

# Transmission of Ultrashort Pulses through Hollow Photonic-Crystal Fibers with Passbands in the Visible and Infrared Spectral Ranges

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**Abstract**—Hollow-core photonic-crystal fibers with passbands in the range of wavelengths from 0.4 to 2.0  $\mu\text{m}$  are demonstrated. Changes in the envelope and the evolution of the spectral phase and the chirp of femtosecond pulses propagating through hollow photonic-crystal fibers are experimentally studied. Envelope and phase distortions of ultrashort pulses transmitted through such fibers are shown to be controlled by the detuning of the carrier frequency of laser pulses from the central frequency of the passband in the transmission of the fiber. Near the passband edges, which map the edges of photonic band gaps of the fiber cladding, ultrashort pulses transmitted through the fiber display considerable envelope distortions, as well as frequency- and time-dependent phase shifts.

## 1. INTRODUCTION

Fibers with a cladding in the form of a two-dimensionally periodic microstructure (two-dimensional photonic crystal) and a hollow core [1, 2] is a new promising type of optical fibers. Such fibers are of special interest for telecommunication applications [1], enhancement of nonlinear-optical processes [3, 4], and laser guiding of small-size particles [5]. The hollow core of photonic-crystal fibers (PCFs) has a lower material dispersion and a higher breakdown threshold as compared with solid-core fibers, suggesting new solutions for the transportation of ultrashort laser pulses, including ultraintense short pulses and pulses produced by technological laser systems [6].

Photonic band gaps of a two-dimensionally periodic fiber cladding, mapped onto well-pronounced peaks in fiber transmission, reduce optical losses of air-guided modes [1, 2], providing a unique possibility to guide laser radiation through a hollow fiber core with a radius of a few microns and allowing a radical enhancement of nonlinear-optical interactions of ultrashort laser pulses [3, 4, 7].

The envelope and phase evolution of ultrashort laser pulses guided through optical fibers may noticeably influence the propagation regime and the efficiency of nonlinear-optical interactions of ultrashort laser pulses, eventually determining the possibility of subsequent spectral and temporal transformation of laser pulses. In this work, we experimentally demonstrate hollow-core PCFs with passbands in the range of wavelengths from 0.4 to 2.0  $\mu\text{m}$  and investigate changes in the envelope,

as well as the evolution of the spectral phase and the chirp of femtosecond pulses transmitted through such fibers. We will show that the propagation of ultrashort pulses through hollow PCFs may be accompanied by frequency- and time-dependent phase shifts and considerable envelope distortions.

## 2. EXPERIMENTAL

To study the envelope and phase evolution of ultrashort pulses, we used hollow-core photonic-crystal fibers having a period of the photonic-crystal cladding of about 5  $\mu\text{m}$  and an inner diameter of approximately 14  $\mu\text{m}$  (the inset in Fig. 1a). These fibers were fabricated with the use of the technology described in detail elsewhere [8]. Transmission spectra of these hollow-core PCFs displayed characteristic well-pronounced isolated peaks (Figs. 1a–1c). The origin of these peaks is associated with the high reflectivity of a periodically structured fiber cladding within photonic band gaps, which substantially reduces radiation losses in guided modes within narrow spectral ranges [1, 2]. Radiation with wavelengths lying outside the photonic band gaps of the cladding leaks from the hollow core. Such leaky radiation modes are characterized by high losses, giving virtually no contribution to the signal at the output of the fiber. The spectra of air-guided modes in hollow-core photonic-crystal fibers can be tuned by changing the fiber cladding structure [8]. To guide femtosecond pulses of a Ti: sapphire laser, we designed and fabri-

