Limiting of microjoule femtosecond pulses in air-guided modes of a hollow photonic-crystal fiber

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Self-phase-modulation-induced spectral broadening of laser pulses in air-guided modes of hollow photonic-crystal fibers (PCFs) is shown to allow the creation of fiber-optic limiters for high-intensity ultrashort laser pulses. The performance of PCF limiters is analyzed in terms of elementary theory of self-phase modulation. Experiments performed with 100 fs microjoule pulses of 800 nm Ti:sapphire laser radiation demonstrate the potential of hollow PCFs as limiters for 10 MW ultrashort laser pulses and show the possibility to switch the limiting level of output radiation energy by guiding femtosecond pulses in different PCF modes.

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I. INTRODUCTION

Hollow-core fibers [1,2] are ideally suited for the transmission of high-intensity laser radiation and applications in strong-field ultrafast nonlinear optics. These fibers can provide large interaction lengths for laser pulses, allowing a radical enhancement of nonlinear-optical processes, including four-wave mixing [3,4] and high-order harmonic generation [5–8]. Hollow fibers have been shown to offer attractive strategies for the compression and chirp control of high-energy ultrashort laser pulses due to the Kerr-nonlinearity-induced self-phase modulation [9,10] and high-order stimulated Raman scattering [11].

The guided modes in standard hollow fibers are leaky, with the magnitude of losses scaling [1] as λ^2/d^3 with the inner fiber diameter d and the radiation wavelength λ, which dictates the choice of hollow fibers with $d \sim 100-500\ \mu$m for nonlinear-optical experiments. Such large-d fibers are essentially multimode, which limits their practical applications in ultrafast photonics. This limitation is removed by hollow-core photonic crystal fibers (PCFs) [12,13]. Such fibers guide light due to the high reflectivity of a two-dimensionally periodic (photonic-crystal) cladding (the inset in Fig. 1) within photonic band gaps (PBGs). Low-loss guiding in a few or even a single air-guided mode can be implemented under these conditions in a hollow core with a typical diameter of $10-20\ \mu$m [12–17]. Hollow PCFs with such core diameters have been recently demonstrated to enhance nonlinear-optical processes, including stimulated Raman scattering [18], four-wave mixing [19], and self-phase modulation [20]. Air-guided modes in hollow PCFs can support megawatt optical solitons [21] and allow femtosecond soliton pulse delivery over several meters [22], as well as a transportation of high-energy laser pulses for technological [23,24] and biomedical [25] applications.

Hollow PCFs not only reduce losses, typical of standard, solid-cladding hollow fibers, but also add interesting aspects related to the switching abilities of PBG structures [26–32], offering the ways to design smart fiber-optic devices for high-intensity laser pulses. In particular, a fiber-optic diode, based on a combination of self-phase modulation and filtering in air-guided modes of hollow PCFs, has been recently experimentally demonstrated by Konorov *et al.* [33], suggesting the possibility to create optical processors and decouplers for high-intensity ultrashort laser pulses A Kerr-nonlinearity-induced profile of the refractive index in hollow PCFs, which changes the spectrum of propagation constants of air-guided modes, effectively shifting the passbands in PCF transmission, has been shown to allow the development of fiber switches for high-intensity laser pulses [34].

In this work, we show that the spectral broadening of laser pulses induced by self-phase modulation (SPM) in air-guided modes of hollow PCF allows the creation of fiber-optic limiters for high-intensity ultrashort laser pulses. The

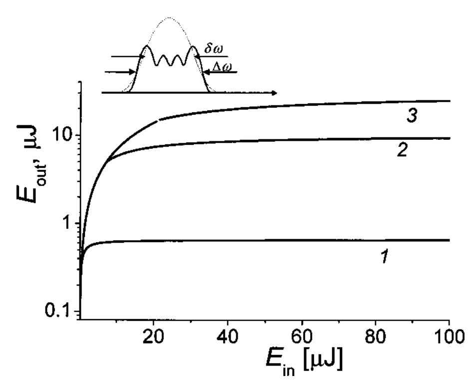

FIG. 1. The energy E_{out} at the output of a hollow photonic-crystal fiber calculated with the use of Eqs. (4) and (5) as a function of the input energy E_{in} for $E_{lim}=0.65\ \mu$J (1), 10 μJ (2), and 50 μJ (3). The inset sketches the spectrum of an SPM-broadened laser pulse with a bandwidth $\Delta\omega$ against the PCF passband with a width $\delta\omega$.

