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Controlled light localisation and nonlinear-optical interactions of short laser pulses in holey fibres

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Abstract. **The influence of the structure of holey-fibre cladding on the effective waveguide mode area and the spectral broadening of femtosecond pulses of titanium–sapphire and forsterite lasers is experimentally studied. These experiments demonstrate that the increase in the air-filling fraction of the holey-fibre cladding may substantially enhance the spectral broadening of laser pulses due to the increase in the degree of light localisation in the fibre core.**

Keywords: *nonlinear-optical effects, ultrashort laser pulses, optical fibres.*

1. Introduction

Holey fibres (HFs) [1 – 11] is a new type of optical waveguides, which is now gaining more and more recognition in modern optics and optical technologies. The cladding in such fibres consists of a two-dimensional (often periodic) array of closely packed capillaries drawn at a high temperature. A fibre with a missing hole may serve as a fibre core [1, 2], guiding light due to total internal reflection. Several missing fibres at the centre of the structure may also provide waveguiding, forming a hollow core [6]. In the latter case, waveguiding in HFs is similar to waveguiding in hollow fibres, but optical losses of HF modes are much lower than optical losses inherent in waveguide modes of hollow fibres.

One of the main advantages of holey fibres is that they support single-mode waveguiding within a remarkably broad spectral range [2, 3]. Other important advantages of these fibres include the possibility to control dispersion by changing the cladding structure [4, 5, 7, 11] and the ability of such fibres to enhance nonlinear-optical processes due to light localisation in the fibre core [12, 13].

Fabrication of HFs with a sub-500-nm-pitch two-dimensional periodic cladding [14 – 16] has recently allowed photonic band gaps tunable within the range from 930 to 1030 nm to be observed in transmission spectra of HFs.

Due to their remarkable properties, holey fibres offer new solutions to many problems of fibre optics [1 – 11], nonlinear optics [8 – 13], atomic optics [17, 18], the physics of photonic crystals and quantum electrodynamics [3, 14 – 18], medical optics [19], optical data transmission [12], and creation of optical frequency synthesisers and high-precision optical frequency measurements [20].

In this paper, we investigate the influence of the structure of the HF cladding on the effective area of the waveguide mode and the spectral broadening of ultrashort laser pulses propagating in holey fibres with different core and cladding geometries and various air-filling fractions of the HF cladding.

2. The waveguide mode area and the efficiency of self-phase modulation in a holey fibre

The efficiency of nonlinear-optical processes in HFs, including the processes resulting in spectral broadening of femtosecond pulses, can be controlled by changing the localisation degree of the light field in the fibre core. The calculation of the light-field distribution in the cross section of a holey fibre is a rather complicated problem. Several numerical methods have been recently developed for such simulations (e.g., see [8, 21]). Below, we will illustrate our idea of controlling field localisation in an HF core using a simple qualitative approach. A microstructured cladding of an HF will be characterised by the effective refractive index [2]

$$n_{\mathrm{cl}} = \frac{\beta_{\mathrm{cl}}}{k}, \tag{1}$$

where β_{cl} is the propagation constant of the fundamental space-filling mode, i.e., the fundamental mode of an infinite structure obtained by periodically translating a unit cell of the HF cladding; $k = 2\pi/\lambda$; λ is the radiation wavelength. Representing the effective refractive index of the cladding in the form (1), we take into account the real spatial distribution of the light field in the fibre cladding. The profile of

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such a distribution can be estimated from two-dimensional images of radiation intensity distribution in the cross section of an HF.

To provide a rough estimate for the effective radius a of the waveguide mode in the HF core, we will employ the following formula for the radius of the waveguide mode in a conventional step-index fibre with a solid cladding [22]:

$$a = w + \frac{1}{p}, \tag{2}$$

where w is understood as the HF core radius; $p^2 = \beta_c^2 - \beta_{cl}^2$ is the transverse component of the wave vector in the fibre core;

$$\beta_c = n_c k \cos\varphi \tag{3}$$

is the propagation constant of the waveguide mode in the fibre core, which meets the conditions

$$n_c k \geqslant \beta_c \geqslant \beta_{cl}; \tag{4}$$

n_c is the refractive index of the fibre core; φ is the incidence angle corresponding to the considered waveguide mode.

