Optical Limiting in Photonic Crystal Fibers

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ABSTRACT

Optical limiters provide sensor protection from laser energy by clamping the energy at a safe level. We present theoretical and experimental results on a new type of optical limiter based on self phase modulation and photonic crystal fibers. This unique combination allows one to engineer the limiting energy level by designing the fiber parameters to suit the particular application. We have shown that the limiting energy depends on the effective mode area of the fiber, the passband width of the propagating fiber mode, the length of the fiber, and the nonlinear refractive index of the gas (or other material) filling the fiber core.

1. INTRODUCTION

Hollow core photonic crystal fibers are unusual in that the guiding medium has an index of refraction that is less than the refractive index of the cladding. The guiding medium is typically air although the core can be filled with other gases, liquids, or even solids. The cladding is constructed of a lattice of glass and hollow space. The cladding has properties similar to a dielectric mirror in that it is highly reflective over a range of wavelengths. The reflecting band is determined by the material properties and the periodicity of the multilayer stack. In other spectral regions the dielectric mirror will not reflect the radiation. Thus, unlike conventional fibers which guide all wavelengths shorter than the cut-off wavelength, hollow core photonic crystal fibers have a series of guided modes and non-guided or lossy modes. For the non-guided modes, the radiation leaks out of the core and is scattered completely out of the fiber or it can be absorbed by a suitable jacket material.

Self phase modulation is a well known phenomenon that causes a propagating optical pulse to spectrally broaden. It is a third order nonlinear process in which the index of refraction of the medium can be changed on a transient time scale by the optical intensity of the pulse. The nonlinearity is typically very small. An optical pulse with an intensity of $10MW/cm^2$ will change the index of refraction of air by only 1 part in a trillion. For solids, the nonlinearity increases roughly in proportion to the density and change is on the order of 1 part in a billion. This appears insignificant, but in a fiber communication network, spectral broadening due to self phase modulation is a serious concern. The reason for concern is that fibers have very small cross sections (typical core diameters of 10 μm) and long propagation lengths (cm to km). The tight confinement yields large intensities and the waveguide provides long propagation lengths. These properties make fibers ideal for nonlinear devices.

In the experiment, a 100 fs long optical pulse having a center wavelength of 800 nm is launched into a photonic crystal fiber. The fiber has a pass band from 760-840 nm, a core diameter of 14 μm, and a length of 10 cm. For pulse energies less than 100 nJ, the output pulse energy is the same as the input pulse energy. As the input energy

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increases, the output energy becomes smaller than the input energy and eventually reaches a maximum output energy of 600 nJ independent of the input energy. The limiting behavior is due to self phase modulation which causes the spectral content of the pulse to broaden beyond the guiding band of the fiber.

1. HOLLOW CORE FIBERS

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].

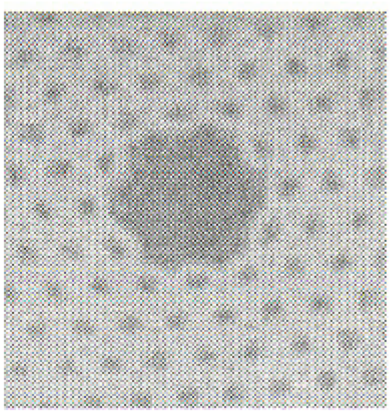

Fig. 1) Typical cross section of a hollow core photonic crystal fiber. The dark areas are air and the lighter areas are silica. The core diameter is ~14 µm.

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 $d \sim 100 - 500$ µm 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 (Fig. 1) within photonic band gaps (PBGs). Fig. 2 shows the unique transmission properties of hollow core photonic crystal fibers. In regions where the fiber transmittance is high, the photonic lattice surrounding the air core reflects the light and confines the radiation within the core.

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 µm [12 - 15]. Hollow PCFs with such core diameters have been recently demonstrated to enhance nonlinear-optical processes, including stimulated Raman scattering [15], four-wave mixing [16], and self-phase modulation [17]. Air-guided modes in hollow PCFs can support megawatt optical solitons [18] and allow transportation of high-intensity laser pulses for technological [19] and biomedical [20] applications.