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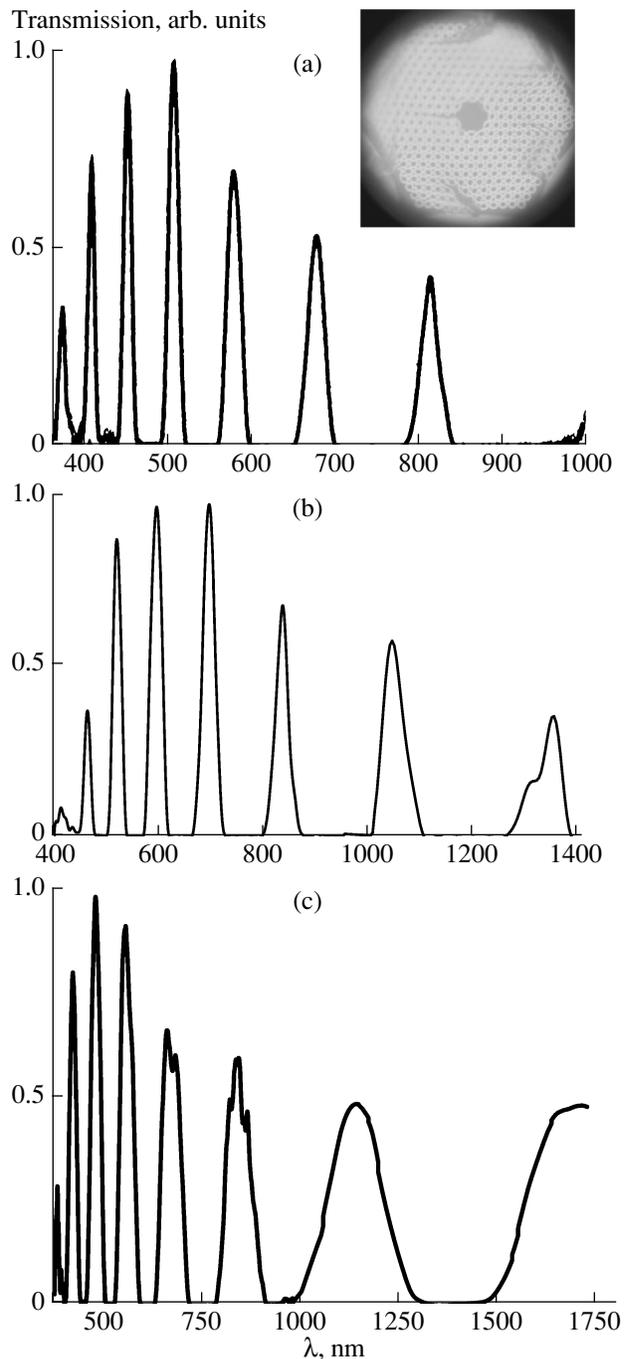
cated hollow-core photonic-crystal fibers providing minimum losses around the wavelength of 800 nm (Fig. 1a). Figure 1b displays the transmission spectrum of a hollow PCF with passbands at the frequencies of fundamental radiation of a Nd: YAG laser and its second harmonic. The hollow PCF with the transmission spectrum presented in Fig. 1c is designed to guide infrared radiation within the range of wavelengths from 1.0 to 1.25  $\mu\text{m}$  and from 1.6 to 2.0  $\mu\text{m}$ .

The laser system employed in our experiments was based on an argon-laser-pumped Ti: sapphire laser, which generated 50–80-fs pulses of 790–810-nm radiation with a pulse energy of 1–3 nJ. Laser radiation was coupled into a hollow PCF (Fig. 2) placed on a three-dimensional translation stage. The envelope, the spectrum, the spectral phase, and the chirp of laser pulses transmitted through hollow PCFs were measured by means of spectral phase interferometry for direct electric-field reconstruction (SPIDER) [9]. The pulse duration and the pulse envelope were additionally measured with the use of the standard autocorrelation technique.

