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Propagation of megawatt subpicosecond light pulses with the minimum possible shape and spectrum distortion in an air- or argon-filled hollow-core revolver fibre

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Abstract. **We have examined the feasibility of undistorted subpicosecond pulse transmission at peak powers of up to 100 MW and a wavelength of 1030 nm in a hollow-core revolver fibre having a core filled with atmospheric air or argon. A hollow-core revolver fibre has been fabricated which has a low-dispersion ($\beta_2 \approx -0.25$ ps^2 km^{-1}) transmission band in the spectral range of ytterbium and neodymium lasers. Conditions for the nonlinear (soliton) regime of megawatt picosecond pulse propagation over up to 1-km lengths of revolver fibre in atmospheric air and argon at pressures in the range 10^{-5} to 1 atm have been found theoretically. We have experimentally demonstrated transmission of pulses of 0.8-ps duration and up to ~100-MW power over an ~3-m length of revolver fibre with the minimum possible distortion of their shape and spectrum.**

Keywords: *subpicosecond pulses, solitons, hollow-core fibre, revolver fibre, Kerr nonlinearity, stimulated Raman scattering.*

1. Introduction

Hollow-core microstructured fibre offers unique possibilities for transmission of high peak power, ultrashort pulses (USPs). A guiding core filled with gaseous media having refractive indices similar to those of vacuum, weak nonlinearity and low dispersion allows femto- and picosecond pulses whose power reaches hundreds of megawatts and more to be transmitted without distortion at a speed approaching the speed of light in vacuum [1–4]. The measured waveguiding loss in some hollow-core fibres is already as low as 1.2–1.7 dB km^{-1} [5], and it is extremely important that, theoretically adjusting the cross-sectional shape and material of optical fibre, such and even lower losses can be obtained in a band of the order of hundreds of nanometres wide in any spectral region from the UV to mid-IR. Not only are these unique properties of gas-filled fibre of interest for a number of applications, such as high-intensity light transmission and laser processing of materials, but they also open up new possibilities for future ultra-high-capacity optical communications [6].

To date, the propagation of high-power subpicosecond pulses has been studied in various types of hollow-core microstructured fibre, and particular attention has been paid to not only the linear but also the nonlinear (soliton) regime of high-power pulse propagation with the minimum possible or controlled changes in the shape and spectrum of the pulses. In particular, successful Raman soliton transfer in a hollow-core photonic crystal fibre filled with atmospheric air over up to 5 m was demonstrated by Ouzounov et al. [1] and Luan et al. [2]. In a 10-m-long Kagome-type hollow-core fibre filled with atmospheric air, Wang et al. [3] demonstrated transmission of pulses with an output energy above 350 μJ at an input pulse duration of 600 fs and energy of 800 μJ. In an air-core fibre, they obtained the soliton regime of pulse propagation over 3 m at a pulse energy above 100 μJ.

Yatsenko et al. [7] investigated the propagation of 100-fs pulses in a revolver fibre having a hollow core filled with atmospheric air. According to their numerical analysis results, the parameters of the fibre enable radiation transmission in the form of megawatt-power Raman solitons over up to 25 m in the telecom range, $\lambda \sim 1.550$ nm, and simultaneous tuning of the emission wavelength over 130 nm. They experimentally demonstrated femtosecond pulse transmission through fibres up to 5 m in length in the linear propagation regime, without distortion of the pulse spectrum, with a dispersion-induced temporal pulse broadening within 20%.

Filling a hollow fibre core with noble gases at low pressure considerably increases the possibilities of obtaining both the linear and soliton propagation regimes for femto- and picosecond pulses, up to gigawatt power levels. At the same time, the effect of characteristics of various gaseous media at low pressures on pulse propagation in the nonlinear regime has not yet been studied in sufficient detail.

In this work, we examine the feasibility of undistorted transmission of picosecond light pulses with a peak power of up to 100 MW at a wavelength of 1030 nm in revolver fibre whose core is filled with atmospheric air or argon at pressures from 10^{-5} to 1 atm. We have fabricated a hollow-core revolver fibre with low waveguide dispersion ($\beta_2 \approx -0.25$ ps^2 km^{-1}) in a spectral range near $\lambda = 1000$ nm, theoretically found conditions for nonlinear (soliton) propagation of picosecond megawatt pulses in atmospheric air and argon in the pressure range 10^{-5} to 1 atm and investigated limiting possibilities of undistorted USP transmission in revolver fibre. Transmission of 0.8-ps pulses ($\lambda = 1030$ nm) through a 2.8-m-long hollow-core fibre has been studied experimentally at various pulse powers and gas pressures.

2. Samples and experimental methods

For this investigation, we fabricated a hollow-core revolver fibre with a core diameter of 74 μm. Its cladding was formed by ten silica glass capillaries (Fig. 1a). The diameter and wall

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thickness of the capillaries were 26.7 and 1.3 μm, respectively. The dispersion and guidance characteristics of the fibre were calculated using COMSOL Multiphysics software. Figure 1b shows calculated optical loss spectra for the fundamental (LP_{01}) and first-order (LP_{11}) modes in the second transmission band (according to the ARROW model [8]). The 0.1 dB m^{-1} transmission bandwidth for the fundamental mode was 220 nm. The theoretical loss in the fundamental mode at a wavelength of 1030 nm was 0.001 dB m^{-1}, whereas that in the LP_{11} mode was about three times higher. The fundamental mode field diameter at $\lambda = 1030$ nm was 55.7 μm.

