Appl. Phys. B 78, 547–550 (2004)
DOI: 10.1007/s00340-004-1417-6

Applied Physics B
Lasers and Optics

S.O. KONOROV[1]
D.A. SIDOROV-BIRYUKOV[2]
I. BUGAR[3]
M.J. BLOEMER[4]
V.I. BELOGLAZOV[5]
N.B. SKIBINA[5]
D. CHORVAT JR.[3]
D. CHORVAT[3]
M. SCALORA[4]
A.M. ZHELTIKOV[1,2,✉]

Experimental demonstration of a photonic-crystal-fiber optical diode

[1] Physics Department, M.V. Lomonosov Moscow State University, 119992 Moscow, Russia
[2] International Laser Center, M.V. Lomonosov Moscow State University, 119992 Moscow, Russia
[3] International Laser Center, Ilkovičova 3, 81219 Bratislava, Slovak Republic
[4] Weapons Sciences Directorate, US Army Aviation and Missile Command, Huntsville, AL 35898-5000, USA
[5] Institute of Glass Structure Technology and Equipment, pr. Stroitelei 1, 410044 Saratov, Russia

Received: 5 January 2004

ABSTRACT Two cascaded hollow-core photonic-crystal fibers with slightly shifted, but still overlapping, transmission peaks are shown to function as an optical diode for ultra-short laser pulses. Submicrojoule 100-fs Ti : sapphire laser pulses with a spectrum falling within the passband of one of the fibers, but outside the passband of the second fiber, experience spectral broadening due to self-phase modulation in the first fiber. A part of this self-phase-modulation-broadened spectrum is then transmitted through the second fiber. Identical short pulses propagating in the opposite direction are blocked by the second fiber with a shifted passband. A forward-to-backward signal ratio exceeding 40 is achieved with the created photonic-crystal fiber diode for 0.9-μJ, 100-fs pulses of 800-nm Ti : sapphire laser radiation.

PACS 42.65.Wi; 42.81.Qb

1 Introduction

Microstructure and photonic-crystal fibers [1] allow the creation of novel optical devices. Highly efficient supercontinuum generators [2] and multiplex frequency converters [3] for nano- and subnanojoule femtosecond pulses can be created with the use of microstructure fibers with a specially designed dispersion profile. Such microstructure-fiber components are intensely used in optical frequency metrology [4–6], laser biomedicine [7], spectroscopy [8], and photochemistry [3]. Hollow-core photonic-crystal fibers (PCFs) [9] radically enhance nonlinear-optical interactions of laser pulses in the gas phase, improving by orders of magnitude the efficiency of stimulated Raman scattering [10], four-wave mixing [11], and self-phase modulation (SPM) [12]. These fibers allow the laser guiding of microparticles [13] and transportation of high-power laser pulses for technological [14] and biomedical [15] applications. Recent experiments [16] have demonstrated the existence of megawatt optical solitons in hollow-core PCFs.

Here we report an experimental demonstration of an optical diode based on two cascaded hollow PCFs, proposed in our earlier work [17], extending the idea of using photonic band gap (PBG) materials for the creation of an optical analogue of an electronic diode [18] to the photonic-crystal-fiber design. The plan of this paper is as follows. In Sect. 2, we explain the concept of a PCF diode. Experimental results are presented in Sect. 3. Our experiments show that submicrojoule 100-fs Ti : sapphire laser pulses with a spectrum falling within the passband of one of the fibers, but outside the passband of the second fiber, experience spectral broadening due to self-phase modulation in the first fiber. A part of this self-phase-modulation-broadened spectrum is then transmitted through the second fiber. Identical short pulses propagating in the opposite direction are blocked by the second fiber with a shifted passband. The results of our work are briefly summarized in Sect. 4.

2 Generic idea

The operation principle of a PCF optical diode is illustrated in Fig. 1. Laser radiation is guided by the hollow core of a PCF due to the high reflectivity of its two-dimensionally periodic cladding within photonic band gaps [9]. These photonic band gaps give rise to peaks in the transmission spectrum of a hollow PCF. These passbands in the transmission of hollow PCFs are essentially a map of PBGs of the fiber cladding, with the central frequencies and widths being determined by those of the respective PBGs [9, 19]. The passbands of hollow PCFs can be tuned by changing the structure of the fiber cladding [20].

