Supercontinuum Generation with 15-fs Pump Pulses in a Microstructured Fibre with Random Cladding and Core Distributions*

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(Received 27 August 2003)

A supercontinuum extending from 350 nm to more than 1700 nm is generated in microstructured fibre (MF) with randomly distributed air holes in cladding and core by using 15-fs pulses of a 790-nm laser. The maximum total power of the supercontinuum is 63 mW with 288 mW pump power from a 100× microscope objective. The wavelength and power of visible light ranging in the supercontinuum can be tuned by adjusting the input end of random the MF (to change pump incident point or incident angle). In particular, white light has been observed. The polarization states and waveguide modes of the visible light change with adjustment of the pump incident point or incident angle.

PACS: 81. 40. Tv, 42. 65. Re, 42. 65. Ky, 42. 60. Jf, 42. 72. Bj, 42. 72. Ai

Supercontinuum (SC) generation is a complex nonlinear phenomenon that is characterized by the dramatic spectral broadening of intense light pulses passing through a nonlinear material.[1,2] SC is an ideal source for applications such as frequency metrology,[3−7] femtosecond-pulse phase stabilization,[3,8−11] optical coherence tomography,[12,13] ultrashort pulse compression, spectroscopy of materials and photonic structures, and fibre characterization. Spectral slicing of SC laser sources has also been proposed as a simple way to create multiwavelength optical sources.[1,14] This concept is potentially useful for dense wavelength-division-multiplexing (WDM) telecommunications, as illustrated by the recent demonstration of the generation of more than 1000 WDM channels from a single laser source.[15] Recently, photonic crystal fibre (PCF), microstructured fibre (MF) and holey fibre (HF) have been used to generate SC.[8,16−25] The maximum spectra in the present study demonstrated that SC spans from 380 nm to 1600 nm, or from 550 nm to more than 1750 nm.

The numerical model described by Monro *et al.* demonstrated that the holey fibre 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 fibre.[26] Li *et al.* reported the SC generation in a holey microstructured fibre with random cladding distribution.[27] In this Letter, we report, for the first time to our knowledge, the SC experiment using a microstructured fibre with randomly distributed air holes in both the cladding and the core. In our experiment, we used a mode-locked Ti:sapphire laser (Model: TEMTOSOURCE, Type: C20, France) operated at wavelength 790 nm with 15-fs (FWHM) pulses and 370 mW average power at 74 MHz repetition rate. The SC spectra with span from 350 nm to more than 1700 nm are generated. The maximum total power of the SC is 63 mW with 288 mW pump power from a 100× microscope objective. The wavelength and power of visible light ranging in the SC can be tuned by adjusting the input end of the random MF (to change the pump incident point or incident angle). In particular, generations of the spatially single-mode and the high-order mode with 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 the

* Supported by the Henan Cultivation Project for University Innovation Talents.
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SC generation process along with random MF are first reported. These findings probably will play an important role to search for the mechanism of SC generation. In addition, they may provide a new idea to manufacture novel types of MF.

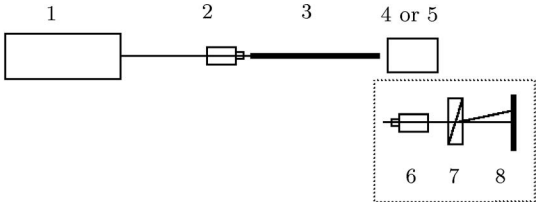

Fig. 1. Experimental setup of SC generation in random MF. 1. Mode-locked Ti:sapphire laser (Type:C20) produced by a TEMTOSOURCE laser, France; 2/6. microscope objective (40×, NA=0.65 or 60×, NA=0.85 or 100×, NA=1.25); 3. 165.81 mm length of random MF with diameter of 0.63–0.65 mm; 4. optical spectrum analyser (S2000 with wavelength range from 350 nm to 1300 nm produced by Ocean Optics Com., France and 86142B with wavelength range from 600 nm to 1700 nm produced by Agilent Technologies, USA); 5. optical power meter (model: DUO, produced by Gentec. EO, France) with probe of PS-310 WB; 7. Rochon prism.

