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Air and silica core Bragg fibers for radiation delivery in the wavelength range 0.6–1.5 μm

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ABSTRACT

This paper presents fundamental characteristics of laboratory designed and fabricated Bragg fibers with air and silica cores at wavelengths of 632, 975, 1064 and 1550 nm. Fibers with the 26-μm-silica core and 5- or 73-μm-air cores in diameters and claddings of 3 pairs of Bragg layers were prepared from one preform. The overall transmittance, attenuation coefficients, coupling losses, bending losses, and damage-intensity thresholds were determined using four continuous-wave laser sources with the maximum output power of 300 mW and a pulsed 9 ns laser with the maximum output energy up to 1 mJ. The lowest attenuation coefficient of about 70 dB/km was determined at 1064 nm with the 73-μm-air-core Bragg fiber. All fibers have been found to exhibit negligible bending losses down to the bending diameters of 5 cm. In comparison with the conventional gradient optical fiber, all the prepared Bragg fibers have approximately six times higher damage intensity threshold of about 30 GWcm^{-2} and therefore they are very suitable for high power laser radiation delivery.

1. Introduction

In last twenty years, telecommunication systems can be hardly imagined without optical fibers [1]. However, optical fibers have also been investigated for high power delivery in medicine [2–4], special electrical power stations [5], lighting and heating systems [6,7], for material processing in industry [8], etc. The energy delivery using optical fibers can provide us an efficient alternative to traditional methods for transfer of heat and electricity [9] or sun light transmission in solar systems [6]. Several types of all-glass optical fibers with solid cores have been tested for high power delivery such as silica fibers, sapphire fibers [2,10], germanium dioxide fibers [11], etc. As standard silica optical fibers are not applicable for delivering radiation of mid-IR lasers, fibers based on sapphire or germanium dioxide can be used in this region.

Due to the defects caused by high energies inside the fiber or at their faces, the performance of optical fibers with solid cores at long-term delivery of high powers can be limited [2]. Moreover, high powers transmitted in solid cores of above mentioned fibers can produce nonlinear optical effects such as higher harmonics generation, four-wave mixing, Kerr effect, various types of stimulated scattering, self-focusing etc. Some of these effects can damage waveguiding structure of the fiber [10].

Recently, hollow fibers (HFs) or hollow-core photonic-band gap (HC-PBG) fibers have been tested for high power radiation delivery, too. In comparison with the solid-core fibers mentioned before, laser radiation of higher intensity can be guided in the air-cores of such fibers. Moreover, in such fibers, the radiation is transmitted through air having very small nonlinear coefficient. HFs are flexible hollow capillaries with an internal surface coating of silver covered by a proper dielectric material [12,13]. Due to the reflection on the air/coating boundary, HFs can guide the radiation from visible to mid-IR wavelengths [12]. However, HFs suffer from bending losses at low bending diameters.

HC-PBG fibers consist of a large air hole surrounded by a periodic two-dimensional (2D) array of air holes forming the fiber cladding [14,15]. Such periodic 2D structures have properties of photonic bandgap materials in which light at some particular wavelengths cannot propagate at the range of angles [16]. Therefore approximately 98% of light can be guided in the central air hole with very low losses at these wavelengths. HC-PBG fibers have been designed and successfully tested for delivery of radiation of a Nd:YAG laser at 1064 nm or an Er:YAG laser at 2940 nm [15,17]. Experimental results reported elsewhere [18] have shown that laser pulses with energy levels higher than 1 mJ and pulse durations of about 10 ns could be coupled into an HC-PBG fiber [18].

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HC-PBG fibers have also been tested for gas mixtures ignition [19]. Recently, so called Kagome-like hollow-core photonic–crystal silica fibers have been developed which exhibit a very low power in the silica part of the fiber at wavelengths up to about 4 μm due to inhibited-coupling guidance rather than the photonic bandgap effect [20]. Although such silica fibers can have great potential for mid-IR applications so far their optical losses are on a level of about 200 dB/km in this wavelength region due to difficulties at their fabrication.

The photonic bandgap effect is employed at Bragg fibers as well. In such fibers the air or solid core is surrounded by a cladding composed of concentric layers of alternating high- and low-index optical materials (Bragg layers) followed by a uniform outer layer. If the cladding is properly designed it makes possible to efficiently confine the transmitted light into the core by means of a finite number of Bragg layers. A numerical approach based on the matrix formalism [21] has been employed for the simulation of Bragg fiber properties.

Bragg fibers with air cores have been fabricated from polymers and chalcogenide glasses [22,23]. Silica-air-Bragg fibers with hollow cores have been developed [24]. By using the MCVD method Bragg fibers with silica cores surrounded by three pairs of Bragg layers have been fabricated [25,26]. Minimum optical losses of about 10 dB/km at 1064 nm have been measured when such fibers were spliced to single-mode fibers at both fiber ends [25]. Several structures of Bragg fibers with claddings of three pairs of Bragg layers, a silica core or air cores of different diameters and two types of Bragg claddings have been designed and fabricated [27–30]. Using continuous-wave and pulsed laser sources operating at 975 [30], 1064 [27–29], or 1550 nm [29,30] optical losses, transmittances, bend losses of the fibers have been determined. It has been shown that these fibers exhibit reduced bending losses and can be employed for delivery high powers of ns- and ps-pulsed Nd:YAG lasers at the wavelength of 1064 nm [27–30].