### 3. RESULTS AND DISCUSSION

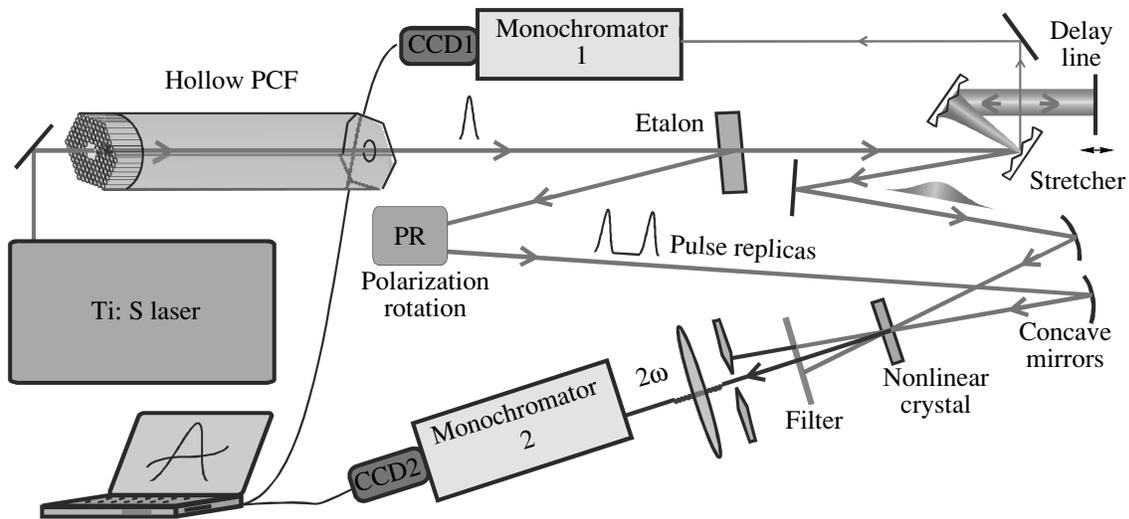
The generic scheme of SPIDER characterization [9] of ultrashort pulses transmitted through a PCF is illustrated in Fig. 2. Two replicas of an output ultrashort pulse with the field spectrum  $E(\omega)$  and the spectral phase  $\varphi(\omega)$ , formed with an etalon and a polarization rotator are mixed in a nonlinear crystal with a chirped pulse, produced with the use of a stretcher and an optical delay line (Fig. 2). Due to the delay  $\tau$  between the replicas of the pulse, sum-frequency generation in the nonlinear crystal gives rise to two pulses,  $E(\omega)$  and  $E(\omega + \delta\omega)$ , with a spectral shear  $\delta\omega$  determined by the delay time  $\tau$  and the chirp of the reference pulse. The interferogram of these two spectrally sheared pulses,  $S(\omega_c) = |E(\omega_c)|^2 + |E(\omega_c + \delta\omega)|^2 + 2|E(\omega_c)E(\omega_c + \delta\omega)|\cos[\varphi(\omega_c + \delta\omega) - \varphi(\omega_c) + \omega_c\tau]$  (where  $\omega_c$  is the central frequency of the transmission band) is detected with a spectrometer (Fig. 2). The phase of the oscillating term in the expression for the interferogram is retrieved by means of one-dimensional Fourier transform. The linear phase  $\omega_c\tau$  is measured independently and is subtracted from the result of this Fourier transform. The spectral phase reconstructed with the use of this procedure and an independently measured spectrum of the main pulse are then used to find the temporal envelope and the chirp of the pulse.

Envelope distortions of femtosecond pulses at the output of a hollow PCF, as can be seen from the analysis of the experimental data presented in Figs. 3–5, are highly sensitive to the detuning of the carrier frequency of femtosecond pulses from the central frequency of the PCF passband. Generally, when the central wavelength of a pulse differs from the center of a PCF passband, femtosecond pulses transmitted through a PCF display noticeable envelope distortions and considerable phase shifts. This regime of pulse transmission is illustrated

