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Laser breakdown with millijoule trains of picosecond pulses transmitted through a hollow-core photonic-crystal fibre

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Abstract
Sequences of picosecond pulses with a total energy in the pulse train of about 1 mJ are transmitted through a hollow-core photonic-crystal fibre with a core diameter of approximately 14 μm. The fluence of laser radiation coupled into the core of the fibre under these conditions exceeds the breakdown threshold of fused silica by nearly an order of magnitude. The laser beam coming out of the fibre is then focused to produce a breakdown on a solid surface. Parameters of laser radiation were chosen in such a way as to avoid effects related to the excitation of higher order waveguide modes and ionization of the gas filling the fibre in order to provide the possibility to focus the output beam into a spot with a minimum diameter, thus ensuring the maximum spatial resolution and the maximum power density in the focal spot.

1. Introduction

Transmission of high-energy laser pulses is a crucial issue in laser technologies. Whenever laser radiation is used to produce a breakdown on a solid surface, in the gas phase, or in a biological tissue, flexible and convenient circuits for the delivery of laser radiation are needed to make the solution technologically attractive, which leaves no alternative to fibre-optic beam delivery. Optical nonlinearities and laser breakdown [1, 2], however, restrict the use of standard optical fibres to laser fluences on the level of breakdown threshold, which is insufficient for numerous applications [3–8], including laser surface processing and modification, laser ignition of combustion processes, laser dentistry and many others. Large-core-area silica fibre intended to guide high-power laser pulses [9, 10] in addition often have durability problems. Approaches to high-energy laser beam delivery allowing these limitations to be overcome would thus promote laser-ablation and laser-processing laser technologies to a qualitatively new level.

Hollow-core fibres allow the fluence of guided laser pulses to be substantially increased relative to standard, silica-core optical fibres, since the gases filling the core of hollow-fibres have much higher laser breakdown thresholds and much weaker optical nonlinearities as compared with fused silica. As shown in [11], hollow-fibres with an internal polymer layer can be used to guide 30 mJ 6–8 ns pulses of Nd : YAG laser radiation. The guidance of 1 ps laser pulses with powers as high as 10 TW has been demonstrated by Borghesi *et al* [12]. Cros *et al* [13] has recently predicted the possibility to use hollow-fibres for guiding subpicosecond laser pulses with intensities up to 10^{18} W cm^{-2} with no damage of fibre walls. The modes guided by hollow-fibres are, however, leaky in their nature, with propagation constants of guided modes in such fibres having nonzero imaginary parts. The magnitude of optical losses in hollow-fibres α increases as a^{-3} with a decrease in the fibre core radius a [14], limiting the guidance length of high-power laser pulses. Excitation of higher order waveguide modes, distorting the beam profile at the output of hollow-fibres, is another problem, which limits the power density and the spatial resolution attainable with high-power laser beams transmitted through hollow-core fibres.

In this paper, we will demonstrate that hollow-core photonic-crystal fibres offer new solutions to the problem of guiding high-power laser pulses. Such fibres, demonstrated for the first time by Cregan *et al* [15], have a two-dimensionally periodic cladding (two-dimensional photonic crystal) and a hollow-core. The photonic band gap in the transmission spectrum of a two-dimensional periodic cladding in these fibres provides high reflection coefficients for electromagnetic radiation propagating along the hollow-core of the fibre, allowing a specific regime of waveguiding to be implemented [15, 16]. This mechanism of waveguiding is of special interest for telecommunication applications, opening, at the same time, the ways to improve, under certain conditions, nonlinear-optical processes, including high-order harmonic generation, in a gas medium filling the fibre core [17]. The possibility of using such fibres for laser manipulation of small-size particles was recently demonstrated by Benabid *et al* [18].

