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RESEARCH ARTICLE

High nonlinear photonic crystal fiber and its supercontinuum spectrum

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Abstract The high nonlinear photonic crystal fiber with pure silica core has been designed and fabricated, and the practical structure parameters of the fabricated fiber sample coincided precisely with the parameters we designed. The core diameter is 1.65 μm; the air hole diameter is 4.75 μm; the distance between the center of two holes is 5.35 μm; the zero dispersion wavelength of the fiber is 1120 nm; the dispersion at 800 nm is −88 ps·(nm·km)$^{-1}$; and the nonlinear coefficient of this photonic crystal fiber is 112 (W·km)$^{-1}$. The broadly spanning supercontinuum emission with a smooth spectrum stretching from 450 to 1400 nm was attained by the injection of 30 fs Ti:sapphire laser pulses into 2 m-long high linear photonic crystal fibers, with an energy up to 5 nJ at a pulse repetition rate of 100 MHz and a central wavelength of 800 nm.

Keywords photonic crystal fiber, nonlinear, fs laser, supercontinuum spectrum

1 Introduction

The nonlinear coefficient of common silica single mode optical fibers is 1.1 (W·km)$^{-1}$, but photonic crystal fibers (PCFs) could have an ultra-high nonlinear (HNL) coefficient as high as 245 (W·km)$^{-1}$ [1] because of the actions of air hole arrays along the optical fiber. Thus, the supercontinuum spectrum could be obtained by using high nonlinear photonic crystal fibers, even under the condition that second-order pumping power is lower than the launching power in common nonlinear optical fibers [2–4]. In photonic crystal fibers, it is possible to shift the zero dispersion wavelength of single mode fibers to a much shorter wavelength, for example, shifting from 670 to 880 nm [5,6]. However, it is impossible to move the zero dispersion wavelength of a silica step-index single-mode optical fiber to a wavelength shorter than 1290 nm. This special performance of small-core high-index contrast PCFs could be exploited to dramatic effect in supercontinuum generation with zero dispersion wavelengths in the range of the Ti:sapphire fs laser systems at 750–850 nm. It was reported that this single broadband light source, exploited with high nonlinear PCFs, could provide 1000 signal light sources for dense wavelength division multiplexing (DWDM) optical communication systems [7–9].

There is a bright future for high nonlinear PCFs, which will have wide applications in the fields of broadband light sources, optical coherence tomography, high-precision frequency measurement, dispersion testing, and biomedical treatment. [10–14].

In this article, the high nonlinear photonic crystal fiber was designed and fabricated, with its nonlinear coefficient at 112 (W·km)$^{-1}$ and a broadband and smooth spectrum from 450 to 1400 nm wavelength was obtained.

2 Fabrication of high nonlinear PCF and its properties

The relations among the nonlinear coefficient γ, nonlinear refractive index and effective area of optical fibers could be formulated in the following equation [15–19]:

$$\gamma = (2\pi/\lambda)(n_2/A_{\mathrm{eff}}), \tag{1}$$

where λ is the wavelength, n_2 is the nonlinear refractive index and A_{eff} is the effective area of optical fibers.

The nonlinear coefficient of optical fibers could be raised by two methods: one is by changing material components of optical fibers, the nonlinear refractive index n_2 could be increased; the other is through the

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reduction of the effective area of optical fibers A_{eff}, which will raise γ. The purpose could be reached by varying the waveguide structure of optical fibers. However, for common silica optical fibers, options to reduce their effective area and the refractive index of fiber core are limited.

Designing and fabricating small-core and high-index contrast photonic crystal fibers with the introduction of many air hole arrays is very flexible. The fraction of air hole in the optical fiber will decide the effective index of fiber cladding. At the same time, they also restrict the distribution of light wave fields in the optical fiber core. When the air filling fraction is very big, close to or above 95%, the light field is restricted and focused on the small core, so the nonlinear coefficient of optical fibers is raised significantly.

