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Generation of a polarised supercontinuum in small-diameter quasi-elliptic fibres

S.M. Kobtsev, S.V. Kukarin, N.V. Fateev

Abstract. **A supercontinuum is generated for the first time and studied in twin tapered fibres with a micron waist upon pumping by femtosecond pulses. The supercontinuum is obtained in the range from 460 to 1070 nm at the −28 dB level with the degree of polarisation up to 97 %. The polarisation and coherent properties of the supercontinuum are studied experimentally.**

Keywords: *tapered fibre, supercontinuum generation, femtosecond pulses.*

1. Introduction

Progress in the technology of manufacturing optical fibres with special properties (varied-dispersion fibres, small-core-diameter fibres, holey fibres, etc.) stimulates the studies of nonlinear effects appearing during the propagation of ultrashort light pulses in the fibres. One of the examples of qualitatively new recent results obtained by several research groups [1 – 4] using new fibres, in particular, small-core-diameter (~ 2 μm) fibres is the generation of a supercontinuum in the region between 400 and 1600 nm upon pumping the fibres by comparatively low-power (pulse energy ~ 1 nJ) femtosecond Ti : sapphire and Cr : forsterite lasers [5, 6].

Earlier, a supercontinuum was generated upon pumping usual fibres and other media by an order of magnitude higher-power light pulses [7]. The lowering of the peak power of pump pulses generating a supercontinuum in new optical fibres opens up the outlook for the development of more efficient radiation sources (converters) with unique properties. These expectations are connected to a great extent with small-diameter fibres, whose core has a diameter of a few micrometres and partially or completely borders air. Such fibres (hereafter, microfibres) can be manufactured based on holey fibres or tapered fibres with a low-diameter waist. The wavelength of the group-velocity zero dispersion in microfibres is shifted to the visible spectral region and the effective mode area in them is small, which provides an increase in nonlinear refraction. Except the supercontinuum generation, a number of nonlinear processes were observed in such microfibres such as the self-shift of the soliton carrier frequency [8 – 11], the third-harmonic generation, etc.

In this paper, we obtained for the first time and studied experimentally the generation a polarised supercontinuum in silica fibres of a new type – twin microfibres with a quasi-elliptic waist cross section, pumped by a femtosecond Ti : sapphire laser.

2. Experimental

Twin microfibres were manufactured from standard SMF-28 Corning fibres. At the initial moment of fibre drawing, a mechanical contact between two fibres was provided over the length of a few centimetres. The drawing was performed in the flame of a hydrogen torch in several stages using the technology described in Ref. [4]. The diameter of fibres was reduced at each stage and the fibres were simultaneously welded together. A twin microfibre manufactured this way had a long waist (of length up to 14 cm) with a quasi-elliptic cross section of micron diameter and two input and two output ends representing the undrawn pieces of an SMF-28 fibre of length 5 – 40 cm. We failed to measure the waist diameter because of its smallness; however the cross section of a twin microfibre at one of the stages of fibre drawing was photographed. Figure 1a shows the photograph of the cross section of a twin microfibre illuminated from one of its input ends. The calculated dimensions of the cross section of the waist of a twin microfibre were four times smaller than these presented in Fig. 1a. The assumed final cross section of the waist is shown in Fig. 1b. The size of the minor axis of the quasi-elliptic profile is $d = 2$–3 μm, and that of the major axis is $D = 1.7d$.

The pump radiation was coupled into the core (of diameter 8 μm) of one of the input ends and then propagated along the tapering part of the fibre and its microwaist that bordered ambient air. After propagation through the microwaist and the expanding part of the fibre, the pump radiation propagated along the cores of the two output ends of the undrawn fibre. The lengths of the tapering and expanding parts of the fibre were 2.5 cm each and the microwaist length was from 6 to 14 cm in different fibres. Thus, the pump radiation was coupled into and coupled out of the microwaist through standard pieces of SMF-28 fibres.

The scheme of the experimental setup used for studying manufactured fibres is shown in Fig. 2. We used in our experiments a femtosecond Ti : sapphire laser pumped by a cw argon laser. The output pulse duration was 60 fs, the

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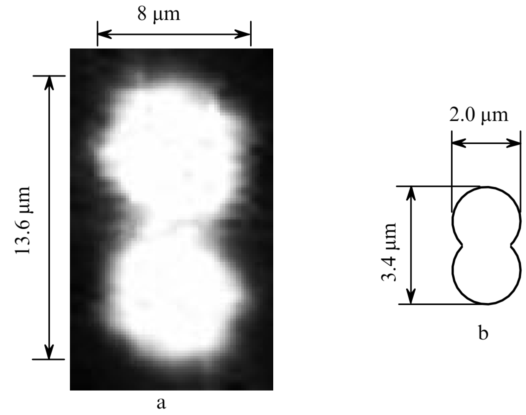

Figure 1. Profiles of the cross section of the waist of a twin tapered microfibre: the photograph of the waist cross section made at the intermediate stage of fibre drawing (a) and the assumed final shape of the waist cross section (b).

