Experimental generation of deep-ultraviolet second-harmonics in an air-silica photonic crystal fiber

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Abstract: We experimentally generate second-harmonics within deep-ultraviolet wavelength range of 334.5 to 306 nm. We combine four-wave mixing and surface nonlinearity polarization by coupling femtosecond pump pulses at ~800 nm into an air-silica photonic crystal fiber.

OCIS codes: (060.5295) Photonic crystal fibers; (190.2620) Harmonic generation and mixing

1. Introduction

Second-harmonic generations (SHGs) have been attracting much research interests because of important applications in basic and applied sciences [1]. In principle, SHGs in optical fibers are limited because silica glass is an amorphous material with inversion symmetry thus does not have the second-order nonlinearity. Effective methods to induce second-order nonlinearity in optical fibers such as surface nonlinearity polarization at the core-cladding interface of the optical fibers and photonic crystal fibers (PCFs) have been demonstrated [2, 3]. However, it is difficult to use surface nonlinearity polarization to directly generate the second-harmonics (SHs) at deep-ultraviolet (UV) spectral region using existing pump lasers. In the past few years, cascaded nonlinear optical effects in PCFs have been reported [4, 5]. It is observed that when the initial four-wave mixing (FWM) process could generate the secondary pump for the SHGs, it is possible to generate deep-UV SHs in the PCFs.

In this paper, we experimentally demonstrate for the first time deep-UV SHGs within the wavelength range of 334.5 to 306 nm. We combine degenerate FWM and surface nonlinearity polarization by coupling femtosecond pump pulses at ~800 nm into the normal dispersion region close to the zero-dispersion wavelength (ZDW) of the fundamental mode of an in-house fabricated air-silica PCF.

2. PCF properties and experiment

By the stack and draw technique, we fabricated the PCF from the purified silica material. The inset of Fig. 1 shows the cross-sectional structure of the PCF, where the core diameter (D) and relative air-hole size (d/Λ) in the cladding region are 2.91 μm and 0.85, respectively. Fig. 1 shows the calculated group-velocity dispersion curve of the fundamental mode, where the ZDW is located at 849 nm. When femtosecond pump pulses at ~800 nm are used, the PCF used is pumped in the normal dispersion region shorter than the ZDW of the PCF.

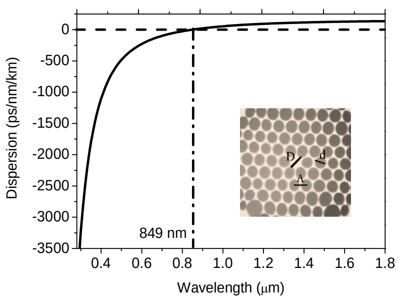

Fig. 1. The calculated dispersion curve of the fundamental mode of the PCF. The ZDW is 849 nm. The inset shows the cross-sectional structure of the PCF used.

In the experiment, a mode-locked Ti:sapphire laser with tunable operating wavelengths from 780 to 900 nm and pulse width of 120 fs is used as the pump source. The pump pulses are coupled by a 40× objective into a span of 30 cm long PCF, and the free-space coupling efficiency is 65%. The output optical spectra are measured by the optical spectrum analyzer (OSA) with a measurement range of 200 to 1100 nm. Several optical filters are inserted before the OSA, to reduce the powers of the residual pump, anti-Stokes wave, and Stokes wave generated so as to prevent damage to the OSA.

3. Results and discussion

The degenerate FWM process can efficiently transfer energy from the pump wave to the anti-Stokes and Stokes waves when the matching conditions of the frequencies and the wave-vectors are satisfied. The phase-mismatch factor $\delta\kappa$ can be written as $\delta\kappa=2\beta(\omega_p)-\beta(\omega_{as})-\beta(\omega_s)-2\gamma P$, where $\beta(\omega_p)$, $\beta(\omega_{as})$, and $\beta(\omega_s)$ are the propagation constants of the pump, anti-Stokes wave, and Stokes wave at angular frequencies ω_p, ω_{as}, and ω_s, respectively. γ is the nonlinear coefficient, and P is the pump peak power. Significant FWM can occur only if $\delta\kappa=0$.

For femtosecond pump pulses with center wavelength λ_p of 810 nm and average input power P_{av} of 650 mW (peak power of 78 kW), the calculated $\delta\kappa$ reaches zero at wavelengths of 668.9 and 1026.2 nm, respectively, as show in Fig. 2(a). Under the same pump condition, Fig. 2(b) shows the output optical spectrum observed from the PCF. From Fig. 2(b), the anti-Stokes and Stokes waves are generated at wavelengths 669 and 1026.3 nm, respectively, which agree well with the calculation in Fig. 2(a). Moreover, the anti-Stokes wave generated at 669 nm serves as the secondary pump for SHG, and the second-harmonic (SH) is observed at 334.5 nm. Surface nonlinearity polarization is considered as the dominant mechanism for the SHG.

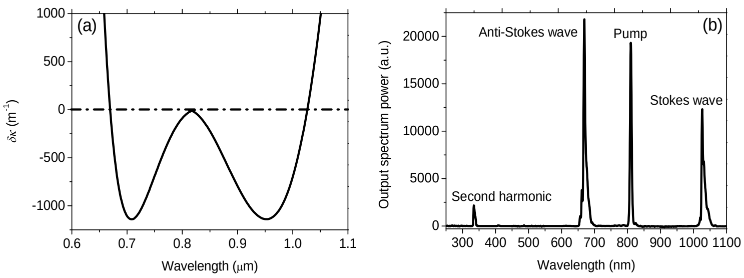

Fig. 2. (a) The calculated phase-mismatch factor $\delta\kappa$ and (b) the output optical spectrum observed from the PCF when femtosecond pump pulses with center wavelength λ_p of 810 nm and average input power P_{av} of 650 mW (peak power of 78 kW) are injected into the PCF.

Fig. 3 shows the observed output spectra of the SHs when λ_p of femtosecond pump pulses at P_{av} of 650 mW changes from 810, to 820, to 830, and to 840 nm, respectively. From Fig. 3, as λ_p gradually approaches the ZDW of the fundamental mode of the PCF, more pump energy is converted into the visible anti-Stokes waves, and the SHs generated at deep-UV wavelengths of 334.5, 328.5, 319, and 306 nm are gradually enhanced.

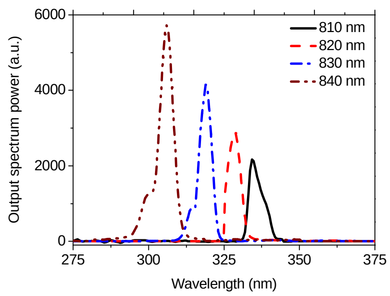

Fig. 3. The observed output spectra of deep-UV SHs from the PCF when femtosecond pump pulses with center wavelength λ_p of 810, 820, 830, and 840 nm and average input power P_{av} of 650 mW (peak power of 78 kW) are injected into the PCF.

4. Conclusion

In summary, the SHs within deep-UV wavelength range of 334.5 to 306 nm are generated experimentally. We combined degenerate FWM and surface nonlinearity polarization by coupling femtosecond pump pulses into an air-silica PCF. The SHs generated can find important applications in basic physics and applied science.

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5. References

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