Long-period refractive index fiber gratings: properties, applications, and fabrication techniques

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ABSTRACT

The article overviews the main properties, fabrication techniques and areas of application of long-period fiber gratings. The basic theoretical equations describing spectral properties of the gratings are given. Experimental investigation of the cladding modes excited by long-period gratings, as well as sensitivity of the long-period grating spectrum to external perturbations are discussed. The most common fabrication techniques of long-period gratings are examined with reference to their advantages and disadvantages. The most important applications of long-period gratings are discussed. Particular attention is paid to the recent results obtained with participation of the authors.

Keywords: fiber Bragg and long-period grating, fiber laser, fiber sensor

1. INTRODUCTION

Refractive index structures induced in a fiber core, so-called fiber gratings, have been actively developed and studied in recent few years. As a rule, such structures are created in germanosilicate fibers by side irradiation of the fiber with UV-radiation either at $\lambda \approx 242$ nm, which falls in the absorption band of germanium oxygen deficient centers [1], or at $\lambda = 193$ nm (excimer ArF-laser radiation) [2]. Fiber gratings have found a plethora of important and unique applications in fiber optic systems (sensors, mirrors of fiber lasers, fiber filters, etc). Fiber gratings are classified into two types in accordance with the grating period: Bragg and long-period gratings (LPG).

Bragg grating couples the fundamental mode to the mode with the opposite direction of propagation. As a result, at certain wavelength λ_{Br}, satisfying the Bragg condition $2n_{eff}^{core}\Lambda_{Br} = \lambda_{Br}$ (where n_{eff}^{core} is the effective refractive index of the fundamental mode, Λ_{Br} is the grating period), narrow-band reflection takes place. To-date, a lot of articles describing the properties of Bragg gratings have been published. The most common fabrication techniques, Bragg grating types and properties, as well as the most important applications are summarized in reviews [3, 4].

Photoinduced LPGs with periods $\Lambda_{LPG} = 10^2 - 10^3$ μm were proposed in [5]. Such gratings couple the fundamental mode with the cladding modes, propagating in the same directions. The excited cladding mode attenuates in the coated fiber part after the grating, which results in the appearance of resonance loss in the transmission spectrum. LPGs have found a number of applications in fiber-optic devices [6, 7]. In contrast to Bragg grating, LPG does not produce reflected light and can serve as spectrally selective absorber. In addition to temperature and strain sensitivity, the LPG spectrum is strongly sensitive to grating bending and dielectric permeability of the external medium, which allows creation of new types of fiber-optic sensors. LPGs are relatively easy to produce. Their spectral properties (resonance wavelength, bandwidth, etc.) can be varied in of wide range. All these features make LPGs very attractive for many applications in telecommunication, laser and sensor systems.

The aim of this paper is to summarize the main experimental and theoretical results related to fabrication, investigation, and application of LPGs. Theoretical description of the main spectral properties of LPGs is given in Section 3. Section 4 presents the results of experimental investigation of the cladding modes excited by a LPG. In Section 5 the most common techniques of LPG fabrication are summarized and compared. Finally, sensitivity of LPG to external influences and some important grating applications are described in Sections 6 and 7, respectively.

2. TYPES OF RESONANCE INTERACTION IN FIBER GRATINGS

The interaction of one mode of a fiber with other modes is commonly described with the help of coupled-mode theory in which only two modes are supposed to be nearly phase-matched and capable of resonant coupling. Based on this theory, quantitative information about the coupling coefficients and spectral properties of fiber gratings can be obtained[8, 9]. Two modes are coupled by a grating with period Λ, if their propagation constants β_1 and β_2 satisfy the phase matching condition:

$$\beta_2 - \beta_1 = 2\pi k/\Lambda, \tag{1}$$

where k is an integer describing the order of the grating, in which the mode coupling occurs.

Fig.1 illustrates a variety of possible couplings of the $HE_{11}(LP_{01})$ core mode with different co-propagating (a - c) and counter-propagating (d – g) modes, for k = 1. The vertical axis presents an effective mode index n_{eff} (n_{core}, n_{clad} and n_{ext} are the effective refractive indices of the core, cladding and external medium, respectively). The positive direction of the axis characterizes radiation, propagating in the same direction with the fundamental mode, while the negative values of this axis correspond to the counter-propagating modes. Dispersion curves of the core ($n_{core} > n_{eff} > n_{clad}$), cladding ($n_{clad} > n_{eff} > n_{ext}$), and radiation (hatched area) modes are depicted in the figure. The dashed curves 1 and 2 give the value of $n_{eff}^{core} - \lambda/\Lambda$ for Bragg and long-period gratings, respectively. Intersections of these curves with the dispersion curves of different modes show the wavelengths at which the phase-matching conditions are satisfied. In fig.1 we also see the relative positions of the resonance wavelengths corresponding to coupling of different modes in Bragg and long-period gratings. The fundamental mode can be coupled with the core (a, f, g), cladding (b, e) and radiation (c, d) modes. It is clearly seen that in different parts of the spectrum the grating can couple the fundamental mode to modes of different types and of different propagation directions. For example, a Bragg grating can excite cladding and radiation modes at shorter wavelengths with respect to the main Bragg resonance, as it is commonly observed in strong gratings [10]. The cladding modes with a larger mode number have a smaller effective index; therefore, the resonance coupling with them takes place in the short-wavelength part of the spectrum in the case of Bragg gratings and in the long-wavelength part in the case of LPGs [11].