The review above demonstrates the potential of optical fibers, especially of hollow-core photonic bandgap fibers or Bragg fibers, for delivery of high power laser radiation. This paper presents a set of novel experimental data for Bragg fibers with a silica core and air cores of a small and large diameters drawn from same preform. Transmission characteristics of the drawn fibers at wavelengths of 632, 975, 1064, and 1550 nm measured with continuous-wave and pulse laser sources are presented. Particularly, attenuation coefficients, coupling efficiencies, bending losses, and spatial profiles of output beams from fibers at these wavelengths are shown in this paper.

2. Experimental details

2.1. Design and preparation of Bragg fibers

Designed refractive-index profiles of the investigated Bragg fibers are schematically shown in Fig. 1. Three fiber-optic structures have been designed which can be fabricated from the same preform by controlling the extent of the preform collapse during fiber drawing. The first structure consists of a large silica core of 26 μm in diameter surrounded by three pairs of Bragg layers. This structure is very similar to that reported elsewhere [25] that was proved to be very suitable for operating at 1064 nm. A refractive-index contrast between the high- and low-index cladding layers of 0.03 and thicknesses of 4 and 5 μm, respectively are assumed on the basis of the reported data [25] and preliminary experiments. Such a structure represents a level-core Bragg waveguide [31] in which bandgap characteristics comes predominantly from the high-index fiber parts.

The next two investigated structures, called air-core fibers, can be imagined to have composite cores consisting of an air part and silica part surrounded by three pairs of Bragg layers (see Fig. 1B). The air-part diameters of 5 and 73 μm are assumed in the design as the values followed from preliminary experiments. The same refractive indices of the high- and low-index cladding layers as those shown in Fig. 1A are taken into account in the design because of the same input preform (see Fig. 1B). From Fig. 1B one can see that a mean refractive index of the composite cores is below that of silica. Such structures can be called as depressed-core ones [31]. In comparison with the fiber structure in Fig. 1A, the thicknesses of the high- and low-index layers are smaller because of the incomplete preform collapse during fiber drawing. However, as a mean refractive-index contrast between the composite cores and the cladding increases with the diameter of the air-part one can estimate by using formulas reported elsewhere [31] that the operating wavelength will not substantially differ from the wavelength of 1064 nm.

Preforms for the designed Bragg fiber were prepared by the MCVD method [26–30]. During the preparation several layers of silica doped with fluorine were deposited onto the inner wall of a high-quality silica substrate tube at first. Then, the high-index Bragg layer was prepared from silica doped with a high content of germanium dioxide and a small content of phosphorous pentoxide. Silicon tetrachloride, germanium tetrachloride and phosphorous oxychloride were used as raw materials to deposit silica, germanium dioxide and phosphorous pentoxide, respectively. The following low-index Bragg layer was composed of silica doped slightly with phosphorous pentoxide that was used to decrease the glass viscosity. Then, the same procedure of preparing the high- and low-index layers was repeated in order to fabricate three pairs of Bragg layers. The last deposited Bragg layer was the silica layer slightly doped with phosphorous pentoxide. The thickness of each deposited layer was controlled by a particular flow rate of silicon tetrachloride. After the deposition of the last layer the tube with applied layers was controllable cooled down in a furnace in order to decrease mechanical stresses in such a multilayered structure and thus to prevent the formation of cracks.

Bragg fibers were drawn from the preform, i.e. the tube with the applied layers, using a graphite resistance furnace Centorr (USA). High temperatures above 2000 °C making possible the full collapse of the preform in a hot furnace zone were used for preparing the Bragg fiber with the solid core (see Fig. 1A). Temperatures slightly below 2000 °C were used when fibers with the air cores (see Fig. 1B) were drawn. Fibers had an outer glass diameter of 170 μm and were coated with a protective polymeric jacket of UV-curable acrylate (De Sotto).

Cross-sections and dimensions of the prepared Bragg fibers were characterized by optical microscopy in the transmission mode. Fiber segments with the length up to 2 cm were used in these measurements. The segments were cut off from prepared fibers using a knife of hard metal without removing the polymeric jacket. Refractive-index profiles of the fibers with silica cores were determined by using a refractive-index profiler S14 (York Technology, GB). Fiber-optic samples for these measurements were prepared by using an optical fiber cleaver FK11 (York Technology, GB). Similar measurements on the Bragg fibers with the air cores were not possible due to a large measurement step of the profiler of 1 μm and due to penetration of the device immersion into the air cores.

2.2. Main fiber characteristics measurements

The fabricated Bragg fibers were characterized using five different laser sources generating radiation at the wavelengths of 632, 975, 1064, and 1550 nm. Principal experimental setups for such characterizations are shown in Fig. 2. For tests of fibers at the wavelength of 1064 nm, two laboratory designed Nd:YAG lasers