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Long-period fibre grating writing with a slit-apertured femtosecond laser beam (λ = 1026 nm)*

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Abstract. **We report on long-period grating (LPG) writing in a standard telecom fibre, SMF-28e+, via refractive index modification by femtosecond pulses. A method is proposed for grating writing with a slit-apertured beam, which enables one to produce LPGs with reduced background losses and a resonance peak markedly stronger than that in the case of grating writing with a Gaussian beam. The method can be used to fabricate LPGs for use as spectral filters of fibre lasers and sensing elements of sensor systems.**

Keywords: *refractive index modification by femtosecond pulses, long-period fibre gratings, spectral filters.*

1. Introduction

Along with fibre Bragg gratings (FBGs), long-period gratings (LPGs) have found wide application as optical fibre elements for equalising the gain spectrum of erbium-doped fibre amplifiers in telecommunication systems [1], as sensing elements in sensor devices [2], as spectral filters in fibre lasers [3], etc. The most widespread approach to the fabrication of LPGs is refractive index modification in the fibre core by UV radiation it is sensitive to [4].

A rapidly developing alternative method for refractive index modification in transparent materials is femtosecond laser writing [5]. The key advantages of this method are the possibility of modifying nonphotosensitive materials, e.g. standard telecom fibres (without preliminary photosensitisation via molecular hydrogen loading) or pure silica core fibres, and the possibility of grating writing through protective coatings (e.g. acrylate and polyimide coatings, transparent in the IR spectral region) without damaging the fibre [2], which significantly improves the mechanical strength of the LPGs and FBGs. One possibility of producing LPGs with the use of femtosecond radiation is point-by-point laser writing: in this method, the refractive index of the fibre core is modified through a nonlinear absorption of laser light focused by a micro-objective [6]. This method, however, has a number of drawbacks, including considerable background losses and poor reproducibility because the modification region is difficult to position in the fibre core over the entire length of the LPG, which may reach several centimetres.

In this paper, we report on LPG writing with a slit-apertured femtosecond laser beam at a wavelength of 1026 nm [7] in a standard telecom fibre, SMF-28e+, which makes it possible to overcome the above drawbacks to point-by-point laser writing: to significantly reduce the background loss level, increase the resonance peak amplitude and improve the reproducibility of experimental data.

2. Experimental setup

LPGs were written using an experimental configuration schematised in Fig. 1. After passing through a system of rotatable mirrors, the femtosecond ytterbium fibre laser beam (wavelength, 1026 nm; pulse duration, 232 fs; pulse repetition rate, 1 kHz) was focused into the fibre core region by an aspherical lens with a focal length f = 11 mm (NA = 0.3). The required pulse energy level was ensured by a beam attenuation system comprising two half-wave plates and a polariser.

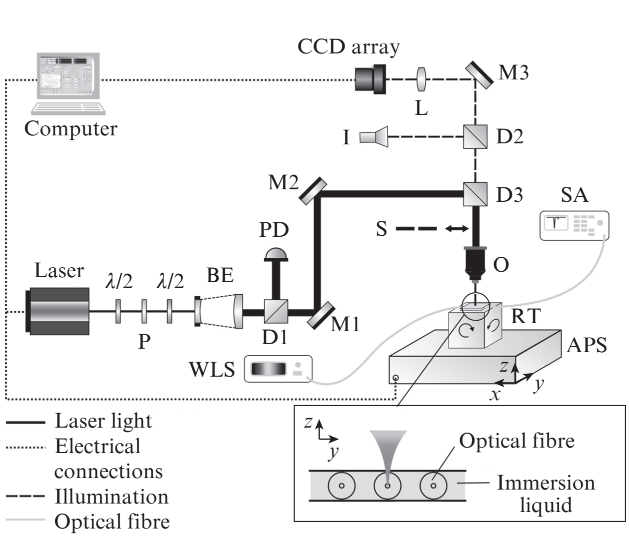

Figure 1. Schematic of the experimental setup used to write LPGs: (APS) automatic positioning stage; (RT) rotary table; (O) focusing optics; (S) slit; (SA) spectrum analyser; (D1 – D3) dichroic mirrors; (M1 – M3) mirrors; (L) lens; (BE) beam expander; (P) polariser; (I) illumination; (WLS) white light source; (PD) pulse energy meter.