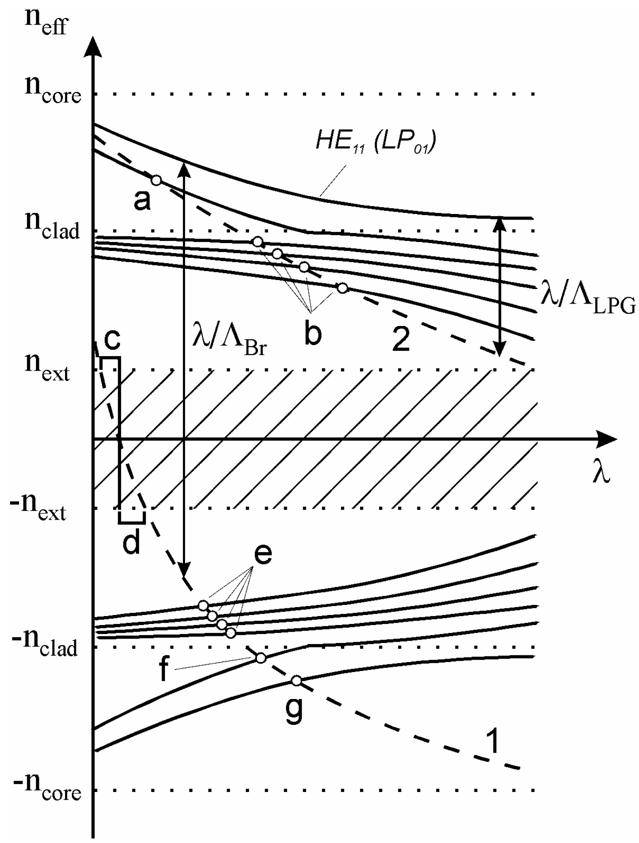

Fig.1. The diagram demonstrating the phase matching conditions for the coupling of the lowest-order core mode (HE_{11}/LP_{01}) with different copropa-gated (a - c) and counterpropagated (d - g) core (a, f, g), cladding (b, e) and radiation (c, d) modes of a fiber.

3. SPECTRAL PROPERTIES OF LONG-PERIOD GRATINGS

Calculation methods of spectral characteristics of LPGs can be found in papers [11, 12]. Below we will consider the most important relations describing the grating properties.

Equation (1) for the resonant coupling of the fundamental mode and one of the cladding modes can be rewritten as

$$\Delta n_{eff} \Lambda_{LPG} = \lambda_{LPG}, \tag{2}$$

where $\Delta n_{eff} = n_{eff}^{core} - n_{eff}^{clad}$, n_{eff}^{clad} is effective refractive index of the cladding mode and λ_{LPG} is the resonance wavelength.

In order to get a complete set of modes HE_{lm} and EH_{lm} (l and m are the azimuthal and radial orders of the mode, respectively), the wave equation for a dielectric cylinder with a certain radial index distribution should be solved. In a single-mode fiber, only HE_{11} mode is guided by the fiber core at $\lambda > \lambda_c$ (where λ_c is the cutoff wavelength) [13]. Normally, a large quantity of modes ($N \sim 10^4$ at $n_{ext} = 1$), can be guided by the cladding. But only some of them have a significant overlap integral I with the fundamental core mode. The integral should be taken the fiber cross-section region, where modulation of the refractive has been induced (for photoinduced gratings, the integration region usually coincides with the fiber core):

$$I = \frac{\int_0^a \int_0^{2\pi} E_{core} E^*_{clad}\, r dr d\varphi}{\sqrt{\int_0^\infty \int_0^{2\pi} E_{core} E^*_{core}\, r dr d\varphi}\sqrt{\int_0^\infty \int_0^{2\pi} E_{clad} E^*_{clad}\, r dr d\varphi}}, \qquad (3)$$

where a is the core radius, E_{core} and E_{clad} are the amplitudes of the electrical field of the core and cladding modes, respectively, r and φ are radial and azimuthal coordinates.

The overlap integral I defines the efficiency of inter-modal conversion. Its value is large only for HE_{1m} ($m > 1$) cladding modes, because only these modes have a sufficiently great electric field component in the fiber core. Fig.2 shows the energy-normalized radial distributions of the electric field for some of HE_{1m} cladding modes [11]. These modes are linearly polarized, their intensity distributions are axially symmetric, and the number of zeroes in the radial direction is m - 1. The overlap integral increases with increasing the radial mode number up to $m \sim 10$, which is accompanied by an increase in the inter-modal coupling intensity. The latter can be seen from the transmission spectra of LPGs (Fig.3). Starting with a certain value of m, the overlap integral decreases to zero and thereafter oscillates with m, the amplitude of the oscillation tending to zero [12].

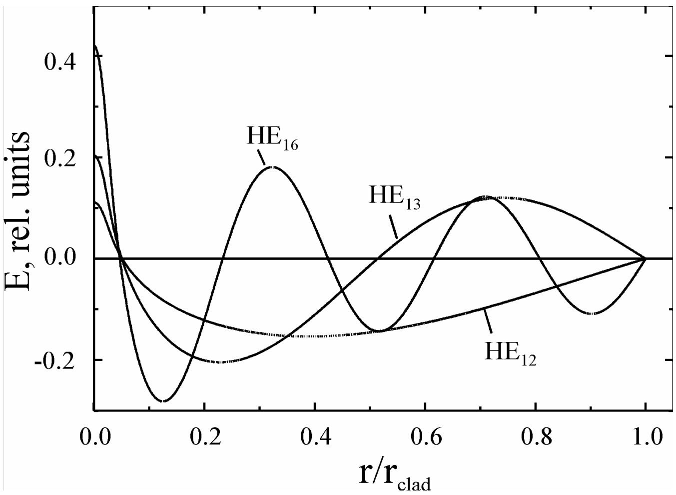

Fig.2. Radial distributions of the electric field amplitude of the cladding modes HE_{12}, HE_{13}, HE_{16} [11].