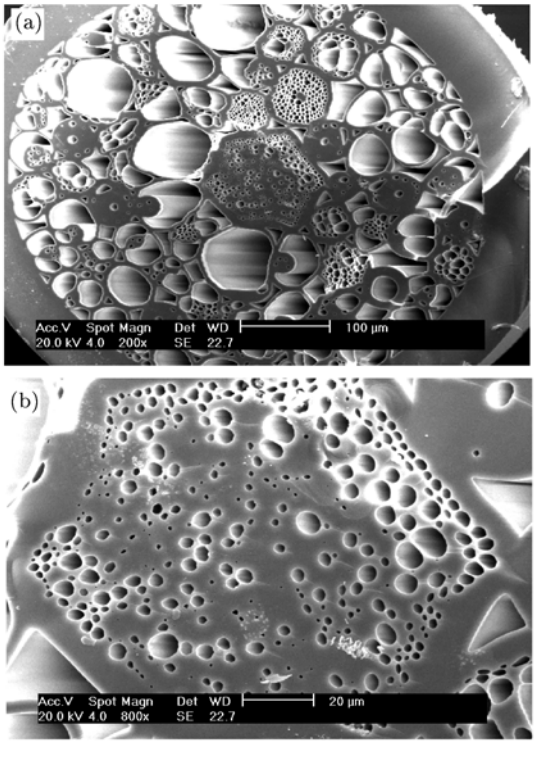

Fig. 2. Scanning electron microscopy of the cleaved end of the random MF: (a) section of the random MF, (b) section of the core of the random MF.

The experimental setup is shown in Fig. 1. Device 1 denotes a mode-locked Ti:sapphire laser (Type: C20) produced by a TEMTOSOURCE laser, France. With a pulse width of 15 fs and a repetition rate of 74 MHz, the laser provides the order of 370 mW average output power. The pump laser is horizontal linearly polarized. Devices 2 and 6 denote the microscope objectives (40×, NA=0.65 or 60×, NA=0.85 or 100×, NA=1.25). The transmissivities of microscope objectives with 40×, 60× and 100× are 76.3%, 68.4% and 75.8%, respectively. Device 3 denotes 165.81 mm length of random MF with diameter of 0.63–0.65 mm. Device 4 denotes the optical spectrum analyser (S2000 with wavelength range from 350 nm to 1300 nm produced by Ocean Optics Com., France and 86142B with the wavelength range from 600 nm to 1700 nm produced by Agilent Technologies, USA). Device 5 denotes an optical power meter (model: DUO, produced by Gentec. EO, France) with probe of PS-310 WB. Device 7 denotes a Rochon prism. The output SC beam from the random MF is split into two beams by the Rochon prism. Rotating the Rochon prism, we may judge the polarization of the SC by observing the change of brightness of the split beams. Device 8 denotes a screen. The random MF was fabricated at Infrared Optical Fibres and Sensors Institute, Yanshan University, and has the structure as shown in Fig. 2. Different size and shape air holes are randomly distributed in core and cladding. The average size of the air holes in the core is much smaller than that of those in the cladding.

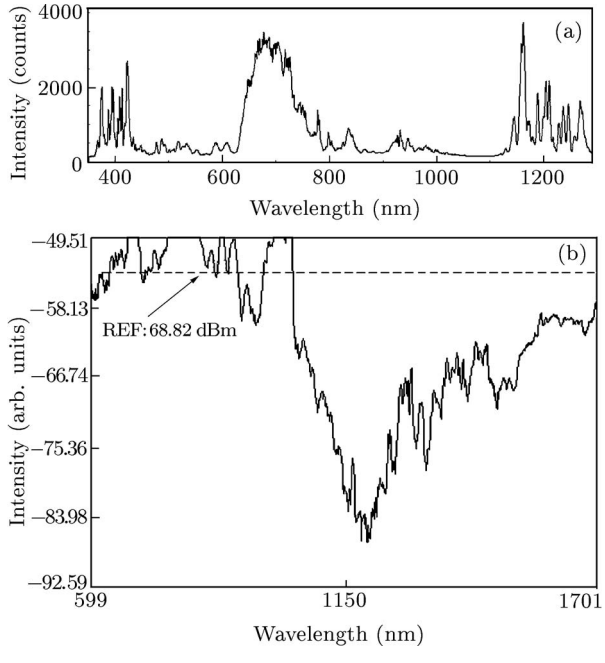

Fig. 3. SC generated in random MF measured by (a) S2000 model of optical spectrum analyser and (b) 86142B model of optical spectrum analyser.

Figure 3 shows the measured emission spectra of the random MF. The total spectral distribution ranges from 350 nm to more than 1700 nm, and a maximum output power of 63 mW has been obtained. For average power of 371 mW, the power coupled inside the

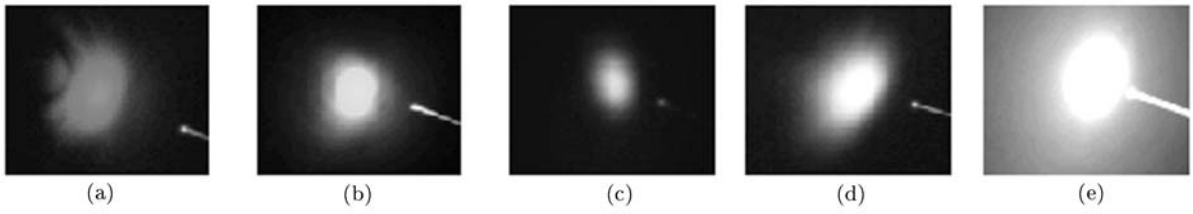

Fig. 4. Photographs of some typical visible light TEM_{00}- mode profiles: (a) red light; (b) green light; (c) blue light; (d) white light with violet light external ring; (e) white light.