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plan of this paper is the following. In Sec. II, we use an elementary theory of self-phase modulation to analyze the performance of PCF limiters. We will, show, in particular, that the limiting level of output radiation energy is controlled by the pulse duration, radiation wavelength, the effective mode area, the passband width, the PCF length, and the nonlinear refractive index of the gas filling the fiber core. Photonic-crystal fibers and the laser setup are described in Sec. III. In Sec. IV, we present the results of experiments performed with 100 fs microjoule pulses of 800 nm Ti:sapphire laser radiation, demonstrating the potential of hollow PCFs as limiters for 10 MW ultrashort laser pulses and showing the possibility to switch the limiting level of output radiation energy by guiding femtosecond pulses in different PCF modes.

II. HOLLOW PHOTONIC-CRYSTAL FIBER AS AN OPTICAL LIMITER

Consider a short laser pulse propagating through a hollow core of a PCF filled with a gas (or any other material) possessing a Kerr nonlinearity. Self-phase modulation induced by the Kerr nonlinearity of the material filling the fiber core gives rise to a nonlinear phase shift of the pulse $\Delta\varphi_{\mathrm{nl}}$. An elementary theory of SPM gives the following expression for this shift [35,36]:

$$\Delta\varphi_{\mathrm{nl}} = \frac{2\pi}{\lambda} n_2 I l, \tag{1}$$

where λ is the laser radiation wavelength, n_2 is the nonlinear refractive index of the material filling the fiber core, I is the laser intensity, and l is the fiber length.

The bandwidth of the pulse at the output of the fiber can then be estimated as

$$\Delta\omega = \Delta\omega_0 + \frac{2\pi}{\lambda} n_2 \frac{Pl}{S\tau}, \tag{2}$$

where $\Delta\omega_0$ is the initial bandwidth of the laser pulse, P is the laser power, S is the effective mode area, and τ is the pulse duration.

As long as the full spectral width of the SPM-broadened laser pulse $\Delta\omega$, given by Eq. (2), is less than the PCF passband width $\delta\omega$ (see the inset in Fig. 1), the radiation energy E_{out} at the output of the hollow PCF is a linear function of the input radiation energy E_{in}, $E_{\mathrm{out}}=E_{\mathrm{in}}T_0$ (here, T_0 is the transmission of the PCF and we assume that $\Delta\omega_0 < \delta\omega$). When the pulse width $\Delta\omega$ becomes larger than the PCF passband width $\delta\omega$, some energy of the SPM-broadened laser pulse dissipates as the frequency components falling outside the PCF passband (the inset in Fig. 1) are characterized by very high losses. In this regime, the output radiation energy E_{out} can be represented as

$$E_{\mathrm{out}} = E_{\mathrm{in}} T_0 \frac{\delta\omega}{\Delta\omega}. \tag{3}$$

Combining Eqs. (2) and (3), we arrive at

$$E_{\mathrm{out}} = E_{\mathrm{in}} \left(\frac{\Delta\omega_0}{T_0\delta\omega} + \frac{E_{\mathrm{in}}}{E_{\mathrm{lim}}} \right)^{-1}. \tag{4}$$

Here,

$$E_{\mathrm{lim}} = \frac{S\tau^2 T_0 c}{n_2 l} \frac{\delta\lambda}{\lambda}, \tag{5}$$

where $\delta\lambda$ is the PCF passband width on the wavelength scale and c is the speed of light.

At high input energies, the output energy, as can be seen from Eq. (4), becomes independent of the input energy (see Fig. 1), tending to E_{lim}, defined by Eq. (5). Formulas (4) and (5) thus show that the Kerr nonlinearity of the material filling the hollow core of a PCF makes this fiber an ideal limiter for ultrashort laser pulses. In the case of a gas-filled PCF, this device is ideally suited to limit high-intensity ultrashort laser pulses, since the breakdown threshold of gases is much higher than the breakdown threshold of standard fiber materials. An important result of this simple analysis is that the limiting level of radiation energy at the output of the hollow PCF, as can be seen from Eq. (5), is controlled by the pulse duration, radiation wavelength, the effective mode area, the passband width, the PCF length, and the nonlinear refractive index of the gas filling the fiber core. Variation of these parameters allows PCF limiters for ultrashort laser pulses to be designed within a broad range of radiation energies. With typical parameters of PCFs and laser pulses used in our experiments (see Secs. III and IV), the inner fiber diameter $d \approx 14\ \mu$m, the fiber length $l=10$ cm, $n_2=5\times10^{-19}\ \mathrm{cm}^2/\mathrm{W}$, $T_0\approx0.7$, and $\delta\lambda/\lambda\approx0.01$, Eq. (5) yields the following estimate: $E_{\mathrm{lim}}\approx0.65\ \mu$J.

