Spectral Broadening in the 1.3 μm Region Using a 1.8-m-Long Photonic Crystal Fiber by Femtosecond Pulses from an Optical Parametric Amplifier*

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Abstract Supercontinuum with a spectral bandwidth of 700 nm (1.09 μm ~ 1.79 μm) was achieved in a 1.8-m-long photonic crystal fiber with an average core radius of 2.0 μm pumped by optical femtosecond pulses at the wavelength of 1.2759 μm, with the average power of 30 mW, the duration of 250 fs and the repetition rate of 250 kHz from an optical parametric amplifier. It was interpreted that the spectral broadening was due to the fission of higher-order solitons and four-wave mixing. The concave profile at the wavelength of about 1.4 μm was resulted from the OH absorption. The broadened spectra were applicable to a multi channel optical source with ultra-short pulsewidth for WDM communication and photonic network systems.

Keywords Photonic Crystal Fiber; Supercontinuum; Optical Parameter Amplifier

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0 Introduction

Photonic crystal fibers (PCFs) based on wavelengthscale microstructuring of fiber cladding are currently a topic of high interest because of their unusual optical properties and their large potential for important applications[1~3]. Since the first realization of a PCF[1], intense research has been conducted to determine the propagation mode characteristics[3] and dispersion characteristics as well as to reduce the propagation loss[2], and realize polarization maintaining characteristics and highly nonlinear characteristics. In a typical realization, a PCF has a central region of pure silica (core) surrounded by air holes. Light is guided by total internal reflection as in standard step-index fibers due to the refractive index difference between the core and the holey cladding. The large difference of the indices for μm-diameter core provides a very strong specifically controlled waveguide contribution to dispersion which leads to significant modification in the optical properties such as single-mode operation over a wide range of wavelengths[4], a shift of zero-dispersion wavelength into the visible region[1,5], and soliton propagation at optical frequencies[1,6]. In a different realization light can also be guided in a hollow core of a PCF due to the photonic band gap of the periodic photonic crystal cladding[7].

Up to now, most of the nonlinear optical experiments with microstructure fibers, including supercontinuum generation and high-precision measurements with femtosecond frequency combs, were performed with Ti:sapphire laser pulses. At the same time the extension of new concepts in ultrafast optics and optical metrology based on the use of PCFs to longer wavelengths seems to be quite promising for biomedical applications and high precision measurements. Supercontinuum (SC), produced by various nonlinear effects in optical fibers such as self-phase modulation (SPM), four-wave mixing (FWM), and cross-phase modulation (XPM), is an attractive technology for providing an economical method to generate ultrashort pulses over a wide spectral range[8]. Recently, SC has been successfully applied in high-speed wavelength-division multiplexing (WDM) and wavelength-division multiplexing over optical-time-division multiplexing (WDM/OTDM) systems[9].

Supercontinuum was generated in a 1.8 m-long PCF in the 1.3 μm region pumped by femtosecond pulses from an optical parametric amplifier system (OPA). The evolution of the pump spectrum into the PCF was studied. The spectral broadening from 1.09 μm to 1.79 μm was achieved.

1 The experimental setup

Fig. 1 shows the schematic diagram of the experimental setup. The optical parameter amplifier (Coherent OPA 9800) was pumped by the ultrashort pulses at 800 nm with the pulse duration of about 200 fs and the repetition rate of 250 kHz which was produced

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by a regeneratively amplified Ti : sapphire laser (Coherent RegA 9000 and Mira 900F). In the experiments, the signal output at the wavelength of 1.2759 μm was applied as the pump light. The laser pulses with the average power of 30 mW, the repetition rate of 250 kHz and the pulse duration of about 250 fs[10], generated by OPA, were focused into a 1.8 m-long PCF (Crystal Fiber A/S). For the focusing, a 25 × microscope objective with a numerical aperture (N. A.) of 0.4 was used in the experiments. The numerical aperture was smaller than that of the PCF, so the pump power can be coupled efficiently into the PCF. The PCF was mounted on a six-dimension translation stage, which can be adjusted with high precision.

