermodal FWM effect is experimentally demonstrated in detail when femtosecond pulses centered at 1550 nm are launched into deeply normal dispersion region of the fundamental guided-mode of a tailor-made air-silica PCF with two ZDWs. The intermodal phase-matching condition is achieved between two pump photons at 1550 nm in the fundamental guided-mode, one anti-Stokes photon around 1258 nm and one Stokes photon around 2018 nm both in the second-order guided-mode. The related nonlinear optical process is analyzed. In addition, the influences of the PCF bending and intermodal walk-off effect are also considered.

II. PCF Properties and Experiment

The air-silica PCF is designed and fabricated from the silica material, which is highly purified by the combined method of rectification and adsorption [27]. Inset 1 of Fig. 1 shows the cross-sectional structure of the PCF. The air holes in the cladding region are arranged in a hexagonal lattice. The core diameter is 2.1 μm, and the relative air hole diameter is 0.86. Fig. 1 shows the group-velocity dispersion curves calculated for the fundamental (1st) and second-order (2nd) guided-modes of the PCF. As seen from Fig. 1, both the dispersion curves are convex within the anomalous dispersion regions. Moreover, for the 1st and 2nd guided-modes of the PCF, the two ZDWs are respectively located at wavelengths of 761 and 1328 nm, and 727 and 1420 nm.

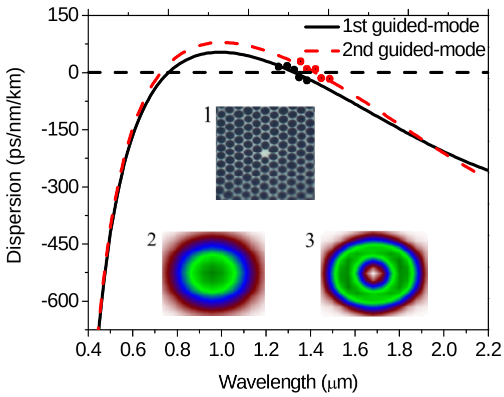


Fig. 1. The calculated group-velocity dispersion curves of the fundamental (1st) (the black-solid curve) and second-order (2nd) (the red-dashed curve) guided-modes of the PCF. The black and red solid dots respectively show the dispersion values of the 1st and 2nd guided-modes measured with the pulse time-delay method. Inset 1 shows the cross-sectional structure of the PCF used. The spatial guided-mode shapes of the 1st and 2nd guided-modes calculated at 1550 and 1258 nm are shown in the insets 2 and 3, respectively.

Fig. 1 shows the dispersion values of the 1st (black solid dots) and 2nd (red solid dots) guided-modes measured with the pulse time-delay method. From Fig. 1, the measured dispersion values are consistent with the results from calculation. For the 1st guided-mode, the nonlinear coefficient γ calculated at wavelength of 1550 nm is up to 0.052 $W^{-1}m^{-1}$. Insets 2 and 3 of Fig. 1 show the corresponding spatial 1st and 2nd guided-mode shapes, which are calculated at wavelengths of 1550 and 1258 nm, respectively. When femtosecond pulses centered at 1550 nm are used as the pump in the experiment, they work in the normal dispersion region far away from the second ZDWs of the considered two guided-modes, and the ZDWs-independent intermodal FWM process between the two guided-modes considered could occur.

The experimental set-up is shown in Fig. 2. The PCF used is pumped with a fiber femtosecond laser at center wavelength of 1550 nm with <200 fs pulse duration, >10 kW peak power, and 50 MHz repetition rate. We used a grating-based compressor in order to introduce the initial positive-chirp, which can broaden the pump pulses to ~370 fs. As the pump pulses are broadened, the peak power reduces rapidly. Thus, the contribution of nonlinearity on the intermodal phase-matching condition could be neglected. After the pump pulses are broadened, they are coupled into the PCF under test by the combination of an optical collimator and a 40× objective with the numerical aperture of 0.65. The coupling efficiency can be up to 63%. In the beginning, the pump beam is launched close to the central axis of the PCF core by adjusting the distance between the microscope objective and the input tip of the fiber (the offset pumping technique [28], [29]). At this time, the 1st guided-mode can be selectively excited. By the cut-back method, the measured propagation loss of the PCF is ~0.74 dB/m at 1550 nm. The output optical spectra from the PCF which is collected by another 40× microscope objective, is coupled into a span of 1 m long large-mode-area fiber with a propagation loss lower than 0.5 dB/km at 1550 nm, and then fed to an optical spectrum analyzer (OSA, Avaspec-NIR-256). Such a short fiber length has negligible effect on the output powers of all optical waves observed.