Several equally interesting and practically important issues have to be considered to assess the abilities of hollow-fibres to guide high-power laser pulses. One of the most important questions is whether it is possible to couple high-intensity laser radiation into a hollow-fibre core without producing damage on fibre walls. Such a possibility, demonstrated for millijoule trains of picosecond pulses, is one of the main experimental results of this paper. We will also present the results of our experimental and theoretical studies of the excitation of higher order waveguide modes in a hollow-fibre. Such higher order modes result in unwanted energy losses and deteriorate the spatial quality of the output beam [19]. Our experimental analysis and experimental data presented below demonstrate that the excitation of higher order modes can be avoided with an appropriate choice of the parameters of fibres and laser pulses. We will also assess the influence of ionization effects accompanying the propagation of high-power laser pulses through a hollow-fibre [20, 21]. Such effects may open an additional channel of energy losses and distort the spatial profile of the output beam. We will finally experimentally demonstrate the possibility to produce a laser breakdown on a metal surface using picosecond laser pulses transmitted through a hollow-core photonic-crystal fibre.

2. Guiding high-energy pulses through hollow-core photonic-crystal fibres: cross-talk of waveguide modes and ionization effects

Once high-energy radiation has been coupled into a hollow-core of a fibre, we have to be sure that laser radiation transmitted through the fibre possesses a sufficiently high spatial quality to allow focusing into a spot with a minimum diameter, ensuring the maximum spatial resolution and the maximum power density in the focal spot. Therefore, special measures should be taken to avoid the excitation of higher order spatial modes guided by a hollow-fibre. Such higher order modes can be excited by the field of the fundamental mode through the third-order optical nonlinearity of the gas filling the fibre, resulting in unwanted energy losses and deteriorating the spatial quality of the output beam.

The evolution of the envelope of higher order waveguide mode excited in this way can be described analytically, as shown in [19, 22], within the framework of the slowly varying envelope approximation including first-order dispersion effects. This approach provides us with compact and physically illustrative equations for the amplitudes of higher order waveguide modes that build up in the field of the fundamental-mode beam. Below, we will present analytical solutions to these equations and discuss the ways of minimizing optical losses and cross-talk effects in a hollow-fibre.

We start our analysis by representing the field of a light pulse propagating in a gas-filled hollow-fibre as a sum of waveguide modes:

$$E = \frac{1}{2}\sum_n f_n(\rho)A_n(z,t)\exp\left[-\mathrm{i}\omega t + \left(\mathrm{i}K_n - \frac{\alpha_n}{2}\right)z\right] + \text{c.c.}, \tag{1}$$

where ω is the central frequency of the light pulse, $f_n(\rho)$, $A_n(z,t)$, K_n, and α_n are the transverse field distribution, the slowly varying pulse envelope, the propagation constant, and the attenuation coefficient, ρ is the distance from the axis of the hollow-fibre.

We assume that the attenuation coefficient for the considered light pulse is small, and the wavelength is much less than the inner radius of the hollow-fibre a [23]:

$$\frac{\omega a}{c} \gg 1, \tag{2}$$

$$\left|\frac{K_n c}{\omega n_{\text{core}}(\omega)} - 1\right| \ll 1, \tag{3}$$

where $n_{\text{core}}(\omega)$ is the refractive index of the gas filling the fibre at the frequency ω. Under these conditions, we can employ approximate analytical solutions for the transverse field distribution, propagation constant and the attenuation coefficient of an electromagnetic field in a hollow-fibre. In the case of EH_{1n} modes of a hollow-fibre, we have [14, 23]:

$$f_n(\rho) = J_0\left(\frac{u_n\rho}{a}\right). \tag{4}$$

Here, $J_0(x)$ is the zeroth-order Bessel function, u_n is the eigenvalue of the EH_{1n} mode.

$$K_n \approx \frac{\omega n_{\text{core}}(\omega)}{c}\left[1 - \frac{1}{2}\left(\frac{u_n c}{a\omega n_{\text{core}}(\omega)}\right)^2\right], \tag{5}$$

$$\alpha_n \approx \frac{2}{a n_{\text{core}}(\omega)}\left(\frac{u_n c}{a\omega}\right)^2 \frac{(\varepsilon_{\text{clad}}(\omega) + n^2_{\text{core}}(\omega))}{2n^2_{\text{core}}(\omega)(\varepsilon_{\text{clad}}(\omega) - n^2_{\text{core}}(\omega))^{1/2}}, \tag{6}$$

where $\varepsilon_{\text{clad}}(\omega)$ is the dielectric function of the fibre cladding at the frequency ω.