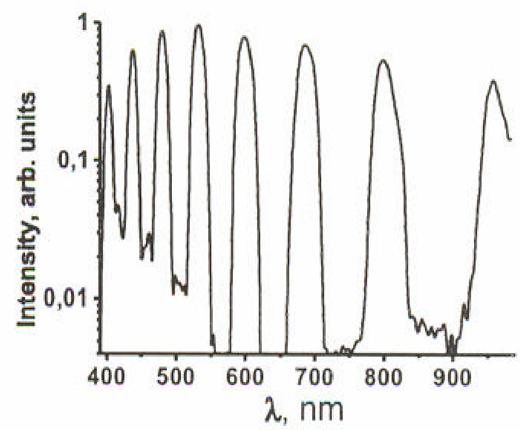

Fig. 2) Transmittance of hollow core, photonic crystal fiber.

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 [21 - 27], 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[28], 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 [29].

3. SELF-PHASE MODULATION

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 $\Delta\phi_{nl}$. An elementary theory of SPM gives the following expression for this shift [30, 31]:

$$\Delta\phi_{nl} = \{2\pi/\lambda\}\, n_2\, I\, l \qquad (1)$$

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

$$\Delta\omega = \Delta\omega_o + \{2\pi/\lambda\}\, n_2\, \{P\, l / S\, \tau\} \qquad (2)$$

where $\Delta\omega_o$ 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.

4. OPTICAL LIMITING

We represent the radiation energy E_{out} at the output of the hollow PCF as

$$E_{out} = E_{in}\, T_o\, \{\delta\omega / \Delta\omega\} \qquad (3)$$

where E_{in} is the input energy, T_o is the transmission of the fiber, and $\delta\omega$ is the width of the PCF passband.

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

$$E_{out} = E_{in}\, \{(\Delta\omega_O / \delta\omega) + (E_{in} / E_{lim})\}^{-1} \qquad (4)$$

Where

$$E_{lim} = \{S\, \tau^2\, T_o\, c / n_2\, l\}\, (\delta\lambda / \lambda) \qquad (5)$$

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

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 $\delta\omega$ and the PCF losses are negligible, the output radiation energy is a linear function of the input radiation energy, $E_{out} = E_{in}\ T_o$, (we assume here that $\Delta\omega_o < \delta\omega$). 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 regions outside the passbands are characterized by very high losses. At high 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). Fig. 3 shows a plot of Eqns 4 and 5 for various levels of E_{lim}.

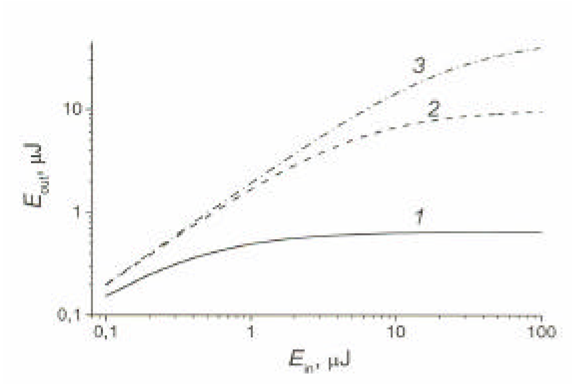

Fig. 3) Output energy of an optical pulse transmitted through a photonic crystal fiber versus the input pulse energy. Curve 1: limiting energy of 0.65 µJ; Curve 2: limiting energy of 10 µJ; Curve 3: limiting energy of 50 µJ.

Formulas (4) and (5) 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, inner fiber diameter d ~ 14 µm, fiber length l ~ 10 cm, $n_2 \sim 5\times10^{-19}$ cm^2/W, T_o ~ 0.7, and $\delta\lambda/\lambda \sim 0.01$, Eq. (5) yields the following estimate: $E_{lim} \sim 0.65$ µJ.

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.

5. WAVEGUIDE MODES

The passbands in the transmission of a PCF are the maps of the photonic band gaps of the fiber cladding. This mapping is defined [12, 32] by crossings of dispersion lines of air-guided PCF modes with PBGs (Fig. 4). 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. 4, 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. Self-phase modulated 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.

6. EXPERIMENTAL APPARATUS

The femtosecond laser system employed in the experiments (Fig. 5) 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 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.