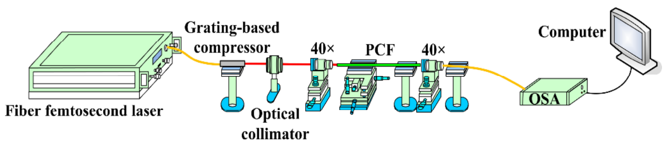
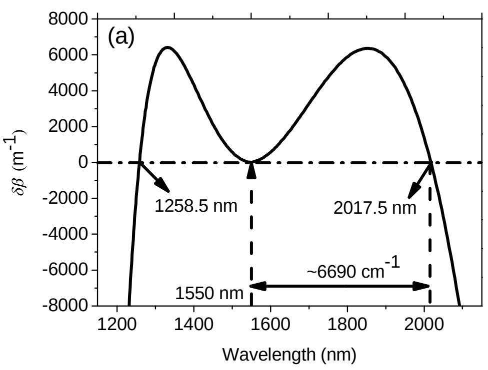


Fig. 2. The experimental set-up.

III. Results and Discussion

In order to achieve intermodal FWM, the intermodal phase-matching condition between the two pump photons in the 1st guided-mode, an anti-Stokes photon in the 2nd guided-mode, and a Stokes photon also in the 2nd guided-mode must be satisfied [17], [20], [21], [24], [25]. Thus, the intermodal phase-mismatching parameter $\delta\beta$ should equal to zero, i.e., $\delta\beta=2\beta_{01}(\omega_p)-\beta_{02}(\omega_{as})-\beta_{02}(\omega_s)=0$, where $\beta_{01}(\omega_p)$, $\beta_{02}(\omega_{as})$, and $\beta_{02}(\omega_s)$ are the propagation constants at the optical frequency ω_p, $\omega_{as}=\omega_p+\Omega$, and $\omega_s=\omega_p-\Omega$ of the considered pump wave, anti-Stokes wave, and Stokes wave, respectively, and Ω corresponds to the Stokes frequency shift. The subscripts 01 and 02 represent the 1st and 2nd guided-modes considered, respectively. In the calculation, $\delta\beta$ can be obtained from the propagation constants of the three optical waves involved, and the corresponding propagation constants can be calculated from the effective refractive indices of the 1st and 2nd guided-modes, which can be derived from group-velocity dispersions of the two guided-modes shown in Fig. 1. In addition, we note that the nonlinear contribution to the phase-matching condition in intermodal FWM can be neglected if the pump peak power is low [18], [24], [25]. In this work, we broaden the initial pump pulses from <200 fs to ~370 fs by introducing a positive chirp. Thus, it is not necessary to include the contribution of nonlinearity to $\delta\beta$.