Then, assuming that the main fraction of light energy is concentrated in the fundamental, EH_{11} waveguide mode, we arrive at the following equation for the envelope of the EH_{12} waveguide mode:

$$\frac{\mathrm{d}A_2(z,\eta_2)}{\mathrm{d}z} + \frac{\alpha_2}{2}A_2(z,\eta_2) = \mathrm{i}\nu A_1(z,\eta_1)|A_1(z,\eta_1)|^2 \times \exp(-\mathrm{i}\Delta k_{21}z). \quad (7)$$

Here, $\eta_n = (t - z/v_n)/\tau$, the subscripts 1 and 2 are related to the EH_{11} and EH_{12} waveguide modes, $\Delta k_{21} = K_2 - K_1$ is the phase mismatch characterizing the cross-talk of waveguide modes, and the nonlinear coefficient ν is given by

$$\nu = \frac{3\pi\omega^2}{2K_2c^2}\chi^{(3)}(\omega;\omega,-\omega,\omega)\frac{\iint f_2(\rho)[f_1(\rho)]^3\rho\,\mathrm{d}\rho\,\mathrm{d}\theta}{\iint [f_2(\rho)]^2\rho\,\mathrm{d}\rho\,\mathrm{d}\theta}. \quad (8)$$

Now, neglecting the influence of the higher order waveguide modes on the fundamental mode, we can solve equation (7) analytically, arriving at the following expression for the envelope of the EH_{12} waveguide mode:

$$A_2(z,\eta_2) = \iota\gamma_2(A_{10}(\eta_1))^3 \exp\left(\mathrm{i}\frac{\gamma_1}{\alpha_1}|A_{10}(\eta_1)|^2 - \frac{\alpha_2}{2}z\right) \times \int_0^z \exp\left(\left(\frac{\alpha_2}{2} - \frac{3\alpha_1}{2}\right)z' - \iota\left(\frac{\gamma_1}{\alpha_1}|A_{10}(\eta_1)|^2\exp(-\alpha_1 z') + \Delta k_{21}z'\right)\right)\mathrm{d}z'. \quad (9)$$

Expression (9) describes the process of excitation of higher order modes in a hollow-fibre and allows the energy lost from the fundamental mode due to the excitation of higher order waveguide modes to be assessed. Formulae similar to equation (9) can be easily derived for other higher order waveguide modes.

The total magnitude of energy losses per unit length of a hollow-fibre can be represented as a sum of losses in all the waveguide modes:

$$\frac{\mathrm{d}W}{\mathrm{d}z} = -\sum_n \alpha_n W_n, \quad (10)$$

where $W = \sum_n W_n$, with

$$W_n(z) = \frac{c}{8\pi}\int \mathrm{d}\eta|A_n(z,\eta)|^2\int \mathrm{d}\varphi\int \rho\,\mathrm{d}\rho|f_n(\rho)|^2, \quad (11)$$

being the energy of the EH_{1n} mode in the hollow-fibre.

Now, if we restrict our analysis, as before, to two lowest order waveguide modes and assume that radiation energy is mainly lost through the EH_{11} and EH_{12} modes, equation (10) is reduced to

$$\frac{\mathrm{d}W}{\mathrm{d}z} = -\alpha_1 W_1 - \alpha_2 W_2, \quad (12)$$

where $W = W_1 + W_2$ and W_1 and W_2 are the energies of the EH_{11} and EH_{12} modes.

Provided that $W_1 \gg W_2$, the mean coefficient of losses can be represented as

$$\alpha = \alpha_1\frac{\langle W_1\rangle}{\langle W\rangle} + \alpha_2\frac{\langle W_2\rangle}{\langle W\rangle} \approx \alpha_1 + \alpha_{\mathrm{hm}}, \quad (13)$$

where $\alpha_{\mathrm{hm}} = \alpha_2\langle W_2\rangle/\langle W\rangle$ is the coefficient characterizing additional energy losses through the EH_{12} mode, $\langle W\rangle = \sum_n\langle W_n\rangle$ and

$$\langle W_n\rangle = \frac{\int_0^L W_n(z)\,\mathrm{d}z}{L} \quad (14)$$

is the energy in the EH_{1n} mode averaged over the fibre length L.