Finite-difference time-domain method was used to design a kind of high nonlinear photonic crystal fiber. The parameters of waveguide structure were as follows: the core diameter $2a$ was 1.55 μm; air hole diameter d was 4.65 μm; the pitch between the centers of two holes Λ was 5.35 μm; and the diameter of air hole domain was 33.60 μm. Its dispersion curve by simulation is shown in Fig. 1. The zero dispersion wavelength of the designed PCF was 1120 nm, and the dispersion at 800 nm was -88 ps·(nm·km)$^{-1}$. The photonic crystal fiber sample was fabricated and shown in Fig. 2. The structure parameters of practical photonic crystal products were as follows: the core diameter $2a$ was 1.65 μm; air hole diameter d was 4.75 μm; and the pitch between the centers of two holes Λ was 5.35 μm. The results showed that the practical structure parameters of the fabricated fiber sample coincided precisely with our design parameters. In addition, the nonlinear coefficient of this photonic crystal fiber was as high as 112 (W·km)$^{-1}$.

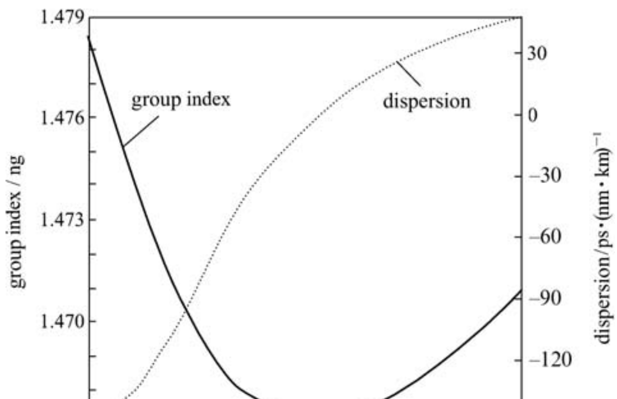

Fig. 1 Dispersion curve of high nonlinear PCF

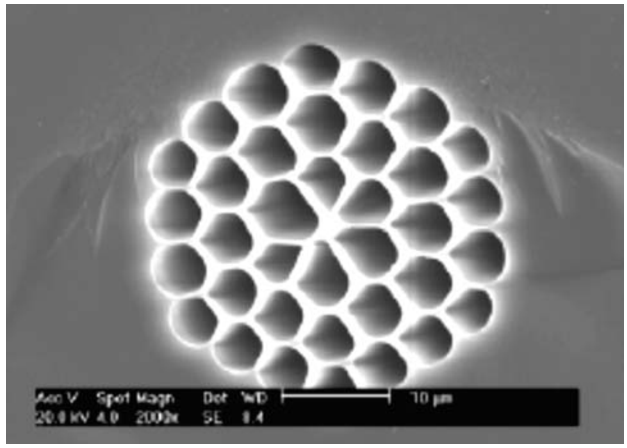

Fig. 2 SEM of high nonlinear PCF

3 Supercontinuum spectrum experiments of high PCF

In 1999, the supercontinuum spectrum in photonic crystal fiber was attained by Ranka et al. [20–22], and the generating mechanism of supercontinuum in PCFs was studied. However, until now, there are no consistent views. Most researchers thought that the nonlinear effect of self-phase modulation and four-wave mixing caused the spectrum [23–26]. When intensive laser pulse power acts on nonlinear media, several different frequencies interact and generate light of new frequencies [27–29]. The more intensive the interaction is, the broader the spectrum will be extended, so the broadband supercontinuum spectrum will be generated over a certain wavelength range.

When pump pulses are launched close to the zero-dispersion wavelength of the nonlinear photonic crystal fiber, the introduction of nonlinear PCFs lead to supercontinuum generation. In general, fiber dispersion plays a key role in short pulse propagation and in phase matching conditions for nonlinear processes. Although the zero dispersion wavelength of this PCF is 1120 nm, the fiber has a negative dispersion of -88 ps·(nm·km)$^{-1}$ at 800 nm, and it still has negative dispersion in the 580–900 nm region pumped with mode-locked Ti:sapphire lasers.

Figure 3 shows the setup of supercontinuum spectrum experiments with HNL PCF. The broadly spanning supercontinuum emission with a smooth spectrum stretching from 450 to 1400 nm was attained by the injection of 30 fs Ti:sapphire laser pulses into 2 m-long high linear photonic crystal fibers, with an energy up to 5 nJ at a pulse repetition rate of 100 MHz and a central wavelength of 800 nm. In addition, the visible light from purple to red could be seen in Fig. 4 [30].

