Quantum Electronics **41** (11) 986 – 988 (2011)

PACS numbers: 42.55.Wd; 42.65.Jx; 42.65.Ky; 42.65.Dr; 42.81.Dp
DOI: 10.1070/QE2011v041n11ABEH014671

Supercontinuum generation in the range 1.6 – 2.4 μm using standard optical fibres

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Abstract. **Experimental evidence is presented that standard optical fibres can be used to efficiently convert nanosecond pulses at 1.59 μm to a supercontinuum in the range 1.6 – 2.4 μm. The highest efficiency of conversion to wavelengths above 2 μm, 38%, has been offered by a multimode graded-index fibre. The spectral density of average power in the range 2 – 2.35 μm in this fibre is about 1 mW nm^{-1} and that of peak power is about 10 W nm^{-1}. In all the fibres studied, the practical long-wavelength limit of generation is 2.35 μm.**

Keywords: *erbium-doped fibre laser, supercontinuum, multimode graded-index fibre.*

1. Introduction

Supercontinuum generation in optical fibres has been the subject of many original research reports and several review articles [1, 2]. The reason for this is that broadband radiation is widely used in a variety of applications. Note that most effort in this area has been concentrated on broadband generation in the visible and near-IR. At the same time, it is of interest to obtain broadband radiation at wavelengths above 2 μm. Sources of such radiation could be used in spectroscopy, atmosphere analysis, medicine and other applications. As a rule, special fibres are employed for supercontinuum generation in this spectral region. In particular, Kim et al. [3] used sapphire fibre, and Buczynski et al. [4] used a microstructured oxide glass fibre of complex composition. Qin et al. [5] demonstrated generation up to 3.8 μm in fluoride fibre pumped by a femtosecond 1.45-μm source. Supercontinuum generation up to 4.8 μm was achieved in ZBLAN glass fibre [6]. One drawback to this approach is that special fibres are poorly compatible with silica glass fibres, which makes it impossible to create a compact all-fibre supercontinuum source suitable for practical applications. At the same time, Kurkov et al. [7] reported supercontinuum generation up to 2.4 μm in silica fibre pumped by a pulsed fibre laser. Note that they demonstrated only 2-μm supercontinuum generation in a multimode optical fibre. The objective of this work was to examine the possibility of efficient pump conversion to wavelengths $\lambda > 2$ μm in standard silica fibres and to optimise the fibre length.

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Received 3 June 2011; revision received 25 July 2011
Kvantovaya Elektronika **41** (11) 986 – 988 (2011)
Translated by O.M. Tsarev

2. Experimental setup and fibres

The nonlinear media used for supercontinuum generation were standard telecom fibres: SM332 and LEAF single-mode fibres and a G-50-125-250 multimode graded-index fibre (j-fiber GmbH). Their parameters are listed in Table 1. The mode field diameter and chromatic dispersion of the single-mode fibres are given for $\lambda = 1.6$ μm (excitation wavelength). The experimental setup is shown schematically in Fig. 1. As a pump source, we used a Q-switched erbium fibre laser [8]. Its active medium was a double-clad erbium-doped fibre with a core diameter of 20 μm [9]. Q-switching was ensured by an intracavity saturable absorber based on Tm-doped fibre. The reflectors used were fibre Bragg gratings (FBGs). The input grating was written into a single-mode fibre and ensured single-mode operation. The output grating was written into a piece of a multimode graded-index fibre. This ensured a good match with the active fibre, which had a large core diameter [10]. The Er-doped fibre was pumped by a 0.98-μm semiconductor laser with an output power of up to 10 W. The fibre laser operated at 1.59 μm and its maximum average output power was about 1 W, with a pulse repetition rate of 4.4 kHz, pulse duration and energy of 35 ns and 0.21 mJ, respectively, and a peak power of 6 kW. The fibre to be studied was fusion spliced to the output end (with an FBG) of the fibre laser. Thus, we used an all-fibre configuration.

Table 1. Parameters of the fibres and characteristics of the supercontinuum.

Fibre	d/μm	σ/ps nm^{-1} km^{-1}	L/m	P/mW	η (%)
SM332	11	20	12	480	33.5
LEAF	9.5	7	7	480	29.9
Multimode graded-index fibre	50	–	20	850	38

Note: d is the mode field (core) diameter, σ is dispersion, L is the fibre length, P is the average supercontinuum power, and η is the percentage of the power in the range 2 – 2.4 μm.