Numerical simulations of the propagation of a light pulse through a hollow-fibre were performed with the use of equations (9)–(14) for a pulse with a Gaussian envelope,

$$A_{10} = A_0\exp\left(-\frac{\eta^2}{2}\right).$$

It was assumed that a hollow-fibre is filled with argon at the pressure $p = 1$ atm. The dielectric constant of the fibre cladding was set equal to $\varepsilon_{\mathrm{clad}} = 2.25$ (fused silica). The data for gas dispersion was taken from [24]. The radiation wavelength was 800 nm, and the pulse duration was $\tau = 35$ fs. The cubic nonlinear-optical susceptibility $\chi^{(3)}(\omega;\omega,-\omega,\omega)$, which appears in expressions for the nonlinear coefficients γ and ν, was estimated from the data for the nonlinear refractive index n_2 presented in [25, 26], $n_2 = 9.8\times10^{-27}\ \mathrm{cm^2\,erg^{-1}\,s^{-1}}$.

Levels of grey scale in figure 1 represent the energy of the EH_{12} waveguide mode normalized to the total pulse energy W_2/W calculated in accordance with equations (9) and (11) as a function of the fibre length L and the inner radius of the fibre a. As can be seen from the presented results, due to the decrease in the phase mismatch between the EH_{11} and EH_{12} modes, already with an inner radius $a = 150\ \mu$m, 20% of energy of a 800 nm light pulse with an intensity of $10^{14}\ \mathrm{W\,cm^{-2}}$ is converted into the EH_{12} mode within the coherence length. An oscillatory character of the dependence of the ratio W_2/W on the fibre length L is due to variations in the phase of energy exchange between the EH_{11} and EH_{12} modes, the energy of the EH_{12} mode reaching its maximum around odd multiples of the mode-cross-talk coherence length: $L = l_{\mathrm{coh}}$, $L = 3l_{\mathrm{coh}}$, $L = 5l_{\mathrm{coh}}$ etc. Excitation of higher order modes is, however, of virtually no importance, as can be seen from figure 1, in the case of hollow-fibres with core diameters less than 100 μm. The results of experimental studies presented in section 4 confirm our conclusion that the excitation of higher order modes can be

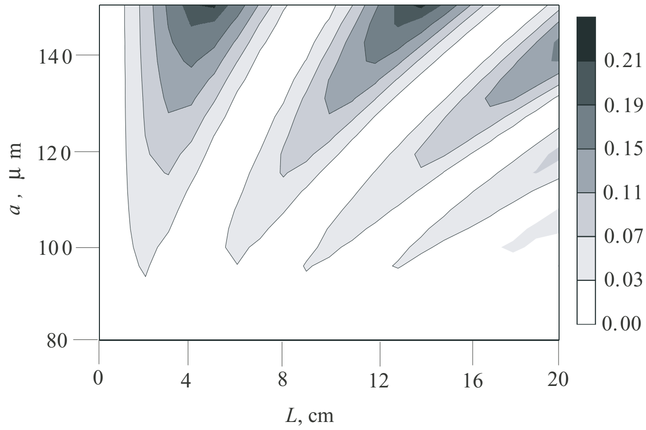

Figure 1. The energy of the EH_{12} waveguide mode W_2 normalized to the total energy W as a function of the length L and the inner radius a of a hollow-fibre filled with 1 atm of argon for radiation with a wavelength of 800 nm and an intensity of $10^{14}\ \mathrm{W\,cm^{-2}}$.

avoided with an appropriate choice of the parameters of fibres and laser pulses.

When high-power laser pulses are transmitted through a hollow-fibre, ionization of the gas filling the fibre may open an additional channel of energy losses and distort the spatial profile of the output beam. Estimates of the ionization probability with the use of the Ammosov–Delone–Krainov formula [27] for typical parameters of gases used in hollow-fibre experiments show that ionization effects start to play an important role for laser radiation intensities exceeding $I_0 \approx 10^{14}\,\mathrm{W\,cm^{-2}}$. Keeping in mind this estimate, we employed laser beams with lower radiation intensities for our experiments.

