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Near-IR supercontinuum generation based on a telecom single-mode fibre in an all-fibre format, and its power combining

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Abstract. **Near-IR supercontinuum (SC) is generated based on a standard telecommunication single-mode (SM) fibre in an all-fibre format. The observed spectrum covers the spectral range from 1050 nm to 1700 nm. High-efficiency combining of the SC power is demonstrated for the first time, and the spectral SC properties are shown to be maintained after power combining. The results may find applications in sensing, spectroscopy and medicine.**

Keywords: *supercontinuum generation, power combining, fibre lasers.*

1. Introduction

Due to the extensive applications in nonlinear optics, supercontinuum (SC) generation in various silica fibres has attracted the interest of researchers in recent years [1–6]. Among the thousands of the published papers devoted to this issue, the main results in this field were obtained using a microstructure fibre and ultra short optical pulses [7–10]. Little attention was given to SC generation in a standard telecom fibre [11–14]. In 2011, Kurkov et al. [14] demonstrated mid-IR SC in a multimode telecom fibre for the first time and V. A. Kamynin et al. [15] also demonstrated mid-IR SC using a standard fibre covering range from 1.55 to 2.4 μm. On the other hand, an application of the mode-locked fibre lasers combined with the standard telecom fibre allows one to simplify the scheme down to a low-cost practical device.

The power scaling of laser radiation is a desired goal for many applications. However, the output power of a single fibre will ultimately be limited by the brightness of the pump source, facet fracture and thermal lens [16]. Power combining is an alternative solution for obtaining ultra-high-power levels. The combining of fibre lasers has been reported widely [17, 18], while the combining of the high-power SC [19–21], to the best of our knowledge, has not been studied before.

In this paper, near-IR SC is generated through a telecom single-mode fibre in an all-fibre format and its power combining is studied for the first time. In contrast to the standard approach, a commercial-off-the-shelf (COTS) telecom single-mode (SM) fibre is used as a nonlinear medium and pumped by a mode-locked all-fibre laser, which has a potential of prompting SC in practical applications.

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2. Experiment setup

The all-fibre scheme to generate SC is shown in Fig. 1. It is constructed in a two stage MOPA configuration: preamplifier and main amplifier. Radiation from a picosecond pulsed mode-locked fibre laser at 1064 nm with a linewidth of ~1.9 GHz (FWHM) and an average output power of ~15 mW at repetition rate of 21 MHz was generated from a linear resonance cavity constructed by using a 1.5 m Yb-doped fibre (YDF). The typical temporal width of the laser pulse is 452.7 ps (FWHM). The mode-locking of the pulsed laser was verified by using an oscilloscope as shown in Fig. 2. One can see from this figure that the mode-locked fibre laser operates at a repetition rate of 21 MHz.

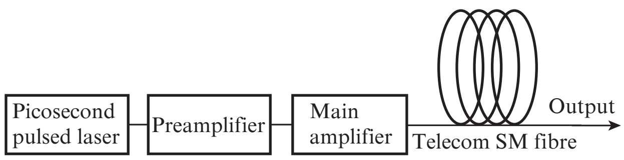

Figure 1. Scheme of the SC generation system.

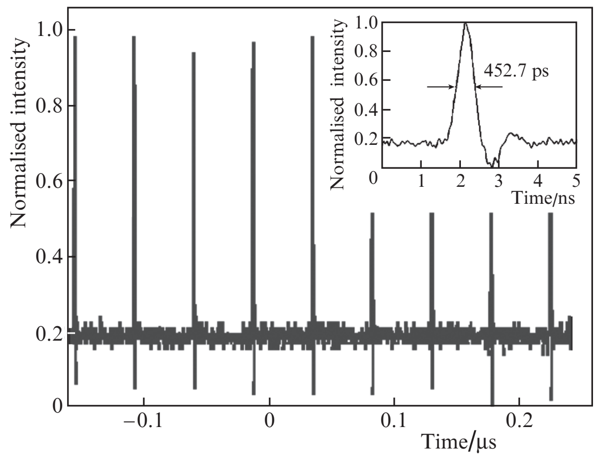

Figure 2. Pulse shapes of the mode-locked seed laser.

