OPTICAL FIBRES

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Second-order Bragg gratings in single-mode chalcogenide fibres

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***Abstract*.** **Bragg gratings with a second-order resonance wavelength in the near-IR spectral region have been inscribed into single-mode chalcogenide (As_2S_3) glass fibre by a He – Ne laser beam using a configuration typical of Bragg grating fabrication in germanosilicate fibre, with the use of a phase mask that ensures effective diffraction of the writing light into the $+1$ and -1 orders. The spectra of the inscribed gratings show no resonances due to cladding mode excitation because the cladding material is photosensitive.**

Keywords: *single-mode chalcogenide fibres, Bragg gratings, phase masks.*

1. Introduction

Chalcogenide glass waveguiding structures are of considerable practical interest because they offer low optical losses in the IR spectral region (1 – 12 μm) [1 – 3]. The high optical nonlinearity of chalcogenide glasses makes them candidate materials for all-fibre tunable optical filters, switches, modulators and other nonlinear devices [4 – 6].

Optical exposure gives rise to a variety of effects in chalcogenide glasses, including refractive-index changes that persist after the exposure. Such changes can be utilised to produce planar waveguides and index gratings [7 – 10].

The fabrication of Bragg gratings in chalcogenide optical fibre has a number of distinctive features relative to that in germanosilicate fibre. Note first of all that use is made of longer writing wavelengths (0.5 – 1 μm), at the fundamental absorption edge of the chalcogenide glasses. It is worth pointing out that, when selecting a laser source for grating inscription in chalcogenide fibre, one should take into account that their core and cladding are similar in glass composition, so the penetration depth of the writing light should be comparable to the fibre diameter rather than to the core diameter, in contrast to germanosilicate fibre, whose undoped silica cladding does not absorb UV radiation. Moreover, chalcogenide glasses have a considerably larger refractive index, which leads to a significant reduction in grating period. In particular, a fibre Bragg grating (FBG) with a resonance wavelength of 1550 nm should have a period of $\sim$ 350 nm for the first-order resonance in As_2S_3-based glass. In combination with the relatively long writing wavelengths, this short grating period significantly complicates Bragg grating inscription in chalcogenide waveguiding structures.

In spite of these difficulties, several techniques have been proposed to date for first-order Bragg grating inscription in single-mode chalcogenide fibre. In particular, Brawley et al. [9] wrote Bragg gratings with a resonance wavelength of 1550 nm in single-mode arsenic selenide (As_2Se_3) glass fibre using a high-index prism and immersion liquid. Florea et al. [10] inscribed first-order Bragg gratings into single-mode As_2S_3 fibres by a He – Ne laser beam inclined at a considerable angle (79°) to the plane of a $0/-1$ phase mask.

Unfortunately, these and other reported techniques for FBG inscription are more complex than and inferior in grating quality to the standard writing technique with a phase mask that ensures diffraction into the $+1$ and -1 orders [11]. Successfully employed to fabricate high-quality first-order Bragg gratings in germanium-doped fibres by exposure to UV light, this technique cannot be used to write first-order Bragg gratings into chalcogenide fibre because of their short period and the long writing wavelength.

To obviate these problems, we propose using high-order Bragg resonances in chalcogenide fibre, which is possible because the photoinduced refractive index change in the chalcogenide glasses is a nonlinear function of exposure dose. Second-order gratings are widely used in the case of germanosilicate fibres, where the writing technique does not ensure a short grating period, e.g. in point-by-point FBG inscription [12, 13]. Moreover, the radiation reflected by an FBG into the second order has first-order phase matching across the fibre axis [14], which allows one to locate the grating and control the spatial distribution of its parameters.

In this paper, we describe a technique for Bragg grating inscription into chalcogenide fibres by scanning a writing beam over a phase mask that ensures light diffraction into the $+1$ and -1 orders.

2. FBG inscription procedure

In our experiments, we used single-mode arsenic sulphide fibre produced from high-purity glass by the double-

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crucible method [15]. The fibre core had the stoichiometric composition ($As_{40}S_{60}$), and the cladding was enriched in sulphur ($As_{38}S_{62}$). The relative core–cladding index difference Δ was ~ 0.3 % and the first higher order mode cutoff wavelength was ~ 1.1 μm. The core and cladding diameters were 4 and 125 μm, respectively. The fibre was coated with an F-42 fluoropolymer (vinylidene fluoride/tetrafluoroethylene copolymer) layer ~ 10 μm in thickness.