In the case of short laser pulses, group-velocity dispersion results in pulse lengthening. The influence of such effects, however, can be reduced to a minimum in the case of hollow-core photonic-crystal fibres, since the dispersion properties of guided modes can be tailored in this case by changing the structure of the fibre and since the group-velocity dispersion of gases filling the core of these fibres is much lower than the group-velocity dispersion inherent in fused silica fibres. As shown in [19, 22], the mode-cross-talk coherence length for typical conditions of hollow-fibre experiments is much less than the mode walk-off and the dispersion spreading lengths. This result allows us to neglect group-delay and dispersion spreading effects in our numerical simulations and partially justifies the use of the slowly varying envelope approximation in our analysis.

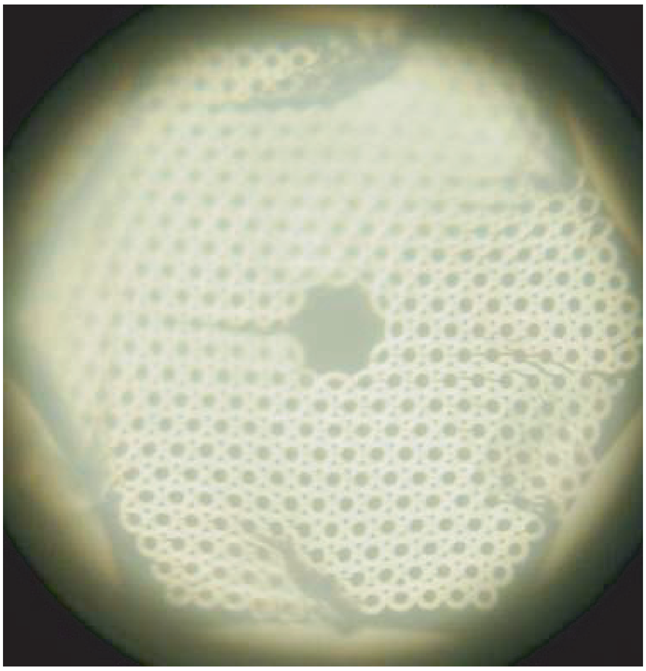

Figure 2. Cross-sectional image of a microstructure fibre with a two-dimensionally periodic cladding consisting of an array of identical capillaries. This periodic cladding supports guided modes in the hollow-core of the fibre due to the high reflectivity of a periodic structure within photonic band gaps. The hollow-core of the fibre is formed by removing seven capillaries from the central part of the structure. The period of the structure in the cladding is about 5 μm and the core diameter is about 13 μm.

3. Experimental

Microstructure fibres were fabricated with the use of a preform consisting of a set of identical glass capillaries. Seven capillaries were removed from the central part of the preform for the hollow-core of photonic-crystal fibres. The cross-section image of a fibre fabricated by drawing such a preform is presented in figure 2. A typical period of the structure in the cladding of the fibre shown in figure 1 is about 5 μm. The diameter of the hollow-core of the fibre is then approximately equal to 13 μm. The length of fibre samples employed in our experiments ranged from several centimetres up to 1 m.

The laser system used in our experiments included a Nd : YAG master oscillator with passive mode-locking and Q-switching, a system for single-pulse selection, and an amplification stage [28]. The laser system was capable of generating either single pulses with a wavelength of 1.064 μm, duration of about 40 ps, and energy up to 10 mJ (with the single-pulse selection system switched on) or trains of 15–20 40 ps pulses with a total energy up to 5 mJ. These pulse trains were preceded by a microsecond-scale sequence of pulses with an energy two-orders of magnitude lower than the energy of the main train of pulses. The time interval between the pulses in the train was equal to 8 ns.

To investigate the spectrum of modes guided in the hollow-core of photonic-crystal fibres, we used a diaphragm to separate radiation transmitted through the hollow-core from radiation guided by the cladding. The spectra of modes supported by the hollow-core of photonic-crystal fibres were measured within the range of wavelengths from 450 up to 1000 nm. These spectra displayed characteristic well-pronounced isolated peaks (figures 3–5). Similar peaks in transmission spectra of hollow photonic-crystal fibres have been observed earlier by Cregan *et al* [15]. The origin of these peaks is associated with the high reflectivity of a periodically structured fibre cladding within photonic band gaps [15, 16, 29, 30], which substantially reduces radiation losses in guided modes within narrow spectral ranges. Radiation with wavelengths lying away from photonic band gaps of the cladding leaks from the hollow-core. Such leaky radiation modes are characterized by high losses,

