Preparation and Characterization of Bragg Fibers for Delivery of Laser Radiation at 1064 nm

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Abstract. *Bragg fibers offer new performance for transmission of high laser energies over long distances. In this paper theoretical modeling, preparation and characterization of Bragg fibers for delivery laser radiation at 1064 nm are presented. Investigated Bragg fibers consist of the fiber core with a refractive index equal to that of silica which is surrounded by three pairs of circular layers. Each pair is composed of one layer with a high and one layer with a low refractive index and characterized by a refractive-index difference around 0.03. Propagation constants and radiation losses of the fundamental mode in such a structure were calculated on the basis of waveguide optics. Preforms of the Bragg fibers were prepared by the MCVD method using germanium dioxide, phosphorous pentoxide and fluorine as silica dopants. The fibers with a diameter of 170 μm were drawn from the preforms. Refractive-index profiles, angular distributions of the output power and optical losses of the prepared fibers were measured. Results of testing the fibers for delivery radiation of a pulse Nd:YAG laser at 1064 nm are also shown.*

Keywords

Bragg fibers, high-index contrast, MCVD method, transmission characteristics.

1. Introduction

Recently, optical fibers have been employed for transmitting high powers, e.g., for delivering laser radiation in medicine [1]-[8], lighting and heating in solar systems [9], [10], in devices for producing electrical power [11], etc. Generally, the transmission of energy by optical fibers is considered as an alternative to the traditional methods for transfer of heat or electricity [10].

Several types of glass optical fibers have been tested for transmitting high powers. They include silica fibers [1]-[4], [9]-[11], sapphire fibers [1], [6], germanium dioxide fibers [7], chalcogenide or fluoride fibers [8]. The most important ones are silica optical fibers, which have been applied in urology [1], [2], lithotripsy [3], dental medicine [4], in solar systems [9]-[11], etc. However, there are some limitations in the ability of conventional silica fibers to transmit high energy because front surface damage might occur [5], [10].

Sapphire fibers [1], [6] have been used in urology to transmit high laser energies required for prostate ablation. These fibers have higher optical losses than silica fibers, but they can transmit light in the mid-IR spectral range. Fibers prepared from germanium dioxide can also efficiently transmit high powers in the mid-IR range. They have been used in endoscopes [7]. As germanium dioxide has a relatively low melting point such fibers are not suitable for tissue ablative procedures.

High powers transmitted in the above mentioned fibers can cause nonlinear optical effects such as the generation of harmonics, four-wave mixing, Kerr effect, various types of stimulated scattering, etc. Some of these effects are accompanied by heating of the fibers which at power densities of about 10 GW/cm^2 can cause fiber damage [10]. This is one of reasons why hollow fibers (HFs) or hollow-core photonic-band gap (HC-PBG) fibers have been tested for transmitting high powers.

HFs are flexible hollow capillaries with an internal surface coating, which has very high reflection at working wavelengths [12]-[15]. The coating usually consists of silver and dielectric films [14]. Glass HFs can transmit laser powers from the visible to mid-IR range [13]. Such fibers enable efficient, high laser power transmission, while still being very durable and chemically stable even after prolonged laser energy transmission. However, they can suffer from power losses e.g. due to fiber bending.

A remarkable reduction of power losses of HFs can be achieved by employing hollow-core photonic band-gap fibers [16]. Approximately 98% of light transmitted through an HC-PBG fiber can be guided with low losses in a large central air hole due to the photonic band gap of the surrounding air/silica matrix [17]. This performance of HC-PGB fibers has already been tested for transmitting high powers of pulse lasers with densities of hundreds of GW/cm^2 [18]-[19]. Such fibers have been tested for delivery of radiation of a Nd:YAG laser at 1064 nm or an Er:YAG laser at 2940 nm [20], [21]. The experiments described elsewhere [22] have shown that single laser pulses with energies higher than 1 mJ and pulse durations of about 10 ns could be coupled into an HC-PBG fiber. A coupling efficiency over 70% and the maximum transmission up to 82% have been achieved.

The preparation of HC-PGBs needs special expertise and precision for setting-up input stacks employed for drawing these fibers. On the other hand silica Bragg fibers, a special case of silica PBG fibers, can be prepared by the MCVD method and employed for transmitting high powers [23], [25], [26]. These fibers have the optical core composed either from silica or air. The core is surrounded by concentric layers of alternating high- and low-index optical materials (Bragg cladding) followed by a uniform outer cladding (see Fig. 1). If the Bragg cladding is properly designed it makes possible to confine the transmitted beam efficiently by means of a finite number of Bragg layers.