Note that the erbium fibre laser used has a better energy performance in comparison with other types of pulsed fibre sources. In particular, mode-locked long-cavity fibre lasers [11] have a pulse energy within several microjoules and a peak power in the order of 100 W. In the case of an ytterbium fibre laser, such energy performance enables efficient supercontinuum generation in the range 1.1 – 1.6 μm [12] but requires that the fibre length in the converter be in the order of 100 m, which is unacceptable in the 2-μm range, where the optical loss reaches 1 dB m^{-1}.

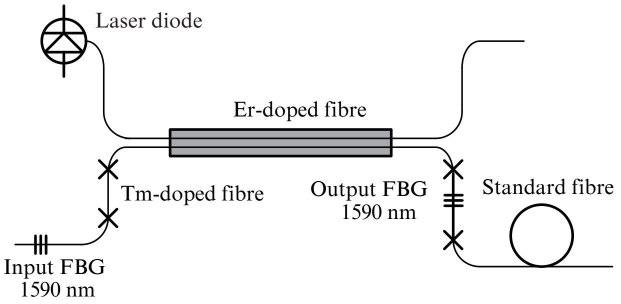

Figure 1. Experimental setup. The crosses represent fusion splices.

The spectral composition of the output radiation was analysed using a monochromator with an InGaAs photodetector that had a spectral range from 1.2 to 2.6 μm and frequency response up to 15 MHz.

3. Experimental results

Figure 2 shows the supercontinuum spectrum measured at the output of a 12-m-long SM332 fibre. The broadening of the spectrum at the base of the pulse is caused by four-wave mixing (FWM). At a higher resolution (Fig. 2, inset), concomitant peaks are well seen. The down-conversion is due to stimulated Raman scattering (SRS) in the region of high anomalous dispersion. In our experiments, we used different lengths of fibres.

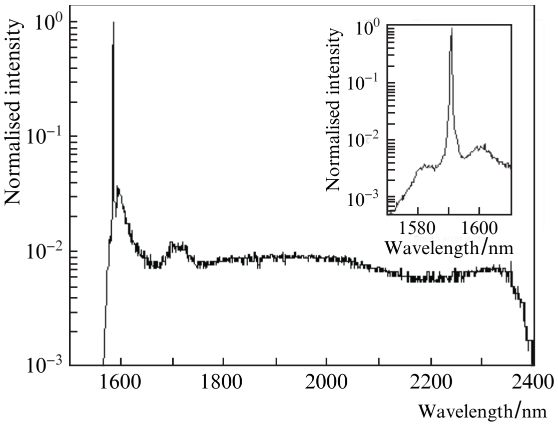

Figure 2. Supercontinuum spectrum of SM332 single-mode fibre.

The fibre length was optimised so as to maximise conversion to the 2-μm range. Short fibre lengths limit the efficiency of the SRS process, and excessive lengths lead to large optical losses at the edge of the phonon absorption band. To optimise the fibre length, the percentage of the power in the range $\lambda > 2$ μm was plotted against fibre length (Fig. 3). The conversion has a maximum at a fibre length of 12 m. Further increase in fibre length is accompanied by a drop in the power between 2 and 2.4 μm because of the rise in optical loss at the edge of the phonon absorption band. The total average power at the fibre output was 480 mW. The reduction in output power as compared to the erbium fibre laser was caused by the fusion splice loss between the test fibre and the output section of the fibre laser. The fraction of the power in the range $\lambda > 2$ μm was 33.5%.

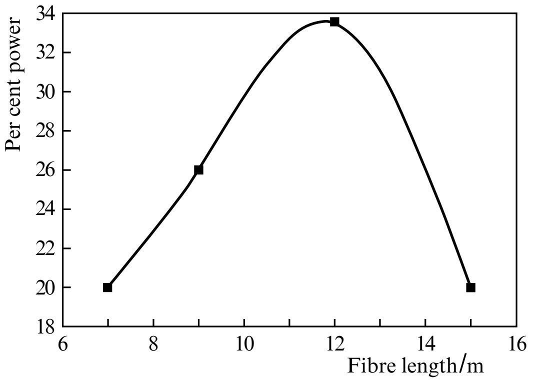

Figure 3. Percentage of the power in the range 2–2.4 μm as a function of SM332 fibre length.