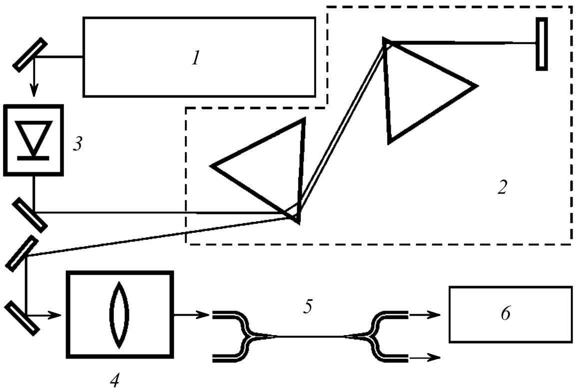

Figure 2. Scheme of the experimental setup for studying microfibres: (*1*) femtosecond Ti : sapphire laser; (*2*) two-prism compressor; (*3*) Faraday isolator; (*4*) microobjective; (*5*) twin microfibre; (*6*) optical spectrum analyser.

pulse repetition rate was 80 MHz, and the average output power of the Ti : sapphier laser was 250 mW. The spectral width of the 786-nm output pulse was 20 nm. The phase modulation (chirp) of the Ti : sapphire laser pulses was controlled with a two-prism compressor. As a rule, the output pulses of a femtosecond laser have a small positive initial chirp, which increases upon their propagation through optical isolation elements, a microobjective, and the initial undrawn part of the fibre. The compressor compensated for this positive chirp, providing the minimal phase modulation of laser pulses in the tapering part of twin fibres. The compressor was adjusted by minimising the duration of laser pulses directly in front of the tapering part of fibres. The pulse duration was preliminary controlled with the help of an autocorrelator after their propagation through a Faraday isolator, the compressor, a microobjective, and the initial undrawn piece of the SMF-28 fibre.

Radiation from the Ti : sapphire laser was coupled into one of the input ends of a twin fibre through a $8^{\times}/0.2$ microobjective. The average pump power at the fibre input was ~ 100 mW (the peak pulse power was ~ 20 kW). The transmission of the fibres was 25 % – 40 % (taking into account the total radiation intensity in two ends of the fibre.) The output emission spectrum was recorded with an automated Angström spectrum analyser in the range from 400 to 1600 nm with a resolution of 3 nm.

3. Experimental results

3.1 Supercontinuum spectrum

Figure 3 shows one of the supercontinuum spectra obtained in a fibre with $d = 2$ μm and the waist length of 10 cm. The spectrum covers the wavelength range from 460 to 1070 nm at the -28 dB level and its width is not smaller than that of supercontinua generated earlier in single tapered microfibres of the same diameter d under the same pump [3, 4], although the effective mode area in the waist of a twin microfibre is substantially larger than that in the waist of a single tapered microfibre with the same diameter d. Note that the calculated dispersion parameters of twin microfibres [12] are close to the dispersion parameters of single tapered microfibres with the same diameter d.

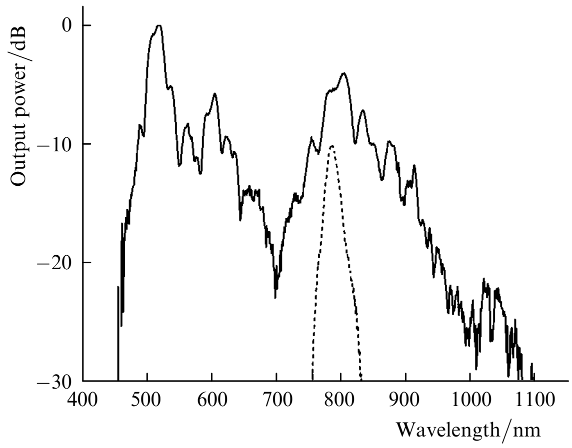

Figure 3. Supercontinuum emission spectrum generated in a fibre with the waist diameter $d = 2$ μm. The dashed curve is the pump radiation spectrum.