When femtosecond pulses at center wavelength of 1550 nm and input average power P_{av}=30 mW are launched into the deeply normal dispersion region above the second ZDW of the 1st guided-mode of the PCF used, the calculated $\delta\beta$ reaches zero at the near-infrared and mid-infrared wavelengths of 1258.5 and 2017.5 nm, respectively, as shown in Fig. 3(a), corresponding to Ω of ~6690 cm^{-1}. Fig. 3(b) shows the output optical spectra from three spans of PCFs with lengths 42, 32, and 22 cm, respectively, which are recorded by the OSA. From Fig. 3(b), the initial pump spectra are broadened by the normal dispersion and self-phase modulation (SPM) effect, and part of the pump powers is converted by the intermodal FWM process to the anti-Stokes and Stokes waves centered at wavelengths of 1258 and 2018 nm during propagation along the longitudinal direction of the PCF. The experimental results are consistent with the calculation results given in Fig. 3(a). Moreover, we observed that as the lengths of the PCF are respectively reduced from 42, to 32, and to 22 cm by the cut-back method, the output powers of the generated anti-Stokes and weaker Stokes waves are gradually enhanced. The increases of the output powers of the anti-Stokes and Stokes waves as the PCF lengths are reduced are mainly due to the wavelength-dependent propagation loss which decreases when the fiber length decreases. Therefore, the fiber length should be appropriately chosen in order to maximize the output powers of the anti-Stokes and Stokes waves. Although shorter fiber length reduces the propagation losses and might further improve the output powers of the anti-Stokes and Stokes waves, the fiber length cannot be too short because of measurement limitation in the experiment. The 22 cm length of the PCF is the shortest length used in the experiments. Insets 1 and 2 of Fig. 3(b) show the evidently different far-field guided-mode shapes at the wavelengths of the residual pump and anti-Stokes wave, which are observed from a span of 22 cm long PCF using a black-and-white CCD camera. Thus, the residual pump and anti-Stokes wave are propagated in the 1st and 2nd guided-modes of the PCF, respectively, agreeing well with the calculation results shown in the insets 2 and 3 of Fig. 1.



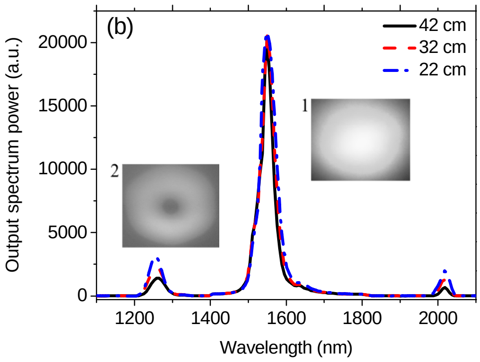
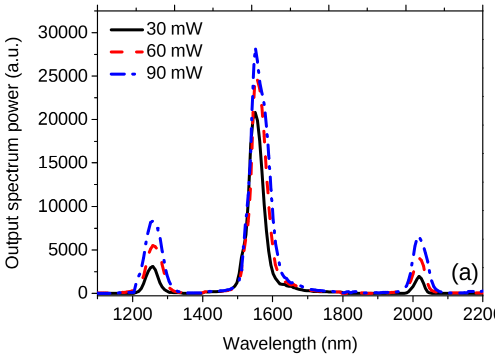


Fig. 3. (a) The phase-mismatching parameter $\delta\beta$ calculated for femtosecond pulses at center wavelength of 1550 nm and input average power P_{av}=30 mW, $\delta\beta$=0 at wavelengths of 1258.5 and 2017.5 nm, corresponding to the Stokes frequency shift of ~6690 cm^{-1}. (b) The output spectra measured for PCF lengths of 42 cm (the black-solid curve), 32 cm (the red-dashed curve), and 22 cm (the blue-dashed-dot curve), respectively, under the same pump condition. The output far-field shapes of the residual pump and anti-Stokes wave for the PCF length of 22 cm, which are recorded by a black-and-white CCD camera, are shown in the insets 1 and 2, respectively.

Fig. 4(a) shows the observed output spectra when femtosecond pulses at 1550 nm and P_{av}=30, 60, and 90 mW are propagated inside a span of 22 cm long PCF. As P_{av} increases from 30, to 60, and to 90 mW, respectively, we note that the output powers of the generated anti-Stokes and Stokes waves are constantly increased, but the anti-Stokes and Stokes wavelengths λ_{as} and λ_s at 1258 and 2018 nm are extremely insensitive to the variation of P_{av}. The insensitive property of λ_{as} and λ_s to the variation of P_{av} is also seen from Fig. 4(b), and attributed to the negligible nonlinearity contribution on $\delta\beta$. Such a property is beneficial in obtaining the stable-wavelength signals by a pump laser source that suffers from the fluctuation of the output power. Moreover, the anti-Stokes and Stokes waves, which are generated in the anomalous and normal dispersion regions of the second-order guided-mode, undergo the spectral broadening because of soliton dynamic and the combined influence of the dispersive and SPM effects.