The optimal length of LEAF fibre, which has a smaller mode field diameter, was determined to be about 7 m. The conversion to the range 2–2.4 μm was about 30%. This can be accounted for by the better phase matching for FWM, which severely broadens the spectrum in the range 1.6–1.8 μm, thereby reducing the power conversion to the range 2–2.4 μm. The supercontinuum spectrum of this fibre is shown in Fig. 4. The total power at its output was essentially the same as above.

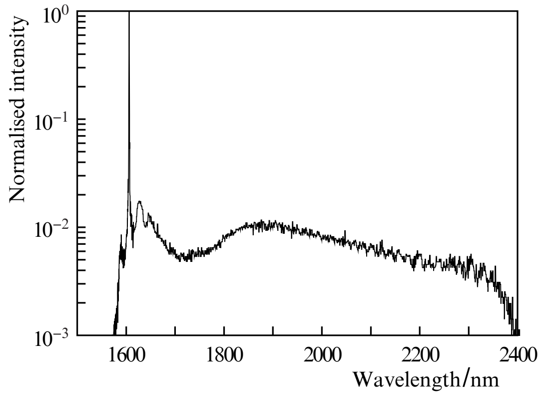

Figure 4. Supercontinuum spectrum of LEAF single-mode fibre.

Using the multimode graded-index fibre for spectral conversion, we obtained a supercontinuum with a maximum average power of 850 mW because there was no splice loss between this fibre and the output section of the seed laser. Since graded-index fibres maintain the input field distribution, the output radiation is concentrated in a region 20–25 μm in diameter. Because the power density in the fibre under consideration is about a factor of 2 lower than that in the single-mode fibres, the optimal fibre length for supercontinuum generation was near 20 m. The supercontinuum spectrum of this fibre is presented in Fig. 5. The spectrum contains a characteristic Stokes peak at 1.7 μm and a rather flat portion between 1.8 and 2.35 μm. The efficiency of the conversion to the range 2–2.4 μm is 38%, with a spectral density of average power in this range near 1 mW nm^{-1} and that of peak power near 10 W nm^{-1}.

Table 1 lists the average powers and conversions to the range 2–2.4 μm for the fibres studied. There are some distinc-

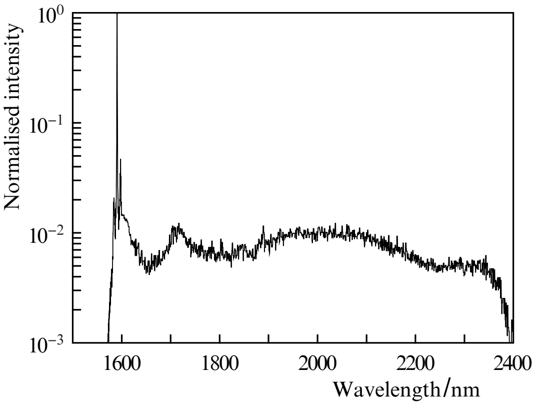

Figure 5. Supercontinuum spectrum of the multimode fibre.

tions between the fibres, but all of them show a sharp drop in emission intensity at wavelengths above 2.35 μm. It seems likely that this wavelength can be considered a practical limit for standard fibres pumped by pulses with a peak power of the order of several kilowatts. Further advance to longer wavelengths can be brought about by reducing the fibre length because the broadening of the spectrum is limited by the sharp increase in optical loss with increasing wavelength. This, in turn, requires either an increase in pump power or fibres with increased nonlinearity.

4. Conclusions

Experimental evidence has been presented that nanosecond pulses at 1.59 μm can be efficiently converted to a supercontinuum in the range 2–2.4 μm using standard optical fibres. The conversion efficiency is shown to significantly depend on fibre length. The highest efficiency of conversion to the mid-IR spectral region, 38%, is offered by the multimode graded-index fibre. The spectral density of average power in the range 2–2.35 μm in this fibre is about 1 mW nm^{-1} and that of peak power is about 10 W nm^{-1}. In all the fibres studied, the practical long-wavelength limit of generation is 2.35 μm.

Acknowledgements. This work was supported by the Russian Foundation for Basic Research (Project No. 10-02-01006-a).

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