Highly efficient and widely wavelength-tunable anti-Stokes signal conversion in the fundamental mode of photonic crystal fiber

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Abstract: Anti-Stokes signals from 645 to 543nm are generated in the fundamental mode. The power ratio of signal at 543 nm to residual pump at 840 nm is 22.6:1, the conversion efficiency P_{as}/P_{p0} being above 45%.

OCIS codes: (060.5295) Photonic crystal fibers, (190.4370) Nonlinear optics, fibers.

1. Introduction

The development of photonic crystal fibers (PCFs) [1] has opened new horizons in nonlinear optics [2], offering new candidates to realize compact and efficient all optical nonlinear signal processing devices [3]. Unique dispersion and enhanced nonlinearity make PCFs an ideal candidate for nonlinear applications [4]. Since the first observation in PCFs [5], the four-wave mixing (FWM) and phase-matching for frequency conversion have been optimized in different ways. The short pulses are usually used to realize highly efficient frequency up-conversion due to high peak power and wide optical spectrum. Moreover, because of easier coupling and better output optical beam quality, the investigation on the anti-Stokes signal conversion of femtosecond pulses in fundamental mode of PCF is focused [6]. However, since the zero dispersion wavelength of the fundamental mode in general multimode PCFs often lies at longer wavelength region, it's difficult to achieve phase-matching condition using the regular short pulse source. Here, with the PCF with zero dispersion wavelength of fundamental mode around 848 nm, the phased-matched FWM processes of femtosecond pulses are shown by pumping at normal dispersion region. The anti-Stokes signals from 645 to 543 nm are efficiently generated, the power ratio of signal at 543 nm to the residual pump at 840 nm is 22.6:1, and the conversion efficiency P_{as}/P_{p0} can be above 45%.

2. The experimental results and discussion

Fig.1 shows the cross-section of PCF. By the following consideration: the phase matching condition can be approximately described by the expansion of $\beta(\omega)$ up to the fifth order around ω_p. The PCF is designed to achieve phase-matching at specific wavelength, the relative air-hole size d/Λ is 0.86, and the core diameter is 2.8 μm.

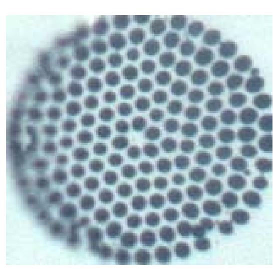

Fig.1. The cross-section of PCF used in experiment.

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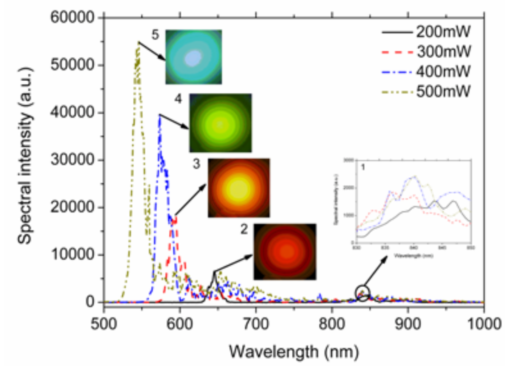
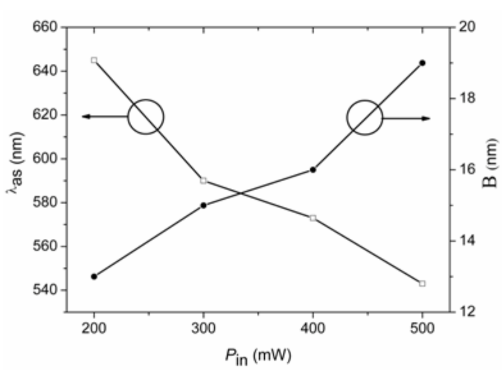
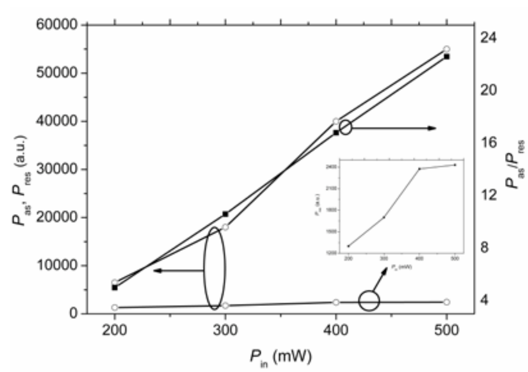
In experiment, the light source is a mode-locked Ti: sapphire laser with working wavelength 840 nm, emitting a pulse train with full width at half maximum (FWHM) of 120 fs at the repetition rate of 76 MHz. By changing the distance between the input tip of the fiber and the lens to exactly adjust the angle between the input beam and the fiber axis, the fundamental mode can be selectively excited. The light pulses are coupled into the PCF span of 50 cm length. The coupling efficiency can be above 50%. The transmission loss is measured to be 6.5 dB/m at 840 nm using the cut-back method.