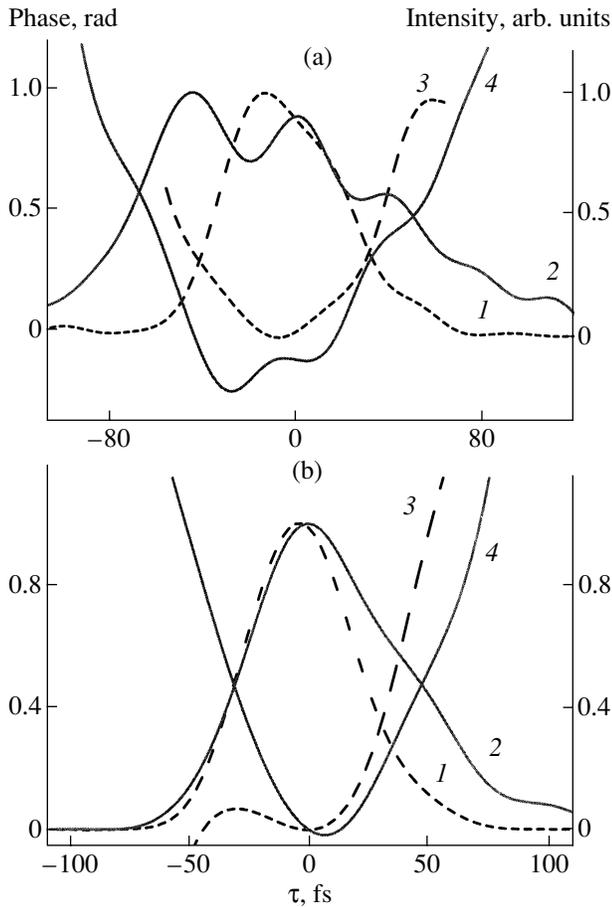


**Fig. 1.** Transmission spectra of hollow-core photonic-crystal fibers designed to transmit (a) femtosecond pulses of Ti: sapphire-laser radiation, (b) the fundamental radiation of a Nd: YAG laser and its second harmonic, and (c) infrared radiation within the range of wavelengths from 1.0 to 1.25  $\mu\text{m}$  and from 1.6 to 2.0  $\mu\text{m}$ . The inset to Fig. 1a shows the cross-section image of the hollow PCF with a period of the cladding equal to 5  $\mu\text{m}$  and the core diameter of about 13  $\mu\text{m}$ .

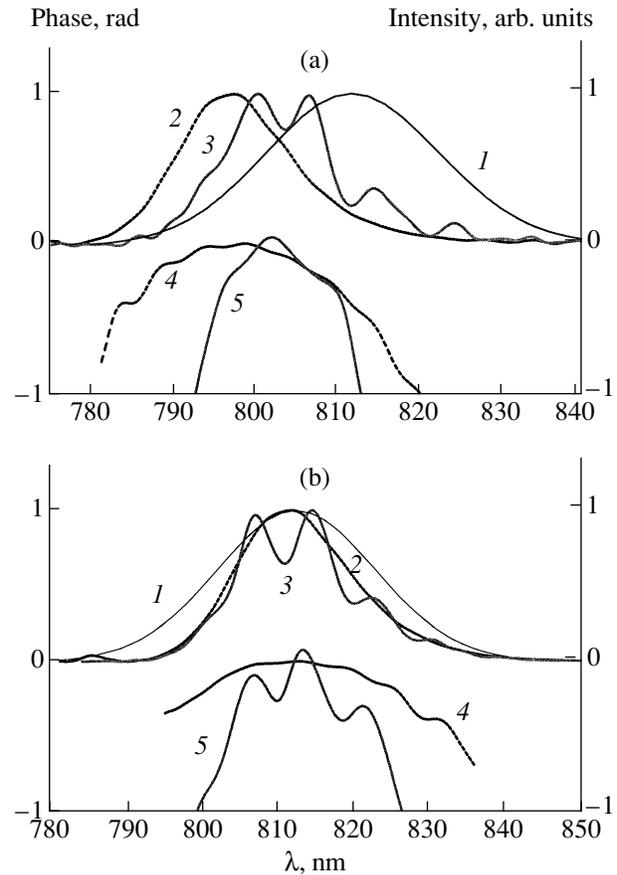
in Figs. 3a, 4a, and 5a. The initial duration of laser pulses coupled into the PCF was approximately 70 fs. The central wavelength of laser radiation was 797 nm. The initial chirp is shown by curve 3 in Fig. 3a. The