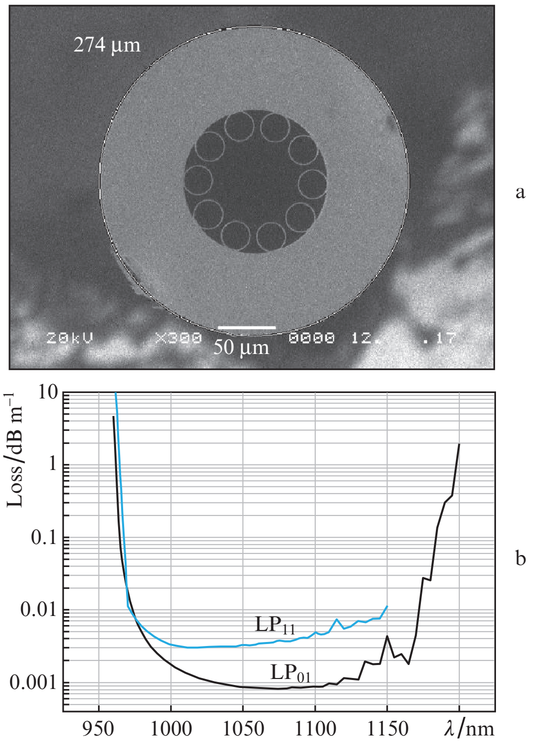

Figure 1. (a) Electron micrograph of the hollow-core fibre and (b) optical loss as a function of wavelength for the LP_{01} and LP_{11} modes in the second transmission band.

In calculating the dispersion properties of the fibre, we took into account the contributions of both the waveguide dispersion in the hollow-core fibre and the index dispersion in the gas present in the hollow core. The dispersion in the gas was evaluated using the Sellmeier formula [9] which took into account the effects of temperature (T) and pressure (p):

$$n_{\text{gas}} = \left[1 + \frac{pT_0}{p_0 T}\left(\frac{B_1}{C_1 - \lambda^{-2}} + \frac{B_2}{C_2 - \lambda^{-2}}\right)_{p_0 T_0}\right]^{0.5},$$

where $p_0 = 1$ atm; $T_0 = 273$ K; and λ (μm) is the wavelength. The coefficients B_1, C_1, B_2 and C_2 for air and argon were borrowed from Ref. [9].

Numerical simulation of USP propagation in the revolver fibre was carried out in the MATLAB environment using built-in algorithms for performing the fast Fourier transform and solving the equation by the fourth-order Runge–Kutta method [7]. We used a generalised nonlinear Schrödinger equation for a complex-valued spectral pulse envelope [10], which took into account higher order dispersion, Kerr nonlinearity and stimulated Raman scattering (SRS). In taking into account the room-temperature Kerr nonlinearity, we assumed the linear relation $n_2(p) = n_2 p$, where p (atm) is the gas pressure and n_2 is the nonlinear refractive index at $p = 1$ atm: 3×10^{-23} and 1.74×10^{-23} m^2 W^{-1} for air and argon, respectively [11, 12].

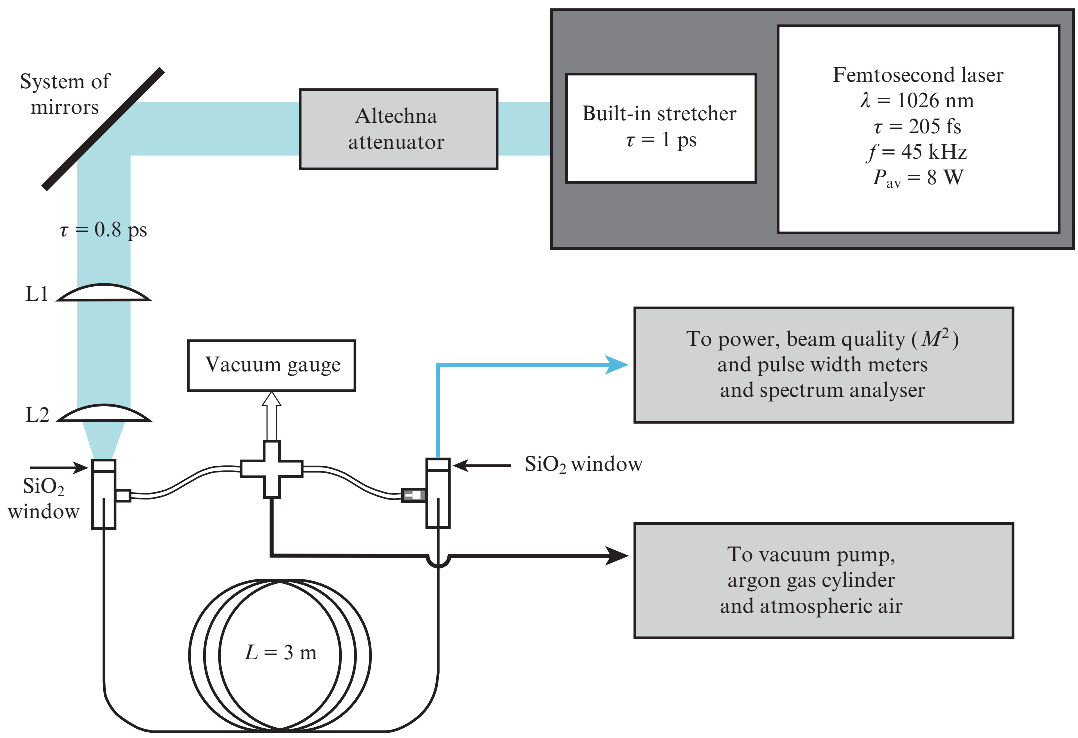

Figure 2. Schematic of the experimental setup.

If the fibre was filled with argon, a monatomic gas, it was unnecessary to take into account SRS. If the fibre was filled with air, we took into account SRS by rotational transitions of atmospheric nitrogen [13–15]. The Raman response function $h_R(t)$ was represented in the following form [13]:

$$h_R(t) = \Omega^2\tau_s\exp\left(-\frac{t}{t_d}\right)\sin\left(\frac{t}{\tau_s}\right),$$

where $\Omega^2 = \tau_s^{-2} + \tau_d^{-2}$; $\tau_s = 1/\omega_R$; ω_R is the cyclic frequency of the transition between the $J = 8$ and $J = 6$ rotational levels of the N_2 molecule ($\omega_R = 1.6\times10^{13}$ s^{-1}); $\tau_d = 1/\Gamma_2$; and $\Gamma_2 = 1.3\times10^{13}$ s^{-1} is the dephasing rate of the dipole moment of the $J = 8$ excited rotational state [14, 15].