FBGs were written by a 20-mW He–Ne laser ($\lambda = 632.8$ nm). The laser beam was focused onto the fibre surface by an $f = 30$ mm cylindrical lens. The dimensions of the elliptical beam spot in the focal plane of the lens were $L \times W \approx 1.5$ mm $\times 10$ μm (Fig. 1). Therefore, the power density in the spot was ~ 133 W cm^{-2}. The fibre was secured to the backside of a silica phase mask having rectangular grooves (50 % duty cycle). The groove depth was optimised so as to minimise the diffraction of the He–Ne laser beam into the zero order. The groove spacing was 1070 nm. The beam polarisation was parallel to the grooves, which was necessary for generating a high-contrast interference pattern. At normal incidence, three diffraction orders (0 and ± 1) emerged, with diffraction efficiencies of ~ 44 % (~ 9 mW) in the ± 1 orders and ~ 12 % (~ 2.45 mW) in the zero order.

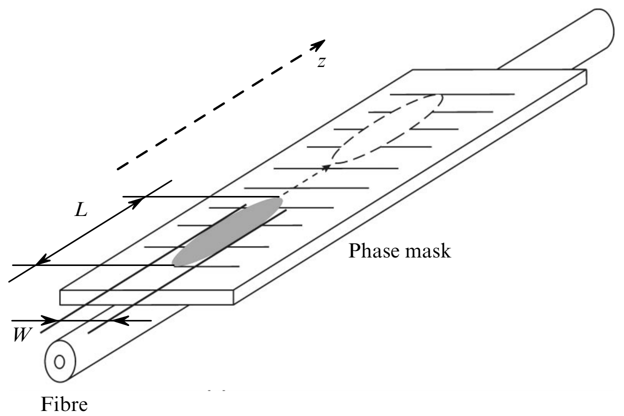

Figure 1. Schematic of Bragg grating inscription into chalcogenide fibre.

The writing beam was scanned over the immobile mask and fibre along the fibre axis at a rate of 11 μm s^{-1} using a linear translation system with a translation range of 20 mm. Under these conditions, the laser fluence delivered to the fibre core during FBG inscription was ~ 20 kJ cm^{-2}. The protective coating of the fibre was not removed because it was transparent at the He–Ne laser wavelength.

The spectral characteristics of the FBGs were measured using an all-fibre supercontinuum source. Its radiation was coupled into the fibre using a $20^{\times}$ objective. To couple out the excited cladding modes, the polymer coating was removed from a length of the fibre near its input end, and it was immersed in liquid gallium, which ensured the desired decay of the cladding modes [3]. The output end of the fibre was butt-coupled to an SMF-28 standard single-mode fibre connected to an ANDO-6317B optical spectrum analyser, whose spectral resolution in our measurements was 0.01 nm. With the described phase mask, the second-order FBG resonance wavelength was ~ 1290 nm.

3. Results and discussion

Figure 2 shows the transmission spectra of the FBGs measured during writing at several positions, z, of the translation system. Note that the length of the FBGs exceeded z by the length of the writing beam spot, $L \sim 1.5$ mm.

As seen, the displacement of the translation system (as the FBG length increases) leads to a monotonic increase in the reflectivity of the FBGs and a decrease in the spectral width of the resonance. The resonance wavelength ($\lambda_{BG} = 1290.6$ nm), determined by the average photoinduced index change, remains unchanged, as expected. Note that, during FBG inscription, no nonselective optical losses were detected in the transmission spectrum. At the same time, almost from the very beginning of exposure the spectrum of the FBG showed an additional peak shifted by 0.85 nm to shorter wavelengths relative to the fundamental mode resonance. Its intensity was found to increase with that of the fundamental resonance peak.

At $z = 20$ mm, we observed distortion of the transmission spectrum of the FBG (Fig. 2). Nevertheless, in spite of its marked nonuniformity, the reflectivity of the grating reached ~ 97 %. The full width at half maximum of the Bragg resonance was then ~ 0.14 nm. We think that the nonuniformity of the spectrum was primarily due to the mechanical instability of the writing system and can be eliminated.

