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Femtosecond writing of refractive index structures in multimode and multicore optical fibres

A.A. Wolf, A.V. Dostovalov, S. Wabnitz, S.A. Babin

Abstract. **The possibility of writing fibre Bragg gratings (FBGs) in optical fibres with a complex spatial structure using femtosecond IR laser pulses is considered. In particular, selective writing of uniform FBGs in individual cores of a seven-core fibre and writing of serial and parallel FBG arrays in the core of a multimode fibre with a gradient refractive index profile are demonstrated.**

Keywords: *fibre Bragg grating, femtosecond laser-induced refractive index modification.*

1. Introduction

Application of multimode and multicore optical fibres is an object of study in various fields: high-speed optical communication lines [1], radio photonics [2], high-power fibre lasers with improved output characteristics [3], sensors of physical quantities with extended functional characteristics [4], and study of the mechanisms of nonlinear propagation of laser radiation through such waveguides [5, 6]. Modification of the refractive index (RI) in multimode and multicore fibres makes it possible to develop important fibre optics elements, such as fibre Bragg gratings (FBGs), waveguide couplers, and interferometers. Currently, exposure of photosensitive fibre core to UV laser radiation is widely applied to write RI structures [7]. In this case, RI modification is performed strictly within the photosensitive material, without being localised in the bulk (fibre cross section). This limitation can be overcome by modifying transparent materials using high-power (with an energy of ~0.1–1 μJ) femtosecond visible or IR laser pulses [8]. A distinctive feature of this method is that the absorption of femtosecond pulses in a transparent material is of nonlinear nature and occurs when a certain threshold radiation intensity is achieved (~10 TW cm^{-2} for silica glass). Thus, when femtosecond radiation is focused into a bulk material, absorption occurs only near the beam focal region, and the volume of the induced RI modification region may reach ~1 μm^3. Exact positioning of the modification region in the longitudinal and transverse fibre cross sections makes it possible to form RI structures in optical fibres with complex geometry.

In this paper, we report the results of femtosecond point-by-point FBG writing in fibres with complex spatial structure: seven-core Fibrecore SM-7C1500(6.1/125) and multimode Corning 62.5/125, having a core with a gradient index profile.

2. Experimental

FBG writing was performed using a Light Conversion Pharos 6W laser (λ = 1030 nm, τ_p = 232 fs) as a femtosecond pulse source. Laser pulses with a repetition rate f = 1 kHz were focused into a specified fibre region with the aid of a Mitutoyo 100x Plan Apo NIR HR microscope objective (NA = 0.7). A special glass ferrule with polished lateral faces made it possible to fix the fibre position with respect to the focusing region, as shown in Fig. 1 [9]. 2D control of the modification region position in the fibre cross section was performed using two CMOS cameras and an additional objective, oriented perpendicular to the main one. Longitudinal periodic RI modulation was implemented due to the fibre motion with a chosen constant velocity $v_{tr} \approx 0.5$ mm s^{-1}, applying a high-precision linear Aerotech ABL1000 translator. The FBG period was determined by the ratio $\Lambda = v_{tr}/f$, and the first-order resonance wavelength was $\lambda = 2n_{eff}v_{tr}/f$. The fibre was fixed on the linear translator by a clamp, which had an angular degree of freedom

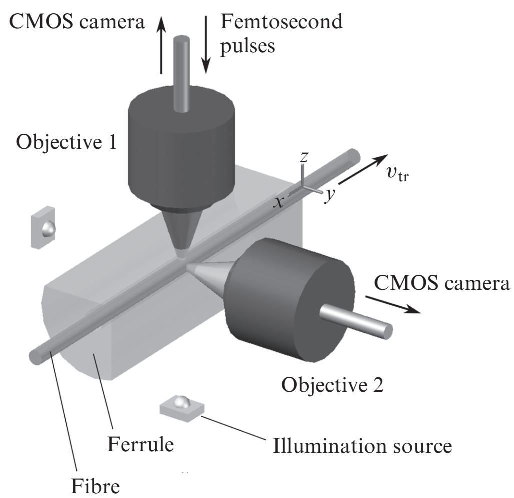

Figure 1. Point-by-point FBG writing by drawing a fibre through a transparent ferrule.

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when writing FBG in a seven-core fibre; this approach made it possible to rotate fibre around its axis.

