Quantum Electronics **32** (6) 542 – 544 (2002)

PACS numbers: 42.81.Dp; 42.65.Tg; 42.70.Qs
DOI: 10.1070/QE2002v032n06ABEH002239

Localisation of light and spectral broadening of femtosecond laser pulses in a fibre with a minimal-microstructure cladding

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***Abstract*. Microstructure optical fibres with a cladding consisting of a single cycle of air holes and the minimum core diameter of 1 μm have been fabricated and studied. Guided modes supported by this fibre are characterised by a high light localisation degree and display the C_{6v} point-group spatial symmetry of the transverse field distribution. A high refractive index step between the core and the cladding in the created fibres strongly confines the light field in the fibre core. The spectral broadening of low-power femtosecond laser pulses in the fibre of this type is experimentally studied.**

Keywords: *microstructure optical fibres, nonlinear optics.*

Microstructure fibres [1 – 3] have been shown recently to be a useful component for nonlinear optics, optics of ultrashort pulses, and optical metrology. Unique properties of these fibres offer the possibilities of tailoring the dispersion of guided modes by changing the core – cladding geometry [4] and achieving a high confinement degree of light field in the fibre core due to a high refractive-index step between the core and the cladding in such a fibre [5, 6]. A combination of these properties allows the whole catalogue of nonlinear-optical processes to be enhanced. Supercontinuum generation with unamplified nano- and subnanojoule femtosecond pulses [7] is one of the most spectacular manifestations of this enhancement and one of the most impressive results achieved with microstructure fibres in recent years. Supercontinuum generation in microstructure fibres has already resulted in revolutionary changes in optical metrology [8 – 10].

The design of the core and the cladding in microstructure fibres is crucial for many functions of such fibres in optical physics [4] and biomedical applications [11, 12]. In particular, microstructure fibres with periodically arranged air holes in the cladding form the class of photonic-crystal fibres [1]. With a special design of the core and the cladding, a microstructure fibre can be made highly birefringent [13, 14].

In this paper, we report on the fabrication of fibres with a minimal-microstructure cladding, i.e., fibres where the cladding consists of a single cycle of air holes surrounding the fibre core. We will present the results of investigations of linear and nonlinear optical properties of such fibres.

The technology employed to fabricate microstructure fibres used in our experiments was similar to the procedure developed in Ref. [1]. However, instead of using a preform consisting of a set of identical capillaries, we started with a preform consisting of fused silica fibres with different diameters. The central part of our preform included a fibre with the minimum diameter surrounded with six capillaries. The cross-sectional image of a fibre with a minimal-microstructure cladding fabricated by drawing the above-described preform is presented in Fig. 1. The minimum diameter of the core in the created MS fibres was equal to 1 μm. The air-filling fraction of the microstructure part of the cladding in the created fibres, as can be seen from Fig. 1, is very high, providing a high refractive index step between the core and the cladding in the fibre.

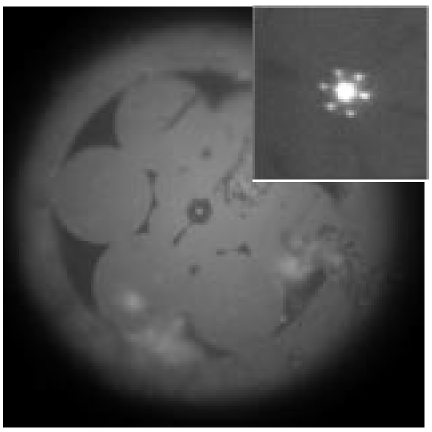

Figure 1. Cross-sectional microscope image of a fibre with a minimal-microstructure cladding and a core diameter of 2 μm. The inset shows a typical light field intensity distribution in the guided mode at the output of the fibre.

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Received 27 February 2002
Kvantovaya Elektronika **32** (6) 542 – 544 (2002)
Translated by A.M. Zheltikov

The degree of light confinement in the fibre core is the key factor leading to the enhancement of nonlinear-optical interactions in microstructure fibres. The spatial structure of the field distribution in the modes guided by such fibres, on the other hand, has a considerable influence on the parameters of light pulses propagating through these fibres, their guiding losses, and the properties of nonlinear-optical processes.

To investigate spatial mode properties and the confinement of the light field in the created fibre, we coupled laser or incoherent radiation into the fibre using an objective with a numerical aperture of 0.3. A similar objective was employed to image the spatial distribution of the light field at the output end of the fibre onto a CCD camera. A typical light field intensity distribution at the output of the created fibre with a minimal-microstructure cladding is shown in the inset to Fig. 1.

The field pattern shown in Fig. 1 indicates a high degree of light confinement in the fibre core. The guided mode, as can be seen from the results of measurements. is characterised by a virtually ideal spatial symmetry of the C_{6v} point group, thus reproducing the rotational symmetry of the microstructure cladding. Six symmetric side lobes visualise the spatial areas where the energy leaks from the guided mode. These channels of energy leakage can be employed to transfer the energy from an external source to the fibre core, suggesting that the created fibres with a minimal-microstructure cladding can be used as components of laser systems or as nonlinear-optical elements.