Hollow PCFs with the above-specified parameters are thus ideally suited for the limiting of microjoule ultrashort laser pulses. In the following sections, we present an experimental demonstration of a PCF limiter for amplified 10 MW femtosecond Ti:sapphire laser pulses. Optical limiters for subgigawatt and even gigawatt ultrashort laser pulses can be designed, on the other hand, by increasing the PCF core diameter or by designing PCFs with broader passbands (curves 2 and 3 in Fig. 1).

The passbands in the transmission of a PCF are the maps of the photonic band gaps of the fiber cladding (shaded areas in Fig. 2). This mapping is defined [12,37] by crossings of dispersion lines of air-guided PCF modes with PBGs (Fig. 2). The width of PCF passbands $\delta\omega$, one of the key parameters of a PCF limiter, can be therefore tuned by modifying the cross-section architecture of a PCF. Dispersion curves of different air-guided modes in a PCF, as illustrated in Fig. 2, cross the PBG edges at slightly different points, giving rise to slightly different projections of the PBGs of the cladding on the wave number axis. These modes, therefore, see slightly different passbands. SPM-induced spectral broadening may also noticeably vary for different PCF modes due to the difference in transverse radiation intensity distribution. These two effects allow the limiting level of output radiation energy for the same PCF to be switched by guiding laser pulses in different PCF modes. This option of PCF limiters will be also demonstrated by the results of our experiments presented in the following sections of this paper.

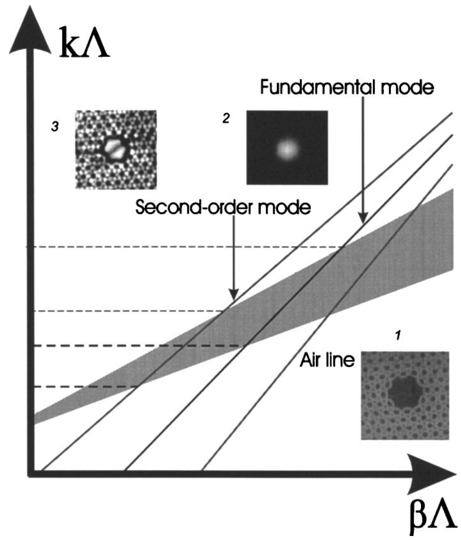

FIG. 2. A $\beta - k$ diagram for a hollow-core photonic-crystal fiber (β is the propagation constant, k is the wave number, Λ is the period of the structure in the PCF cladding). Solid lines show dispersion relations for a plane wave in atmospheric air with no waveguide, the fundamental mode of the PCF, and a higher order air-guided mode in the PCF. The shaded area shows the photonic band gap of the cladding. The dashed vertical lines project crossings of dispersion relations and PBG edges on the wave-number axis. The insets show (1) the cross-section view of the hollow PCF and transverse intensity distributions in the fundamental (2) and higher order (3) guided modes.

III. LASER SYSTEM AND HOLLOW PHOTONIC-CRYSTAL FIBERS

The femtosecond laser system employed in our experiments (Fig. 3) consisted of a Ti:sapphire master oscillator, a stretcher, an amplifier, and a pulse compressor. The Ti:sapphire master oscillator was pumped by 4 W cw radiation of a diode-laser-pumped $Nd:YVO_4$ Verdi laser. The master oscillator generated laser pulses with a duration of 50–100 fs, a typical average output power on the order of 250 mW, and a pulse repetition rate of 100 MHz. Femtosecond pulses produced by the master oscillator were stretched up to 800 ps and launched into a multipass Ti:sapphire amplifier pumped with a nanosecond Nd:YAG laser with intracavity second-harmonic generation. Amplified 1 kHz picosecond pulses with an energy up to 300 μJ were then compressed to a duration of 100–130 fs in a single-grating pulse compressor. Our experiments were performed with amplified laser pulses with an initial pulse duration of about 100 fs and input energies ranging from 0.1 up to 10 μJ.