To create a bending strain sensor, an FBG was written in individual cores of a seven-core Fibrecore SM-7C1500 (6.1/125) fibre having the following characteristics: cladding diameter 125 μm, core spacing 35 μm, and mode field diameter (for each core) 5.7–6.5 μm at a wavelength of 1550 nm. FBGs with a length of 2.5 mm were formed in the central and three peripheral fibre cores, located in the vertices of equilateral triangle. FBGs were written successively; the initial grating positions were aligned along the longitudinal coordinate axis. The period and resonance wavelength of each individual FBG changed during writing. Figure 2 shows a micrograph of seven-core fibre cleavage in the FBG array writing region, which was obtained in a differential interference contrast optical microscope. It can be seen that RI modification occurred strictly in the region of chosen fibre core.

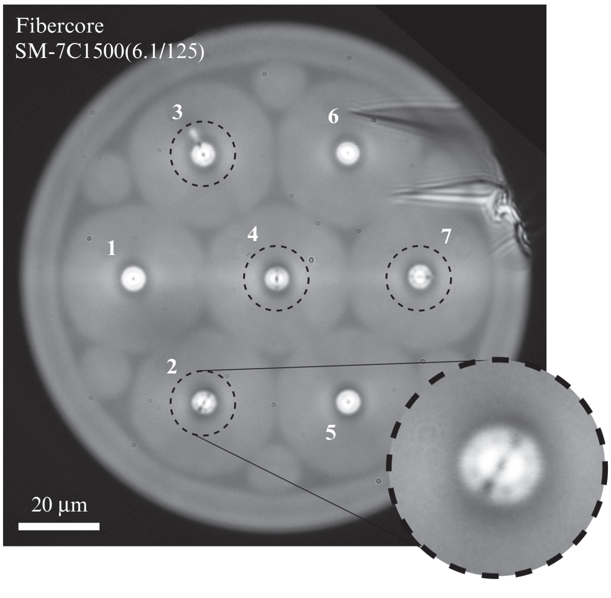

Figure 2. Micrograph of seven-core fibre cleavage in the region of FBG array writing, with indication of cores 4, 2, 3, and 7, where writing was performed.

The FBG reflection spectra were measured using a Yokogawa AQ6370 analyser and a superluminescent diode (SLD). The diode radiation arrived at the input of fibre circulator and then was successively directed to each individual fibre core with the aid of a specialised Fibrecore FAN-7C fan-out. The measurement results are shown in Fig. 3a. Since bending of the multicore fibre leads to extension and compression of the fibre cladding material, we measured reflection spectra from an FBG-containing fibre section fixed on the surface of a cylinder 65 mm in diameter (Fig. 3b). As can be seen in Fig. 3b, the resonance wavelengths for cores 2 and 7 were shifted by $\Delta\lambda_2 = -1.15$ nm and $\Delta\lambda_7 = 1.09$ nm, respectively. At the same time, the resonance wavelengths corresponding to central core 4 and peripheral core 3 did not exhibit any significant shift. This situation correspond to the optical fibre orientation in which core 7 is located closer to the cylinder surface than core 2, while cores 3 and 4 lie on a line parallel to the cylinder surface.

The shifts of FBG resonance wavelengths for different cores can be used to calculate the bending radius and direction,

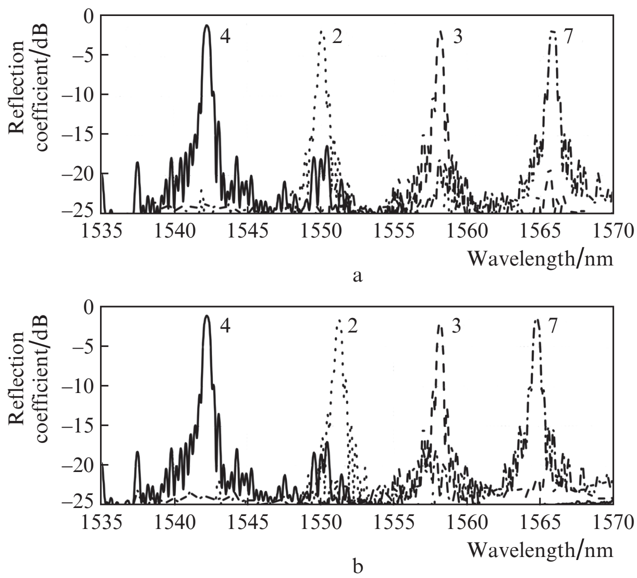

Figure 3. FBG reflection spectra, measured for cores 4, 2, 3, and 7 of a seven-core fibre in the cases where the FBG-containing section of fibre was (a) straightened and (b) fixed on the surface of a cylinder 65 mm in diameter.