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The beam size at the input of the focusing optics was determined by a beam expander. In our experiments aimed at LPG writing with a slit-apertured beam, a slit was placed immediately in front of the focusing lens so that its long side was parallel to the fibre axis. The fibre was located on an Aerotech ABL 1000 automated precision three-axis stage, which enabled the sample to be translated at a constant speed during the writing process. The time interval between the instants at which the laser shutter was opened and closed was determined by the LPG period. The mechanical rotary table allowed us to adjust the plane of the sample surface throughout the writing region. Using illumination and a camera, we adjusted the position of the focusing region in the fibre core. The laser pulse energy was monitored with a Coherent J-10MT-10KHZ energy sensor. LPGs were inscribed in Corning SMF-28e+ fibre (cladding diameter, 125 μm; core diameter, 8.2 μm; cutoff wavelength, 1260 nm) after stripping its polymer jacket. To compensate for the effect of fibre surface curvature on beam focusing, the fibre was sandwiched between parallel fused silica plates, and the space between them was filled with an immersion liquid. The refractive index of the immersion liquid was close to that of the optical fibre in order to reduce the index difference across the interface. Spectra of the fibre gratings were measured using a Yokogawa AQ4305 white light source and Yokogawa AQ6370 optical spectrum analyser.

3. Results

To verify the effectiveness of the proposed focusing scheme, we performed point-by-point trial index grating writing with a 50-μm period in the fibre core at a laser pulse energy of 2 μJ and fibre translation speed of 5 μm s^{-1} (Fig. 2). It is seen that the modification region covers the fibre core and that its position with respect to the core remains unchanged along the fibre. Therefore, the approach under consideration can be used for LPG writing.

Figure 3 illustrates the effect of grating length on the transmission spectrum of LPGs produced as described above and having the following parameters: total grating length L = 28 mm, pulse energy E = 375 nJ and grating period Λ_{LPG} = 500 μm. It is seen that, in the initial portion of the grating (grating length within 16 mm), the absorption peak around 1340 nm increases, reaching 9.3 dB. The corresponding background losses are 1 dB in the shorter wavelength region ($\lambda < \lambda_{LPG}$ = 1340 nm, where λ_{LPG} is the resonance wavelength of the strongest absorption peak of the LPG) and 0.5 dB in the longer wavelength region ($\lambda > \lambda_{LPG}$). Increasing the LPG length to 28 mm reduces the depth of the absorption peak in question to 3.4 dB and gives rise to resonance peaks at other wavelengths, suggesting that there is effective coupling with other cladding modes. Another drawback to the point-by-point direct grating writing process is the high sensitivity of the transmission spectrum to the position of the modification region in the fibre core, which leads to poor reproducibility of results.

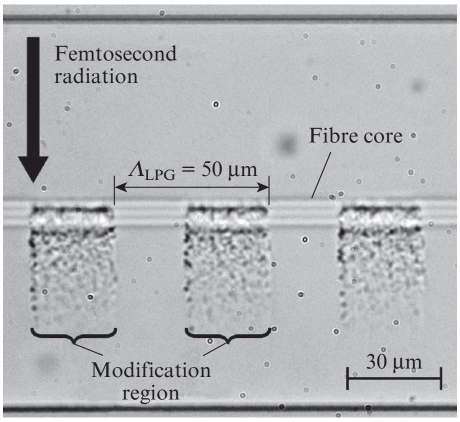

Figure 2. Portion of a trial LPG inscribed in SMF-28e+ standard optical fibre.