In experimental studies of picosecond pulse propagation in the revolver fibre, we used a setup schematised in Fig. 2. As a light source, we used a PHAROS femtosecond laser (Light Conversion). The laser operated in fixed mode, generating linearly chirped 0.8-ps pulses at a wavelength of 1026 nm. The laser emission bandwidth was $\Delta\lambda \approx 7.8$ nm, the pulse repetition rate was 45 kHz, and the average output power was 8 W. The optical power coupled into the fibre was controlled by an external attenuator. After the attenuator, the light was launched into the hollow-core fibre by lenses L1 ($f = 500$ mm) and L2 ($f = 75$ mm). By adjusting the separation between the lenses, we were able to obtain a beam waist diameter equal to the mode field diameter of the fibre under study. The launch efficiency exceeded 90% over the entire range of peak powers examined (up to ~100 MW). The fibre length was 2.8 m. The ends of the hollow-core fibre were hermetically cemented into miniature cuvettes, which had quartz glass windows for light incoupling and outcoupling. In addition, the cuvettes allowed the hollow core to be filled with gases or pumped down simultaneously through both fibre ends. The light from the output end of the fibre under study was directed to a power meter, optical spectrum analyser or autocorrelator.

3. Dispersion and nonlinear lengths of the gas-filled revolver fibre and conditions of the soliton regime

To qualitatively understand the pulse transmission process, it is necessary to estimate the dispersion (L_d) and nonlinear (L_{nl}) lengths for picosecond pulse propagation in the gas-filled revolver fibre under study.

The total dispersion in the fibre depends little on the pressure and nature of the gas (air or argon) at pressures $p \leqslant 1$ atm (Fig. 3). The major contribution to the dispersion characteristic is made by the waveguide dispersion in the fibre, β_2, which is -0.11 ps^2 km^{-1} (for the fundamental mode) at a laser emission wavelength of 1030 nm. At $p = 1$ atm and wavelengths in the range 800–1200 nm, the dispersion in air and argon is an order of magnitude lower in absolute value ($\beta_2 = 1.6\times10^{-2}$ ps^2 km^{-1} for atmospheric air and $\beta_2 = 1.8\times10^{-2}$ ps^2 km^{-1} for argon). For a Gaussian pulse with a full width at half intensity $t_0 = 1$ ps, the dispersion length is $L_d = (t_0/1.665)^2/\beta_2 = 3.3$ km ($\lambda = 1030$ nm, $p \leqslant 1$ atm). Thus, a transform-limited picosecond pulse can propagate through the fibre in the linear regime without dispersion-induced broadening over kilometre lengths. In the case of shorter pulses ($t_0 \leqslant 100$ fs), the dispersion length does not exceed a few tens of metres ($t_0 = 100$ fs, $L_d = 33$ m), which makes them difficult to use in the linear regime for long-haul undistorted transmission.

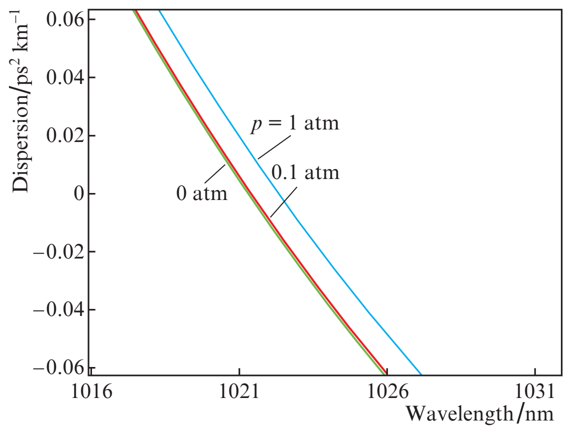

Figure 3. Second-order dispersion for the fundamental mode in the second transmission band of the hollow-core fibre filled with argon to pressures in the range 0–1 atm.

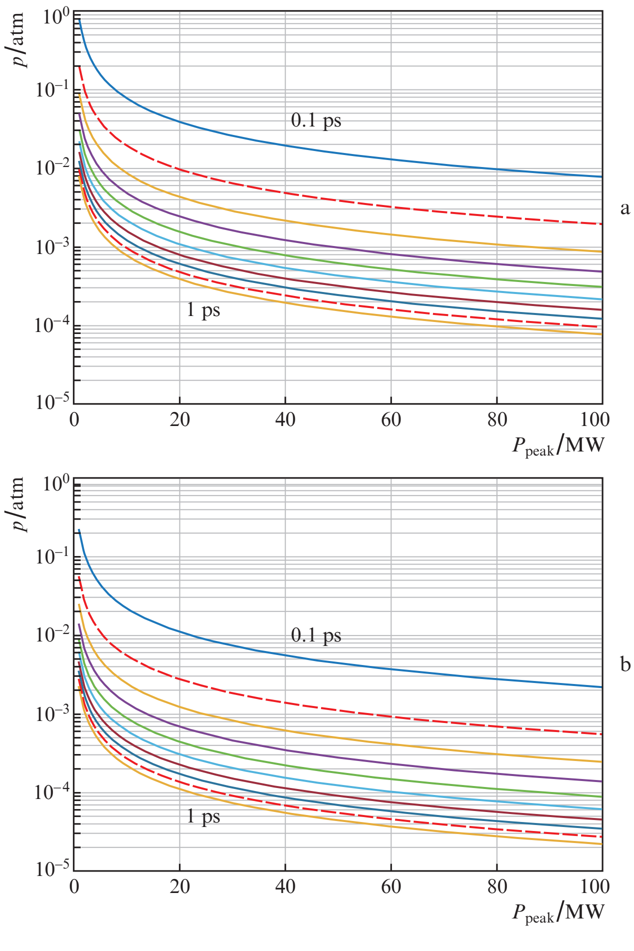

Figure 4. Characteristic dependences of the gas pressure on pulse peak power, necessary for obtaining the soliton regime in the revolver fibre filled with (a) argon and (b) air and calculated for the input transform-limited pulse duration varied from 0.1 to 1 ps in 0.1-ps steps.