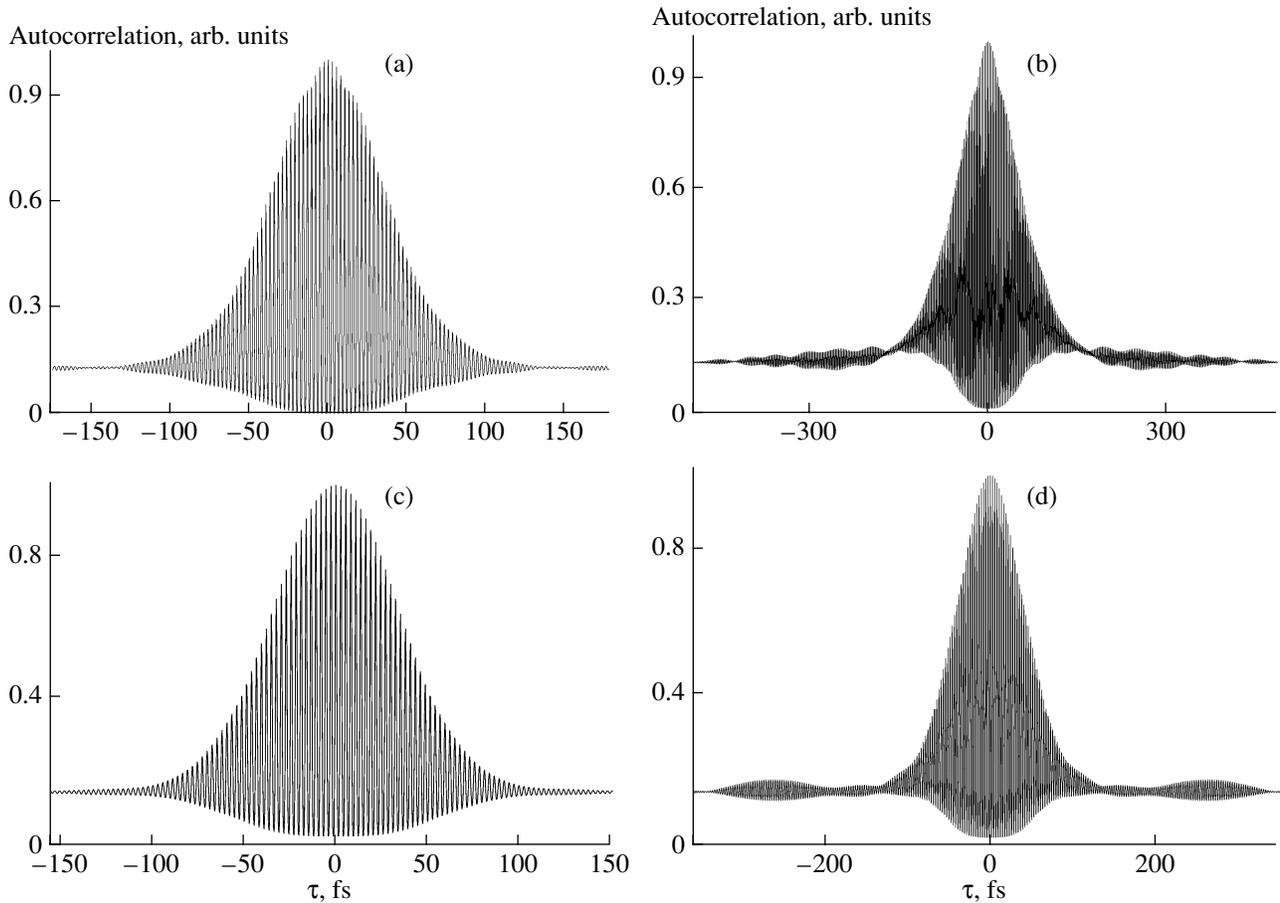
**Fig. 2.** Diagram of the experimental setup for studying the envelope and phase evolution of femtosecond pulses in hollow photonic-crystal fibers.



**Fig. 3.** The envelope (1, 2) and the chirp (3, 4) of a Ti:sapphire-laser pulse transmitted through a 3-cm hollow-core photonic-crystal fiber with the structure of the cross section shown in the inset to Fig. 1 (solid lines) and a pulse at the output of the Ti:sapphire laser (dotted lines). The wavelength of laser radiation is (a) 797 nm and (b) 812 nm.



**Fig. 4.** Evolution of the spectrum and the spectral phase of a Ti:sapphire-laser pulse transmitted through a hollow-core photonic-crystal fiber: (1) the passband of the PCF, (2) the initial spectrum of the pulse, (3) the spectrum of the pulse transmitted through a 3-cm PCF, (4) the initial spectral phase of the pulse, and (5) the spectral phase of the pulse transmitted through a 3-cm PCF. The wavelength of laser radiation is (a) 797 nm and (b) 812 nm.



**Fig. 5.** Autocorrelation traces for (a, c) Ti: sapphire-laser pulses and (b, d) pulses transmitted through the hollow PCF. The wavelength of laser radiation is (a, b) 797 nm and (c, d) 812 nm.

pulse envelope at the output of a 3-cm PCF segment (curve 2 in Fig. 3a) noticeably differs from the initial pulse shape (curve 1 in Fig. 3a). The chirp and the spectral phase of the pulse transmitted through the PCF (Figs. 3a, 4a) indicate a considerable influence of phase delays and group-velocity dispersion. Substantial changes in the pulse duration are also visualized by the comparison of autocorrelation traces measured for laser pulses transmitted through the PCF (Fig. 5b) and pulses at the output of the laser system (Fig. 5a).