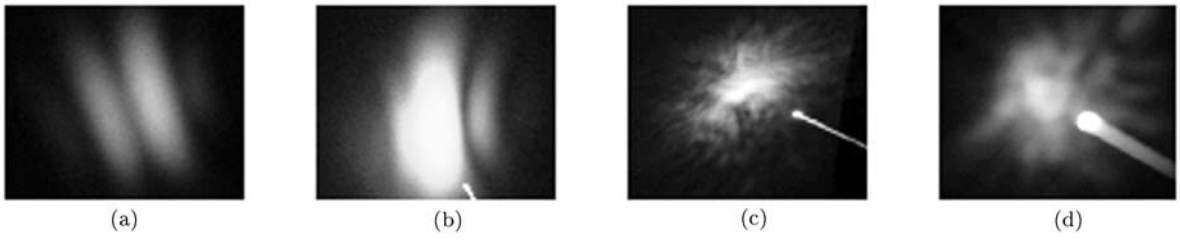

Fig. 5. Photographs of high-order waveguide mode profiles of visible light: (a) red light; (b) green light; (c) colorful (including white and violet and blue) light; (d) colourful (including green and red) light.

Table 1. Properties of SC generated in random MF.

Light pattern	Objective	Pump power (mW)	Total output power (mW)	Polarization	
				Polarization state	Polarization direction (relative to horizontal)
Red light similar as Fig. 4(a)	100×	288	16.3	elliptical	Rotates 45° anticlockwise
			63	circular	
	60	248	17.6	linear	rotates 30° clockwise
	40×	273	15.8	linear	rotates 90°
Green light similar as Fig. 4(b)	100×	288	15.4	linear	rotates 10° clockwise
	60×	248	31.1	linear	rotates 45° clockwise
Blue light similar as Fig. 4(c)	60×	248	24	linear	rotates 30° anticlockwise
	100×	288	17.2	elliptical	rotates 5° clockwise
TEM_{00} White and high-order mode violet light similar as Fig. 4(d)	60×	248	45	circular	
	40×	273	15.3	elliptical	rotates 20° clockwise
		273	17.4	elliptical	rotates 10° clockwise
		273	18.6	elliptical	rotates 12° clockwise
White light similar as Fig. 4(e)	100×	288	16	elliptical	rotates 30° anticlockwise
	60×	248	29	circular	
Colorful light similar as Fig. 5(a)	60×	248	16.3	linear	rotates 15° anticlockwise
		248	18.6	linear	rotates 30° anticlockwise
Colorful light similar as Fig. 5(b)	60×	248	31	linear	0°
Colorful light similar as Fig.5(c)	100×	288	16	elliptical	rotates 30° anticlockwise
Colorful light similar as Fig. 5(d)	100×	288	20.3	circular	
		288	21	elliptical	rotates 20° clockwise
		288	13	linear	0°

random MF is smaller than 100 mW by 40×, 60× and 100× microscope objectives in our experiment. Therefore, the increase of the intensity of the pump laser by exchanging of microscope objective cannot expand the SC wavelength range obviously.

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

In our experiment we can tune the output SC wavelength by adjusting the input end-surface of the random MF. In particular, we can obtain white light output. Figure 4 shows the red, green, blue, violet, and white light photographs and so on.

The output power of visible light also changes with adjustment of the input end-surface of the random

MF. For example, when output is red light as shown in Fig. 4(a), the total output power ranges from 16.3 mW to 63 mW under 288 mW pump power from the 100× objective. The total output powers for various tuning processes are listed in Table 1.

The visible light has a complicated far-field spatial pattern with adjustment of the input end-surface of the random MF, as shown in Fig. 5. This indicates the presence of high-order waveguide-modes.

Various polarization states for a certain wavelength visible light, such as linear polarization, circular polarization and elliptical polarization, are observed by adjusting the input end-surface of the MF when keeping fixed the polarization direction of the pumping laser. 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 light similar to those illustrated in Figs. 4 and 5 are listed in Table 1.

The results of experimental studies presented here demonstrate the following conclusions. (1) The microstructured fibre with randomly distributed air holes in cladding and core has generated some unusual features, such as tunable SC wavelength, which are not presented in periodical MF, periodical holey fibre and photonic crystal fibre. (2) The SC wavelength tunable property in the random MF may provide a new way to construct the optical parameter oscillator and the tunable laser. Moreover, the visible light of various wavelengths generated in the random MF has the potential to provide a novel light source to be used in laser colour display. (3) The wavelength tunable and polarization properties of SC generated in random MF can be used to study the mechanism of SC generation.

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