The fibre length over which undistorted transmission of high-power pulses is possible at a gas pressure of ~1 atm is limited primarily by Kerr nonlinearity. Given that the effective area of the fundamental mode is $A_{eff} = 2.4\times10^{-5}$ cm^2, the nonlinearity coefficient $\gamma = 2\pi n_{2K}/(\lambda A_{eff})$ at a wavelength of 1030 nm is 7.5×10^{-8} m^{-1} W^{-1} ($n_{2K} = 3\times10^{-23}$ m^2 W^{-1} [11]) for air and 4.2×10^{-8} m^{-1} W^{-1} ($n_{2K} = 1.74\times10^{-23}$ m^2 W^{-1} [12]) for argon. Thus, at a pulse peak power $P_{peak} = 50$ MW, the nonlinear Kerr length $L_{nl} = 1/(\gamma P_{peak})$ in the fibre filled with air or argon to $p = 1$ atm is 26 or 47 cm, respectively. At such power, a significant effect of Kerr nonlinearity on the spectrum of a pulse should be expected even at lengths of the order of a few metres. In the case of air, an additional contribution to nonlinear distortion is made by SRS. At $P_{peak} = 50$ MW, the nonlinear fibre length L_R related to SRS in atmospheric nitrogen [$L_R = A_{eff}/(g_R P)$, where $g_R = 0.025$ cm TW^{-1}] is just 19.5 cm.

Thus, for undistorted transmission of megawatt pulses over ~1-km lengths, the nonlinearity coefficient should be reduced by lowering the gas pressure to below 1 atm. In such a case, the maximum pulse power that can be transmitted without pulse shape or spectrum distortion, with an accuracy determined by the effect of higher order dispersion and nonlinear terms in the nonlinear equation should correspond to the condition for the soliton propagation regime: $N = \sqrt{L_d/L_{nl}} = 1$. Figure 4 shows characteristic dependences of the gas pressure on peak power, which are necessary for obtaining the soliton regime in the revolver fibre filled with argon and air. It can be seen that, for the propagation of a transform-limited pulse of 1-ps duration and 50-MW power in the soliton regime, the argon pressure should be $\sim1.56\times10^{-4}$ atm and the air pressure should be $\sim4.05\times10^{-5}$ atm.

4. Numerical analysis of USP propagation in the gas-filled revolver fibre

Figure 5 presents numerical simulation results on the propagation of transform-limited pulses of 1-ps duration and 50-MW power in a 3-m-long hollow-core fibre. If the core is filled with air to a pressure of 1 atm, self-phase modulation (SPM) leads to a considerable broadening of the spectrum and the effect of SRS shows up as a slight asymmetry of the spectrum. At the same time, the pulse duration changes by no more than 3% (Fig. 5a). Changes in pulse duration no greater than 20% are possible at fibre lengths of up to 6 m, whereas the bandwidth changes by 20% after propagation through a fibre segment as short as 25 cm. If the core is filled with argon to a pressure with 1 atm, the broadening of the spectrum is considerably smaller, because there is no SRS and the Kerr nonlinearity is lower (Fig. 5b). In this case, the fibre length at which the distortion of the pulse duration does not exceed 20% is 14 m, whereas transmission of the spectrum with distortion under 20% is possible over lengths of up to 60 cm.

Numerical simulation results suggest that, at reduced argon and air pressures corresponding to the soliton regime (Fig. 4), transform-limited input pulses of 1-ps duration and 100-MW power can propagate without distortion of their shape or spectrum over a 1-km distance (Fig. 6a). In such a case, there is no Raman shift in the fibre filled with air to $p = 2.21\times10^{-5}$ atm and we observe only a 20% reduction in pulse power due to the 1 dB km^{-1} theoretical loss used in our calculations for the fundamental mode (Fig. 6b). Similar undistorted transmission of 1-ps Gaussian pulses was obtained for the fibre filled with argon to a pressure of 7.8×10^{-5} atm, corresponding to the soliton regime.

As the input pulse duration decreases, we observe typical distortions of the soliton shape and spectrum, determined by the higher order dispersion and nonlinear terms in the nonlinear equation. Figures 7 and 8 illustrate the propagation of transform-limited Gaussian pulses of 0.1-ps duration and

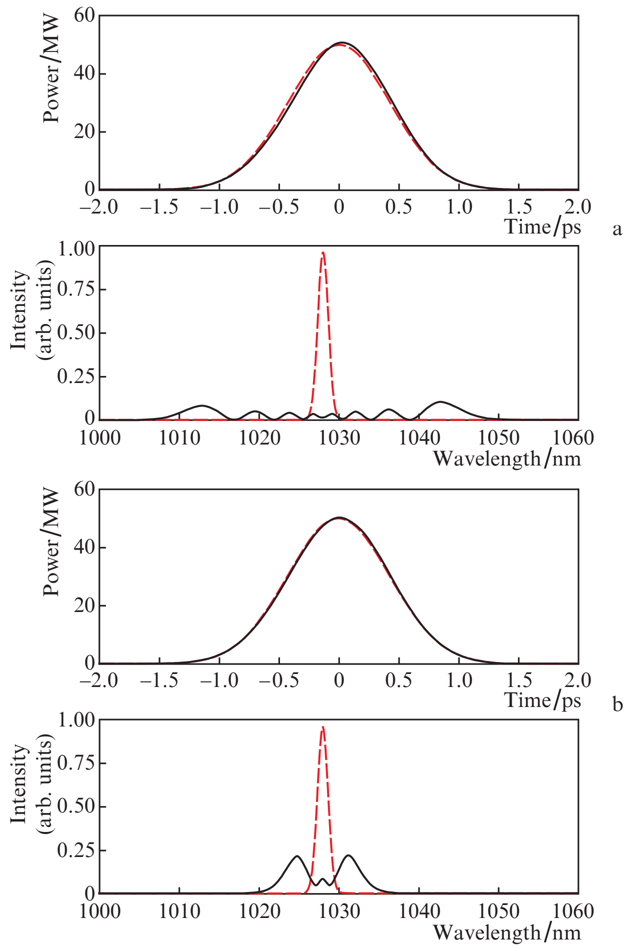

Figure 5. Temporal envelope and spectrum of a pulse at the input of a 3-m-long fibre filled with (a) air and (b) argon to a pressure of 1 atm for a transform-limited input pulse of 1-ps duration and 50-MW power. Here and in Figs 6–8, the dashed lines represent pulses at the fibre input.