The dependence of anti-stokes signals on wavelength is shown in Fig.2 (a), the insert 1 shows the residual pump components from 830 nm to 850 nm, and the inserts 2 to 4 show the output near fields corresponding to different anti-Stokes signals. Fig.2 (b) shows the relations between anti-Stokes signal central wavelengths (λ_{as}) and bandwidths (B) and input pump powers (P_{in}). The relations between output powers of anti-Stokes signals (P_{as}) and residual pumps (P_{res}), and the output power ratios of anti-Stokes signals and residual pumps (P_{as}/P_{res}) and input pump powers are shown in Fig.2 (c), the insert showing the residual pump powers at 840 nm.



(a)





(b) (c)

Fig.2. The output spectra with P_{in} increasing from 200 mW to 500 mW, the inset 1 and inset 2 to 5 showing the output spectra of residual pump components from 830 to 850 nm and the output near fields of different anti-Stokes signals (red, yellow, weak-green and deep-green light). (b) λ_{as} (square-solid-line) and B (circle-solid-line) as a function of P_{in}. (c) P_{as} (up-circle-solid-line), P_{res} (down-circle-solid-line), and P_{as}/P_{res} (square-solid-line) as a function of P_{in}, the inset showing the residual pump powers at 840 nm.

Because the working wavelength of femtosecond laser approaches to the zero dispersion wavelength of fundamental mode, the phase mismatch $\delta\beta=\beta(\omega_a)+\beta(\omega_s)-2\beta(\omega_p)+2\gamma P$ approaches zero, where a pump and a Stokes wave at frequency ω_p and ω_s produce a signal wave at $2\omega_p$-ω_s, and $\beta(\omega_p)$, $\beta(\omega_a)$ and $\beta(\omega_s)$ correspond to the propagation constants of pump, anti-Stokes, and Stokes signals. Thus, the FWM effect becomes more remarkable, and the anti-Stokes signals are efficiently generated within the wavelength range of 645 to 543 nm, as shown in Fig.2 (a). Moreover, the signal qualities are better (as shown in inserts 2 to 5), and the output signal interference can be depressed due to lower residual pump components (as shown in insert 1) and no emergence of multi-peak structures and other trivial components along with anti-Stokes signals. In Fig.2 (b), the output λ_{as} and B change evidently with P_{in} varying whereas nearly inverse changing trends. The larger changing slopes indicate that higher wavelength-tunable sensitivity and larger signal bandwidth have been achieved. As seen from Fig.2 (c), the P_{as} increase 8.46 times with P_{in} changing from 200 to 500 mW, and the maximal output power ratio of P_{as} at 543 nm and P_{res} at 840 nm is about 22.6:1. The anti-Stokes radiation is above 85 % of the total power, calculated from the Manley-Rowe relations of photon conservation.

Based on Refs [7], considering the depletion of pump, a constant value for nonlinearity, a single effective overlap integral, and no loss, the maximum value of P_{as}/P_{p0} can be calculated. Using λ_p=840 nm, λ_{as}=543 nm, P_p=12 kW, n_2=3x10^{-20} m^2/W, A_{eff}=5 μm^2, L=50 cm and considering the phase-mismatching parameter $\delta\beta$=0, the maximal conversion efficiency of 48.5% is theoretically obtained, and the experimental result is above 45%. The discrepancy may arise from pulse walk-off between pump and anti-Stokes wave due to the wavelength separation when they propagate through the PCF, inducing the phase-matching deviations and mode overlap integrals, and coupling and scattering loss of fundamental mode due to much larger index contrast between the core and cladding regions. As in Ref [6], because of higher coupling efficiency and conversion efficiency in the experiment, the FWHM of initial pump pulse of 120 fs is broaden to about 560 fs due to dispersion and nonlinear effect, and the estimated FWHM of anti-Stokes signal pulse with pump working wavelength of 840 nm and power of 500 mW is 55 fs.

3. Conclusion

The highly efficient and widely wavelength-tunable anti-Stokes signal conversions by phase-matched four-wave mixing in fundamental mode of PCF are achieved by pumping at normal dispersion region. The influences of input pump powers on the conversion efficiency and wavelength-tunable range of signals are shown. High power and widely wavelength-tunable anti-Stokes signals find growing applications in ultrafast photonics.

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