It has been found that Bragg fibers with large mode areas allow us to reduce radiation and bending losses in comparison with standard silica fibers. Theoretical calculations have shown that radiation losses of such fibers can be decreased by increasing the refractive-index contrast between the high- and low-index layers in the fiber cladding. Optical losses of such fibers of about 10 dB/km at 1064 nm have been reported [23].

The review above demonstrates the potential of optical fibers, especially of Bragg or hollow-core photonic band gap fibers, for delivery of high power laser radiation. There are still open issues with these fibers such as decrease of radiation and bent losses, or optimized preparation of these fibers their excitation, etc. Some of these issues, namely the preparation of Bragg fibers with high refractive-index contrasts by the MCVD method, are addressed in this paper.

2. Experimental

2.1 Design of Bragg Fibers

A design of the refractive-index profile of Bragg fibers described in this paper is schematically shown in Fig. 1. This profile is similar to that reported elsewhere [23]. The fiber consists of a large silica optical core surrounded by the cladding of three pairs of alternating high- and low-index layers. These layers are characterized by a refractive-index contrast of about 0.03 and by thicknesses on a level of 3 μm.

2.2 Preparation of Bragg Fibers

Preforms for drawing designed Bragg fibers were prepared by the MCVD method. At experiments several layers of silica doped with fluorine were deposited at first onto the inner wall of a substrate tube. Then, the high-index preform layer was prepared by depositing several thin layer of silica doped with germanium oxide. The following low-index preform layer was obtained by depositing several thin layers of silica doped slightly with phosphorous pentoxide. In order to obtain three pairs of the designed Bragg layers the same procedure of preparing the high- and low-index layers was repeated. Finally, several thin layers of silica slightly doped with phosphorous pentoxide were deposited for obtaining the preform core. By collapsing the tube with the deposited layers a rod, the preform, was prepared.

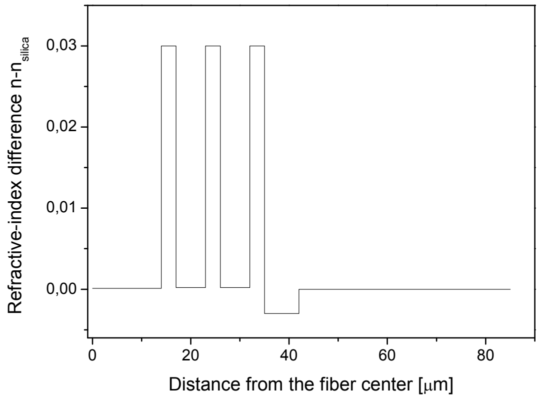


Fig. 1. Designed refractive-index profile of Bragg fibers.

Fibers with a diameter of 175 μm were drawn from the prepared preforms. They were coated with a protective polymeric jacket of UV-curable acrylate (De Sotto).

2.3 Characterization of Bragg Fibers

Cross-sections and dimensions of prepared Bragg fibers were characterized by optical microscopy in the transmission mode. Fiber segments with a length up to 2 cm were used in these measurements. No special procedure was employed for preparing the segment ends. The segments were cut off from prepared fibers by a knife of hard metal without removing the polymeric jacket.

Refractive-index profiles of prepared fibers were determined. For this purpose a refractive-index profiler S14 (York Technology, GB) was employed. Fiber-optic samples for these measurements were prepared by using an optical fiber cleaver FK11 (York Technology, GB).

Optical losses of prepared fibers were measured by the cut-back method. In these measurements light from a halogen lamp was focused into a fiber with a length of about 10 m. The fiber was coiled on a spool with a diameter of about 200 mm. A spectrum of the output power from the fiber was measured by a spectrometer ANDO (GB). Then the fiber was cut to a length of about 2 m and a reference spectrum was measured.

Angular distributions of the output optical power from prepared Bragg optical fibers were measured at a wavelength of 670 nm. In these measurements a collimated laser beam from a solid-state red laser diode with collimation optics was launched into the input fiber end fixed in the center of rotation of the laser (see Fig. 2). The output power from the fiber was measured by a silicon detector. By changing the angle of inclination α the output power $P(\alpha)$ from the fiber was changed and the angular distribution $P = P(\alpha)$ was measured.