Due to the high degree of light confinement in the fibre core, the created fibre allows high efficiencies of spectral broadening of femtosecond laser pulses to be achieved. Our experiments were performed with the use of femtosecond pulses produced by a Ti : sapphire laser system. This laser system included a Ti : sapphire master oscillator and a regenerative amplifier and was capable of generating 50-fs pulses of 790-nm radiation. The maximum energy of femtosecond pulses was about 0.2 mJ per pulse, with the radiation energy coupled into the fibre typically ranging from 1 up to 50 nJ. The length of the fibre employed to investigate the spectral broadening of femtosecond laser pulses was equal to 5 cm.

Femtosecond laser pulses propagating through the fibre displayed a considerable spectral broadening starting with energies of radiation coupled into the fibre on the order of a few nanojoules. Figure 2 presents the results of measurements carried out with the use of the fibre with a minimal-microstructure cladding having a core diameter of 3.5 μm. To analyse the results of these experiments, we use an expression from the elementary theory of self-phase modulation to estimate the spectral broadening $\Delta\omega$ of a laser pulse with a frequency ω [15]:

$$\frac{\Delta\omega}{\omega} = \frac{n_2 P_0 L}{cS\tau},$$

where n_2 is the nonlinear refractive index; c is the speed of light; P_0 is the peak power of the laser pulse; S is the effective area of the waveguide mode; τ is the pulse duration, and L is the fibre length. Applying this formula, we arrive at the following estimate on the effective area of the waveguide mode in our fibre: $S \approx 25\ \mu m^2$. This estimate is consistent with the results of direct measurements of the area of the waveguide mode performed on the image of the spatial distribution of the light field intensity at the output end of the fibre. The high degree of light confinement in the fibre core, as can be seen from the results of our experiments, leads to the enhancement of nonlinear-optical interactions in the fibre.

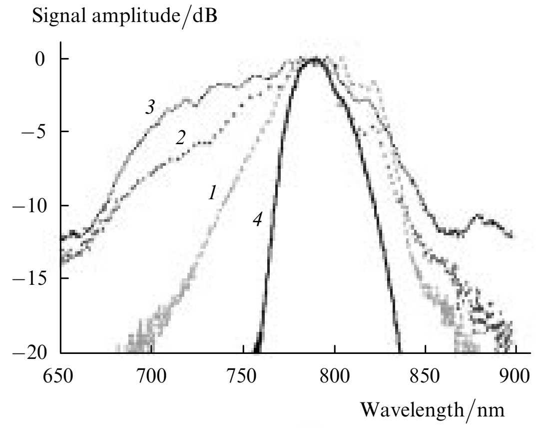

Figure 2. Spectral broadening of femtosecond pulses with energies of (*1*) 6, (*2*) 11, and (*3*) 16 nJ in a minimal-microstructure-cladding fibre with a core diameter of 3.5 μm. The initial duration of pulses coupled into the fibre is 50 fs. The fibre length is 5 cm. The initial spectrum of the laser pulse is shown by curve (*4*).

Minimal-structure-cladding fibres with a core diameter ranging from 1 up to 2.5 μm allowed us to observe enhanced spectral broadening of femtosecond pulses propagating through the fibre core. In particular, Ti:sapphire-laser pulses with an initial duration of 50 fs and an energy of 10 nJ had a bandwidth of 180 nm at the 1/e level at the output of an MS fibre with a core diameter of 2 μm and the length of 6 cm. Supercontinuum emission with a bandwidth exceeding an octave was observed when the energy of laser pulses coupled into the fibre was increased up to 30 nJ. The details of experiments devoted to the generation of supercontinuum in these fibres will be published elsewhere [16].

Thus, the created microstructure optical fibre whose cladding consists of a single cycle of air holes and the minimum core diameter is 1 μm supports guided modes with a strongly confined light field displaying the C_{6v} point-group spatial symmetry. Fibres of this type can be employed for spectral transformations of ultrashort pulses for the purposes of spectroscopy, optical metrology, optical coherence tomography, and pulse compression. Such fibres allow a methodologically consistent analysis of the basic properties of guided modes in microstructure fibres. A high refractive index step between the core and the cladding in the created fibres strongly confines the light field in the fibre core, suggesting the way of substantially enhancing nonlinear-optical interactions of low-power femtosecond laser pulses.

Acknowledgements. We are grateful to A.B. Fedotov, A.N. Naumov, D.A. Sidorov-Biryukov, and S.O. Konorov for their help and stimulating discussions. This study was supported in part by the President of the Russian Federation (Grant No. 00-15-99304), the Russian Foundation for Basic Research (Grant No. 00-02-17567), the Volkswagen Foundation (Grant I/76 869), the CRDF Award No. RP2-2266, and the 'Fundamental Metrology' Federal Program of the Russian Federation.

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