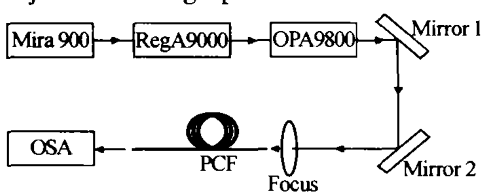

Fig. 1 The schematic diagram of the experimental setup

Fig. 2 shows the center micrograph of the PCF. The parameters, such as the average core size of 2.0 μm, the air hole pitch (Λ) in the cladding layer of 3.2 μm and the average pitch to hole size ratio of 0.9, were designed to achieve low dispersion and high nonlinearity. The zero dispersion wavelength (λ_{ZDW}) of the fiber was about 690 nm. A high average numerical aperture (N. A.) of 0.47 was obtained due to the large index step between the air hole cladding and the fiber core. Using approximately the area of the center core as the effective core area (A_{eff}) of the PCF[11~14], the nonlinear parameter γ ($\gamma = \frac{n_2 \omega}{c A_{eff}}$) of the PCF at the wavelength of 1.3 μm was calculated to be about 46 $W^{-1} km^{-1}$, Here the nonlinear refractive index of the PCF $n_2 = 2.6 \times 10^{-20}\ m^2/W$, the center angular frequency ω and the velocity of light in vacuum c were applied in the calculation.

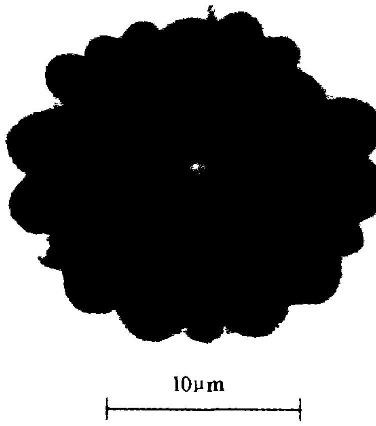

Fig. 2 The center micrograph of the PCF

2 Results and discussion

Supercontinuum generation was achieved by injecting 250 fs ultrashort optical pulses produced by OPA into the PCF. Figure 3a shows the OPA output spectrum with the average pump power of 30 mW and the corresponding energy of 120 nano-joules per pulse measured by the optical spectrum analyzer (OSA) (AV6361). Before injecting the PCF, the center wavelength and the full width of half maximum (FWHM) of the spectrum were measured to be 1.2759 μm and 34 nm, respectively. The pump wavelength lied in the anomalous dispersion region of the PCF.

Fig. 3b ~ d show the evolution of the spectral broadening at the output of the PCF when the focus was moved parallelly relative to the fiber axes. Compared Fig. 3b with 3a, it can be observed that the spectrum was broadened to be about 170 nm (1.187 ~ 1.357 μm) and there occurred a new and obvious red-shifted peak and as well the new blue-shifted frequency components, and the output power from the PCF was measured to be about 0.35 mW. It was attributed that the new red-shifted peak was corresponding to the Raman soliton resulted from the soliton self-frequency shift (SSFS). It was interpreted that due to the pump wavelength lied in the anomalous dispersion region of the PCF, the balance of GVD and self-phase modulation (SPM) led to the formation of solitons[15]. The intra-pulse Raman effect transferred energy to the long wavelength and contributed to the formation of the Raman soliton. At higher pump amplitudes, a higher-order soliton was formed. Because of the influence of third-order dispersion (TOD), the higher-order soliton split into fundamental red-shifted soliton and lost energy by emitting blue-shifted nonsolitonic radiation (NSR) whose phase matched to the corresponding soliton. So the fission of higher-order solitons[16] gave rise to the new red-shifted and blue-shifted frequencies, which together with the coinstantaneous effect of FWM led to the whole spectral broadening. It was explained that the input energy coupled into the PCF was changed by adjusting the relative position between the pump focus and the PCF. As the focus was moved further close to the crosssection of the PCF, the output power from the PCF was measured to be 0.67 mW. The broadened spectrum was shown in Fig. 3c. Both the red-shifted and blue-shifted components gradually shift further into the red and blue region respectively. There was one more red-shifted peak and more blue-shifted frequency components, and the whole spectrum was broadened to be over 280 nm