100-MW power in the soliton regime in air and argon, respectively. In both cases, a soliton is formed, whose bandwidth decreases and pulse duration increases. These parameters differ markedly from those of the input pulse after propagation over several tens of metres along the fibre. Comparison of Figs 7 and 8 shows that, after propagation through a 1-km fibre, comparable shifts in soliton spectra emerge in both gases (4 nm in argon and 6 nm in air), which are determined by the self-steepening effect in the former case and by the combined effect of self-steepening and SRS in the latter [16].

Figure 9a illustrates the effect of argon pressure on the revolver fibre length at which the distortion of the temporal shape and spectrum of an input pulse of 100-MW power and 100-fs duration does not exceed 20%. The solid line represents the fibre length at which both the temporal shape and spectrum can be transmitted without distortions. The maximum in the curve (70 m) is located at a pressure of 7.8×10^{-5} atm, corresponding to the soliton regime.

Figure 9b shows the maximum fibre length at which a Gaussian transform-limited pulse of 100-MW power can propagate with distortions no greater than 20% as a function of input pulse duration in the range 0.1–1 ps at pressures corresponding to the soliton regime. It is seen that undistorted transmission over a 1-km length, limited by a 1-dB waveguid-

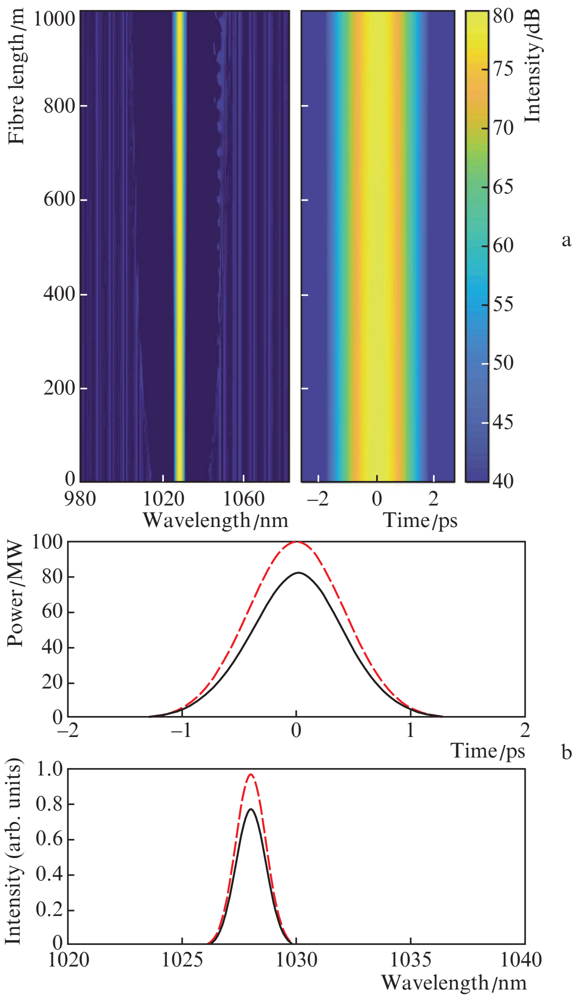

Figure 6. (Colour online) (a) Rainbow colour maps illustrating the propagation of a transform-limited Gaussian input pulse of 1-ps duration and 100-MW power through a 1-km-long revolver fibre filled with air to a pressure of 2.21×10^{-5} atm; (b) temporal envelopes and spectra of pulses at the fibre input and output.

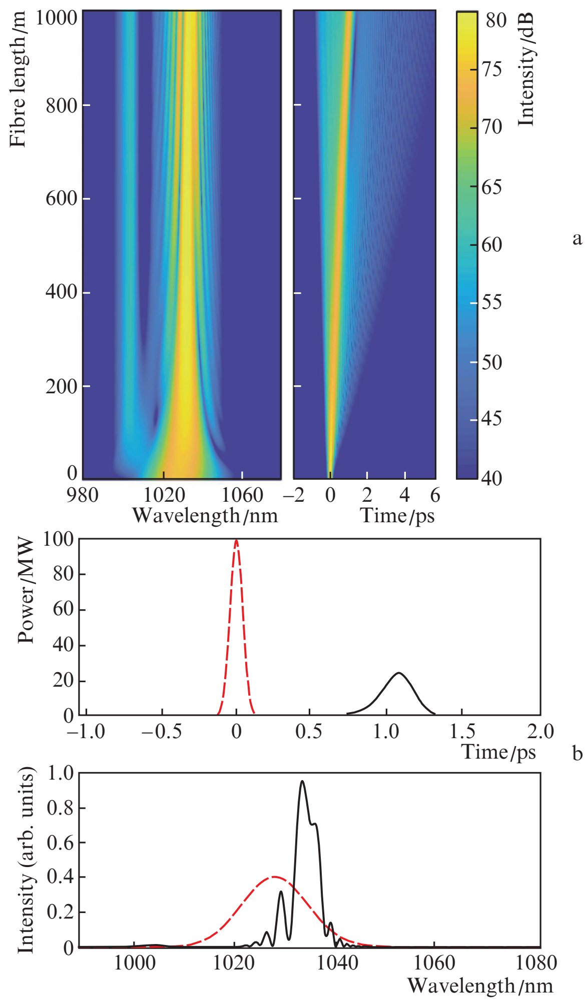

Figure 7. (Colour online) (a) Rainbow colour maps illustrating the propagation of a transform-limited Gaussian input pulse of 0.1-ps duration and 100-MW power through a 1-km-long revolver fibre filled with air to a pressure of 2.21×10^{-3} atm; (b) temporal envelopes and spectra of pulses at the fibre input and output.