Using Eqs (1)–(3), we arrive at the following estimate for the radius of the waveguide mode:

$$a = w + \frac{\lambda}{2\pi(n_c^2\cos\varphi - n_{cl}^2)^{1/2}}. \tag{5}$$

As can be seen from Eqn (5), the localisation degree of light field in a fibre core can be increased and, consequently, the efficiency of nonlinear-optical processes can be improved by increasing the difference between the refractive index of the core n_c and the effective refractive index of the cladding n_{cl}. Physically, the field localisation degree can be increased in fibres with large differences between n_c and n_{cl} due to the fact that modes with large differences of propagation constants may exist in the core and the cladding of such fibres. The transverse component p of the wave vector of the mode propagating in the fibre core decreases under these conditions, which implies higher localisation degrees of light field in the fibre core.

The relative deviation of the the frequency ω of a laser pulse induced by self-phase modulation (SPM) due to the nonlinear additive to the refractive index $\Delta n = n_2 I$ can be estimated with the use of the formula [23]

$$\frac{\Delta\omega}{\omega} = \frac{n_2}{c}\frac{P_0}{S\tau}L, \tag{6}$$

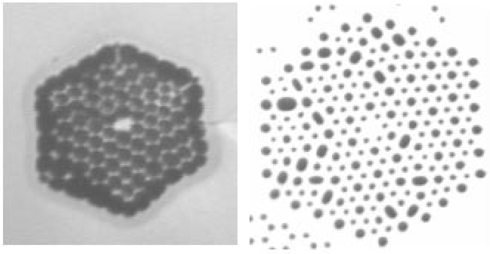
where c is the speed of light; P_0 is the peak power of the laser pulse; $S = \pi a^2$ is the effective waveguide mode area; τ is the pulse duration; L is the fibre length.

One can see from Eqn (6) that a decrease in S due to the increase in the air-filling fraction in a fibre core enhances the SPM-induced spectral broadening of a laser pulse. The difference between the refractive indices of the core and the cladding in HFs can be increased by changing the structure of the cladding and making the air holes in the cladding larger. In our study, we employed this method to control light localisation in the fibre core and to enhance nonlinear-optical processes in holey fibres.

3. Holey fibres

The technology employed to fabricate HFs used in our experiments was similar to the process described in our earlier papers [1, 13–16]. Briefly, the fabrication process involved drawing identical glass capillaries stacked into a periodic preform at an elevated temperature, cutting the resulting structure into segments, and repeating the technological cycle again. Special precautions were taken to fill in the air gaps between the capillaries when it was necessary.

This procedure allowed the fabrication of HFs with a pitch of the cladding ranging from 400 nm up to 32 μm (see [14–16]). The ratio of the hole diameter to the pitch of the structure was varied within a broad range (Fig. 1). A capillary made of glass of another type was used to produce the fibre core.



a b

Figure 1. Cross sectional microscopic images of holey fibres with the air-filling fractions of the cladding equal to (a) 65 and (b) 16 %. The pitch of the cladding is equal to 2 μm.

4. Experimental procedure

Titanium–sapphire and forsterite femtosecond laser systems were employed in our experiments as sources of ultrashort light pulses. A Ti:sapphire laser consisted of a master oscillator and a multipass amplifier pumped by the second harmonic of a pulsed Nd : YAG laser, operating at a repetition rate of 1 kHz. Laser pulses produced by this system had a duration $\tau \simeq 70$ fs and an energy up to 1 mJ.