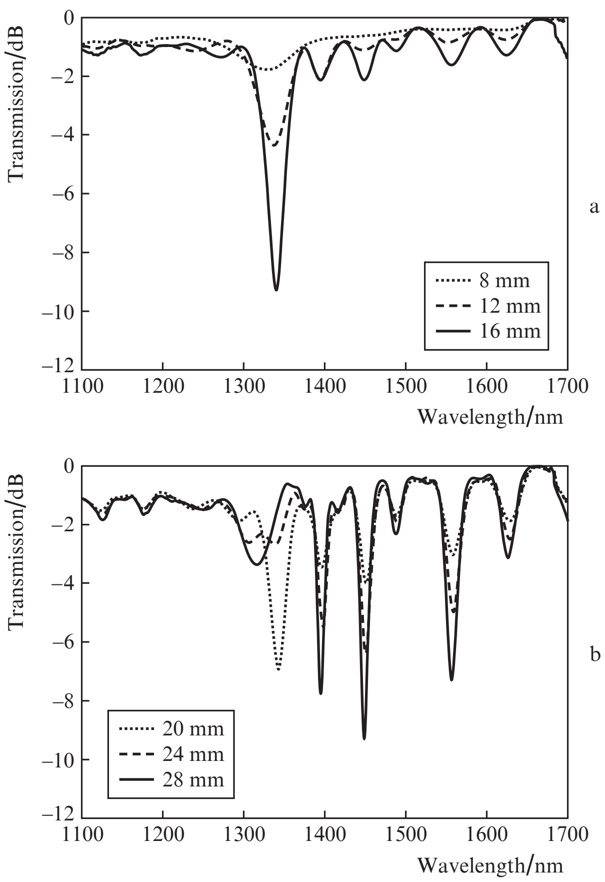

Figure 3. Transmission spectra of LPGs produced by point-by-point laser writing: grating lengths of (a) 8, 12, 16, (b) 20, 24 and 28 mm.

These problems have also been pointed out in other reports concerned with point-by-point direct LPG writing by femtosecond laser radiation [8]. They arise primarily from the asymmetry in the dimensions of the modification region in the longitudinal and transverse directions. Moreover, the increase in background losses is caused by the formation of inhomogeneities, which scatter light [9]. In addition, since the transverse size of the modification region (1.4 μm) is considerably smaller than the core diameter, accurate adjustment of the laser beam position relative to the core over the entire length of the grating is critical. For example, at a grating length of 10 mm and a deviation from the initial position at a level of 2 μm, the fibre should be aligned with an accuracy better than 0.01°.

For this reason, a writing method that would allow the transverse size of the modification region to be increased without considerable changes in its longitudinal size might significantly improve the spectral characteristics of LPGs and the reproducibility of results. In previous work concerned with the femtosecond laser modification of optical fibres, various approaches have been proposed for increasing the overlap of the modification region and core mode field, including continuous scanning across the fibre axis [10] and the use of small numerical aperture focusing optics [11]. This ensured an increase in the amplitude of the major peak, but the background loss level also increased, because of the stronger scattering by inhomogeneities in the fibre core and the non-uniform distribution of the modification region.

To ensure radially symmetric index modification in the bulk of transparent materials, writing with an astigmatic beam using a cylindrical lens [12] and with a slit-apertured beam [13] has been demonstrated. The fact that no high adjustment accuracy is required and the possibility of rapidly changing the beam geometry make grating writing with a slit-apertured beam better suited for writing waveguide structures. For example, Ams et al. [7] showed that, when fused silica was modified by slit-apertured beams, the cross section of the index modification region had a radially symmetric distribution. For this reason, the method under consideration is attractive for writing LPGs with a radially symmetric distribution of refractive index changes across fibres.

Figure 4a shows a schematic of LPG writing with a slit-apertured beam. After passing through a slit, an initially circular beam (of diameter D_0) has different dimensions along (D_0) and across (D_s, dependent on the slit width) the fibre. Figures 4b and 4c show intensity distributions in the yz plane for the standard focusing of a Gaussian beam and for a slit-apertured beam. The intensity distribution in the Gaussian beam has the form [14]

$$I_c(x,y,z) = \frac{1}{1+z^2/z_0^2}\exp\left[\frac{-2(x^2+y^2)}{r_0^2(1+z^2/z_0^2)}\right], \quad (1)$$

and that in an elliptical beam is given by [13]

$$I_e(x,y,z) = \frac{1}{\sqrt{1+z^2/z_0^2}}\,\frac{1}{\sqrt{1+z^2/z_0^{*2}}} \times \exp\left[\frac{-2x^2}{r_0^2(1+z^2/z_0^2)}\right]\exp\left[\frac{-2y^2}{r_0^{*2}(1+z^2/z_0^{*2})}\right]. \quad (2)$$