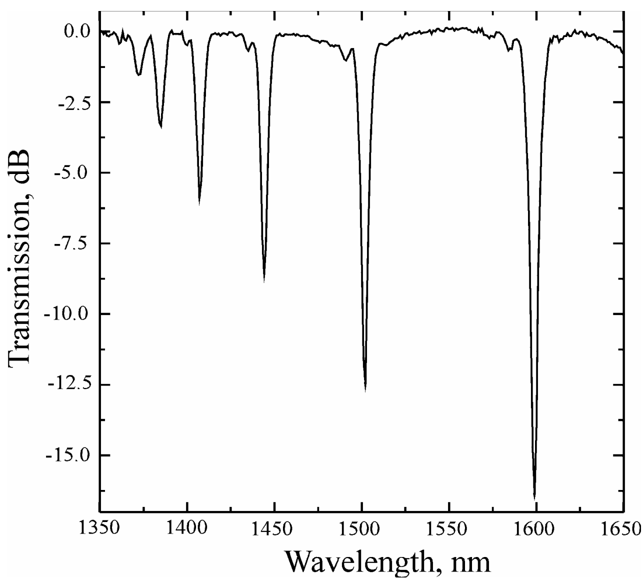

Fig.3. A typical transmission spectrum of a LPG.

The solution of coupled mode equations [8] in the approximation of two interacting modes travelling in the same direction and in the assumption of small amplitude of induced index modulation in comparison with the silica glass index, gives the following energy exchange law (for initial conditions $R(0) = 1$, $S(0) = 0$):

$$\begin{aligned} R(z) &= \cos^2(z\sqrt{\eta^2+\delta^2}) + \delta^2 \sin^2(z\sqrt{\eta^2+\delta^2})/(\eta^2+\delta^2), \\ S(z) &= \eta^2 \sin^2(z\sqrt{\eta^2+\delta^2})/(\eta^2+\delta^2) \end{aligned} \qquad (4)$$

where $R(z)$, $S(z)$ are the normalized energies of the core and cladding modes, respectively, considered as a function of z-coordinate along the fiber axis (the beginning of the grating corresponds to $z = 0$);

$$\delta = \frac{\pi \Delta n_{eff}\, d\lambda}{\lambda^2_{LPG}} = \frac{\pi}{\Lambda}\frac{d\lambda}{\lambda_{LPG}}, \qquad (5)$$

is the normalized frequency, which describes the deviation from the exact synchronism (2), η is the coupling coefficient defined by a relation:

$$\eta = C\pi \Delta n_{mod} I/\lambda_{LPG}; \tag{6}$$

Δn_{mod} is the induced index modulation amplitude of the fiber core, related with the total induced index change Δn_{ind} via relation $\Delta n_{mod} = \Delta n_{ind}/2$, C is a constant equal to the first coefficient in the Fourier transform of the grating pitch shape. If the index profile is sinusoidal, this constant is equal to unity. For a rectangular profile, which is more typical for LPG, $C = 4\sin(\pi d/\Lambda)/\pi$, where d is the size of the irradiated part of the fiber within one grating period.

At the exact resonance ($\delta = 0$), equation (4) gives a sinusoidal law of the energy exchange, showing a possibility of mutual energy transfer from one mode to another:

$$\begin{aligned} R(z) &= \cos^2(\eta z) \\ S(z) &= \sin^2(\eta z) \end{aligned}. \tag{7}$$

With the help of equations (4) and (5) it is possible to determine the total spectral width, which follows from the first zero of the grating spectrum:

$$\Delta\lambda_0 = \frac{2\lambda_{LPG}^2\sqrt{\pi^2 - (\eta L)^2}}{\pi L \Delta n_{eff}} = \frac{2\lambda_{LPG}\Lambda\sqrt{\pi^2 - (\eta L)^2}}{\pi L}. \tag{8}$$

Equation (8) allows one to obtain $\Delta\lambda_0$ in the assumption of a constant Δn_{eff} within the grating bandwidth. However, the presence of dispersion of Δn_{eff}, in some cases, can give a significant discrepancy between the experimental bandwidth and the calculated one. In [14] was shown, that the first term in Δn_{eff} expansion into a Taylor series in the vicinity of λ_{LPG} is sufficient to estimate the bandwidth to an acceptable accuracy.

4. PROPERTIES OF THE CLADDING MODES EXCITED BY A LONG-PERIOD GRATING

As was mentioned above, the standard diameter of silica cladding is large enough and the cladding can guide plenty of modes. A LPG allows selective excitation of an individual cladding mode. This fact makes it possible to investigate the field distribution of the cladding mode excited by the grating.

Fig.4 shows the intensity distributions measured by the near-field technique for a group of cladding modes [15]. All the modes, as follows from theoretical consideration, have pronounced axial symmetry, which corresponds to azimuthal number l = 1. The number of rings is equal to the radial mode number m.

It should be noted that the energy of a cladding mode excited by a LPG can be transferred to another cladding mode with a close propagation constant, if the fiber has intrinsic or an artificially induced heterogeneity (variations of the refractive index, diameter, etc. along the fiber axis). Fig.5 illustrates the intermodal coupling in the case of transformation of the HE_{14} mode into other modes guided by the fiber cladding [15]. The near-field distribution of the initial mode (the fiber segment behind the grating is unperturbed) is given in Fig.5a, whilst Fig.5b shows the near-field distribution, when this fiber segment, ~ 1 cm in length, is fixed by a metal plate with a mass of several grams. We see that even a slight transverse stress, arising in the fiber, and/or a perturbation of the silica/air interface lead to a significant inter-modal interaction and, as a result, to practically complete disappearance of the initial cladding mode.