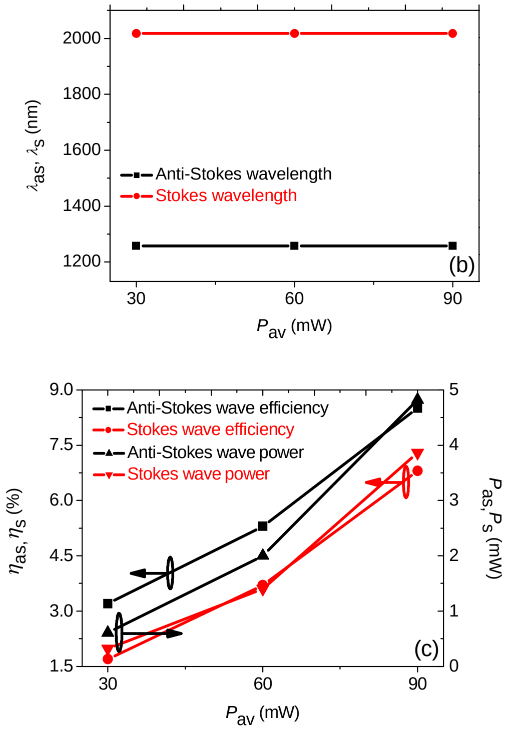


Fig. 4. (a) The output spectra measured when femtosecond pulses at center wavelength of 1550 nm and input average power P_{av}=30 mW (the black-solid curve), 60 mW (the red-dashed curve), and 90 mW (the blue-dashed-dot curve), respectively, are propagated into a span of 22 cm long PCF. (b) The dependences of the generated anti-Stokes and Stokes wavelengths λ_{as}(black solid squares) and λ_s (red solid circles) on P_{av}. (c) The dependences of the generated anti-Stokes and Stokes wave conversion efficiency η_{as} (black solid squares), η_s (red solid circulars), and power P_{as} (black solid up-triangles), P_s (red solid down-triangles), on P_{av}.

At the output end of the PCF, the output powers of the anti-Stokes and Stokes waves generated can be measured with the combination of optical filters at different wavelengths and an optical powermeter. Fig. 4(c) shows the dependences of the anti-Stokes and Stokes wave power P_{as} and P_s and the corresponding conversion efficiency η_{as} and η_s, which are defined as the power ratio of spectrally-isolated anti-Stokes and Stokes waves and the incident pump, on P_{av}. Taking the pump coupling efficiency of 63% into account, P_{as} is measured to be 0.61, 2, and 4.82 mW, and P_s to be 0.32, 1.4, and 3.86 mW for P_{av}=30, 60, and 90 mW, respectively. The corresponding η_{as} are increased from 3.2, to 5.3, and to 8.5%, and η_s are from 1.7, to 3.7, and to 6.8%, respectively. Thus, the anti-Stokes and Stokes waves are efficiently generated through the intermodal FWM process. The theoretical calculation result of η_{as} is 11.3% for the PCF length of 22 cm and P_{av}=90 mW when the pump depletion, a constant nonlinearity coefficient, and no loss are considered [5], [6], [30]. The difference from the experimental result (8.5%) could be resulted from the intrinsic absorption loss of the silica material, coupling loss of the second-order guided-mode to other higher-order guided-modes, and leaky and scattering losses, which could be mainly induced by the large PCF core-cladding index contrast and the PCF geometric structure fluctuation along the propagation direction. Certainly, when we consider a very short piece of preform for only 22 cm long PCF during the fabrication, the influence of the PCF non-uniformity could be neglected. In future work, by optimizing the parameters of the PCF geometric structure and the pump pulses, it is believed that the conversion efficiency of the intermodal FWM-based nonlinear process can be significantly enhanced.