It is well known that SC generation in the fibre is induced by such nonlinear effects as stimulated Raman scattering (SRS), which need a high-peak power. When the signal distribution along the fibre is assumed uniform, the SRS threshold can be estimated to be $16A_{\mathrm{eff}}/(g_{\mathrm{R}}L)$ [22, 23]. In our experiment, a 1-km telecom SM fibre is used. Let the Raman coefficient be $g_R = 1 \times 10^{-13}$ m W^{-1}. Then, the peak power required to induce the SRS at the mode area A_{eff} of 30 μm^2 is about 4.5 W. However, the average and peak powers of the pulsed laser was only 9.6 mW and 1 W, which is far from reaching the SRS threshold. In order to generate SC effectively, two amplifiers were implemented in our experiment to provide enough power for inducing nonlinear effects in the telecom SM fibre. The pulses are first amplified to about 75 mW of average power. A SM YDF is core pumped by a 976-nm laser diode (LD) through a wavelength division multiplexer (WDM). The main-amplifier stage uses a large mode area (LMA) double clad YDF amplifier, which is clad pumped by two double clad fibre pigtailed 976-nm LDs through a (2 + 1) × 1 signal pump^{-1} combiner. The core diameter of the main amplifier is 6 μm. The laser power can be boosted to be 7 W in this stage. The unabsorbed pump power is dumped.

The optical spectrum of the pulsed laser after the main amplifier over a spectrum analyser at 21-MHz repetition rates is shown in Fig. 3 (the inset shows the optical spectrum of the seed laser). The optical spectra are measured by an optical spectrum analyser (OSA) (86142B, Agilent company) with a spectral resolution of 0.06 nm. One can see from Fig. 3 that no amplified spontaneous emission (ASE) is observed when the pump power of the main amplifier is 6 W (the output power of the main amplifier is 4 W). It appears slightly when the pump power is 12 W at the output power of 7 W. The pulse shape of the mode-locked fibre laser after the main amplifier is shown in Fig. 4 at a pump power of 12 W. The inset shows a typical oscilloscope trace of the laser pulses, whose FWHM duration is slightly broadened to about 589 ps after amplification. The peak power for this case is 565.9 W.

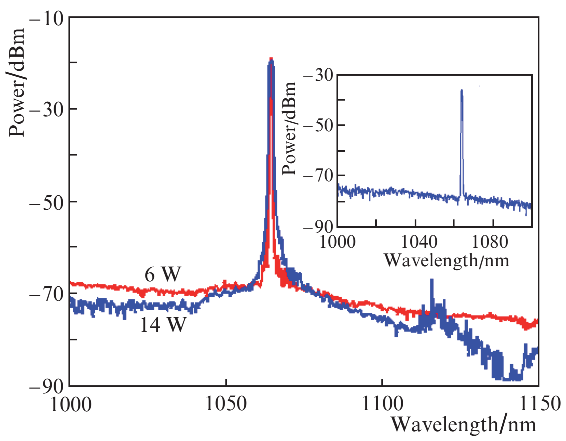

Figure 3. Spectra of the pulsed laser at a pump power of 6 and 14 W.

3. Experimental results and discussions

The output port of the main amplifier was spliced with a 1-km telecom standard SM fibre. Figure 5 illustrates the emission spectrum from the output of the telecom SM fibre. The average output power of the SC is 2.5 and 4.5 W at 4-W and 7-W injecting pump powers, respectively. One can see the spectra cover the range from 1050 to 1700 nm. The variation under 1300 nm is less than 25 dB, while less than 10-dB variation is obtained above 1300nm. When higher pump powers are provided for the telecom SM fibre, the emission spectrum starting from 1350 nm becomes more flat. Several components

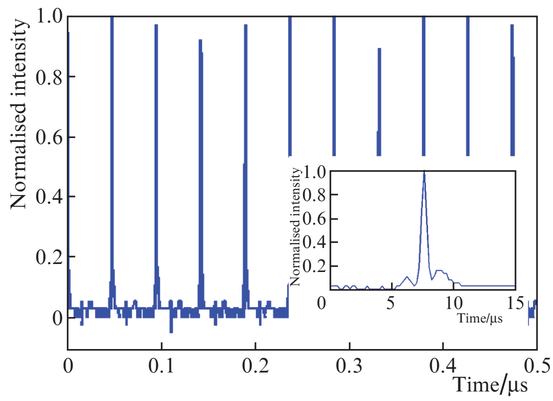

Figure 4. Amplified pulses of a seed laser at a pump power of 12 W.

corresponding to SRS are clearly distinguishable, which indicates that the SC generation is mainly caused by the cascade Raman scattering in the field of the anomalous dispersion and smoothed by spectral broadening of the pump pulses in the fiber amplifier [23].