Let us consider two cascaded PCFs (Fig. 1) with passbands having the central frequencies ω_1 and ω_2 and widths Δ_1 and Δ_2, respectively. To create an optical diode, we need PCFs with slightly shifted, but still overlapping, passbands. Mathematically, these requirements are written as

$$\omega_1 \neq \omega_2, \tag{1}$$

$$|\omega_1 - \omega_2| < (\Delta_1 + \Delta_2)/2. \tag{2}$$

We will demonstrate now that a sequence of two hollow PCFs with the above-specified transmission properties can function as an optical diode for a short pulse with a central frequency ω_0 and a spectrum falling within the passband of PCF1, but outside the passband of PCF2 (see Fig. 1):

$$|\omega_1 - \omega_0| < (\Delta_0 + \Delta_1)/2, \tag{3}$$

$$|\omega_2 - \omega_0| > (\Delta_0 + \Delta_2)/2, \tag{4}$$

where Δ_0 is the bandwidth of the laser pulse.

✉ Fax: +7-95/939-5174, E-mail: zheltikov@top.phys.msu.su

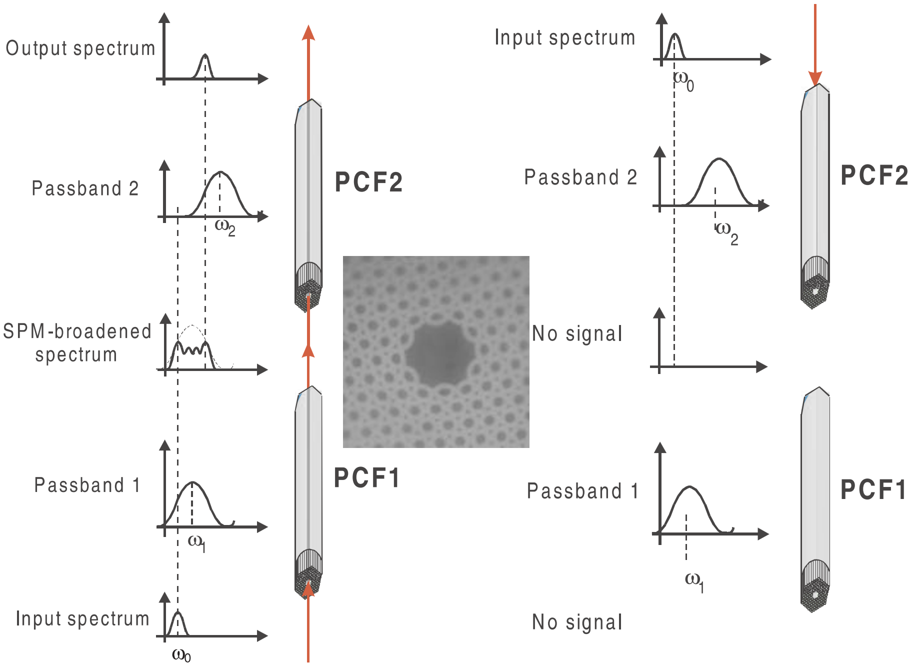

FIGURE 1 Operation of an optical diode consisting of two photonic-crystal fibers with slightly shifted, but still overlapping, peaks in transmission spectra. **a** A short laser pulse with a spectrum falling within the passband of one of the fibers (PCF1), but outside the passband of the second fiber (PCF2), experiences spectral broadening due to self-phase modulation as it propagates through the first fiber. A part of its spectrum is then transmitted through the second fiber. **b** An identical short pulse propagating in the opposite direction is blocked by the second fiber. The *inset* shows an image of the PCF cross section with an inner diameter of approximately 14 µm and a period of the photonic-crystal cladding of about 5 µm

A laser pulse meeting the requirements of (3) and (4) is transmitted through PCF1. The propagation of this pulse through the fiber is accompanied by spectral broadening due to self-phase modulation, related to the nonlinear change in the refractive index of the gas filling the hollow core of PCF1. The elementary theory of self-phase modulation, which is based on the slowly varying envelope approximation and which is limited to first-order dispersion effects, yields [21] the following expression for the spectral broadening of the laser pulse at the output of PCF1:

$$\Delta_{\mathrm{SPM}} = \frac{\omega_0}{c} n_2 \frac{\partial\,|E(t)|^2}{\partial t} L, \tag{5}$$

where n_2 is the nonlinear refractive index, $E(t)$ is the envelope of the laser pulse, and L is the length of PCF1.