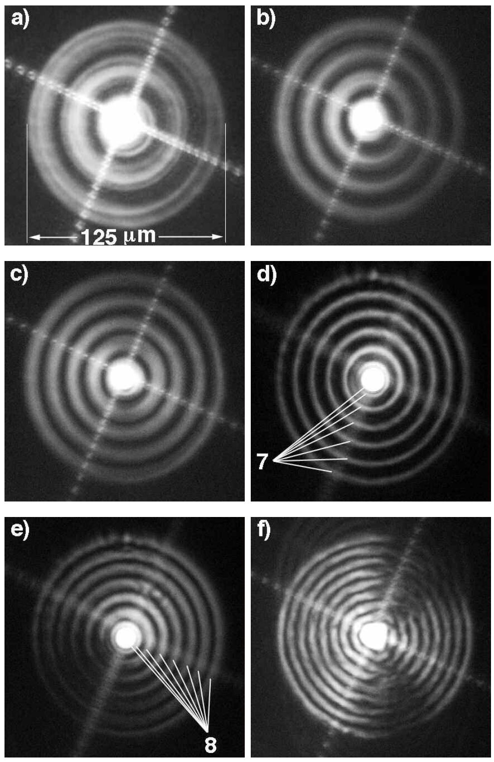

Fig.4. Near-field intensity distributions of HE_{1m} cladding modes with m = 4 (a), 5 (b), 6 (c), 7 (d), 8 (e), 10 (f) [15].

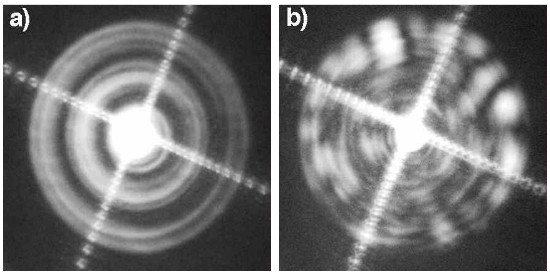

Fig.5. Near-field distribution of the HE_{14} cladding mode measured for the unperturbed fiber end (a) and for the fiber end fixed by a metal plate (b) [15].

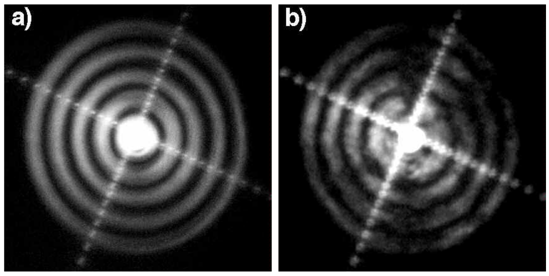

Fig.6. Near-field distribution of the HE_{16} cladding mode observed in fiber pieces of different length after a LPG: 1 cm (a) and 75 cm (b) [15].

As a rule, intrinsic heterogeneity of the fiber is insignificant and, therefore, a cladding mode can propagate to significant distances. This fact allows creation of long gratings and devices with several spatially separated gratings. In ref. [15] it was shown that the contrast of the near-field pattern of the cladding mode is impaired as the mode propagates along the fiber. Nevertheless, the near field distribution retained its main features even after 75 cm fiber length (fig.6), testifying that a significant portion of the power still remained in the initial cladding mode.

The analysis of the near- and far-field distributions of cladding modes gives a qualitative insight into the behavior of cladding modes in the process of propagation along the fiber. Quantitative data can be obtained with the help of other techniques. For example, in ref. [16] an optical low-coherent reflectometry (OLCR) technique was applied to measure the group index of the cladding modes n_{gr}^{clad}.

Fig.7 demonstrates the OLCR signal as a function of the OLCR delay for different fiber lengths L after the grating. Three peaks are observed. The strongest peak (*a*) corresponds to the fundamental mode reflected by the fiber end to the back-propagating fundamental mode. Peak (*b*) is due to a cladding mode excited by the grating and reflected back at the fiber endface to the same cladding mode. The OLCR distance between peaks (*a*) and (*b*) gives the difference between the optical pathways of the fundamental and the cladding modes $2L(n_{gr}^{core} - n_{gr}^{clad})$. The presence of a relatively weak peak (*c*) indicates partial excitation of the cladding mode from the fundamental mode at the fiber endface, and vice versa. With the help of the OLCR technique the group index of a cladding mode can be measured to an accuracy better than 10^{-4}. In addition, the change of the intensity of peak (*b*) numerically characterizes the cladding mode attenuation (due to inter-modal coupling, absorption, etc.) in the process of propagation along the fiber.

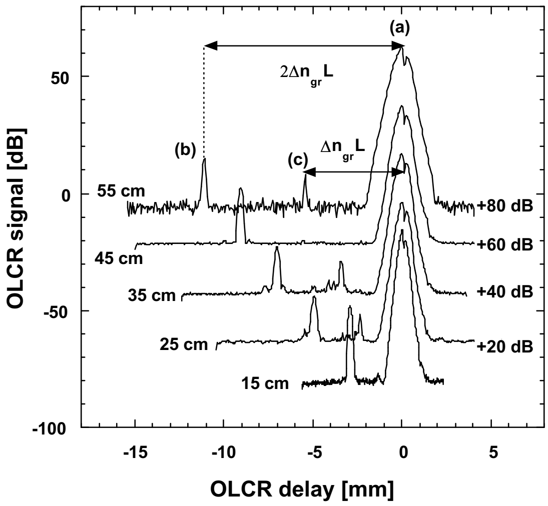

Fig.7. OLCR signal of the fundamental mode (peak (a)) and cladding mode $HE_{1\,10}$ (peaks (b) and (c)) for different fiber lengths [16].

