Supercontinuum generation with 15-fs pump pulses in microstructured fiber with combination core and random cladding

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We demonstrate the generation of supercontinuum (SC) of over 1350 nm by injecting 790-nm, 15-fs, 74-MHz optical pulses into a 183-mm-long microstructured fiber with combination core and random cladding. The maximum total power of SC is 73 mW with 290-mW pump power from 40× microscope objective. The wavelength and power ranging in SC as well as the polarization states and waveguide modes of the visible light can be tuned by adjusting the input end of MF. In particular, white light has been observed. To our knowledge, this is the first report of tunable properties in SC generation process using microstructured fiber with combination core and random cladding.

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For the past several years, supercontinuum (SC) generation in photonic crystal fiber (PCF), microstructured fiber (MF) and holey fiber (HF) by ultrashort-pulse propagation has become a subject of intense worldwide study[1-16]. SC has found applications in fields such as frequency metrology, optical coherence tomography, ultrashort pulse compression, spectroscopy of materials and photonic structures, and fiber characterization. The maximum spectra in the present authors' demonstrated SC span from 380 to 1600 nm, or from 550 to more than 1750 nm.

The numerical model described by T. M. Monro *et al.*[17] demonstrated that the holey fiber with randomly distributed air holes in cladding has many unusual features such as single-mode operation over a wide wavelength range and highly tailorable optical properties presented in periodical holey fiber. S. G. Li *et al.*[18] reported the SC generation in holey micorstructured fiber with random cladding distribution. Here, we report, to our knowledge, the first SC experiment using MF with combination core and random cladding.

SC spectra that span from 350 to more than 1700 nm are generated in experiment. The maximum total power of SC is 73 mW with 290 mW pump power from 40× microscope objective. The wavelength and power of visible light ranging in SC can be tuned by adjusting the input end of the MF (to change the pump incident point or incident angle). In particular, the generations of spatially single-mode and high-order mode white light SC have been observed in the tuning process. The polarization states and waveguide modes of the visible light change with adjustment of pump incident point or incident angle. To our knowledge, the tunable properties of wavelength and power, high-order waveguide modes and polarization in SC generation process with MF with combination core and random cladding are first reported. We attribute these special properties to the special structure of MF. These findings probably will play important role in study on the mechanism of SC generation. In addition, they could provide new idea to manufacture novel types of MF.

The experimental setup is shown in Fig. 1. In experiment, a piece of 183-mm-long MF with diameter of 0.78 mm is employed. The MF was fabricated at Infrared Optical Fibers and Sensors Institute, Yanshan University, and has the structure shown in Fig. 2. Air holes of different size and shape randomly distributed in cladding of MF. And the core of the fiber consist of three hexagonal sub-MF, so we call it combination core. The pump pulse source is a mode-locked Ti:sapphire laser (type: C20, from TEMTOSOURCE Laser, France) owned by Research Center of Laser Fusion, CAEP, which produces 15-fs (FWHM) horizontal linearly polarized pulses at a repetition rate of 74 MHz with an average power up to 380 mW. The light was coupled into the fiber by a microscope objective (40×, NA = 0.65 or 60×, NA = 0.85 or 100×, NA = 1.25). The transmissions of microscope objectives with 40×, 60× and 100× are 76.3%, 68.4% and 75.8%, respectively. The spectra of the generated SC are detected by S2000 and 86142B optical spectrum analyzers (produced by Ocean Optics Com., France and Agilent Technologies, USA, respectively). The wavelength

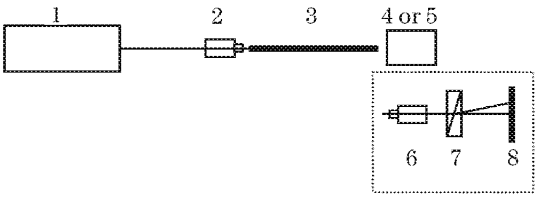

Fig. 1. Experimental setup of SC generation in MF with random cladding and combination core. 1: Mode-locked Ti:sapphire laser; 2, 6: microscope objective; 3: MF with random cladding and combination core; 4: optical spectrum analyzer; 5: optical power meter; 7: Rochon prism; 8: screen.

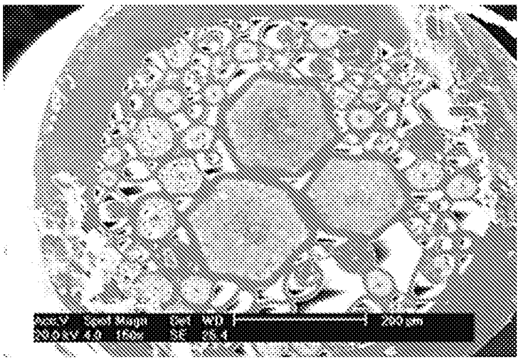

Fig. 2. Scanning electron micrograph of the cleaved end of MF with random cladding and combination core.

range of the S2000 optical spectrum analyzer is from 350 to 1300 nm. And the wavelength range of the 86142B is from 600 to 1700 nm. Optical power meter (model: DUO, produced by Gentec. EO, France) with probe of PS-310WB was used to measure power. And we judge the polarization of the SC using a Rochon prism. The output SC beam from MF was splitted up into two beams through the Rochon prism. Rotating the Rochon prism, we may judge the polarization of the SC by observing the change of brightness of the splitted beams.