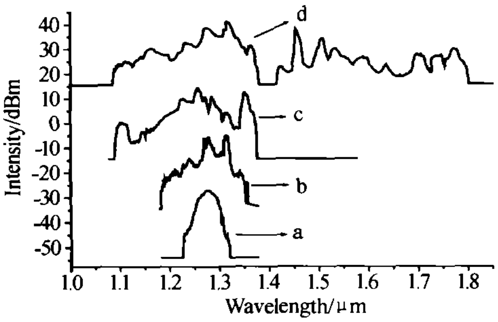

Fig. 3 The evolution of the spectral broadening with the average pump power of 30 mW and the energy of 120 nanojoules per pulse (the spectral curves were all scaled vertically for comparison)

(1.092-1.375 μm). It was noted that the abrupt drop of the spectrum in the longer wavelength was attributed to the OH absorption, which affect the further spectral broadening to longer wavelength.

By adjusting the relative position between the focus and the PCF at the end, the output power from the PCF was achieved to be about 1mW, there were new frequencies in the range of 1.42 ~ 1.79 μm, as shown in Fig. 3d, but in the longer wavelength it was beyond the spectral response range. The supercontinuum profile generated in the wavelength range from 1.09 μm to 1.375 μm became flatter and the flatness in this wavelength range was obtained to be about 15 dB, which was applicable to a multi channel optical source with ultra-short pulsewidth for WDM communication and photonic network systems. The broadened spectrum from 1.09 μm to 1.79 μm was achieved in a 1.8 m-long PCF, it was interpreted that the concave profile at the wavelength of about 1.4 μm was resulted from the OH absorption. The maximum total power of supercontinuum with the optimized coupling efficiency was measured to be about 3 mW with 30 mW pump power. With respect to the loss of the microscope objective, the conversion efficiency was calculated to be about 17%.

3 Conclusions

Efficient supercontinuum generation in the 1.3 μm region was achieved using a 1.8 m-long PCF pumped by 30 mW, 250 kHz, 250 fs optical pulses with center wavelength of 1.2759 μm produced by optical parameter amplifier. The broadened optical spectrum was obtained from 1.09 μm to 1.79 μm and to be about 700 nm. In the anomalous dispersion region of the PCF, the fission of higher-order solitons, together with the coinstantaneous effect of FWM led to the whole spectral broadening. The concave profile inside of the broadened spectrum, it was considered, was caused by the OH absorption.

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飞秒脉冲泵浦光子晶体光纤产生 1.3 μm 区域的光谱展宽

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摘 要 采用 OPA 产生的中心波长为 1.2759 μm、平均输出功率为 30 mW、重复频率为 250 kHz、脉冲宽度为 250 fs 的光脉冲作为泵浦源,研究了 PCF 输出光谱随泵浦焦点与光纤端面的相对移动的光谱演变. 在纤芯直径为 2.0 μm、长度为 1.8 m 的光子晶体光纤中获得了近 700 nm 的光谱展宽,展宽的光谱从 1.09 μm 到 1.79 μm,分析认为是高阶孤子的分裂和四波混频导致的光谱展宽,而在 1.4 μm 左右的光谱凹陷是由于光纤中 OH 离子的吸收造成的. PCF 输出的光谱可应用在 WDM 通信和光互连网的超短脉冲多通道光源中.

关键词 光子晶体光纤;超连续谱;光参量放大器

Yu Yongqin was born in Jan. 1976 and received her Ph. D. degree in State Key Laboratory of Crystal Materials, Shandong University in July 2003. At present, she is working as a postdoctor in Shenzhen University. Her research interests include nonlinear optics in photonic crystal fibers and femtosecond laser micromachining.

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