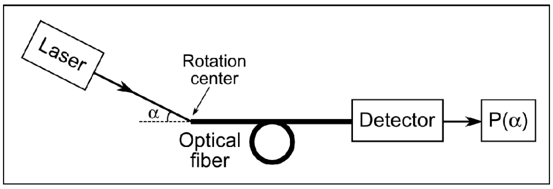


Fig. 2. A scheme of a set-up for measuring angular distributions of the output optical power from an optical fiber.

2.4 Delivery of Laser Radiation at 1064 nm

For delivery of a high peak power laser radiation a laboratory-designed quasi-continuously pumped Nd:YAG laser in bounce geometry was used as a radiation source. The laser was passively mode-locked by a semiconductor saturable absorber and actively stabilized by an acousto-optical modulator. The laser operated at 1.06 μm and enabled the generation of 20 ps long single pulses at a repetition rate of 5 Hz with the energy of 9 μJ [27].

3. Theoretical Modeling

Transmission properties of Bragg fibers have been evaluated theoretically by using waveguide optics. In this approach an electrical and magnetic fields in each fiber part were described by a combination of Bessel functions of the first and second kinds. A step-index approximation of an experimentally measured refractive-index profile was considered in each fiber part. Using proper boundary conditions on boundaries of fiber parts a determinant equation for a complex propagation constant β was derived [28], [29]. This equation was used for the determination of the propagation constant for the fundamental mode TE01.

Radiation loss of a particular optical mode was obtained from an imaginary part of the determined propagation constant β_i using (1)

$$Loss = \frac{40\pi}{\lambda \ln(10)} \mathrm{Im}\left(\frac{\beta_i}{k}\right) \tag{1}$$

where λ is the wavelength and $k = 2\pi/\lambda$ is the wave vector.

4. Results and Discussion

Bragg fibers with a silica core and cladding of three pairs of high- and low-index layers characterized by a high refractive-index contrast have been investigated. Similar fibers have been found as good candidates for achieving low optical losses and large mode diameters [23]. However, the fibers described in this paper have the maximum refractive index increased by about 0.6% in order to investigate effects of this increase on radiation losses in Bragg fibers. Dimensions of high- and low-index cladding layers were also slightly modified in comparison with those previously published [23].

An example of the cross-section of prepared fibers measured by transmission optical microscopy is shown in Fig. 3. This picture shows that the fiber consists of three alternating high-index layers (bright ones) and low-index layer (grey ones). Thicknesses of these layers decrease in the direction from the fiber centre. Defects on the dark outer region (silica) can be related to small pieces of the polymeric cladding releasing from the sample preparation.

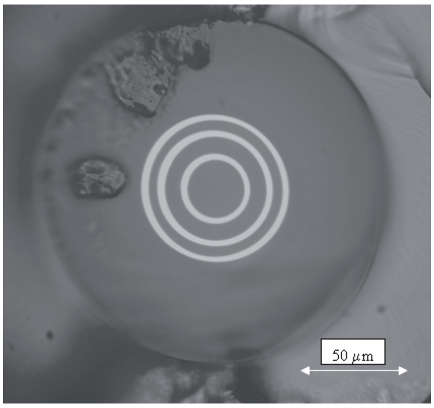


Fig. 3. Photo of the cross-section of a prepared Bragg fiber.

A typical refractive-index profile of prepared fibers is shown in Fig. 4. One can see some similarity of this profile with that reported elsewhere [23]. However, dimensions and refractive-index difference of both the profiles differ. A refractive-index difference of about 0.03 can be determined from Fig. 4 which is higher than of about 0.02 reported elsewhere [21]. It is evident that this difference is not the same for all the high-index layers. This fact can be related to a scanning step of 1 μm of the refractive-index profiler used. Thus, this profiler provides us with averaged refractive-index profiles. Moreover, high doping levels in high-index layers and high processing temperatures above 1500 °C can induce increased internal mechanical tensions in preforms and fibers [30]. These tensions can change the refractive index due to the photoelastic effects. Some prepared preforms actually internally cracked due to high internal tensions induced at their preparation.

An example of measured spectral losses of prepared Bragg fibers is shown in Fig. 5. In these measurements optical modes propagating in the high-index fiber layers were not eliminated. Thus, the measured losses include some contribution from these modes which can be important especially for short lengths of the fibers. Consequently, the measured losses are higher than those corresponding only to Bragg modes. Optical modes transmitted in high-index layers can be eliminated by splicing the Bragg fiber to single-mode fibers [23]. Experiments on investigations of ways for exciting Bragg modes only are prepared. The spectral-loss curve shown in Fig. 5 is similar to curves of spectral losses measured with standard single-mode fibers. No increase of base-line losses is observed at longer wavelengths as published elsewhere [23]. Two bands on the curve can be attributed to Bragg modes transmitted in the fiber.