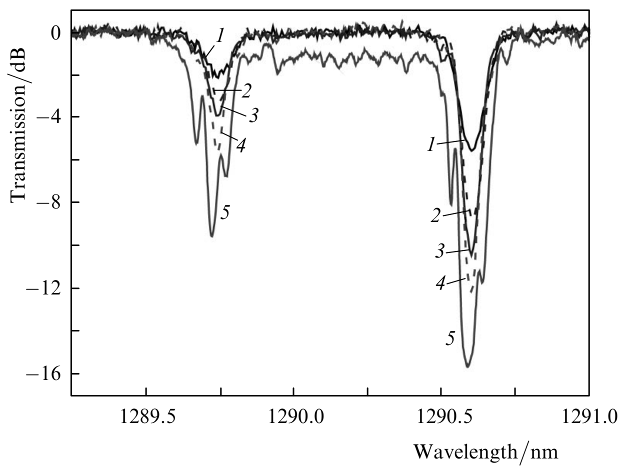

Figure 2. Transmission spectra of the FBGs measured during writing at several positions of the translation system: $z = 3$ (*1*), 4.5 (*2*), 6.5 (*3*), 8 (*4*) and 20 mm (*5*).

At FBG lengths under 10 mm, the measured transmission spectra were well represented by spectra calculated for a uniform grating. Figure 3 compares the measured and calculated transmission spectra of an FBG for $z = 3$ mm. The modulation amplitude of the photoinduced index change in the second diffraction order was $\sim 2 \times 10^{-4}$.

The agreement between the calculated and measured spectra is on the whole good, but the resonance in the measured spectrum is somewhat deeper at the centre wavelength. A similar deviation of experimental data from calculation results was observed for curves (*2–4*) in Fig. 2. Such a deviation appears, e.g., when the FBG

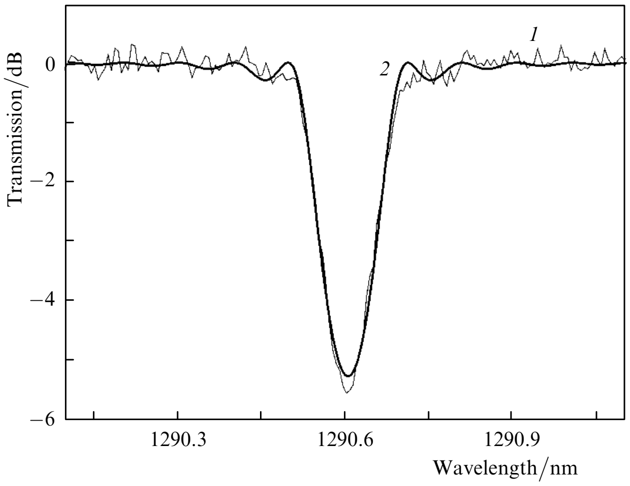

Figure 3. (*1*) Transmission spectrum of an FBG around its fundamental resonance for $z = 3$ mm; (*2*) theoretical fit.

spectrum having a relatively small polarisation splitting is measured with unpolarised light. Birefringence in Bragg gratings written in chalcogenide fibre may be both intrinsic, due to fibre fabrication process imperfections, and induced by the writing light [2, 16]. In our experiments, the birefringence value was $\sim 3 \times 10^{-5}$.

To find out the origin of the shorter wavelength resonance in the transmission spectra of the FBGs (Fig. 2), we measured the reflection spectrum of the FBG with $z = 20$ mm using an optical circulator. The spectrum showed two peaks, corresponding to the minima in the transmission spectrum (Fig. 4). This suggests that the shorter wavelength peak in the reflection spectrum is due to the excitation of the LP_{11} mode in the fibre core. The point is that, even at a small grating tilt angle or when the FBG lines are radially nonuniform, there may be significant coupling between the LP_{01} and LP_{11} modes [17]. It seems likely that it is the grating tilt which is responsible for the coupling between these modes, because the radial nonuniformity of the photoinduced index change should not be large as the absorption coefficient of the chalcogenide glass is relatively small at the He–Ne laser wavelength.