For average power of 380 mW from the mode-locked Ti:sapphire laser, the power coupled into MF is smaller than 100 mW by 40×, 60× and 100× microscope objectives respectively in our experiment. So the increase of the intensity of the pump laser by exchanging of microscope objective can not expand the SC wavelength range obviously. Figure 3 shows the measured emission spectrum of MF. The total spectral distribution ranges from 350 to more than 1700 nm.

The fiber probe of S2000 optical spectrum analyzer detects the scattering from signal light, while the fiber probe of 86142B optical spectrum analyzer detects normal incidence portion of signal light. Due to parts of the SC waveguide-modes are high-order, both probes could detect only part of waveguide-modes SC, or have different detecting ratio for different wavelength SC. Therefore the real SC wavelength range of MF is more abundant than that shown in Fig. 3.

In experiment we can tune the output SC wavelength by adjusting the input end-surface of MF. Especially, we can obtain white light output. Figure 4 shows photographs of some waveguide mode profiles of visible light. The visible light has complicated near-field spatial pattern with adjustment of the input end-surface of MF. It indicates the presence of high-order waveguide-modes.

The output power of visible light also changes with adjustment of the input end-surface of MF. For example, when output is green light shown in Fig. 4(b), the total output power range from 42 to 73 mW under 290-mW pump power from 40× objective. The total output powers for various tuning processes are listed in Table 1.

Various polarization states for a certain wavelength visible light, such as linear polarization, circular polarization and elliptical polarization, are observed by adjusting input end-surface of MF when keeping fixed polarization direction of pumping laser. And the polarization direction of the linear polarization varied from 0° to 360° in the adjusting process. The polarization principal axis of elliptical polarization light also varied from 0° to 360°. Various polarization states of some typical lights are listed in Table 1.

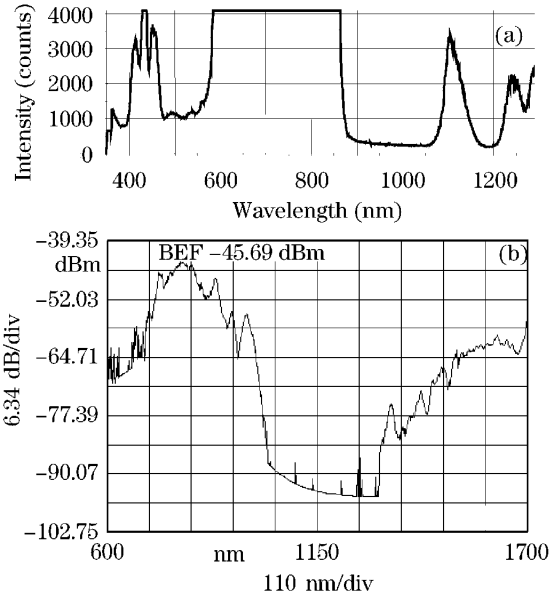

Fig. 3. SC genered in MF with random cladding and combination core. (a) Measured by S2000 model of optical spectrum analyzer, (b) measured by 86142B model of optical spectrum analyzer.

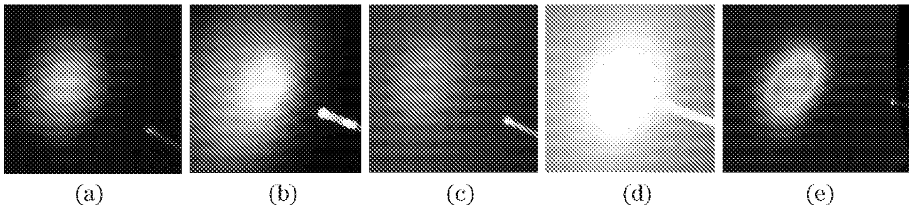

Fig. 4. Photographs of some waveguide mode profiles of visible light. (a) Red light, (b) green yellow light, (c) blue light, (d) white light, (e) blue light with violet light external ring.

Table 1. The Properties of SC Generated in MF with Random Cladding and Combination Core

				Polarization	
Light Color	Objective	Pump Power (mW)	Total Output Power (mW)	Polarization State	Polarization Direction (Relative to Horizontal)
Red	40×	290	68	Circular	
	60×	260	61	Circular	
			20	Linear	0°
	100×	288	21.4	Linear	Rotates 20° Anticlockwise
			20.6	Elliptical	Rotates 30° Clockwise
Green	40×	290	73	Circular	
			55	Linear	Rotates 45° Clockwise
			42	Elliptical	0°
	60×	260	34	Elliptical	Rotates 30 ° Clockwise
	100×	288	18.9	Elliptical	Rotates 30° Clockwise
			28	Elliptical	Rotates 20° Anticlockwise
			25	Linear	0°
Blue	40×	290	38	Circular	
	60×	260	36	Elliptical	0°
	100×	288	28	Elliptical	Rotates 45° Clockwise

Visible lights of certain wavelengths generated in experiment have various polarization states. And average total output power of SC changes greatly with the variation of the polarization states. So four-wave mixing plays important role in the visible light wavelength range of SC (locates in the normal dispersion region of MF). At different input position, the phase-mismatching degree of the four-wave mixing is different. The less the phase-mismatching degree is, the higher the outpower is.

The results of experimental studies are demonstrated as follow concludes: 1) These findings confirmed experimentally that periodicity is not needed for efficient SC generation in MF. 2) The SC wavelength tunable property in MF with combination core and random cladding may provide a new way to construct the optical parameter oscillator and the tunable laser. Moreover, the visible light of various wavelengths generated in MF with combination core and random cladding provides a novel light source used in laser color display. 3) The wavelength tunable, output power changeable and polarization properties of SC generated in MF with combination core and random cladding can be used to study the mechanism of SC generation.

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