which makes it possible to design vector bending sensors for robotics and structural health monitoring. The possibility of choosing parameters for each individual FBG is promising for developing multiparameter sensors; it also makes it possible interrogate these sensors through one port, because signals from wavelength-separated FBGs can be summed via a fibre combiner. In addition, the modification of individual cores using femtosecond laser pulses allows one to design FBGs playing the role of mirrors in lasers based on multicore fibres [10].

The other fibre used in experiments on writing FBGs was a telecommunication multimode optical fibre Corning 62.5/125, having a core with a gradient index profile and a diameter $d_0 = 62.5$ μm as well as a numerical aperture NA = 0.275. The electric field distribution for the LP_{mp} mode in this fibre has the form

$$E_{mp}(\rho,\varphi) \sim \rho^{|m|}/\rho_0^{|m|+1} L_{p-1}^{|m|}(\rho^2/\rho_0^2)\exp(-\rho^2/2\rho_0^2)\exp(\mathrm{i}m\varphi), \quad (1)$$

where p and m are, respectively, the radial and azimuthal numbers and $L_p^m(x)$ is the Laguerre–Gauss polynomial.

In the first order, coupling of transverse modes with the FBG structure written in the core and having having a period Λ is realised when the phase-matching condition is satisfied: $\beta_\mu - \beta_\nu = 2\pi/\Lambda$, where $\beta_i = 2\pi n_{\mathrm{eff}}^i/\lambda$ is the ith-mode propagation constant and n_{eff}^i is the effective RI of the ith mode. The FBG coupling coefficient for the transverse modes μ and ν can be written as [11]

$$k_{\mu\nu} \approx \int_0^{2\pi}\int_0^{+\infty} \Delta\varepsilon(\rho,\varphi) E_\mu(\rho,\varphi) E_\nu^*(\rho,\varphi)\rho\,\mathrm{d}\varphi\,\mathrm{d}\rho, \quad (2)$$

where $\Delta\varepsilon(\rho,\varphi)$ is the transverse component of the disturbance in permittivity, which is due to the presence of an FBG. Hence, one can see that the possibility of FBG positioning in the fibre cross section makes it possible to change the grating coupling coefficient and thus select spectrally a desired group of transverse modes.

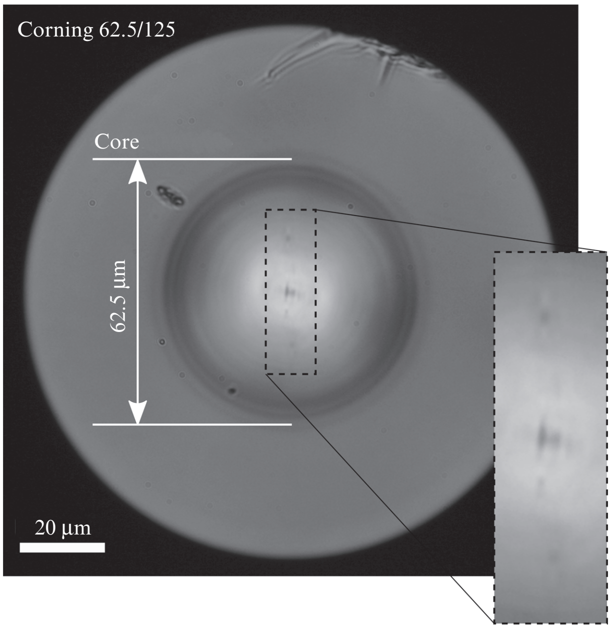

Figure 4. Micrograph of multimode fibre cleavage in the FBG writing region.

Figure 4 shows a micrograph of multimode fibre cleavage in the FBG writing region. Femtosecond pulses with an energy of 300 nJ were focused into the central part of the core. The longitudinal size of the modification region was ~30 μm, which provided its simultaneous overlap with several groups of transverse modes.