We determined the dependence of the supercontinuum spectrum generated in twin microfibres on the orientation of the quasi-elliptic cross section of the waist with respect to the polarisation plane of input radiation. A change in the angle α between the polarisation plane of input radiation and the major axis of the quasi-elliptic cross section of the waist, produced by rotating the waist of a twin microfibre around the direction of propagation of radiation at fixed input and output undrawn fibre ends, was accompanied by variations in the width and shape of the generated supercontinuum spectrum (Fig. 4). In this case, the relation between the supercontinuum radiation powers at the output fibre ends changed from 1 : 1 to 0.8 : 1.2, the total radiation power being invariable.

The spatial characteristics of the supercontinuum emission at each of the output fibre ends were identical. Figure 5 shows the transverse distribution of the supercontinuum emission at the output fibre ends and the approximation of this distribution by a Gaussian. A good approximation of the distribution of the output emission by a Gaussian proved to be somewhat unexpected because higher-order modes can appear in the waist with a quasi-elliptic cross section [13]. However, the transverse distribution of the

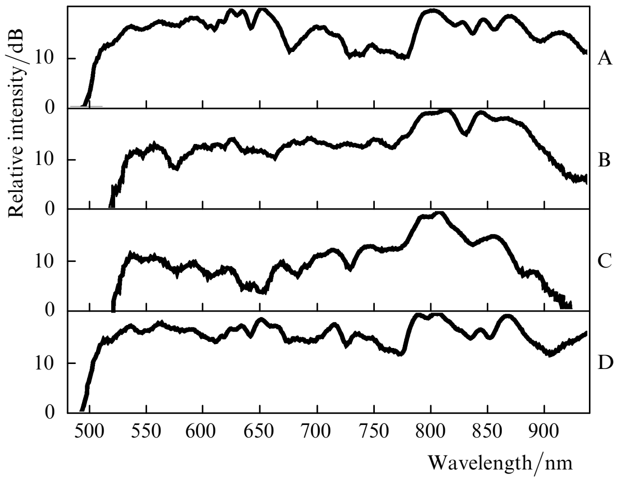

Figure 4. Supercontinuum spectra for the angle $\alpha = 0$ (A), 120° (B), 225° (C), and 270° (D).

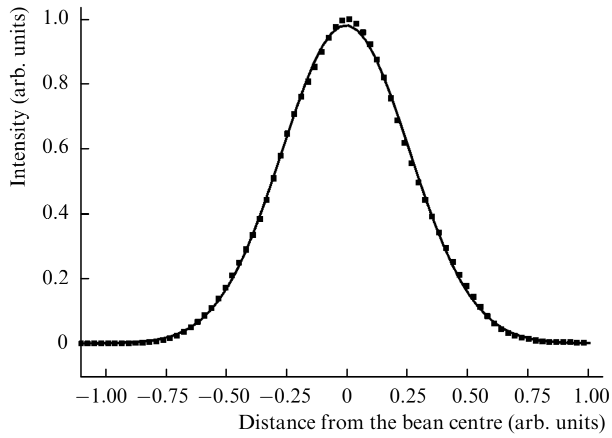

Figure 5. Experimental transverse distribution of the supercontinuum emission at the microfibre end (squares) and its approximation by a Gaussian (solid curve).

supercontinuum emission at the end of many fibres is close to a Gaussian.

3.2 Supercontinuum coherence

It is known that a supercontinuum generated by a train of ultrashort laser pulses contains many equidistant spectrally narrow emission lines separated by the frequency interval coinciding with the pump pulse repetition rate. The generated frequencies are phase matched; however, the degree of their coherence can vary depending on the parameters of the medium, in our case, an optical fibre and the pump parameters. The numerical study of the degree of coherence of different spectral components of the supercontinuum generated in holey and tapered microfibres showed that the degree of coherence of the supercontinuum frequencies decreased with increasing the pump pulse duration, the waist length in the optical fibre, and the pump wavelength.

To study the coherent properties of the supercontinuum generated in twin microfibres at the specified pump parameters, we performed the following experiment. The diverging polarised supercontinuum emission beams emerging from two output fibre ends were combined on a translucent plate and directed at a screen, one of the fibre ends being fixed on a high-precision stage with a micrometre screw. The supercontinuum pulses arriving at the translucent beamsplitter from two fibre ends were made coincident in time with the help of this stage. When the stage was appropriately adjusted, a distinct interference pattern was observed on the screen, which was stable for a long time. Figure 6 shows the photograph of this interference pattern. The rings of the interference pattern were white or slightly tinted (red – pink or dark blue – blue) depending on the fibre, indicating to a greater radiation power density in the corresponding spectral region. A rather high contrast of the interference patterns confirms a high degree of coherence of different supercontinuum emission frequencies generated in twin microfibres.