5. METHODS OF LONG-PERIOD GRATING FABRICATION

After the discovery of stable UV-induced refractive index change in the core of doped silica fibers, it became possible to form index gratings by launching radiation through the lateral surface of the fiber. There are two most widespread ways of UV-writing of LPGs: 1) the amplitude mask technique [5, 6], in which the periodic structure is formed by a slot-hole mask (fig.8a), and 2) the step-by-step technique [17], in which the required index structure is formed via mechanical translation of the fiber relative to the focused laser beam (fig.8b). The amplitude mask technique, at which all elements of a grating are formed simultaneously, is more attractive, if a pulsed UV-source, such as an excimer laser, is used. This is explained by the following reasons. The value of induced index is defined mainly by the cumulated UV-dose. At the same time, the relatively low threshold of destruction of silica glass (~ 1 J/cm^2) makes it impossible to increase the UV-power density. Therefore, to write a separate grating pitch, it takes the same irradiation time as for the entire grating photoinscription via an amplitude mask. Continuous sources, on the contrary, are preferable for local index formation, because an increase in the UV-power density results in a reduction of the irradiation time [18]. The step-by-step technique of LPG fabrication appears to be more flexible. It allows forming various grating shapes (apodization, chirp, etc), it is much easier as compared to the amplitude mask technique. For example, in ref. [19] such an opportunity was taken to suppress the grating side-lobes and resonance bands caused by high harmonics of the main grating period.

It should be mentioned that the requirements on the UV-source for LPG writing are less stringent than in the case of Bragg grating writing. In particular, there are no basic restrictions on the coherence length of UV-radiation. Besides, owing to a rather large grating period, mechanical stability of the writing system may be sufficiently low.

The refractive index profile in a fiber can be changed by heating the fiber up to temperatures T > 1000 °C. As a result of such thermal treatment a profile variation can occur owing to a number of reasons:

1) mechanical deformation of the fiber, change of its size [20];

2) stress-optic effect due to redistribution of elastic stresses in the fiber [21, 22];

3) spatial redistribution of chemical composition of the glass due to thermo-induced diffusion of dopants [23, 24].

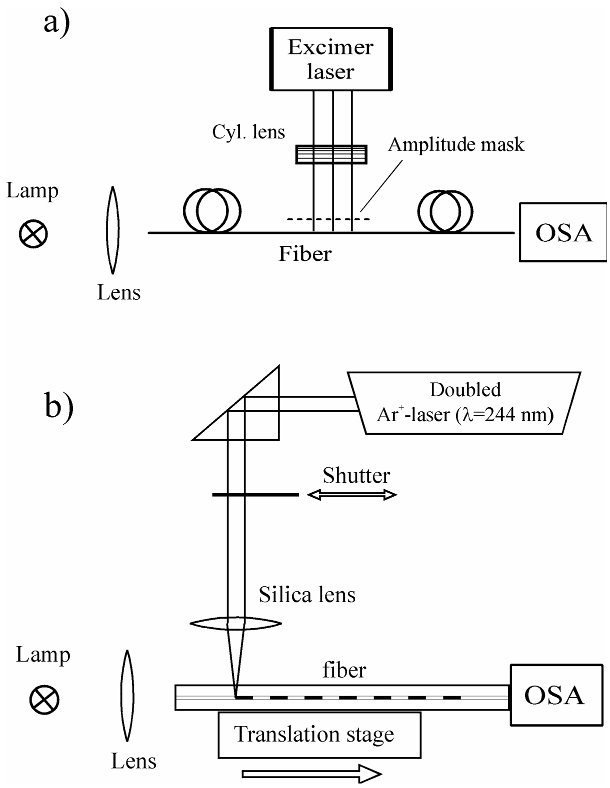

Fig.8. Amplitude mask (a) and step-by-step (b) techniques of the LPG fabrication.

Local fiber heating can be produced by IR laser sources (CO_2-laser [25, 26] or CO-laser [23, 24, 27]) or by localized electrical discharge [28, 29]. Such grating type can be written in fibers insensitive to UV-light, for example, in pure-silica-core fibers [21]. Thanks to a large coupling coefficient which can be achieved by the methods pointed out, strong thermo-induced gratings consisting just of several pitches ($N \sim 20$) can be written. Being prepared by local fiber heating up to the temperature close to the melting point of silica glass, thermo-induced gratings have higher temperature stability in comparison with the photoinduced gratings and retain their spectral properties even at temperatures of about 1000°C [27].

At the same time, thermo-induced gratings have several disadvantages as compared to the photoinduced ones. First of all, they typically possess spectrally independent losses caused by mechanical deformation of the fiber during the writing process. Secondly, the thermo-induced processes strongly depend upon the temperature. For this reason, high reproducibility of the heating time and temperature from pitch to pitch is required for the grating to be uniform. As a rule, reproducibility is insufficient, which may result in heterogeneity of the grating spectrum. The latter was observed in a majority of papers [23-29]. In addition, heat transfer along the fiber axis limits the minimum grating period to $\Lambda_{LPG} \sim 200$ µm.

In ref. [30] a tunable fiber filter based on coupling of the fundamental and cladding modes induced by an acoustic wave with a frequency of about 2 MHz was demonstrated. Coupling efficiency and spectral position of the resonance are defined by the amplitude frequency of the RF-signal. The length of the fiber portion, from which the polymer coating has been removed, defines the spectral width of the resonance. An important feature of such a filter is flexible control of its spectral parameters and an opportunity to create several resonance maximums, when several RF-signals are fed simultaneously.

6. SENSITIVITY OF LONG-PERIOD GRATING TO EXTERNAL INFLUENCES

Sensitivity of spectral properties of LPGs to external influences, such as change of temperature, mechanical stress, or bending, should be taken into account in designing fiber-optic systems. In many cases, it is important to have a stable grating spectrum insensitive to the environmental influences. At the same time, if a grating constitutes a sensing element, or is used for light modulation via the stress-optic effect and the like, an increased sensitivity to certain external influences may be required.