The first-order FBG sample under study had a length of 5.26 mm and a period of 0.526 μm. Its spectral characteristics were measured using the scheme presented in Fig. 5a. A superluminescent Thorlabs SLD1550S-A2 diode was chosen to be a broadband optical signal source; its radiation arrived at a single-mode circulator. Having passed through the circulator, the signal arrived at an FBG-containing multimode fibre. When single- and multimode fibres were spliced, their core centres were aligned. Reflected and transmitted signals were measured using an optical spectrum analyser (OSA). The reflection spectrum (Fig. 5b) contains four groups of modes; the resonance peak amplitude significantly decreases with an increase in the group number. This is caused by the power redistribution at the splice between the single- and multimode fibres: most of the optical signal power passed to the fundamental mode LP_{01}, while the remaining power was distributed over groups of modes with higher numbers.

A measurement of the transmission spectrum of written FBG sample (Fig. 6) showed that the resonance dips for all nine (*1*–*9*) visible groups of modes (wavelengths 1537–1551 nm) have amplitudes of 10.5–17 dB, which is indicative of effective overlap of the field of these groups of modes with the FBG structure. The intermodal coupling is also enhanced with an increase in the group number, as evidenced by the enhancement of the intermediate resonances. The resonances located in the short-wavelength region (below 1537 nm) are due to the coupling between the core modes and fibre cladding. When measuring the transmission spectrum of a grating placed in an immersion liquid, the resonances disappear (Fig. 6b), because the total internal reflection condition is violated for cladding modes, and the optical signal emerges from the cladding into the environment.

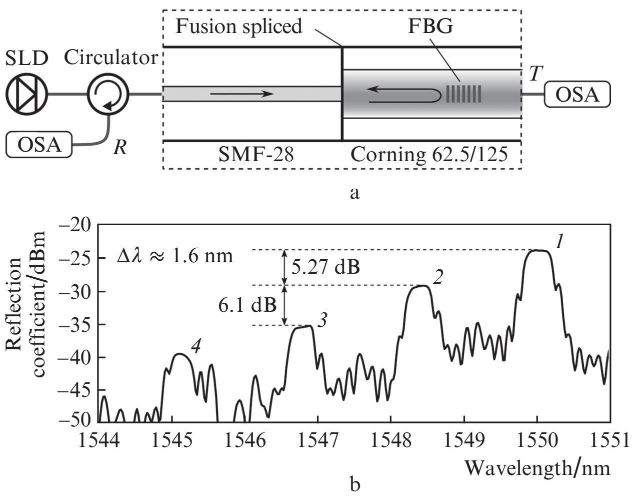

Figure 5. (a) Measurement scheme and (b) reflection spectrum of an FBG written in a multimode fibre with a gradient RI profile; numbers *1*–*4* indicate groups of modes.

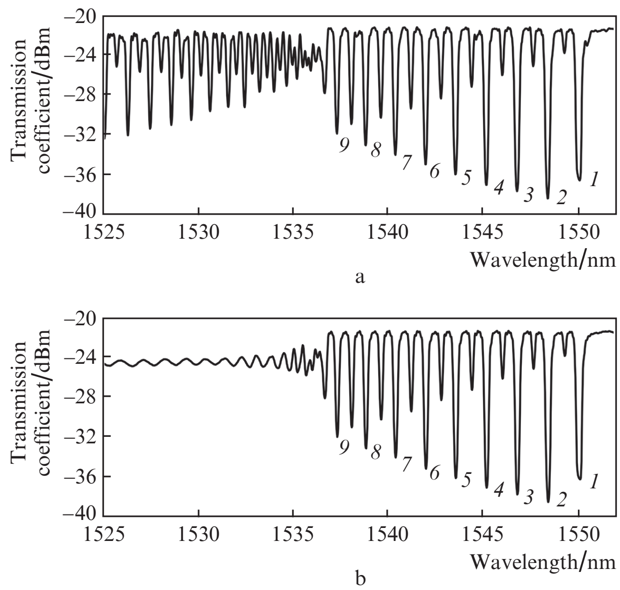

Figure 6. Transmission spectra of an FBG written in a multimode fibre with a gradient RI profile, measured in (a) air and (b) immersion liquid.

In the next experiment, we wrote two FBG arrays in the multimode fibre. The first array consisted of three uniform 5.26-mm-long gratings, written serially one by one in the central part of the fibre. The femtosecond pulse energy was reduced to 180 nJ in order to make the modified region smaller. All three gratings had different periods and resonance wavelengths, which made it possible to separate resonances in the reflection spectrum (Fig. 7a). It can be seen that the amplitude of the LP_{11} mode (group *2*) is much lower than the resonance amplitude of the LP_{01} mode (group *1*) for all gratings. The amplitude difference varied from 15.3 to 21.6 dB, exceeding significantly the corresponding difference for the FBGs written with higher energy pulses (Fig. 5).