Experiments were also performed with an all-solid-state self-starting Cr^{4+}:forsterite laser [19, 24], which produced light pulses with durations less than 40 fs and radiation wavelength tunable within the range from 1.21 to 1.29 μm. A nonlinear crystal was used to double the frequency of this radiation. The master oscillator of this laser system included a Nd:YAG-pumped 19-mm Cr^{4+}: forsterite crystal. The cavity of the master oscillator consisted of a high reflector and a 4.5 % output coupler with a radius of curvature equal to 100 mm. As an option, a semiconductor-saturable-absorber reflector could be used as a rear cavity mirror. Self-starting mode locking in this system can be implemented both with and without semiconductor saturable-absorber mirrors.

The energy of laser radiation in our experiments was varied using a half-wave plate and a Glan prism. A micro-objective used to couple laser radiation into a holey fibre provided a coupling efficiency of 10 % – 25 %, depending on the size of the fibre core. The spectra of light pulses emerging from the fibre were analysed with a spectrometer and a CCD camera.

5. Results and discussion

To study the possibilities of controlling nonlinear-optical processes in holey fibres by changing the ratio of refractive indices of the core and the microstructured cladding, we employed short HF samples with a length of 3 – 4 cm. Spectral broadening was investigated for 70-fs Ti:sapphire laser pulses coupled into HF samples within the range of radiation energies where no supercontinuum generation was observed.

The data presented in Figs 2 – 4 and in the text below are normalised to include coupling losses of radiation, which were estimated by measuring the energies of light pulses at the output of HF samples. The appearance of the anti-Stokes component in the spectrum of a pulse emerging from a holey fibre, indicating the initial phase of supercontinuum generation, was observed with laser pulse powers of the order of 10 kW (Fig. 2). The length of fibres was also chosen sufficiently small in order to avoid effects related to group-velocity dispersion, which would otherwise have a considerable influence on short pulses (Fig. 3).

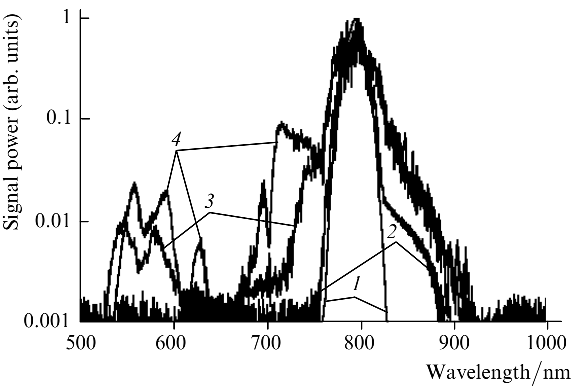


Figure 2. The spectra of Ti:sapphire laser pulses with $\tau = 70$ fs (*1*) at the input and (*2*–*4*) at the output of a holey fibre with a length of 3 cm and the pitch of the cladding equal to 3 μm for pulse energies of (*2*) 0.7, (*3*) 15, and (*4*) 35 nJ.

The bandwidth of laser pulses transmitted through a holey fibre increased with the growth in the energy of laser pulses (Fig. 4). At the initial phase, this process can be approximately described by Eqn (6), which allows an estimation of the influence of the cladding structure and the air-filling fraction of the cladding on the efficiency of SPM, resulting in the spectral broadening of laser pulses.

Figure 4 presents the spectral broadening of Ti:sapphire laser pulses at $\lambda = 800$ nm and $\tau = 70$ fs at the output of a 2-μm-pitch HF sample with a length of 3 cm and different air-filling fractions of the cladding as a function of radiation energy coupled into the fibre. The results of these measurements show that the increase in the air-filling fraction of the HF cladding leads to a considerable enhancement of self-phase modulation. In particular, by increasing the air-filling fraction of the cladding from 16 up to 65 %, we observed the enhancement of spectral broadening of Ti:sapphire laser pulses by a factor of about 1.5.