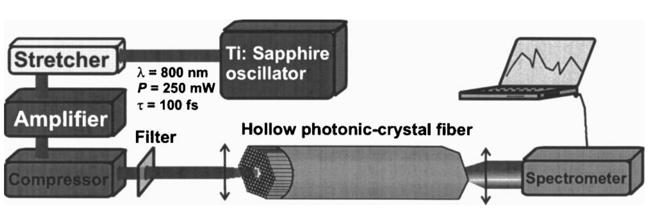

FIG. 3. The laser setup for the investigation of transmission and self-phase modulation of femtosecond laser pulses in a photonic-crystal fiber.

Hollow-core PCFs designed for the purposes of these experiments had an inner diameter of approximately 14 μm and a period of the photonic-crystal cladding of about 5 μm. A typical structure of the PCF cross section is shown in inset 1 to Fig. 2. The PCFs were fabricated [14,38] 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 PCFs. Transmission spectra of these hollow-core PCFs measured in our experiments displayed characteristic well-pronounced isolated peaks (inset 1 to Fig. 4), related to PBGs of the cladding [12]. The spectra of air-guided modes in hollow PCFs were tuned by changing the fiber cladding structure [23]. A typical magnitude of optical losses in PCFs for the central wavelength of 800 nm was estimated as 0.08 cm^{-1}. In view of this result, optical limiting was demonstrated with PCF sections having a typical length of 9 cm.

To model waveguide modes of a hollow PCF, we developed a numerical procedure solving the vectorial wave problem for the transverse components of the electric field $\vec{E}(z,t)=\vec{E}\exp[i(\beta z-ckt)]$, where $\vec{E}=(E_x,E_y,E_z)$, β is the propagation constant, k is the wave number,

$$\left[\frac{\nabla_\perp^2}{k^2}+n^2(x,y)\right]E_x+\frac{1}{k^2}\frac{\partial}{\partial x}\left(E_x\frac{\partial\ln(n^2)}{\partial x}+E_y\frac{\partial\ln(n^2)}{\partial y}\right)=\frac{\beta^2}{k^2}E_x, \tag{6}$$

$$\left[\frac{\nabla_\perp^2}{k^2}+n^2(x,y)\right]E_y+\frac{1}{k^2}\frac{\partial}{\partial y}\left(E_x\frac{\partial\ln(n^2)}{\partial x}+E_y\frac{\partial\ln(n^2)}{\partial y}\right)=\frac{\beta^2}{k^2}E_y. \tag{7}$$

Here, $\nabla_\perp$ is the gradient in the (x,y) plane, $n=n(x,y)$ is the two-dimensional profile of the refractive index, and the prime in the second term on the left-hand side stands for differentiation. The profile of $n^2(x,y)$ was approximated, similar to Refs. [39,40], with a series expansion in Hermite-Gaussian polynomials and trigonometric functions. Figure 4(a) displays a one-dimensional (1D) cut (top) and a two dimensional (2D) profile (bottom) of $n^2(x,y)$ synthesized with 80×80 Hermite-Gaussian polynomials and 150×150 trigonometric functions. The E_x and E_y components of the electric field were represented as series expansions in Hermite-Gaussian polynomials. A substitution of the series expansions for E_x, E_y, and $n^2(x,y)$ into Eqs. (6) and (7) reduces the problem to an eigenfunction and eigenvalue problem of a matrix equation, which allows the propagation constants and transverse field profiles to be determined for the air-guided modes of hollow PCFs.

Figure 4(b) illustrates dispersion properties and presents typical field intensity profiles for the fundamental and higher order guided modes in our hollow PCFs. The fundamental mode has the maximum propagation constant β [solid curve in Fig. 4(b)], and the electric-field intensity in this mode reaches its maximum at the center of the fiber core, monotonically decreasing off the center of the fiber [inset 1 in Fig. 4(b)]. Higher order modes form degenerate multiplets, with