In these formulas, the origin coincides with the position of the geometrical focus of the beam; $r_0 = \lambda/(\pi \mathrm{NA})$ is the beam waist size at the focal point; λ is the laser wavelength; $z_0 = kr_0^2/2$ is the Rayleigh length; $k = k_0 n$ is the wavenumber; n is the refractive index of the medium; k_0 is the wavenumber in vacuum; $r_0^* = (R_x/R_y)r_0$; $z_0^* = kr_0^{*2}/2$; and R_x and R_y are the semi-axes of the ellipse. Thus, the intensity of a slit-apertured beam has an almost radially symmetric distribution, and the transverse size of the modification region increases considerably.

To test the writing method under consideration, the refractive index of a fibre was modified by a slit-apertured beam at different pulse energies in the range 1.1 – 1.6 μJ and exposure times from 0.5 to 1 s (Fig. 4d). It is seen that, in this case, the modification region has different dimensions across (w_s) and along (w_0) the fibre. The w_s/w_0 ratio is about 5 and depends on the ratio of the beam diameter (D_0 = 6 mm) to the slit width (D_s = 1 mm): at a given beam diameter, the narrower the slit, the greater size of the modification region across the fibre axis can be obtained. It is seen in Fig. 4 that, at a given beam size, a 1-mm-wide slit allows one to completely modify the fibre core, so this slit width is optimal at the fibre core diameter in question. For this reason, this slit width was used in our subsequent experiments.

Figure 5 shows transmission spectra of LPGs at different grating lengths. The gratings were written using a slit-apertured beam with parameters E = 1 μJ, L = 34 mm and Λ_{LPG} = 500 μm. The loss in the shorter wavelength region dropped to 0.17 dB, and that in the longer wavelength region, to 0.2 dB. We were able to inscribe a longer grating, and the depth of the absorption peak increased to 12.6 dB. Thus, we have demonstrated that the proposed writing method ensures better characteristics of gratings.

It is known that the re-exposure of a previously modified region to femtosecond radiation may further increase the refractive index modulation depth in this region [10]. In view of this, to increase the index modulation depth in LPGs and, hence, the amplitude of their resonance peak, we used a repeated grating writing process: after the first writing cycle, a second pass was performed, starting at the same x as before, but with a small (~1 μm) displacement across the fibre in the z direction. Figure 6 shows spectra of LPGs inscribed in several passes using a Gaussian beam (E = 375 nJ, L = 20 mm, Λ_{LPG} = 500 μm) and a slit-apertured beam (E = 1.05–1.1 μJ, L = 20 mm, Λ_{LPG} = 500 μm).