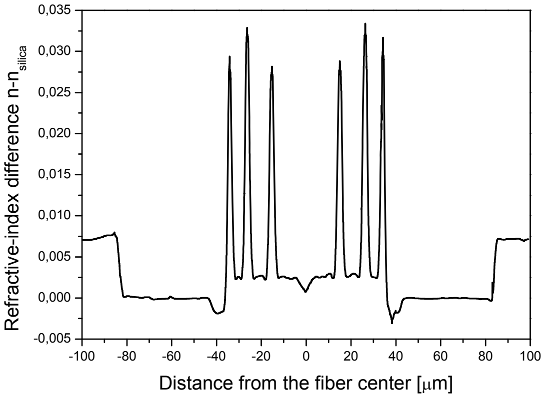


Fig. 4. Refractive-index profile of the Bragg fiber.

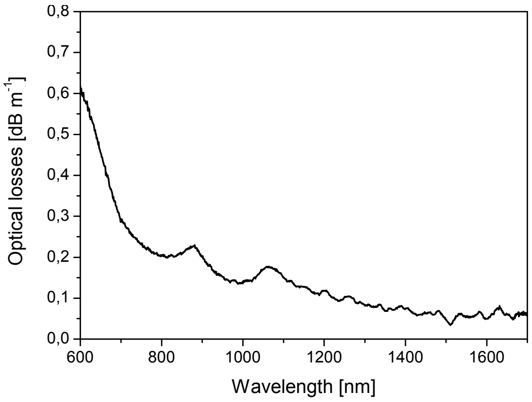


Fig. 5. Spectral optical losses of the Bragg fibers (a fiber length was 11.5 m).

Examples of angular distributions of the output power measured with prepared Bragg fibers are shown in Figs. 6 and 7. From Fig. 6 one can see that such a distribution is composed of two distinct parts. The first one is characterized by angles of incidence in a range of about 0-6 deg. The second part corresponds to angles above 6 deg. The first part can be attributed to optical modes transmitted mainly in the fiber core. However, these modes have also their electric fields outside the core. The optical power transmitted in this fiber part can be lost due to high optical losses of the polymeric jacket. Thus, in measurements with longer fibers these modes are more attenuated and narrower angular distribution are measured (compare the curves in Fig. 6).

By coiling the Bragg fiber onto cylindrical mandrels, angular distributions of the output power are broadened (see Fig. 7, Tab. 1). The symmetry of these distributions deteriorates in comparison with the straight fibers (compare Fig. 6 and Fig. 7). The fiber coiling causes that optical modes transmitted in the fiber have stronger electrical fields in the silica part of the fiber and they can be attenuated in the polymeric jacket. Consequently, they can transmit lower optical powers (see the last column in Tab. 1).

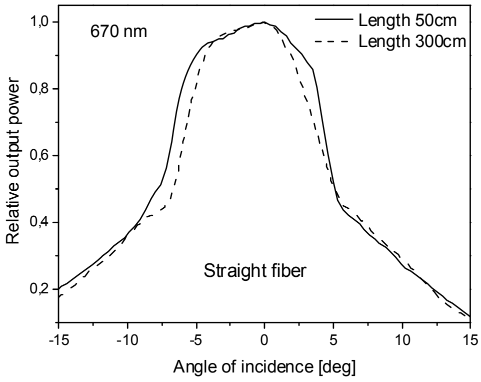


Fig. 6. Angular distributions of the output power from the straight Bragg fiber measured for two fiber lengths.

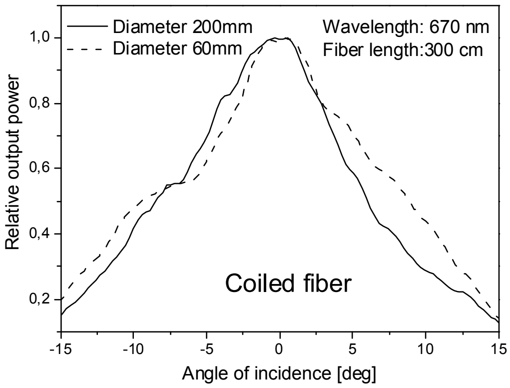


Fig. 7. Angular distributions of the output power from the Bragg fiber with a length of 3 m coiled on a mandrel with a diameter of 200 mm or 60 mm.