6.1. Temperature sensitivity

The temperature effect on the LPG spectrum reveals itself mainly in changing the grating resonance wavelength. Temperature sensitivity of the resonance wavelength of LPGs $\Delta\lambda_{LPG}/\Delta T$ depends on the order of the coupling cladding mode and, as a rule, is 0.03 – 0.1 nm/°C. The ratio describing temperature sensitivity of a LPG can be obtained from (2), taking into consideration that the effective mode indices are wavelength dependent [31]:

$$\frac{\Delta\lambda_{LPG}}{\lambda_{LPG}} = \frac{\dfrac{1}{\Delta n_{eff}}\dfrac{\partial(\Delta n_{eff})}{\partial T} + \dfrac{1}{\Lambda}\dfrac{d\Lambda}{dT}}{1-\Lambda\dfrac{\partial(\Delta n_{eff})}{\partial\lambda}} \cdot \Delta T \cdot \qquad (9)$$

Because the temperature expansion coefficient of silica glass is relatively small, the second term in the nominator can be neglected in comparison with the first one. Thus, the major factors determining temperature sensitivity of LPGs are the difference of thermo-optic coefficients of the core and cladding materials (the first term in the nominator), as well as dispersion of the modes (denominator). It should be noted that the decrease of the denominator with growth of the cladding mode order results in an increase of temperature sensitivity observed in many experiments [6, 31].

Temperature sensitivity of LPGs is typically several times larger than sensitivity of Bragg grating; therefore, temperature stabilization of the LPG spectrum is of much practical interest. In ref. [32] a reduction of $\Delta\lambda_{LPG}/\Delta T$ was achieved by modification of the refractive index profile of the fiber cladding. This allowed compensation of the material term in equation (9) by an appropriate choice of the waveguide contribution. As a result, a grating sensitivity of -0.0045 nm/°C was demonstrated. The main disadvantage of this method is that it requires manufacturing of a fiber with a significantly altered cladding structure, which complicates the technology. Another approach was demonstrated in ref. [33], where temperature sensitivity of a grating was compensated by a temperature change of the refractive index of a special polymer coating covering the grating. In this way $\Delta\lambda_{LPG}/\Delta T$ was reduced by more than one order of magnitude. The both methods allow compensation of temperature sensitivity only for certain cladding mode and in a relatively narrow spectral range. It appears that the most efficient way of reducing temperature sensitivity of LPGs is to use a fiber in which the thermo-optic coefficient of the core material is approximately equal to that of the cladding. This was recently demonstrated by the example of GeO_2-B_2O_3 co-doping of the fiber core [34].

Increasing of $\Delta\lambda_{LPG}/\Delta T$, useful for temperature-controlled tuning of the resonance wavelength and for temperature sensing, can be achieved by covering the grating with a material having a high thermo-optic coefficient. It was shown in ref. [35] that in a certain temperature range the temperature sensitivity of a grating immersed in a solution of glycerin and water can be as great as 5 nm/°C. At the same time, at such a large temperature sensitivity, the grating spectrum changes dramatically owing to strong changes of the cladding mode field, when the external index approaches the index of silica cladding. In ref. [36] a polymer with a negative thermo-optic coefficient was inserted in the cladding area of the fiber. This allowed increasing of temperature sensitivity up to 0.7 nm/°C, with the temperature dependence of the resonance wavelength displacement retaining good linearity and changes of the resonance intensity and bandwidth being relatively small.

6.2. Strain sensitivity

Strain sensitivity of LPGs was tested in several papers [6, 37]. It was found that depending on fiber type the strain sensitivity of the loss peak could be varied in a wide range from 15 to -7 nm/%ε [6]. It was supposed that the magnitude and sign of strain sensitivity are defined by the difference between the strain-optic coefficients of the core and cladding regions. Nevertheless, further investigations should be performed in order to clarify the features of strain sensitivity of LPGs.

6.3. Bending sensitivity

The transmission spectrum of a LPG is highly sensitive to bending. On the one hand, this necessitates caution in handling gratings; on the other hand, opens up prospects for creation of sensitive optical fiber sensors of mechanical deformations. The bending sensitivity of a grating spectrum is so great that a curvature radius of more than 1 meter can be detected [38]. Grating bending leads to reduction of the resonance amplitude and its displacement to longer wavelengths [38, 39]. An exact theory of the bending effect is still to be developed. As follows from the experimental data, grating bending results in changes of the field distributions of the core and cladding modes, which reduces the overlap integral I. The resonance shift to longer wavelengths, as follows from equation (2), points to an increase of Δn_{eff}. In our earlier work [31], a bending-induced splitting of the initial grating peak was observed. This result was recently confirmed in ref. [40], where the resonance splitting was observed in a straight LPG written in a fiber with large core concentricity error (CCE). It was demonstrated that in such a fiber the bend-induced splitting has clear asymmetry with respect to rotation angle. Based on these experiments it can be suggested, that the resonance splitting is attributed to the excitation of EH_{1n} cladding modes (these are the even cladding modes in terms of the model proposed by Erdogan [12]). These modes have relatively small overlap integral I with the core mode in straight gratings written in the fibers with low CCE. Breaking of symmetry caused by CCE or/and grating bending leads to the increase of I for EH_{1n} modes and to appearance of additional loss peaks in the grating transmission spectrum.

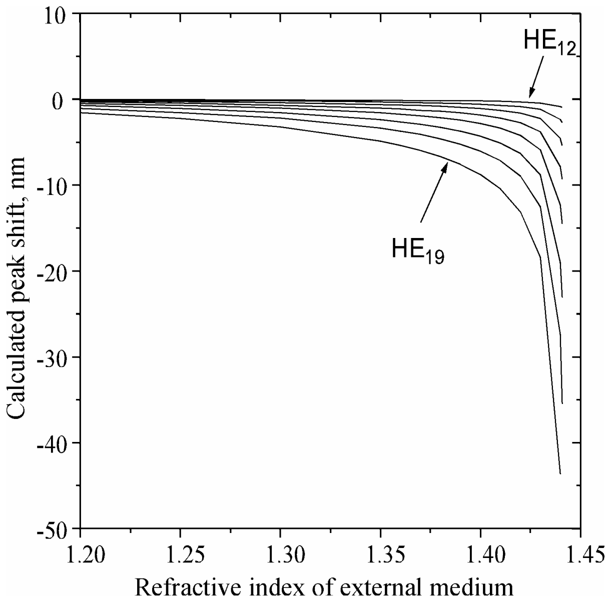

Fig.9. Calculated dependence of the displacement of the resonance wavelengths of a LPG on the refractive index of the external medium [31].