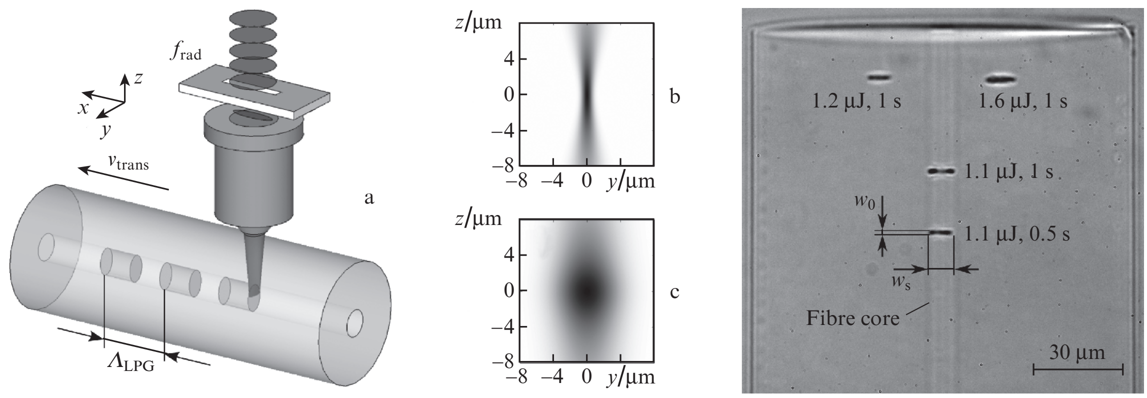

Figure 4. Schematic of LPG writing with a slit-apertured beam (a), calculated intensity distributions for the standard focusing of a Gaussian beam (b) and for a slit-apertured beam (c) and changes induced by a slit-apertured beam (d).

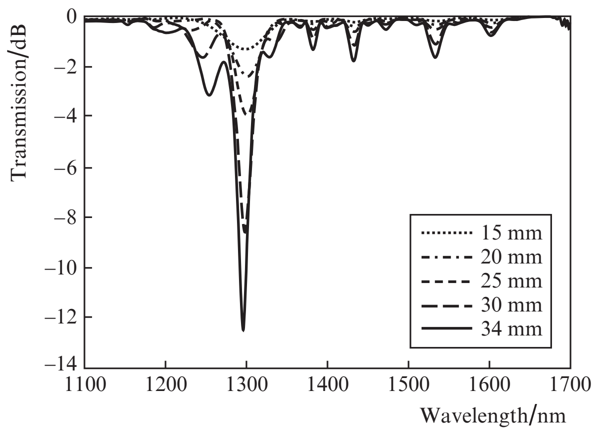

Figure 5. Transmission spectra of LPGs written using a slit-apertured beam at different grating lengths.

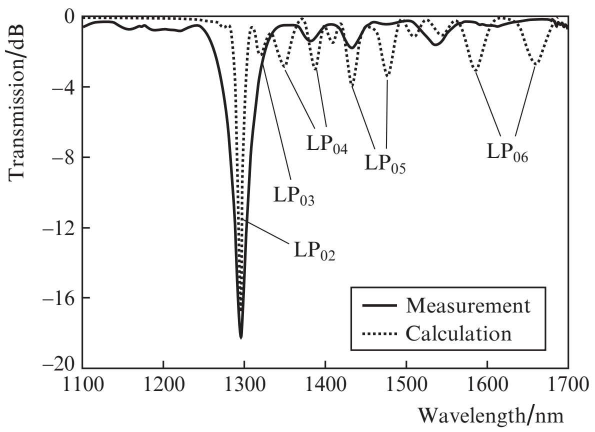

Figure 7. Comparison of a measured and a calculated spectrum of an LPG.

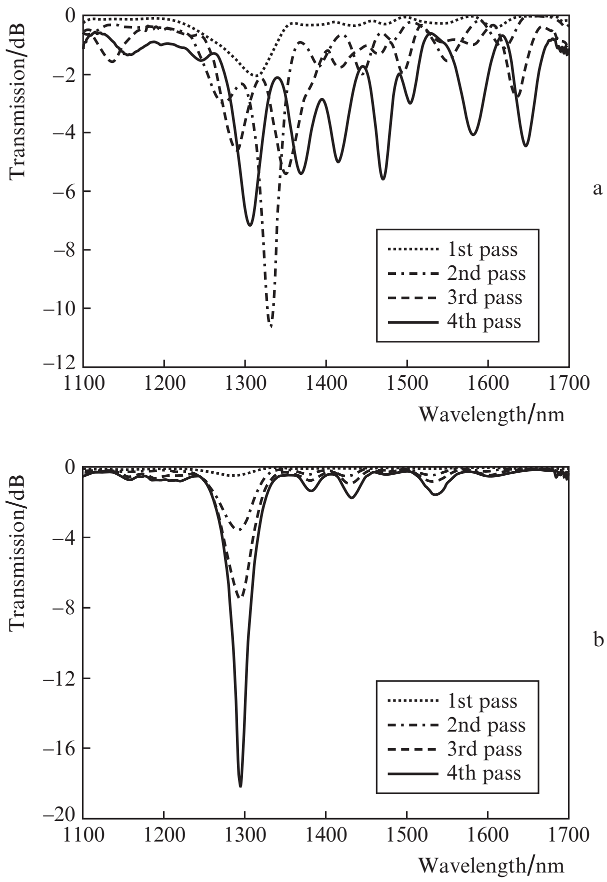

Figure 6. Transmission spectra of LPGs inscribed in several passes using (a) a Gaussian beam and (b) a slit-apertured beam.