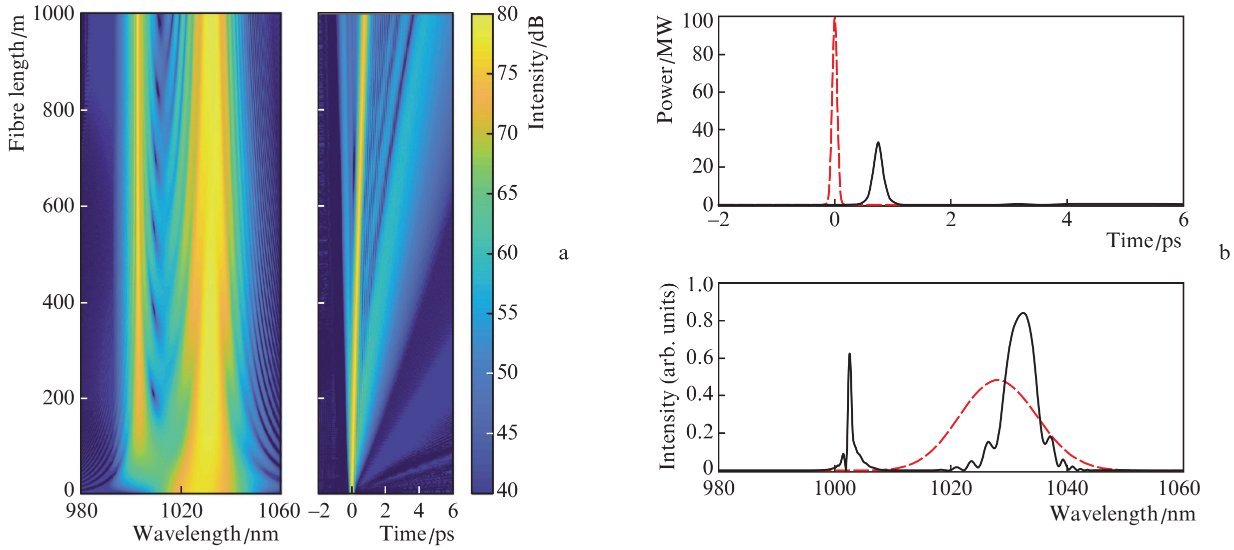

Figure 8. (Colour online) (a) Rainbow colour maps illustrating the propagation of a transform-limited Gaussian input pulse of 0.1-ps duration and 100-MW power through a 1-km-long revolver fibre filled with argon to a pressure of 7.8×10^{-3} atm; (b) temporal envelopes and spectra of pulses at the fibre input and output.

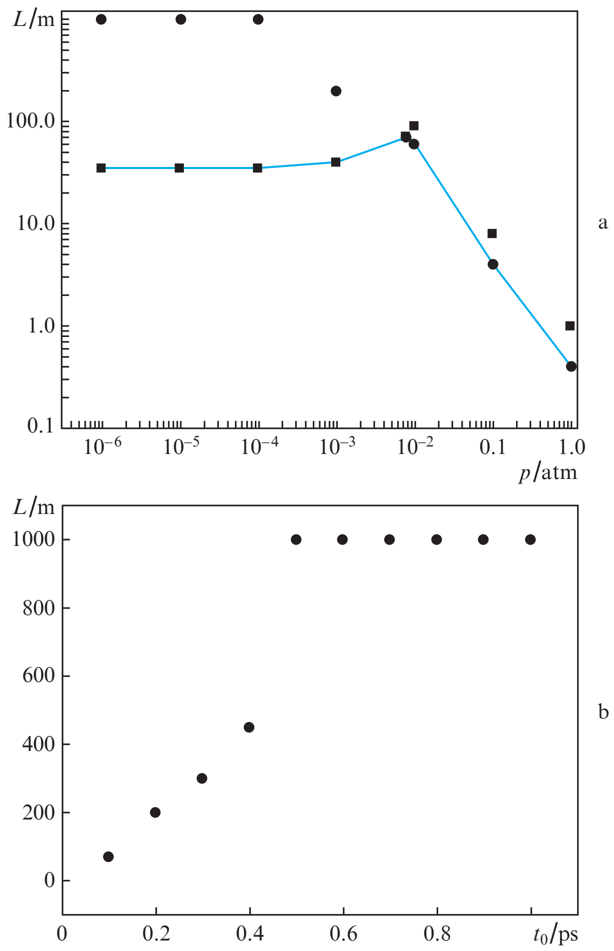

Figure 9. Revolver fibre length at which the shape (■) and spectrum (●) of a transform-limited Gaussian pulse of 100-MW power can be transmitted without distortions vs. (a) argon pressure at a pulse duration of 0.1 ps and (b) pulse duration at argon pressures corresponding to the soliton regime.