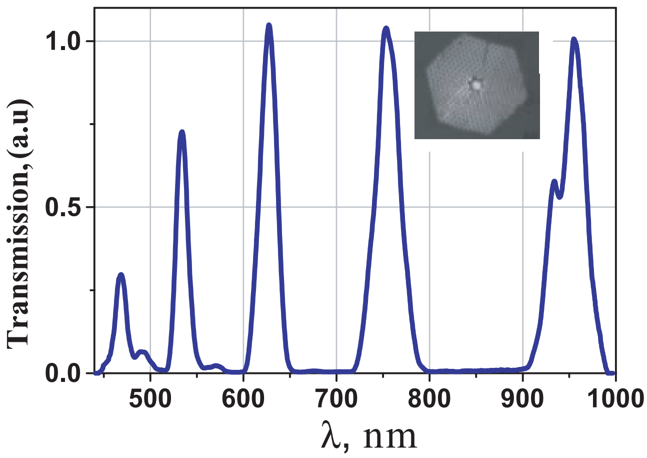

Figure 3. Transmission spectrum of a hollow photonic-crystal fibre (figure 2) with a period of the structure in the cladding of about 5 μm and a core diameter of approximately 13 μm. The inset shows radiation intensity distributions measured in the cross-section of the fibre, supporting the fundamental waveguide mode of 633 nm diode-laser radiation.

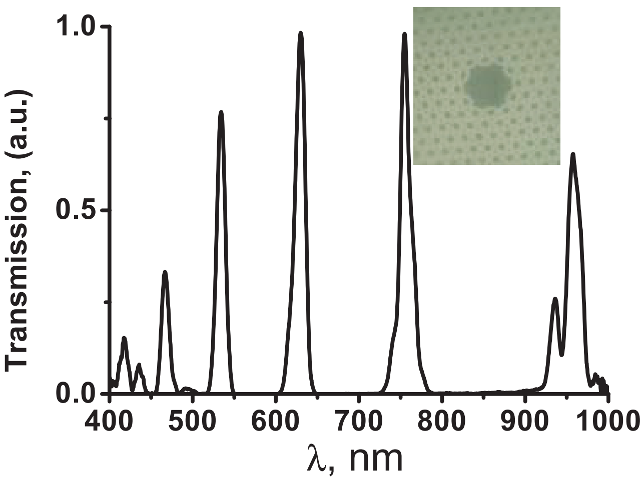

Figure 4. Transmission spectrum of a hollow-core photonic-crystal fibre designed to provide a transmission peak at 532 nm. The inset shows the cross-section image of this fibre.

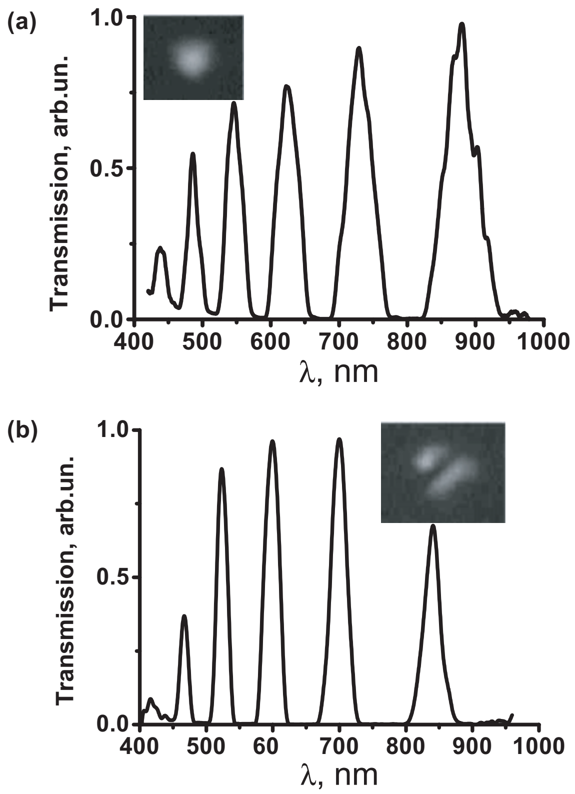

Figure 5. Transmission spectra of hollow photonic-crystal fibres with a period of the structure in the cladding of about 5 μm, different air filling fractions of the cladding, and the core diameter of approximately 13 μm. The insets show radiation intensity distributions measured in the cross-section of fibres, supporting the fundamental (*a*) and higher order (*b*) waveguide modes of 1.06 μm Nd : YAG-laser radiation.