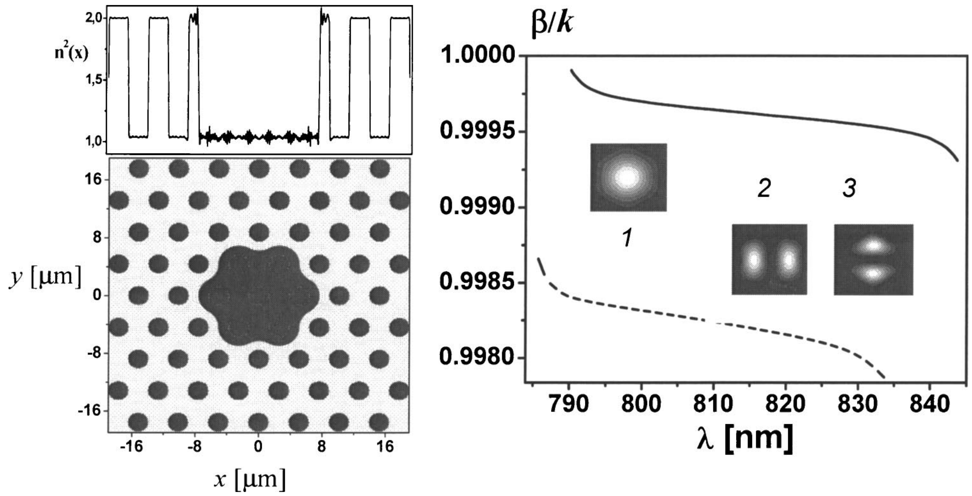

FIG. 4. (a) The profile of $n^2(x,y)$ in the cross section of a hollow PCF synthesized with 80×80 Hermite-Gaussian polynomials and 150×150 trigonometric functions: (top) 1D cut, (bottom) 2D profile shown by levels of gray scale. (b) Propagation constant β normalized to the wave number k as a function of the wavelength for the fundamental (solid curve) and the second-order (dashed curve) air-guided modes of a hollow PCF with a core diameter of approximately 14 μm and a period of the photonic-crystal cladding of about 5 μm. The insets show intensity profiles for the fundamental (1) and the second-order air-guided modes (2,3) of the hollow PCF.

their superposition supporting the full symmetry of the fiber [41]. The second-order mode is fourfold-degenerate [37], displaying a two-lobe intensity profile [insets 2, 3 in Fig. 4(b)]. Dispersion of the second-order air-guided modes of a hollow PCF is shown by the dashed line in Fig. 4(b). Waveguide modes of this type will be used in our experiments to demonstrate the limiting performance of a hollow PCF.

IV. RESULTS AND DISCUSSION

Parameters of PCFs used in our experiments and durations of laser pulses were chosen in such a way that the bandwidth of the input pulses of 800 nm Ti:sapphire laser radiation coupled into the fiber was less than the width of the PCF passband (the transmission spectrum of the PCF is shown in the inset to Fig. 5). Low-intensity femtosecond pulses were, therefore, transmitted through the PCF with minimal losses, estimated as approximately 30% for a 9 cm PCF. As the energy of input pulses increases, self-phase modulation comes into play, broadening the spectrum of laser pulses propagating through the fiber (Fig. 5). When the bandwidth of SPM-broadened laser pulses starts to exceed the passband width, the PBGs of the PCF cladding can no longer confine the whole spectrum of laser radiation in the hollow core of the fiber. The spectral components falling outside the passband leak out of the fiber core into the fiber cladding, resulting in a dissipation of some part of radiation energy. As the dissipating radiation energy increases with the growth in the input laser energy, the energy of laser pulses transmitted through the hollow PCF is limited (the inset in Fig. 6), with the level of this limiting controlled by the passband width, the effective fiber core area, the initial pulse duration, and the nonlinearity of the material filling the fiber core.

The shifting of passbands and the difference in SPM-induced spectral widths for different PCF modes, as outlined in Sec. II of this paper, suggest the ways to switch the limiting level of output radiation energy by guiding femtosecond

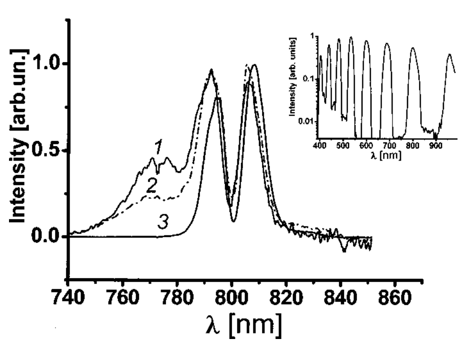

FIG. 5. Spectra of Ti:sapphire laser pulses transmitted through the hollow PCF in the fundamental (1) and higher order (2,3) air-guided modes. The inset shows the transmission spectrum of the fiber.