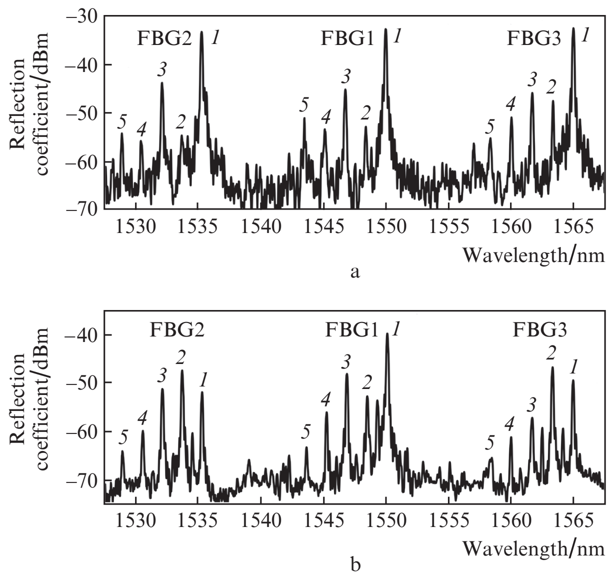

Figure 7. Reflection spectra of an FBG array written in a multimode fibre with a gradient RI profile under different conditions: (a) serial writing in the central part of the core and (b) parallel writing of all gratings (FBG1 in the central part of the core, and FBG2 and FBG3 spaced at ∼10 μm).

The second FBG array consisted of three uniform gratings, written parallel to each other. First FBG1 was written in the central part of the core at a pulse energy of 180 nJ, then FBG2 and FBG3 were written in the peripheral part of the core at a pulse energy of 270 nJ. All FBGs were aligned along the longitudinal coordinate axis and spaced at ∼10 μm along the transverse axis. Figure 8 shows a micrograph of multimode fibre cleavage in the writing region of this FBG array. As can be seen in the reflection spectrum (Fig. 7b), for the resonances corresponding to the peripheral gratings (FBG2 and FBG3), the largest amplitude is observed for the peak

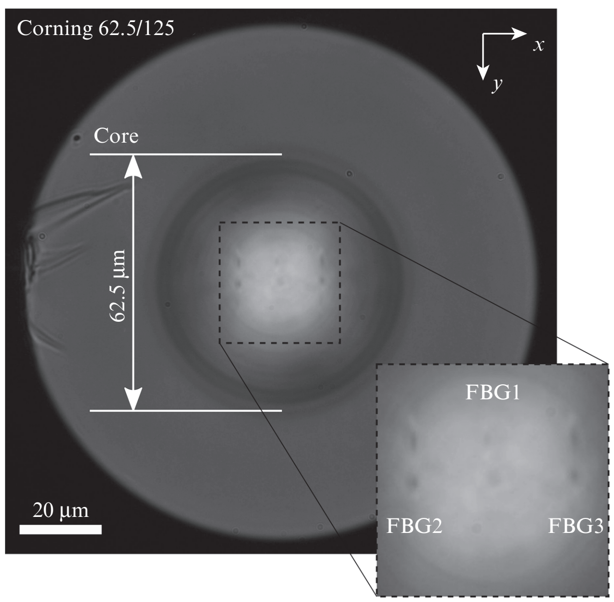

Figure 8. Micrograph of multimode fibre cleavage in the FBG array writing region.

related to the LP_{11} mode (group *2*), although the fraction of optical signal power in this mode is much smaller than for the LP_{01} mode (group *1*). This fact indicates that groups of modes having a field distribution beyond the central part of the core in a multimode fibre can be subjected to efficient spectral selection.

Thus, we demonstrated the potential of femtosecond writing for forming FBGs in fibres with a complex spatial structure. An FBG array was fabricated in a seven-core fibre, in which uniform gratings with different periods were written in chosen fibre cores. It was shown by an example of multimode fibre with a gradient RI profile that exact positioning of RI modification in the transverse direction makes it possible to select spectrally different groups of modes. The results obtained can be used to design sensors of physical quantities and multimode fibre lasers with a controlled mode composition.

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