Fiber	Length [cm]/ Mandrel diameter [mm]	Halfwidth [deg]	Maximum power [a.u.]
Straight	60/ ∞	13.2	$1.1\ 10^{7}$
Straight	300/ ∞	12.1	$4.9\ 10^{6}$
Coiled	300/ 200	14.4	$4.8\ 10^{6}$
Coiled	300/ 60	18.3	$3.0\ 10^{6}$

Tab. 1. Characteristics determined from angular distributions.

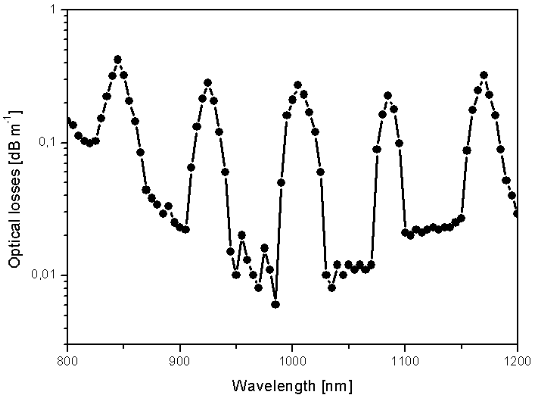
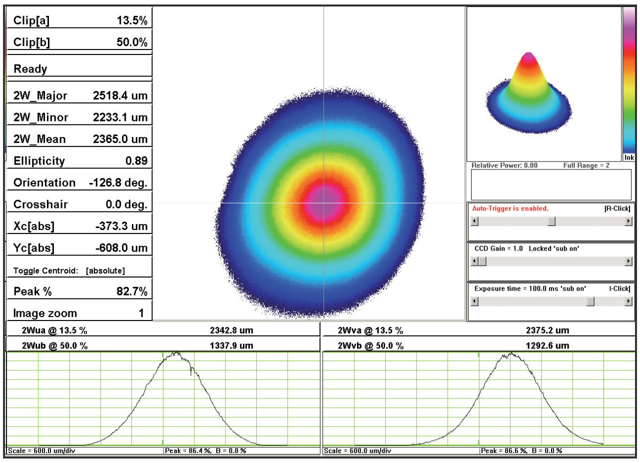


Fig. 8. Spectral losses of the TE01 mode of the Bragg fiber calculated on the basis of waveguide-optics and (1). The symbols show calculated values.

Spectral losses of the TE01 mode for the Bragg fiber with a step-index profile approximating the refractive-index profile depicted in Fig. 4 and calculated on the basis of the theoretical modeling and (1) are shown in Fig. 8. In the approximate step-index profile dimensions of all fiber parts were taken from Fig. 4. Constant refractive indices with values corresponding to maximum experimental values in Fig. 4 were considered for each fiber part. The curve in Fig. 8 is comparable with that presented elsewhere [21]. It shows that the prepared fibers are suitable for delivery laser power in a region around a wavelength of 1064 nm.

A sample of the prepared optical fiber with a length of 30 cm was successfully tested for the delivery of radiation of the mode-locked Nd:YAG laser at 1060 nm. Four lenses with different focal lengths (25, 35, 50, or 75 mm) were employed for the laser beam focusation and coupling into the fiber. Optimal results from the point of energy transmission and transmitted beam spatial profile were obtained with the lens with the focal length of 50 mm. Using this lens, the laser beam diameter of 36 μm was measured at the focal point placed approximately at the input fiber face. This value approximately corresponds to the core diameter of the tested fiber. The radiation transmission of about 80 % and the spatial profile of the fundamental mode shown in Fig. 9 have been determined.



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Scale = 600.0 um/div Peak = 86.6 %, B = 0.0 %

Fig. 9. Spatial structure of the 20 ps laser pulse transmitted through the 30 cm long prepared Bragg fiber.

The flocculation with the 25 mm lens (the focal point beam diameter of about 20 μm) caused some deterioration of the input fiber face. Using the lens with the focal length of 75 nm the fiber transmission drop of to 68 % was observed together with a slightly worse spatial profile of the transmitted radiation.

5. Conclusions

In the paper the preparation of Bragg fibers with the refractive-index contrast of about 0.03 by the MCVD method is shown. Optical losses below 0.1 dB/m can be achieved with such fibers. High-power 20 ps laser pulse radiation delivery has also been tested and the transmission of the laser radiation in the fundamental mode up to 80 % has been determined. Future research will deal with hollow-core Bragg fibers with a comparable refractive-index contrast.

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