When the injection peak power was 0.8 kW, the spectrum intensity was low, while the spectrum was

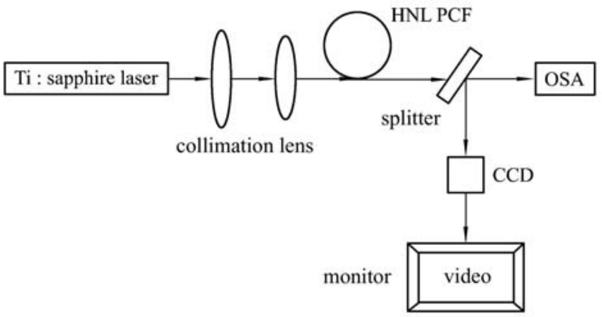

Fig. 3 Setup of supercontinuum spectrum experiments with HNL PCF

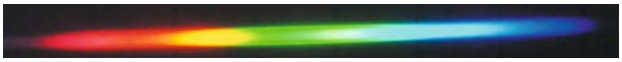

Fig. 4 Supercontinuum spectrum photo of HNL PCF

narrow and coarse as shown at the curve in Fig. 5. By further increasing the pulse peak power to 5 kW, the spectrum was promptly widened and covered the wavelength range from 400 to 1400 nm as shown in Fig. 5. However, the shift of 5 kW and the shift of 0.8 kW spectrum intensity was still low, and there was also an obvious dip at 1000 nm in the curve. While the injection pulse peak power was increased to 10 kW, the smooth features and spectrum intensity were greatly improved as shown in Fig. 5. Further research could later enable doping of germanium or other materials into fiber cores. The nonlinearity of the PCF will be significantly raised, and a much broader and smoother supercontinuum spectrum could be attained.

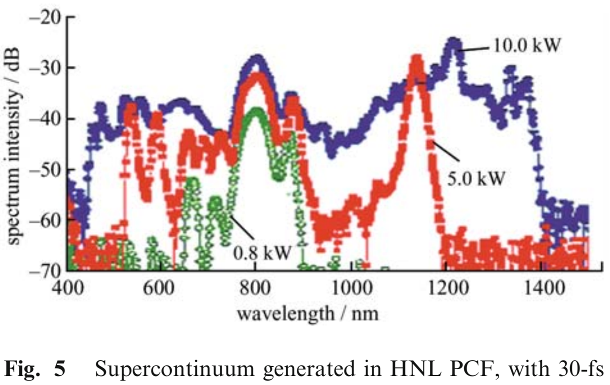

Fig. 5 Supercontinuum generated in HNL PCF, with 30-fs Ti:sapphire laser pulses at peak power

4 Conclusions

The high nonlinear photonic crystal fiber with pure silica core has been designed and fabricated, and the practical structure parameters of the fabricated fiber sample coincided precisely with the parameters designed. The core diameter is 1.65 μm; the air hole diameter is 4.75 μm; the distance between the center of two holes is 5.35 μm; the zero dispersion wavelength of the fiber is 1120 nm; the dispersion at 800 nm is -88 ps·(nm·km)$^{-1}$; and the nonlinear coefficient of this photonic crystal fiber is 112 (W·km)$^{-1}$. The broadly spanning supercontinuum emission with a smooth spectrum stretching from 450 to 1400 nm was attained by the injection of 30 fs Ti:sapphire laser pulses into 2 m-long high linear photonic crystal fibers, with an energy up to 5 nJ at a pulse repetition rate of 100 MHz and a central wavelength of 800 nm.

Supercontinuum sources are a novel type of light source that provide a combination of desirable features: high output power, broadband and flat spectrum, and a high degree of spatial coherence. In many fields such as the measurement of fibers, component attenuation, and spectroscopy, supercontinuum sources can often dramatically improve the signal-to-noise ratio, reduce measurement time and widen spectral range. The research result and successful fabrication of high nonlinear photonic crystal fibers in this article have established strong technical groundwork for homemade supercontinuum spectrum applications. Above all, this research will promote the development of more novel optoelectronic devices and upgrade relative industry in the future.

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