The ratio of the effective mode areas in holey fibres with different structures can be estimated, in accordance with Eqn (6), as the ratio of the slopes of the spectral broadening of laser pulses at the output of a fibre as a function of radi-

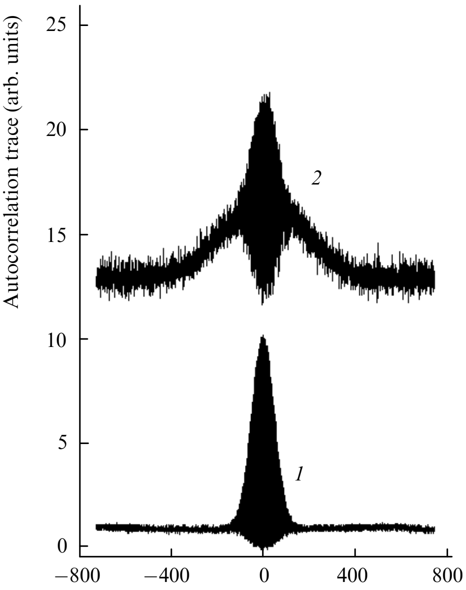


Figure 3. Autocorrelation traces of fundamental radiation pulses of a forsterite laser (*1*) at the output of the laser system and (*2*) at the output of a holey fibre with a length of 15 cm and the pitch of the cladding equal to 15 **μm.**

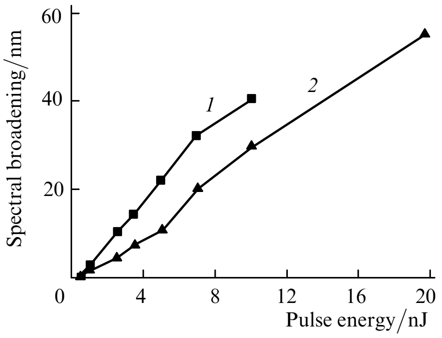


Figure 4. The spectral broadening of Ti : sapphire laser radiation pulses with $\lambda = 800$ nm and $\tau = 70$ fs transmitted through a 2-μm-pitch HF sample with a length of 3 cm and the air-filling fraction equal to (*1*) 65 and (*2*) 16 % as a function of radiation energy coupled into the fibre.

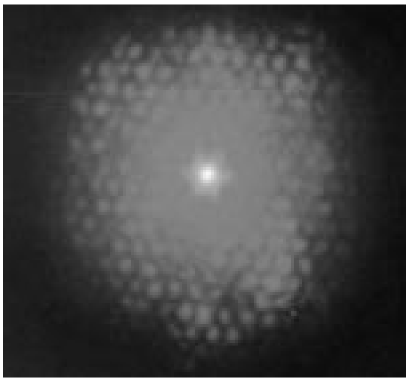


Figure 5. Waveguiding of the second harmonic of forsterite laser radiation with $\tau = 40$ fs through a photonic-crystal fibre. A bright spot at the centre corresponds to the waveguide mode excited in the fibre core.

ation energy coupled into the fibre (Fig. 4). Such estimates for the compression ratio of the effective waveguide mode in a holey fibre agree well with the results of measurements based on the imaging of the output fibre end (Fig. 5). This circumstance indicates that the enhancement of spectral broadening of laser pulses in our experiments is mainly due to the decrease in the effective mode area of radiation propagating in a holey fibre.

6. Conclusions

Thus, our experiments indicate the possibility of controlling the properties of light localisation and the efficiency of nonlinear-optical interactions of ultrashort laser pulses in holey fibres by changing the structure of a fibre. By increasing the air-filling fraction in the cladding of a holey fibre from 16 up to 65 %, we were able to improve the efficiency of spectral broadening of 70-fs pulses of Ti : sapphire laser radiation by a factor of about 1.5 due to the increase in the light localisation degree in the fibre core.

The possibility of changing the parameters of waveguide modes by modifying the structure of the HF cladding, which was demonstrated in this paper, is also very important for controlling the dispersion properties of holey fibres. Creation of holey and photonic-crystal fibres with controllable dispersion would allow a considerable progress to be achieved in many areas, including fibre optics, information technologies, ultrafast optics, and nonlinear optics and spectroscopy.

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