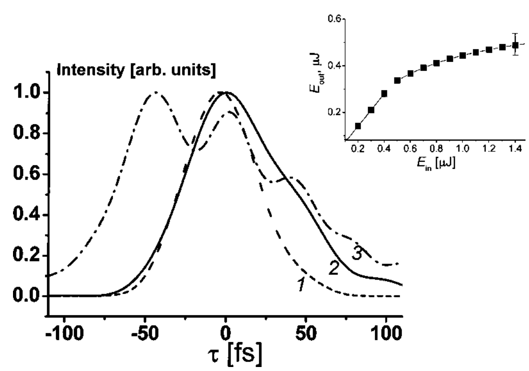

FIG. 6. The envelopes of laser pulses transmitted through the hollow PCF in the fundamental air-guided mode. The input pulse energy is (1) 0.1, (2) 1.4, and (3) 3 μJ. The inset shows the output energy measured as a function of the input energy for the fundamental mode of the PCF.

pulses in different PCF modes. To demonstrate this tunability of laser-pulse limiting in PCFs, we coupled 100 fs pulses of Ti:sapphire laser radiation into different modes of the hollow PCF by slightly changing the angle between the input beam and the fiber axis. This approach allowed a selective excitation of several air-guided modes with typical transverse intensity distributions shown in insets 2 and 3 to Fig. 2 (see also insets 1–3 in Fig. 4), leading to noticeable changes in the spectra of radiation measured at the output of the PCF (Fig. 5). With the passbands for higher order PCF modes redshifted with respect to the passband of the fundamental mode (see, e.g., Ref. [37], Fig. 2), the short-wavelength wing of the SPM-broadened spectrum of output pulses becomes suppressed as the input pulses are coupled into higher order wave guide modes (Fig. 5). The main features of spectral changes observed in these experiments are adequately reproduced with a simple model of SPM-broadened pulse transmitted through a fiber with a narrow passband (cf. Figs. 1 and 5). The tunability range of radiation energy limiting level (5–10% in our experiments) can be substantially expanded with a careful design of the dispersion of higher order modes in PCFs.

The method of short-pulse limiting implemented in this work intrinsically involves spectral filtering of laser pulses by PCF passbands, which inevitably leads to distortions of the pulse envelope. To assess the influence of this effect, we studied the behavior of the output pulse envelope as a function of the input energy using cross-correlation-frequency-resolved optical gating (XFROG) [42]. An XFROG signal was generated in our experimental scheme [43] by mixing the signal transmitted through the hollow PCF with the fundamental-wavelength output of the Ti:sapphire laser in a BBO crystal. A two-dimensional XFROG sonogram was then plotted in a standard way [42] by measuring the XFROG signal as a function of the delay time between the reference Ti:sapphire laser pulse and the pulse transmitted through the PCF. Figure 6 displays the output pulse envelopes extracted from XFROG traces measured with Ti:sapphire laser pulses with an initial duration of 50 fs and input energies ranging from 0.1 up to 4 μJ. These measurements show that, within the range of input pulse energies from 0.1 up to 1.4 μJ, SPM leads to a moderate broadening of laser pulses. PCF passbands block only low-energy wings of pulse spectra under these conditions, allowing high-energy parts of the spectra to be transmitted with virtually no additional losses. This regime of pulse limiting is characterized by minimal distortions of output pulse envelopes (cf. curves 1 and 2 in Fig. 6). For high input radiation energies, however, distortions of temporal pulse profiles may become a crucial issue for the operation of a PCF limiter (curve 3 in Fig. 6). Attractive strategies to solve this problem may include pulse prechirping and preshaping, as well as using PCFs with a special dispersion profile, designed to shape smooth field waveforms at the output of a PCF limiter.

V. CONCLUSION

We have demonstrated in this work that the spectral broadening of laser pulses induced by self-phase modulation in air-guided modes of hollow-core PCFs allows the creation of fiber-optic limiters for high-intensity ultrashort laser pulses. Our analysis of such PCF limiters shows that the limiting level of radiation energy at the output of the fiber is controlled by the pulse duration, radiation wavelength, the effective mode area, the passband width, the PCF length, and the nonlinear refractive index of the gas (or another material) filling the fiber core. Variation of these parameters allows PCF limiters for ultrashort laser pulses to be designed within a broad range of radiation energies. Our experiments, performed with 100 fs microjoule pulses of 800 nm Ti:sapphire laser radiation, demonstrate the potential of hollow PCFs as limiters for 10 MW ultrashort laser pulses and show the possibility to switch the limiting level of output radiation energy by guiding femtosecond pulses in different PCF modes. Optical limiters for subgigawatt and even gigawatt ultrashort laser pulses can be designed by increasing the PCF core diameter or by designing PCFs with broader passbands.

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