6.4. Sensitivity to refractive index of external medium

Because the cladding mode field partially penetrates into the external medium, the spectrum of a LPG depends not only on the parameters of the fiber itself, but also, according to (2 - 4), on the dielectric permeability of the grating environment [6, 31]. When a grating is immersed in a medium with a refractive index higher than that of the air, n_{eff}^{clad} rises, which is accompanied by a shift of the peaks in the grating transmission spectrum to shorter wavelengths. The value of this displacement, as follows from fig.9, strongly depends on the mode order and n_{ext}, and reaches tens nanometers, when n_{ext} tends to n_{clad}. As n_{ext} increases, the cladding mode field penetrates deeper into external medium. Consequently, the efficiency of the interaction with the fundamental mode decreases. At a certain value of n_{ext} the interaction disappears at all, because the cladding mode can no longer be guided by the structure (the wavelength became larger than the cut-off wavelength of the cladding mode). When $n_{ext} > n_{clad}$ the cladding mode propagates in accordance with Fresnel reflection from the cladding boundary, which is accompanied by the re-appearance of the grating peak [41].

High sensitivity of the LPG spectrum to n_{ext} allows using such gratings as an optical fiber sensor of the refractive index of the environment, for example, in studying chemical and biological media.

6.5. Sensitivity to the cladding diameter

Cladding mode propagation constant $\beta_{clad} = 2\pi n_{eff}^{clad} / \lambda$ depends on the cladding diameter. This fact permits irreversible alteration of the resonance wavelength of LPGs [42]. The cladding diameter can be easily decreased by etching the fiber section containing the grating in a HF acid solution. This will significantly shift the resonance wavelength to longer wavelengths without affecting the coupling efficiency. As is shown in fig.10, the resonance wavelength displacement increases with the cladding mode order and amounts to 100 nm and over for the highest cladding modes.

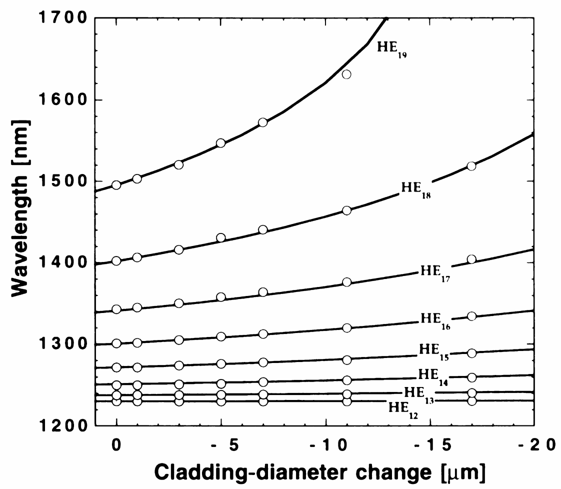

Fig.10. Experimental (circles) and theoretical (curves) resonance wavelengths' positions of a LPG as a function of cladding-diameter change [42].

6.6. Long-period gratings in birefringent fibers

In ref. [43] spectral characteristics of LPGs written in a birefringent fiber were investigated. In particular, it was shown that the resonance peak is splitted on two peaks, each of them corresponding to coupling of the fundamental mode of a certain polarization state with the same polarization of the cladding mode. For a 5-cm-length grating written in a fiber with birefringence of 4×10^{-4} the splitting of peaks of more than 40 nm was achieved, the intensity of the both peaks being more than 10 dB. Such a large splitting in comparison with the peak bandwidth (~ 5 nm) allows one to create narrow-band polarization filters. Such filters can be profitably applied in single-polarization fiber lasers.

7. APPLICATION OF LONG-PERIOD GRATINGS

As follows from the above consideration, LPGs can be used in various fiber devices, such as fiber sensors [6, 31, 38], narrow-band loss filters [5, 44], including tunable filters [45], modulators of optical radiation [46], etc. Several important applications of LPGs will be detailed below.

7.1. Flattening of gain and luminescence spectra

One of the most important applications of LPGs in telecommunication systems is related to flattening gain spectrum of fiber amplifiers used in WDM/DWDM systems and to flattening spectra of broadband luminescence sources. The possibility of using LPGs for gain spectrum flattening of Er-doped fiber amplifiers was demonstrated in [47]. The gain spectrum variation of less than 1 dB at a gain of more than 30 dB was obtained in a wide spectral range 1526 – 1560 nm (Fig.11). This result turned out to be comparable with the values attainable with the best flattening techniques. By using several LPGs, gain spectrum flatness of ~0.2 dB was achieved [7]. The main advantages of this method is simplicity of the grating fabrication, a wide spectral range and a high gain value of the flattened spectrum, low insertion loss at the pump wavelength, and the absence of back-reflected light.