Envelope and phase distortions of ultrashort pulses transmitted through hollow PCFs were radically reduced when the central wavelength of laser pulses was chosen close to the central frequency of a PCF passband. This regime of PCF transmission of ultrashort pulses is illustrated by Figs. 3b, 4b, and 5b. The wavelength of laser radiation was equal to 812 nm in this case. The initial pulse duration was about 50 fs. The initial chirp of pulses coupled into the PCF is presented by curve 3 in Fig. 3b. The duration of laser pulses at the output of the PCF was estimated as 75 fs in this regime (curve 2 in Fig. 3b). Envelope distortions (curve 2 in Fig. 3b), phase shifts, and group delays (curve 4 in Fig. 3b and curve 5 in Fig. 4b) in this regime of pulse transmission are much less than analogous

changes in pulse parameters in the regimes where the carrier frequency of laser pulses substantially differs from the central frequency of the PCF passband. This conclusion is confirmed by the comparison of autocorrelation traces measured for laser pulses transmitted through the PCF (Fig. 5d) and pulses at the output of the laser source (Fig. 5c).

The results of experiments presented above reveal important properties of air-guided modes supported by hollow-core PCFs. In particular, the spectral phase measured for pulses transmitted through PCFs (Figs. 4a, 4b) gives insights into the phase mismatch for nonlinear-optical processes in hollow PCFs and suggests strategies of PCF optimization for the enhancement of nonlinear-optical interactions of ultrashort pulses in air-guided modes of PCFs. These spectral phase data were used to enhance four-wave mixing in hollow PCFs [4] and to radically improve the sensitivity of gas-phase analysis with the use of nonlinear-optical processes in such fibers [10].

Analysis of the experimental results presented in Figs. 3–5 shows that the spreading of ultrashort pulses transmitted through photonic-crystal fibers is not only due to the spectral limiting of these pulses by the pass-

bands of photonic-crystal fibers, but also due to the waveguide dispersion. Physically, the strong dispersion of guided modes in photonic-crystal fibers is related to the mechanism of waveguiding by photonic band gaps. Strong dispersion of periodic structures has been extensively discussed earlier in the context of applications of photonic crystals (see, e.g., [11, 12]). Dispersion spreading of ultrashort pulses in air-guided modes of photonic-crystal fibers has, in fact, the same physical origin as, for example, compression in systems of chirped mirrors [13, 14]. Similar effects and related phenomena can be observed in dispersive elements [12] and delay lines [11] based on photonic crystals. Our experimental findings are also consistent with the results of calculations performed earlier for the dispersion of hollow photonic-crystal fibers [15] and coaxial Bragg waveguides [16, 17]. These calculations have demonstrated that, far from the edges of photonic band gaps of a periodic fiber cladding, the frequency profile of the group-velocity dispersion in hollow-core photonic-crystal fibers can be satisfactorily approximated by a similar dependence for a hollow metal waveguide [16]. Hollow PCFs provide optimal conditions for the transmission of ultrashort pulses under these conditions. Although the material dispersion of the gas filling the hollow fiber core is typically much lower than the material dispersion of standard, fused silica fibers, the group-velocity dispersion may still play a noticeable role in the case of hollow photonic-crystal fibers with a very small core diameter due to the waveguide dispersion, which rapidly grows with a decrease in the core diameter. Waveguide dispersion becomes stronger around the edges of photonic band gaps of the fiber cladding (Figs. 3–5), leading, as shown in this work, to considerable distortions of the envelope, chirp, and the spectral phase of ultrashort pulses.

#### 4. CONCLUSION

We have demonstrated hollow-core PCFs with broadly tunable passbands in the range of wavelengths from 0.4 to 2.0  $\mu\text{m}$ . In particular, hollow PCFs designed to transmit femtosecond pulses of Ti: sapphire-laser radiation, as well as the fundamental radiation of a Nd: YAG laser and its second harmonic have been fabricated and tested. Transmission of infrared radiation with wavelengths up to 2.0  $\mu\text{m}$  has been demonstrated. Experiments presented in this paper give insights into the evolution of the envelope, spectral phase, and chirp of femtosecond laser pulses propagating through hollow photonic-crystal fibers. The results of these studies indicate that envelope and phase distortions of ultrashort pulses guided through hollow photonic-crystal fibers are determined by the detuning of the carrier frequency of laser pulses from the central frequency of the PCF passband. Distortions of the pulse envelope, as well as time- and frequency-dependent phase shifts become especially noticeable around the edges of PCF passbands, corresponding to the edges of photonic band gaps of the fiber cladding. Away from the edges of these

photonic band gaps, hollow photonic-crystal fibers can provide optimal conditions for the transmission of ultrashort pulses. However, waveguide dispersion effects may play a noticeable role in hollow photonic-crystal fibers with a small core diameter, leading to considerable distortions of the envelope, chirp, and the spectral phase of ultrashort pulses.

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