giving virtually no contribution to the signal at the output of the fibre. Modifying the core-cladding configuration of the fibre or even slightly changing the geometric sizes of the cladding, we were able to tune transmission peaks in the spectra of fibre modes (cf figures 3–5), thus achieving maximum transmission for a desirable radiation wavelength. Changing the fibre structure, we could also modify the transverse distribution of radiation intensity in the fibre core, implementing waveguiding in the fundamental and higher order guided modes (see the insets in figures 3–5).

4. Results and discussion

To demonstrate a high transmission of our photonic-crystal fibre within the wavelength ranges corresponding to the photonic band gap of the cladding, we used 633 nm radiation of a diode-laser. This wavelength falls within one of the passbands in figure 3, corresponding to the guided modes of our fibre. The maximum throughput achieved with an 8 cm photonic-crystal fibre at this wavelength is estimated as 20%. This result demonstrates that optical losses in hollow-core photonic-crystal fibres are much lower than typical optical losses in leaky modes of standard hollow-fibres with a solid cladding. Indeed, the magnitude of optical losses of 633 nm radiation guided in the fundamental mode of a standard hollow-fibre with a solid cladding and a core diameter of 13 μm would be on the order of 10–15 cm^{-1}. Optical losses in such a fibre would be unacceptably high even for fibres with a length of a few centimetres.

A high transmission of laser pulses was also achieved in experiments with 532 nm second-harmonic radiation of the picosecond Nd : YAG laser described in section 3. A photonic crystal fibre with a transmission peak at 532 nm was designed for these experiments (figure 4). The cross-section image of this fibre is shown in the inset to figure 4. Less than 20% of 532 nm radiation energy was lost in a few-centimetres long sample of such a fibre.

To show the ability of hollow-core photonic-crystal fibres to transport high-energy laser pulses, we studied the transmission of picosecond pulse trains of 1.06 μm radiation produced by the Nd : YAG laser system described in section 3. Although the design of the photonic-crystal fibre is still to be optimized for this wavelength, this radiation was chosen in view of many practical applications, including laser-ablation, material processing, and micromachining technologies, as well as laser dentistry systems.

The choice of parameters of laser pulses of 1.06 μm radiation for our experiments was based on the results of our theoretical analysis and the recipes of earlier theoretical studies [19]. In order to avoid effects related to the ionization of the gas filling the fibre core and the excitation of higher order waveguide modes, we chose to work with trains of 40 ps pulses with an energy around 1 mJ. Such pulse trains were coupled into the hollow-core of a 20 mm photonic-crystal fibre with a period of the cladding of approximately 5 μm. The transmission of photonic-crystal fibres for 1.06 μm radiation in our experiments was on the order of 10%. The above-described experiments with 633 and 532 nm radiation, however, show that the transmission can be substantially improved by accurately matching the position of the relevant peak in the transmission spectrum of the fibre with the wavelength of laser radiation coupled into the fibre.

Our photonic-crystal fibres allowed us to transport trains of 40 ps pulses with a total energy up to 1 mJ. Such an energy of laser pulses coupled into a hollow-core of a photonic-crystal fibre with a core diameter of $\sim$14 μm corresponds to a fluence of 90 J cm^{-2}, which is an order of magnitude higher than the typical breakdown threshold of fused silica. With 0.8 mJ pulse trains coupled into the fibre, the energy of radiation transmitted through the fibre and a collimating objective was equal to 70 μJ. Different types of photonic-crystal fibres enabled us to deliver 1.06 μm laser radiation in either fundamental or higher order waveguide modes. The spatial beam profile in figure 5(*a*) indicates a robust single-mode waveguiding of 1.06-μm radiation in the fundamental mode of the fibre. The image presented in figure 5(*b*), on the other hand, is typical of a higher order mode waveguiding regime. Importantly, no cross-talk between the fundamental and higher order waveguide modes has been observed in our experiments, which agrees well with the results of our calculations presented in section 2. A high quality of beam profiles at the output of the fibre indicates also that ionization effects play a negligible role as laser pulses with above-specified parameters are guided through the fibre, which is also consistent with our theoretical predictions.