It is seen that, in the former case (Fig. 6a), this process leads to a considerable increase in background loss relative to the first writing cycle. Moreover, because of the excitation of other cladding modes, the resonance peak amplitude stops growing and, in contrast, decreases markedly. In the case of grating writing with a slit-apertured beam (Fig. 6b), the background loss level increases only slightly, whereas the absorption peak depth increases to 18.3 dB.

Figure 7 compares a measured and a calculated spectrum of an LPG. The calculated spectrum was obtained by using the above parameters of LPGs and fibres and a mathematical model based on coupled-mode theory and solving coupled equations by the T-matrix method [15]. In the calculation, the refractive index modulation depth in the LPG was taken to be 8.2×10^{-4}. Comparison of the spectra demonstrates that the absorption peak of the LPG at λ = 1295 nm corresponds to coupling between the LP_{01} and LP_{02} modes, whereas the other absorption peaks are resonances related to higher order modes: LP_{04} and LP_{05}.

Coupling between cladding and core modes is known to depend on the refractive index of the ambient medium [2]. The transmission spectrum of an LPG written in several passes using a slit-apertured beam was measured in air (Fig. 8). The observed shift of the peaks of the LPG to shorter wavelengths in the presence of the immersion liquid correlates with results obtained in studies concerned with the application of LPGs in refractometry [16]. Moreover, comparison of spectra of LPGs under various external conditions also suggests that there is coupling between the LP_{01} and LP_{02} modes for the major absorption peak of the LPG, because the shift of the lower order modes is known to be much smaller than that of the higher order modes [17]. It is worth pointing out that the above spectra of the LPGs are atypical of conventional LPGs, in which the peak height increases with cladding mode number [18], but such behaviour of the spectrum of an LPG

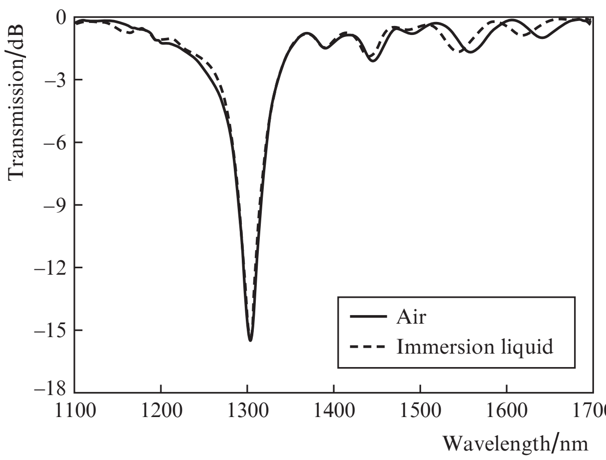

Figure 8. Comparison of transmission spectra of an LPG in an immersion liquid and air.

inscribed into SMF-28 fibre using femtosecond radiation was observed by Sun et al. [19].

4. Conclusions

We have demonstrated LPG writing in nonphotosensitive fibres using a slit-apertured femtosecond laser beam. Owing to a more uniform refractive index modification in the fibre core, this method enables one to fabricate LPGs with background losses no higher than 0.2 dB and a resonance peak markedly stronger than that in the case of grating writing with a Gaussian beam. The present results demonstrate that the absorption peak of LPGs can be increased to 18.3 dB using a repeated grating writing process. The proposed method can be used to fabricate LPGs for use as spectral filters of fibre lasers, because it allows one to produce gratings in nonphotosensitive fibres with extremely low background losses, and as sensors, because it enables LPG writing without stripping the protective coating.

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