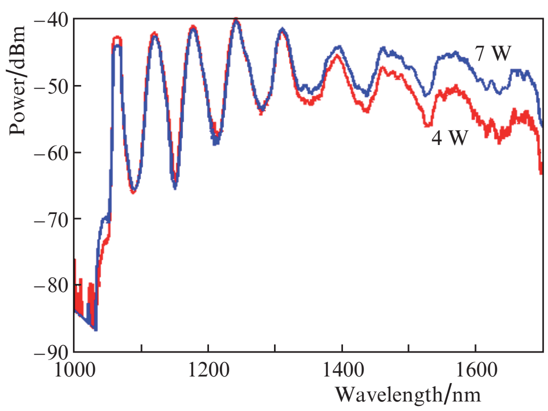

Figure 5. Output spectra of the generated SC at an injecting pump power of 4 and 7 W.

In order to validate the feasibility of power combining of SC, we built a second all-fibre SC system with the same configuration as shown in Fig. 1. The average power of the second SC is 4.2 W. The schematic configuration for power combining of two near-IR SCs is shown in Fig. 6. A 7 × 1 power combiner (PC) is used to achieve the power combining and only two pump ports are used. At the PC input there are seven 9/125 SM fibres, which can be fused with the output port of the telecom SM fibre without loss, while the output fibre is a 105/125 multi-mode fibre. The insert loss of the PC is less than 0.5 dB.

The power combining emission spectra are presented in Fig. 7. It is shown that the spectrum character of the SC is well maintained after the power combining. The maximum variation is less than 22 dB. When the total power injected into the PC is 8.7 W, the output power of the PC is 8 W, which indicates a power combining efficiency of 92%.

4. Conclusions

Thus, near-IR SC is experimentally demonstrated by using a telecom single-mode fibre in an all-fibre format, and its power

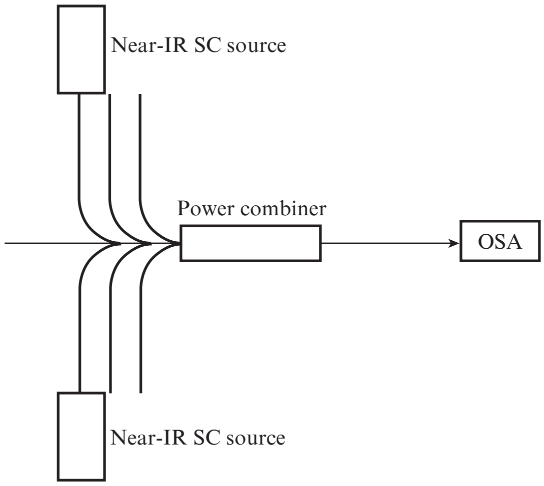

Figure 6. Schematic configuration of telecom-SM-fibre-based SC power combining.

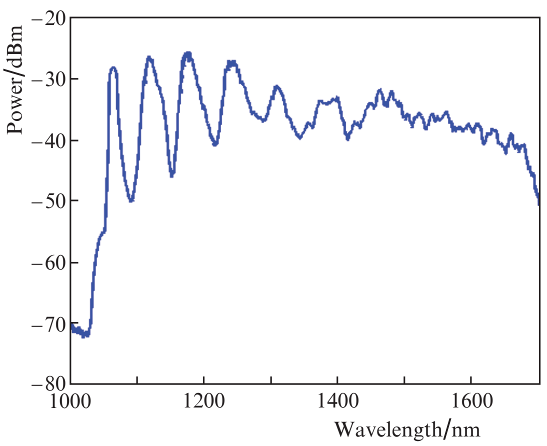

Figure 7. Output spectrum of the SC after power combining.

combining is investigated. The broadband spectrum covering the 1050-to-1700 nm range with a maximum power variation less than 25 dB is achieved. Power combining of the SC is investigated for the first time and the power combining efficiency obtained is up to 92%. The spectral property of the SC is well maintained after combining. The results obtained can find multiple applications in optical coherence tomography, frequency metrology and spectroscopy for its all-fibre structure, broad bandwidth and low cost.

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