We require now that the spectral width of the SPM-broadened pulse at the output of PCF1 should meet the following condition:

$$|\omega_2 - \omega_0| < (\Delta_{\mathrm{SPM}} + \Delta_2)/2. \tag{6}$$

If this inequality is satisfied, then some part of the spectrum of the SPM-broadened laser pulse can be transmitted through PCF2 (see Fig. 1a), giving a nonzero optical signal at the output of the considered sequence of two PCFs.

Suppose now that the laser pulse meeting the requirements of (3) and (4) propagates in the opposite direction (Fig. 1b). Since the spectrum of this pulse falls outside the passband of PCF2, the backward-propagating pulse can excite only leaky modes in PCF2. These modes are characterized by very high losses, leaking from the hollow core of the fiber. PCF2, thus, blocks the backward pulse, giving no signal at the output of PCF1. We have, thus, demonstrated that a sequence of two hollow PCFs meeting the requirements of (1)–(6) can operate as an optical diode.

3 Experimental

The femtosecond laser system employed in our experiments (Fig. 2) consisted of a Ti : sapphire master oscillator, a stretcher, an amplifier, and a pulse compressor [22]. 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

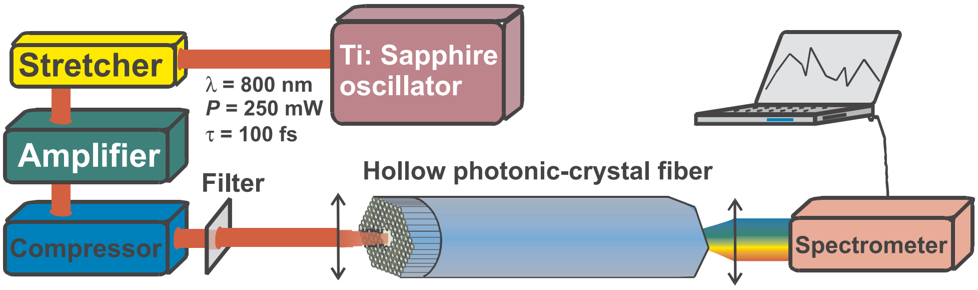

FIGURE 2 The laser setup for the investigation of transmission and self-phase modulation of femtosecond laser pulses in a photonic-crystal fiber

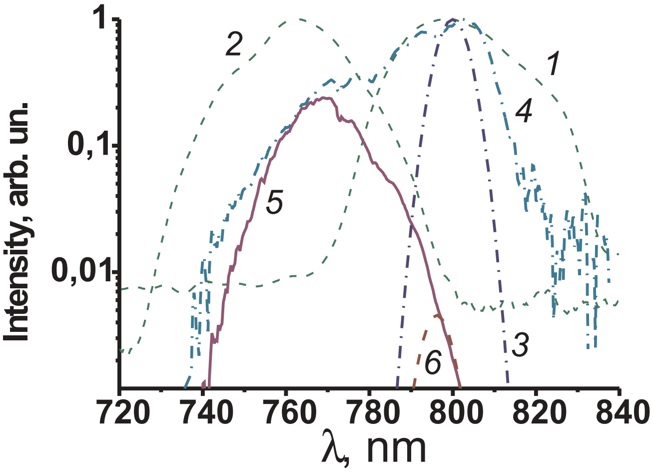

FIGURE 3 Performance of a PCF diode demonstrated with a 100-fs, 0.9-μJ Ti : sapphire laser pulse: *dashed lines 1 and 2* transmission peaks of the first and second PCFs, *dash–dotted line 3* spectrum of an input pulse of Ti : sapphire laser radiation, *dash–dotted line 4* spectrum of the pulse at the output of the first PCF broadened due to self-phase modulation, *solid line 5* spectrum of the SPM-broadened pulse transmitted through the second PCF, and *dashed line 6* spectrum of an identical pulse propagating in the opposite direction, transmitted first through PCF2 and then through PCF1

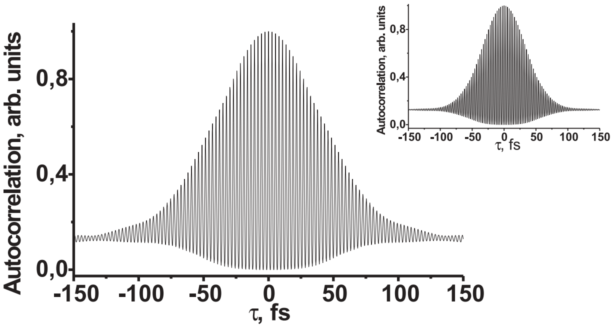

FIGURE 4 An autocorrelation trace measured with a 1-mm-thick BBO crystal for unamplified 2-nJ pulses of Ti : sapphire laser radiation at the output of a 5-cm section of a photonic-crystal fiber. An autocorrelation trace of the input pulse is shown in the *inset*

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.

