Experimental demonstration of intermodal four-wave mixing by femtosecond pump pulses at 1550 nm

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Abstract: Intermodal four-wave mixing is experimentally demonstrated by coupling femtosecond pulses at 1550 nm deep into normal dispersion region away from the second zero-dispersion wavelengths of the first two guided-modes of a homemade photonic crystal fiber.

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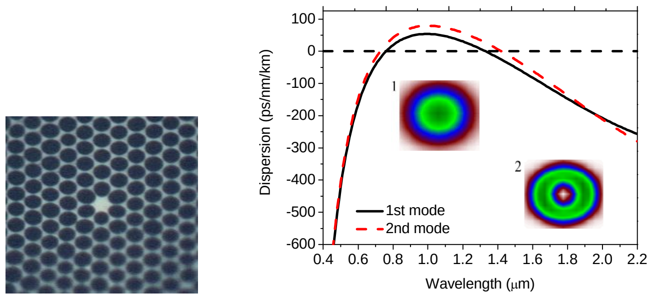
1. Introduction

Four-wave mixing (FWM) leads to energy coupling between optical waves at different frequencies and guided-modes. Since its first experimental observation in a multimode optical fiber [1], the intermodal FWM effect has been studied in higher-order guided-mode optical fibers [2, 3] and photonic crystal fibers (PCFs) [4, 5] for pump pulse sources operating at visible and near-infrared wavelengths of 532, 800, and 1064 nm. Here, we utilize intermodal FWM to convert the energy from the pump waves to wavelengths at which no mode-locked lasers is available when the phase-matching condition for intramodal FWM is not satisfied. We experimentally demonstrated intermodal FWM by launching femtosecond pump pulses at 1550 nm deep into the normal dispersion region away from the second zero-dispersion wavelengths in the fundamental and second-order guided-modes of a homemade PCF.

2. PCF properties and experiment

Fig. 1(a) shows that the PCF fabricated from the silica material has a core diameter of 2.1 μm and the relative air hole diameter of 0.86. Fig. 1(b) shows the group-velocity dispersion profiles of the fundamental (1st) and second-order (2nd) guided-modes. From Fig. 1(b), the two zero-dispersion wavelengths (ZDWs) of the 1st and 2nd guided-modes are located at 761 and 1328 nm, and 727 and 1420 nm, respectively. The calculated nonlinear coefficient γ of the 1st guided-mode at 1550 nm is 0.052 $W^{-1}m^{-1}$. Insets 1 and 2 show the spatial guided-mode patterns of the 1st and 2nd guided-modes calculated at 1550 and 1258 nm, respectively. Thus, for the femtosecond pump pulses at 1550 nm, the PCF is pumped deep in the normal dispersion region away from the second ZDWs of the 1st and 2nd guided-modes considered.



(a) (b)

Fig. 1. (a) The cross-section of the PCF, and (b) the group-velocity dispersion profiles calculated for the fundamental (1st) and second-order (2nd) guided-modes. Insets 1 and 2 show the spatial guided-mode patterns of 1st and 2nd guided-modes calculated at wavelengths of 1550 and 1258 nm, respectively.

In the experiment, the PCF is pumped with a fiber femtosecond laser at 1550 nm with pulsewidth <200 fs, peak power >10 kW, and repetition rate at 50 MHz. A grating-based compressor is used to introduce a positive chirp, and the initial pump pulses are broadened to ~370 fs. The pump light is coupled into a 22 cm-long PCF by an optical collimator and a 40× microscope objective. The free-space coupling efficiency is up to 63%. The fundamental guided-mode is excited with the offset pumping technique. By the cut-back method, the propagation loss measured at 1550 nm is about 0.74 dB/m.