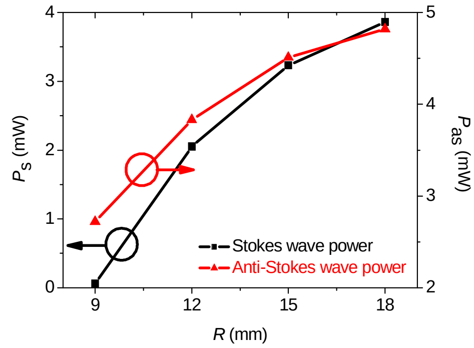


Fig. 5. The measured dependences of the generated Stokes and anti-Stokes wave power P_s (black solid squares) and P_{as} (red solid triangles) on the PCF bending radius R at the entrance end changed from 18, to 15, to 12, and to 9 mm for femtosecond pulses at 1550 nm with average input power P_{av}=90 mW propagation in a span of 22 cm long PCF.

Because the PCF used in the experiment has a large relative hole diameter in the cladding region, the leaky loss of the spontaneously established Stokes waves, which propagate in the second-order guided-mode and play a crucial role in the unseeded FWM, is greatly reduced if the PCF is bent. Thus, the energy conversion process based on the intermodal FWM effect is expected to be insensitive to the PCF bending at the entrance end. Fig. 5 shows that for femtosecond pulses at 1550 nm with P_{av}=90 mW, P_s is reduced from 3.86, to 3.23, to 2.05, and to 0.06 mW, and P_{as} is reduced from 4.82, to 4.51, to 3.83, and to 2.72 mW, respectively, when the bending radius of the PCF R is changed from 18, to 15, to 12, and to 9 mm, respectively. The variation rates of P_s and P_{as} with R are 0.422 and 0.233 mW/mm, respectively. Compared to the results reported in Ref [25], where the corresponding variation rates for the Stokes wave around 1445 nm and the anti-Stokes wave around 553 nm are 0.247 and 0.13 mW/mm, respectively, the influence of the PCF bending in this work can be completely acceptable especially when considering the Stokes and anti-Stokes waves located around the longer wavelengths of 2018 and 1258 nm.

Next, we considered the intermodal walk-off effects between the 1st and 2nd guided-modes of the PCF used [23]-[25]. The intermodal walk-off factor D_{12} can be written as $D_{12}=1/v_g^{(1)}(\lambda)-1/v_g^{(2)}(\lambda)$, where $v_g^{(1)}(\lambda)$ and $v_g^{(2)}(\lambda)$ correspond to the group-velocities of the 1st and 2nd guided-modes, respectively. The calculated D_{12} is shown in Fig. 6. It can be seen from Fig. 6 that D_{12} at the pump wavelength of 1550 nm is ~5.08×10^{-2} ps/mm. Moreover, the initial positive-chirp, which is introduced to the incident pump pulses by the grating-based compressor, broadens evidently the pump pulses from <200 fs to ~370 fs. Therefore, the intermodal walk-off effects are effectively suppressed, and noticeable intermodal FWM-based frequency conversion process can be achieved in a longer walk-off length in which all involved optical waves are well co-propagated.

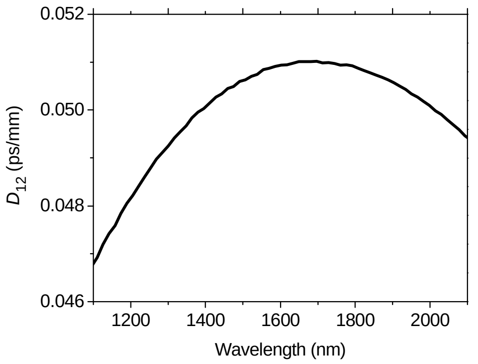


Fig. 6. The calculated intermodal walk-off factor D_{12} between the 1st and 2nd guided-modes of the PCF.

IV. Conclusion

In summary, we demonstrated experimentally intermodal FWM effect by launching femtosecond pulses at 1550 nm into deeply normal dispersion region of the 1st guided-mode of an air-silica PCF with two ZDWs. By the intermodal phase-matching condition, the anti-Stokes and Stokes waves both in the second-order guided-mode are efficiently generated. In addition, the influences of the PCF bending and intermodal walk-off on intermodal FWM are confirmed to be very small. The results will provide an effective way to achieve effective PCF-based frequency conversion from the pump wavelength at 1550 nm to wavelengths that cannot be achieved by existing mode-locked lasers.

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