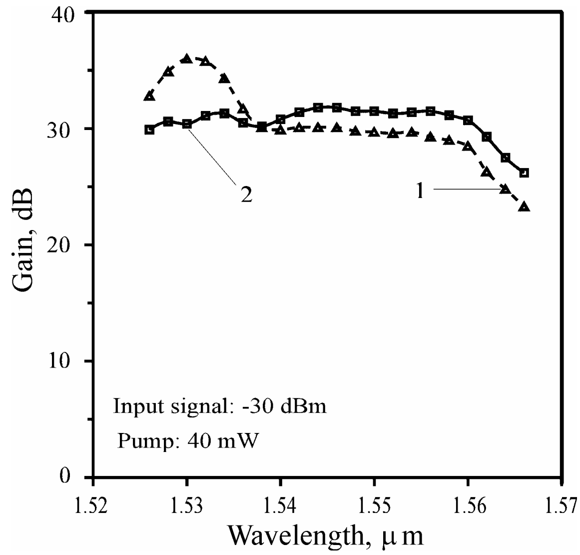

Fig.11. Gain spectrum of an Er-doped fiber amplifier: initial (1) and flattened by a LPG filter (2) [47].

LPGs are also efficient at smoothing amplified spontaneous luminescence spectra of Nd^{3+} (Ref. [48]) and Er^{3+} (Ref. [30]) ions. The power of such fiber broadband sources with flattened emission spectrum can achieve tens and hundreds of milliwatts.

7.2. Measuring induced refractive index change in the fiber core

UV-induced refractive index is commonly estimated from the Bragg grating reflection coefficient (amplitude of index modulation), or from the wavelength displacement observed during the Bragg grating formation (average induced index) [49, 50, 51]. However, Bragg grating writing requires a stable interference pattern of UV-radiation during a prolonged time. This imposes stringent requirements on coherence of the UV-source and on the stability of writing system.

LPGs can be employed with advantage in investigation of the refractive index induced in the fiber core by UV-radiation. LPG writing does not require a high-coherence source and precise mechanical stability of the writing system. As in the case of Bragg grating, the photoinduced index value is directly related to the depth of the resonance, and Δn_{ind} is determined from equations (6, 7).

As was shown in ref. [52], when a LPG is written through an amplitude mask, it is possible to monitor Δn_{ind} by measuring the resonance wavelength displacement. The displacement of the LPG resonance is more than $n_{eff}^{core} / \Delta n_{eff} \approx 10^2$ times

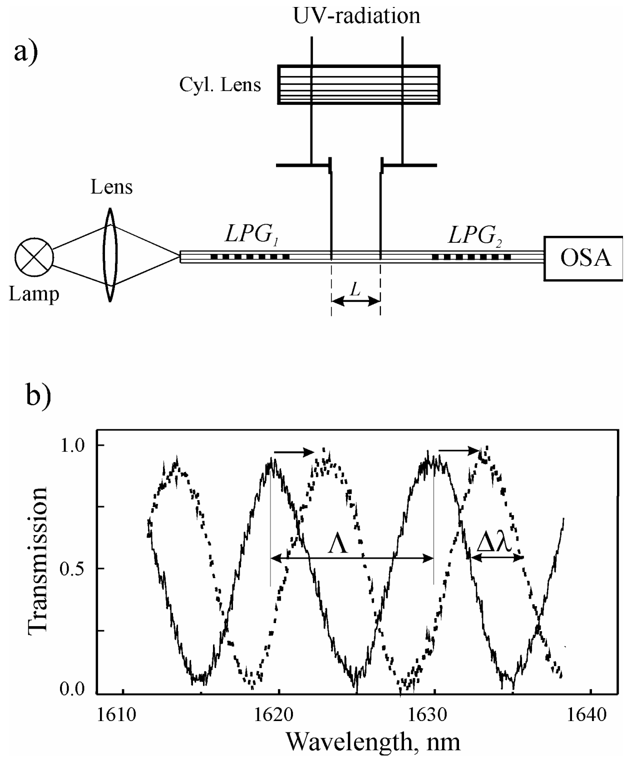

Fig.12. Setup for measuring refractive index change in a fiber core (a); UV-induced displacement of the interference pattern (b) [54].

greater than for Bragg gratings. This fact allows one to get an accuracy of Δn_{ind} measurement better than 10^{-5} (Ref. [52]).

Another useful way of measuring induced refractive index is based on application of a Mach-Zehnder interferometer formed by two LPGs (Fig.12a) [53]. The first grating directs a half of the fundamental mode power to the cladding mode. Thus, a part of light power covers the distance between gratings G_1 and G_2 in the fundamental mode (core arm of the interferometer) and the other part in the cladding mode (cladding arm). These two waves interact in grating Gr_2 in accordance with the phase difference between the interferometer arms $\Delta\varphi$. The interferometer transmission spectrum depends on $\Delta\varphi$. Because the portion of the cladding mode power propagating in the core is rather small, the index increase in the fiber core practically does not affect the propagation constant of the cladding mode. Therefore, by measuring the phase shift of the interference pattern during side UV-irradiation of some fiber section between the gratings, one can determine the induced refractive index in the fiber core. In ref. [54] the measured value was the spectral displacement of the interference pattern $\Delta\lambda$ (fig.12b), which is related with Δn_{ind} by the following equation: $\Delta n_{ind} \approx \lambda\Delta\lambda/(L\Lambda\eta)$, where λ is measuring wavelength, L is the length of the irradiated fiber portion, Λ is the interference period, η is the fraction of the fundamental mode power contained in the core. The interferometer scheme described above provides high accuracy of Δn_{ind} measurement ($\sim 10^{-6}$) and features excellent temperature stability.

8. CONCLUSIONS

The above description of the main properties and fabrication techniques of long-periood fiber gratings shows that these gratings can be applied in a new generation of telecommunication systems, fiber lasers and sensors. As it was shown LPGs are a sensitive tool for measuring the induced refractive index change in fibers, which is important for better understanding of glass photorefractivity phenomenon. The importance of LPGs is confirmed by the growing interest displayed to them by research groups allover the world. At the same time, we can conclude that some grating features, for example, strain and bending sensitivity, are not completely understood at the present time, and further research should be undertaken.

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