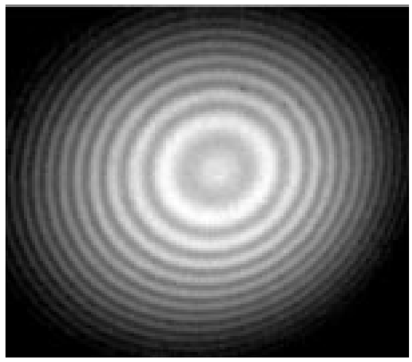

Figure 6. Photograph of the interference rings appearing upon the spatial overlap of the wave fronts of the beams and the time coincidence of supercontinuum pulses emerging from the output ends of a twin microfibre.

3.3 Supercontinuum polarisation

The presence of asymmetry in the transverse profile of the waist of twin microfibres results in the generation of a polarised supercontinuum. This is demonstrated in Fig. 7, where the results of measurements of the degree δ of supercontinuum polarisation in a fibre with the waist diameter $d = 2.2$ μm of length 9 cm are presented. The measurements were performed for different angles α. The angle α was varied by rotating the waist of the twin

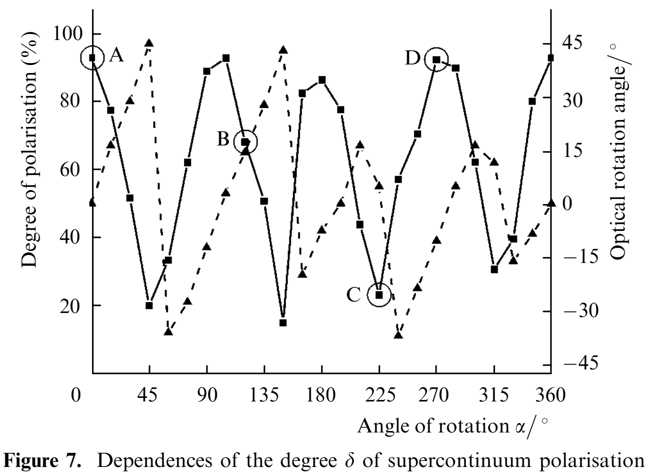

Figure 7. Dependences of the degree δ of supercontinuum polarisation (solid curve) and the optical rotation angle (dashed curve) on the angle of rotation α. Symbols A, B, C, and D correspond to the spectra in Fig. 4.

microfibre around the direction of propagation of radiation at fixed input and output undrawn fibre ends. The degree of polarisation δ (in %) was determined from the measured maximum (I_{max}) and minimum (I_{min}) intensities of the supercontinuum emission propagated through a rotatable polariser (Glan prism) using the expression

$$\delta = 100(I_{max} - I_{min})/(I_{max} + I_{min}).$$

Figure 7 shows that the maxima of the dependence $\delta(\alpha)$ are achieved at angles α close to 0, 90°, 180°, and 270°, i.e., when the direction of polarisation of the input radiation is close to the direction of one of the two symmetry axes of the quasi-elliptic cross section of the waist. As the angle α was increased from values $(1+2n) \times 45°$, where n is an integer, the direction of the supercontinuum polarisation drastically changed. The maximum degree of the supercontinuum polarisation for this fibre was 93 %. For the fibre, whose spectrum is shown in Fig. 3, the degree of polarisation was 97 %. A comparison of the results presented in Fig. 7 with the supercontinuum spectra in Fig. 4 shows that the maximum width of the output emission spectrum is achieved when the degree δ of emission polarisation is maximal. For the spectra in Fig. 4, we have $\delta = 93\,\%$, $\alpha = 0$ (A), $\delta = 68\,\%$, $\alpha = 120°$ (B), $\delta = 23\,\%$, $\alpha = 225°$ (C), $\delta = 93\,\%$, $\alpha = 270°$ (D).

Similar dependences of the degree of polarisation and the optical rotation angle on α were also observed for radiation from a 0.63-μm cw helium-neon laser coupled into twin tapered fibres. This indicates that the dependences $\delta(\alpha)$ obtained for the supercontinuum are not inherent in the continuum itself but are typical for twin tapered fibres irrespective of whether the incident radiation is pulsed or continuous wave.

4. Conclusions

We have generated a polarised supercontinuum in the region 460 – 1070 nm in twin tapered silica fibres with the quasi-elliptic micron cross section of the waist pumped by ~ 1 nJ femtosecond pulses from a Ti : sapphire laser. The maximum width and the most smooth shape of the supercontinuum are achieved when the polarisation plane of the pump radiation coincides with the major axis of the quasi-elliptic profile of the waist of a twin tapered microfibre. In this case, the maximum degree of polarisation (up to 97 %) is also achieved. The supercontinuum frequencies are highly coherent and its intensity distribution at the fibre output is described by a Gaussian.

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