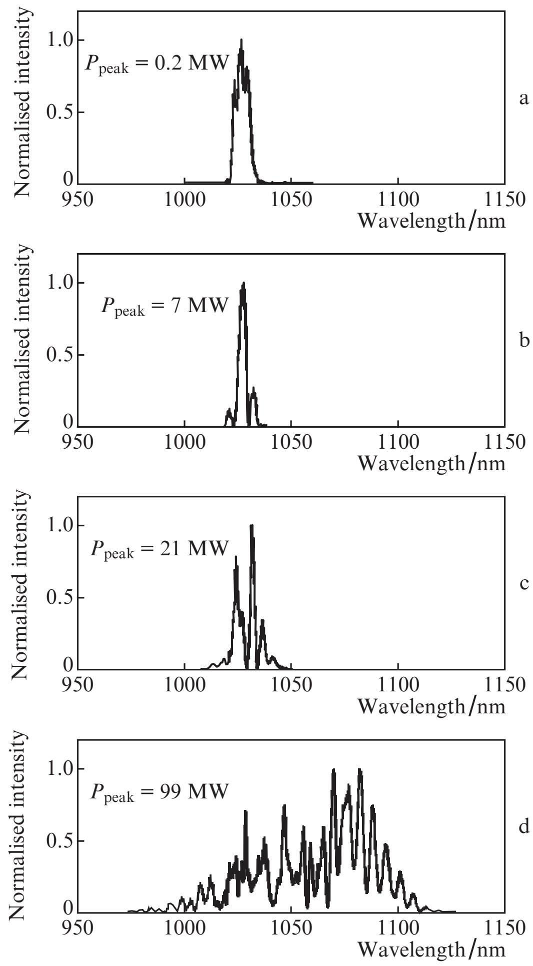

Figure 10. Normalised emission spectra at the output of a 2.8-m-long hollow-core fibre at various input pulse peak powers. The core is filled with air to a pressure of 1 atm. The duration of linearly chirped pulses and the input emission bandwidth are 800 fs and 7.8 nm, respectively.

ing loss, is possible at pulse durations in the range 0.5–1 ps. Reducing the pulse duration to 0.1 ps reduces the transmission distance to 70 m.

5. Experimental: transmission of picosecond pulses with a peak power of up to 100 MW in the gas-filled revolver fibre

In our experimental studies of transmission of chirped picosecond (t_0 = 0.8 ps) pulses at a wavelength of 1026 nm, we used a 2.8-m length of the revolver fibre (Fig. 1a). Note that, over the entire range of input peak powers studied ($P_{peak} \leqslant$ 100 MW), the transmittance of the fibre was 92 ± 1 %. In addition, the quality factor M^2 of the output beam did not exceed 2, pointing to effective predominant excitation of the fundamental mode of the fibre, in spite of the large mode field diameter.

The emission spectrum at the output of the air-filled revolver fibre depended significantly on the input peak power (Fig. 10). At a low peak power ($P_{peak} \leqslant$ 0.2 MW), the emission bandwidth $\Delta\lambda$ of laser pulses propagating through the fibre remained constant at 7.8 nm (Fig. 10a), corresponding to the emission bandwidth of the femtosecond laser used. Raising the input peak power led first to a reduction in the width of the output spectrum (Fig. 10b, $P_{peak} \sim$ 7 MW) and then to its broadening (Fig. 10c, $P_{peak} \sim$ 21 MW), and the spectrum acquired an oscillating structure. Here, the predominant contribution to the spectral changes is made by self-phase modulation, which narrows down the spectrum at ~7-MW power levels, compensating for the negative chirp of input pulses by the positive chirp produced by it, and broadens the spectrum, without shifting it to longer wavelengths, at ~21-MW power levels. As the input peak power is raised further ($P_{peak} \leqslant$ 100 MW), the bandwidth at the fibre output reaches ~65 nm, which is eight times the laser emission bandwidth (7.8 nm) (Fig. 10d). This is accompanied by a power redistribution to longer wavelengths, due to the contribution of SRS by rotational transitions of nitrogen molecules.

To suppress distortions of the spectrum of laser pulses, the air was removed from the hollow core by pumping down to ~10^{-4} atm. During the pumping process, we measured output emission spectra, while maintaining the peak power at the fibre input constant at 84 MW (Fig. 11). It is seen that evacuation of the air indeed allows the broadening of the spectrum to be eliminated. At an air pressure in the core no higher than 4×10^{-3} atm, there is essentially no SRS-related distortion of the spectrum, and the contribution of SPM is considerably reduced.

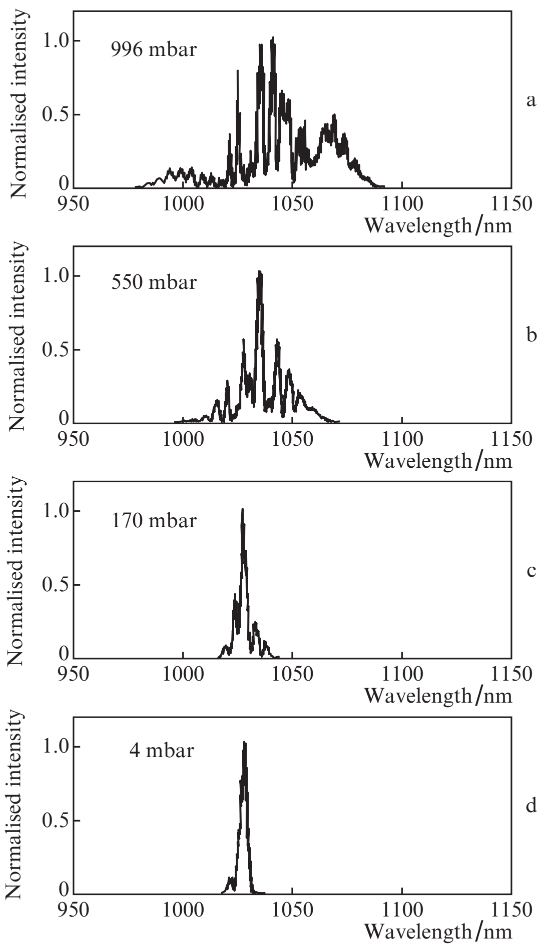

Figure 11. Normalised emission spectra at the fibre output at different air pressures in the hollow core. The peak power at the fibre input was maintained constant at 84 MW.