3. Results and discussion

Fig. 2(a) shows the calculated intermodal phase-mismatching parameter $\delta\beta$ without considering the nonlinear contribution [4, 5]. When femtosecond pump pulses at 1550 nm and input average power P_{av}=30, 60, and 90 mW are launched deep into the normal dispersion region beyond the second ZDWs of the 1st and 2nd guided-modes of the PCF, $\delta\beta$ equals to zero at the near-infrared wavelengths of 1258.5 and 2017.5 nm. Fig. 2(b) shows the observed output spectra. As P_{av} are increased from 30, to 60, and to 90 mW, the output powers of the anti-Stokes and Stokes waves generated are gradually increased, but the wavelengths centered at 1258 and 2018 nm are insensitive to the variation in P_{av}. Such property will be useful to obtain stable output from a laser pump source that suffers from output power fluctuation. Insets 1 and 2 of Fig. 2(b) show the far-field guided-mode patterns at the residual pump and anti-Stokes wavelengths for P_{av}=30 mW, which agree well with those shown in the insets 1 and 2 of Fig. 1(b).

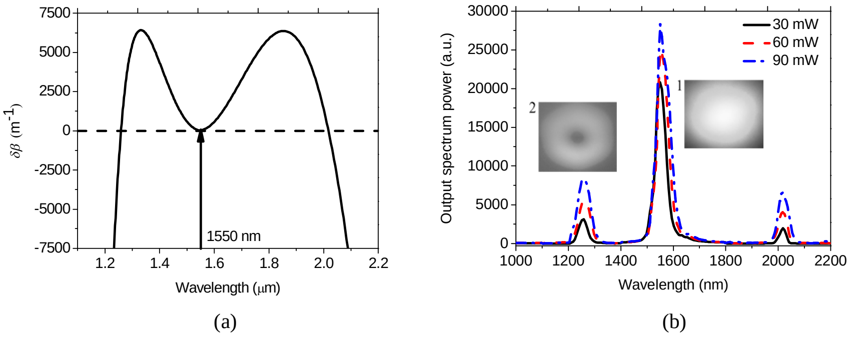


Fig. 2 (a) The calculated phase-mismatching parameter $\delta\beta$ for the pump pulses at 1550 nm and the input average power P_{av}=30, 60, and 90 mW. (b) The measured output spectra when the pump pulses are launched into a span of 22 cm-long PCF. Insets 1 and 2 show the output far-field distributions of the residual pump and anti-Stokes wave for P_{av}=30 mW recorded by a black-and-white CCD camera.

In the following, we study the effect of bending loss. Fig. 3 shows that for femtosecond pump pulses at 1550 nm and at P_{av}=90 mW, the measured P_{as} is reduced from 4.82, to 4.51, to 3.83, to 2.72, and to 0.56 mW, and P_s is reduced from 3.86, to 3.23, to 2.05, to 0.06, and to 0 mW, respectively, when the PCF bending radius R at the entrance end changes from 18, to 15, to 12, to 9, and to 6 mm. The rates of variation of P_{as} and P_s with R are only 0.355 and 0.422 mW/mm, respectively. Therefore, the energy conversion process based on the intermodal FWM effect is insensitive to PCF bending.

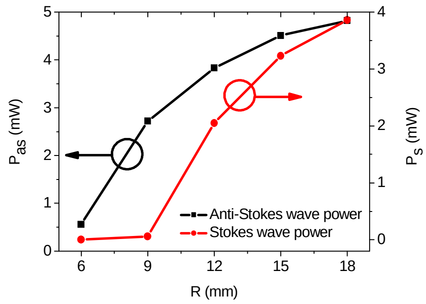


Fig. 3. The dependences of the generated anti-Stokes and Stokes wave power P_{as} (black solid-square line) and P_s (red solid-circular line) on the PCF bending radius R when femtosecond pump pulses with center wavelength 1550 nm and average input power P_{av}=90 mW are propagated inside a 22 cm-long PCF.

4. Conclusion

In summary, the intermodal FWM is experimentally demonstrated by launching femtosecond pulses at 1550 nm in a PCF with two ZDWs. We demonstrated that the intermodal FWM process is insensitive to PCF bending.

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5. References

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