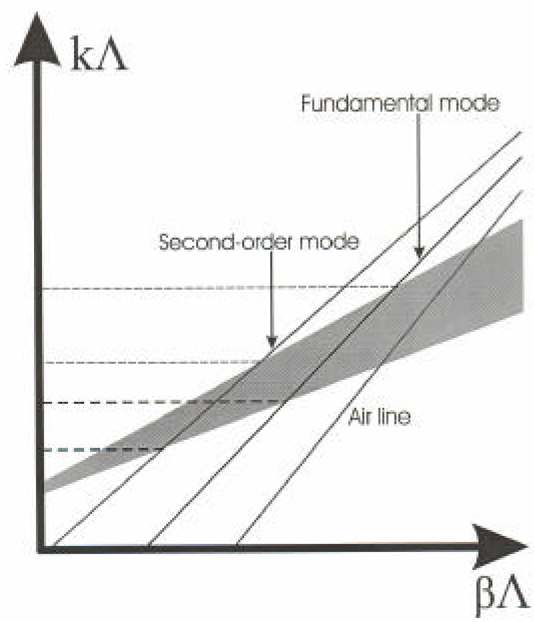

Fig. 4) A β-k diagram for a hollow-core photonic-crystal fiber (β is the propagation constant, k is the wave number, Λ is the period of the structure in the PCF cladding). Solid lines show dispersion relations for (1) a plane wave in atmospheric air with no waveguide, (2) the fundamental mode of the PCF, and (3) 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.

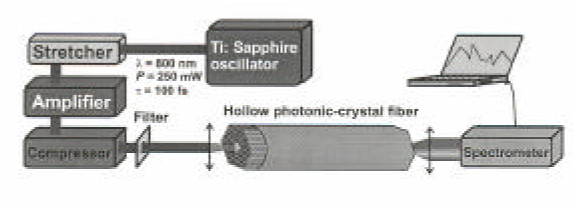

Fig. 5) Experimental apparatus for measuring the optical limiting behavior of photonic crystal fibers.

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. The PCFs were fabricated [14, 33] 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 (Fig. 2), related to PBGs of the cladding [12]. The spectra of air-guided modes in hollow PCFs were tuned by changing the fiber cladding structure [19]. Vectorial modeling of PCF modes was performed with the use of numerical approaches developed in earlier work [33] in order to design PCF limiters for femtosecond Ti: sapphire laser pulses. 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.

7. EXPERIMENTAL RESULTS

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. 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. 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 (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.

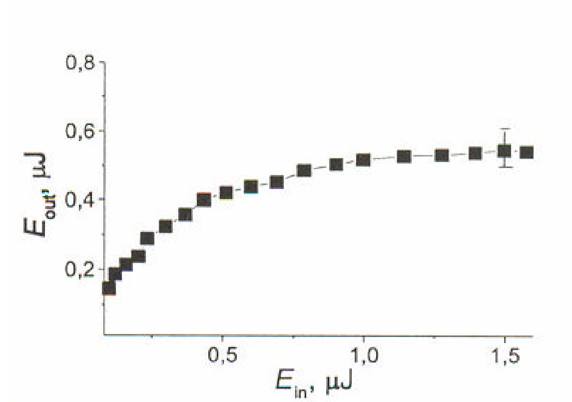

Fig. 6) Experimental results of optical limiting in hollow core photonic crystal fibers.

The shifting of passbands and the difference in SPM-induced spectral widths for different PCF modes, suggest the ways to switch the limiting level of output radiation energy by guiding femtosecond 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 leading to noticeable changes in the spectra of radiation measured at the output of the PCF. Since the passbands of higher order PCF modes are red-shifted with respect to the passband of the fundamental mode, the short-wavelength wing of the SPM-broadened spectrum of output pulses becomes suppressed as the input pulses are coupled into higher order waveguide modes. 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. 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.

8. CONCLUSIONS

We have demonstrated 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.

The beauty of the hollow core photonic crystal fiber is that the limiting pulse energy can be designed into the fiber. For example, optical limiters for gigawatt pulses can be designed by increasing the core diameter or by designing the photonic crystal fiber with a broader guiding band. For limiting of longer optical pulses or lower pulse energies (which broaden due to self phase modulation at a slower rate), the fiber length can be increased or a gas, liquid, or solid material with a larger nonlinear coefficient than air can be introduced into the core. To protect a sensor in an imaging system, the fiber can be bundled together similar to conventional fiber imaging bundles. We have just begun to explore the range of possibilities for optical limiting in photonic crystal fibers.

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