A pair of hollow-core PCFs was designed for the purposes of these experiments. These PCFs 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 the inset to Fig. 1. The PCFs were fabricated [19, 20] 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. 3), related to PBGs of the cladding [9, 19]. The spectra of air-guided modes in hollow PCFs were tuned by changing the fiber cladding structure [20]. Vectorial modeling of PCF modes was performed with the use of numerical approaches developed in earlier work [20, 23] in order to design PCFs meeting conditions of (1) and (2). The first PCF provided maximum transmission for 800-nm radiation of a Ti : sapphire laser (the corresponding transmission peak is shown by the dashed line 1 in Fig. 3). The second PCF had a transmission peak slightly shifted from, but still overlapping with, the 800-nm passband of the first fiber (dashed line 2 in Fig. 3). For the first of these PCFs, the magnitude of optical losses at 800 nm was estimated as 0.08 cm^{-1}. Comparison of autocorrelation traces measured for an input unamplified 60-fs Ti : sapphire pulse (Fig. 4) and the pulse coming out of a 5-cm section of the first PCF (Fig. 4) shows that the created PCFs are capable of transmitting femtosecond pulses with minimum or no distortions of the pulse shape.

To demonstrate a PCF diode, we used 100-fs pulses of 800-nm Ti : sapphire laser radiation with an energy of 0.5–3 μJ. The initial spectrum of such pulses is shown by the dash–dotted curve 3 in Fig. 3. In view of transmission properties of our PCFs, laser pulses with such parameters allowed us to satisfy conditions of (3) and (4). Propagation of these pulses through the first PCF was accompanied by self-phase modulation. The dash–dotted line 4 in Fig. 3 shows the spectrum of radiation coming out of a 6-cm PCF measured with 0.9-μJ Ti : sapphire laser pulses coupled into the fiber. The spectral width of the SPM-broadened laser pulse at the output of the PCF was estimated as approximately 30 nm under these conditions. The spectrum of the laser pulse at the output of the first PCF is now broad enough to excite guided modes in the second PCF. The spectrum of SPM-broadened pulses transmitted through both PCFs is shown by the solid line 5 in Fig. 3. A laser pulse with the same energy (0.9 μJ), central wavelength (800 nm), and pulse duration (about 100 fs) propagating in the opposite direction sees the second PCF first and can excite only highly lossy modes in this fiber. The transmission of the considered sequence of fibers is extremely low under these conditions (dashed line 6 in Fig. 3). The amplitude of the signal transmitted through our PCF diode in the forward direction, as can be seen from the comparison of lines 5 and 6 in Fig. 3, is more than 40 times higher than the amplitude of the signal transmitted in the backward direction.

4 Conclusion

We have experimentally demonstrated the possibility of creating an optical diode using a sequence of two photonic-crystal fibers with slightly shifted, but still overlapping, peaks in transmission spectra. A short laser pulse with a spectrum falling within the passband of one of the fibers, but outside the passband of the second fiber, experiences spectral broadening due to self-phase modulation as it propagates through the first fiber. A part of the spectrum of this fiber is then transmitted through the second fiber. An identical short pulse propagating in the opposite direction is blocked by the second fiber with a shifted passband. Hollow-core photonic-crystal fibers allowing the creation of an optical diode for femtosecond pulses of 800-nm Ti : sapphire laser radiation have been created. For 0.9-μJ, 100-fs pulses of 800-nm radiation, the amplitude of the signal transmitted through a sequence of such PCFs in the forward direction was more than 40 times higher than the amplitude of the signal transmitted in the backward direction. Such an optical diode can be employed to switch and decouple ultra-short laser pulses within a broad range of laser intensities, including laser pulses of high intensities.

ACKNOWLEDGEMENTS We are grateful to A.B. Fedotov and V.P. Mitrokhin for their help and useful discussions. This study was supported in part by the President of the Russian Federation (Grant No. MD-42.2003.02), the Russian Foundation for Basic Research (Project Nos. 03-02-16929 and 02-02-17098), and the Civilian Research and Development Foundation (Project No. RP2-2558). This material is also based upon work supported by the European Research Office of the US Army under Contract No. 62558-03-M-0033.

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