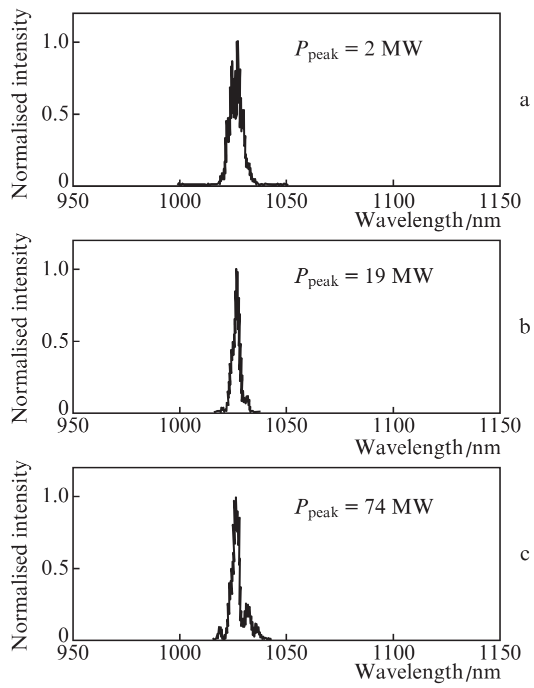

Figure 12. Effect of input peak power on the emission spectrum at the output of the revolver fibre filled with argon to a pressure of 1 atm.

An alternative approach for maintaining the bandwidth of picosecond pulses propagating in a hollow-core fibre is to fill the core with other gases. In our experiments, we used argon, a monatomic gas without Raman nonlinearity. Moreover, Kerr nonlinearity in argon is lower than in air. Figure 12 shows output emission spectra of the fibre filled with argon to a pressure of 1 atm. It is seen that, as the input peak power rises to ~74 MW, the bandwidth remains essentially unchanged and there are only slight changes in the shape of the spectrum due to Kerr nonlinearity.

We assessed the effect of input peak power on the output pulse duration at different gas pressures and compositions in the fibre core. Figure 13a shows characteristic autocorrelation traces (ACTs) of a pulse at the fibre output. It is seen that, even though the input peak power is varied from 1 to 90 MW, the main ACT peak changes little and is well fitted by a Gaussian. The ACTs in question were measured for the core filled with air to a pressure of 1 atm. Similar ACTs, without any additional features, were obtained after evacuating the air and filling the core with argon.

The pulse duration at the fibre output varied in the range 1.18–1.45 ps, depending on the input peak power (Fig. 13b). Note that neither the composition nor the pressure (within 1 atm) of the gas had a significant effect on the output pulse duration. This correlates with the above theoretical calculation results.

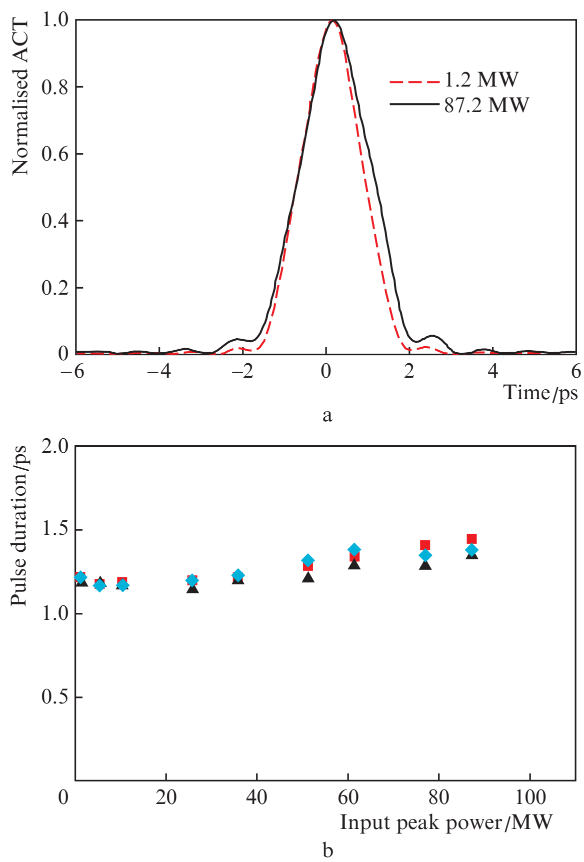

Figure 13. (a) ACTs of light pulses at the output of a 2.8-m-long revolver fibre whose core is filled with air to a pressure of 1 atm in the cases of low (1.2 MW, dashed line) and high (87.2 MW, solid line) input peak powers; (b) output pulse duration as a function of input peak power for a hollow core filled with air (1 atm, ▲), argon (1 atm, ◆) and air (10^{-4} atm, ■).

6. Conclusions

The propagation of USPs with the minimum possible distortion of their shape and spectrum in a revolver fibre filled with argon or air has been studied theoretically and experimentally. The present numerical simulation results suggest that the soliton regime of laser pulse propagation allows for undistorted pulse transmission over up to 1-km lengths of revolver fibre at a peak power of 100 MW and pulse durations in the range 0.5 – 1 ps. To ensure the soliton regime, the hollow core of the fibre should be pumped down to a pressure of $\sim 10^{-5}$ atm, depending on the input pulse duration and power.

A lower vacuum is needed to ensure the soliton regime of pulse propagation in argon than in air, which has a larger nonlinearity coefficient γ. Moreover, in air this regime is only possible in the form of Raman solitons with a shift of the spectrum. At a given soliton power, the Raman shift Ω_R of the spectrum varies with dispersion and pulse duration as $\Omega_R \sim \beta_2/t_0^4$ [17]. The obvious advantage of the revolver fibre is the low waveguide dispersion ($|\beta_2| < 0.2$ ps^2 km^{-1}) in a wide wavelength range. In addition, this fibre design allows zero dispersion to be ensured at any particular wavelength. Thus, the Raman shift in the soliton regime can be minimised at low air pressures.

Transmission of pulses of 0.8-ps duration and 100-MW power over an $\sim$3-m length of revolver fibre has been demonstrated experimentally. It has been shown that distortions of the spectrum of pulses over such lengths of fibre filled with air to a pressure of 1 atm can be effectively suppressed by evacuating the air to a pressure of $\sim 10^{-4}$ atm or replacing the air by argon at a pressure no higher than 1 atm.

The results obtained here suggest that the use of revolver fibre filled with a gaseous medium to a pressure below 1 atm is potentially attractive for long-haul undistorted megawatt pulse transmission.

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