Focused on the surface of a steel target with an additional microobjective, this radiation induced a laser breakdown on the metal surface (figure 6). This result demonstrates the potential of hollow-core photonic-crystal fibres to guide laser pulses with fluences sufficient to initiate laser-induced breakdown of different materials. Laser pulses with higher energies can be guided in the single-fundamental-mode regime in hollow-core photonic-crystal fibres with larger core diameters. The results of our calculations presented in section 2 demonstrate that the hollow-core photonic-crystal fibres with core diameters up to 130–150 μm can be employed to guide laser pulses without noticeable cross-talk between the fibre modes. Since no evidence of ionization effects has been observed in our experiments, we can scale the results of our measurements, requiring the constancy of the laser field intensity to avoid ionization effects, to estimate the maximum energy of light pulses that can be transmitted through a hollow-core fibre in a single-mode regime with no cross-talk and no ionization in hollow-core photonic-crystal fibres. With this approach, we can predict that picosecond pulse trains with an energy up to 0.1 J can be transported with the use of hollow-core photonic-crystal fibres.

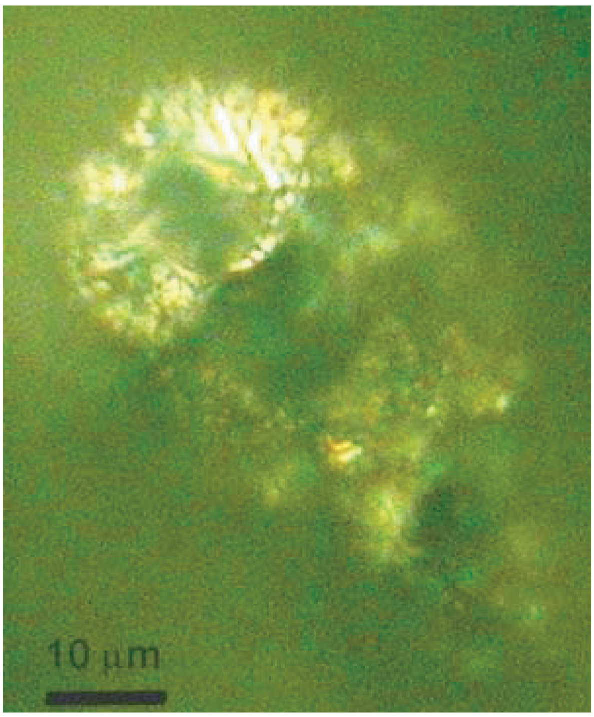

Figure 6. A microscope image of a trace produced on the surface of a stainless steel target moving with respect to the laser beam by a sequence of picosecond pulses transmitted through a hollow-core photonic-crystal fibre.

5. Conclusion

The results of experimental and theoretical studies presented in this paper demonstrate that hollow-core photonic-crystal fibres offer new solutions to the problem of transportation of high-power laser pulses. We demonstrated that sequences of picosecond pulses with a total energy in the pulse train of about 1 mJ can be transmitted through a hollow-core photonic-crystal fibre with a core diameter of approximately 14 μm with no ionization and cross-talk effects. The fluence of laser radiation coupled into the core of the fibre under these conditions exceeds the breakdown threshold of fused silica by nearly an order of magnitude. The results of our experimental studies demonstrate that the excitation of higher order modes can be avoided with an appropriate choice of the parameters of fibres and laser pulses. The laser beam coming out of the fibre possesses a high spatial quality characteristic of single-mode waveguiding. When focused on a metal target, this beam induced a breakdown on the target surface, demonstrating the potential of hollow-core photonic-crystal fibres as beam-delivery components for laser-ablation, laser micromachining, and laser microprocessing applications. Our estimates show that picosecond pulse trains with an energy up to 0.1 J can be transported through hollow-core photonic-crystal fibres with properly chosen parameters in a single-mode regime with no cross-talk and no ionization. The proposed technique of transportation of high-energy laser pulses also offers much promise for the delivery of high-power femtosecond laser pulses, as dispersion pulse spreading can be substantially reduced in the case of photonic-crystal fibres with an appropriate design of the fibre cladding.

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