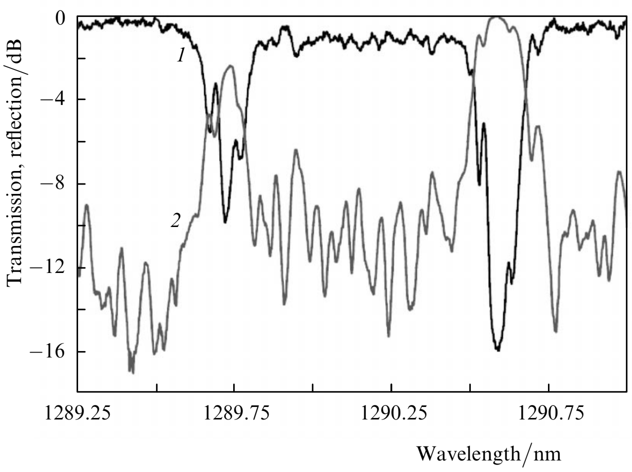

Figure 4. (*1*) Transmission and (*2*) reflection spectra of the FBG with $z = 20$ mm.

That the shorter wavelength reflection peak is due to coupling between the LP_{01} and LP_{11} modes is also evidenced by the good agreement between the calculated spectral shift, $\Delta\lambda$, of this peak relative to the fundamental FBG resonance (0.86 nm), which can be found in the case under consideration as $\Delta\lambda \approx \lambda_{BG} B\Delta/2$ (B is the longitudinal phase constant for the fundamental mode of the fibre [18]), and the experimentally determined shift (0.85 nm).

As mentioned above, the cladding of chalcogenide fibre is photosensitive, as is its core. For this reason, cladding modes are difficult to excite at FBGs in such fibre [19, 20]. Indeed, the transmission spectra of the FBGs in Fig. 2 show no resonances due to cladding mode excitation.

Experiments aimed at assessing the thermal stability of the photoinduced index change showed that annealing for 30 min at 75 °C had an insignificant effect on the spectral characteristics of the FBGs. At the same time, annealing at 100 °C for 30 min reduced the modulation amplitude of the photoinduced index change in the second diffraction order by 10 %.

4. Conclusions

We have proposed and implemented a new technique for FBG inscription into single-mode chalcogenide fibre by a He–Ne laser beam. The technique employs a geometry typical of FBG inscription into germanosilicate fibre, with the use of a phase mask that ensures effective diffraction of the writing light into the +1 and −1 orders. Because the photoinduced refractive index change in chalcogenide glasses is a nonlinear function of exposure dose, this technique enabled inscription of uniform second-order FBGs with a resonance wavelength in the near-IR spectral region. The inscribed FBGs offer a high reflectivity and small spectral width. Note that, because the chalcogenide fibre cladding is photosensitive, the transmission spectra of the FBGs contain no resonances due to cladding mode excitation. The proposed technique can be used to fabricate Bragg gratings in chalcogenide-glass planar optical waveguides.

References

1. Seddon A.B. *J. Non-Cryst. Solids*, **184**, 44 (1995).
2. Zakery A., Elliott S.R. *J. Non-Cryst. Solids*, **330**, 1 (2003).
3. Devyatykh G.G., Dianov E.M., Plotnichenko V.G., Pushkin A.A., Pyrkov Yu.N., Skripachev I.V., Snopatin G.E., Churbanov M.F., Shiryaev V.S. *Proc. SPIE Int. Soc. Opt. Eng.*, **4083**, 229 (2000).
4. Asobe M., Kanamori T., Kubodera K. *IEEE J. Quantum Electron.*, **29**, 2325 (1993).
5. Harbold J.M., Ilday F.Ö., Wise F.W., Sanghera J.S., Nguyen V.Q., Shaw L.B., Aggarwal I.D. *Opt. Lett.*, **27**, 119 (2002).
6. Nguyen H.C., Yeom D.-I., Mägi E.C., Kuhlmey B.T., de Sterke C.M., Eggleton B.J. *J. Opt. Soc. Am. B*, **25**, 1393 (2008).
7. Saliminia A., Villeneuve A., Galstian T.V., LaRochelle S., Richardson K. *J. Lightwave Technol.*, **17**, 837 (1999).
8. Asobe M., Ohara T. , Yokohama I., Kaino T. *Electron. Lett.*, **32**, 1611 (1996).
9. Brawley G.A., Ta'eed V.G., Bolger J.A., Sanghera J.S., Aggarwal I.D., Eggleton B.J. *Electron. Lett.*, **44**, 846 (2008).
10. Florea C., Sanghera J.S., Shaw B., Aggarwal I.D. *Opt. Mater.*, **31**, 942 (2009).
11. Hill K.O., Malo B., Bilodeau F., Johnson D.C., Albert J. *Appl. Phys. Lett.*, **62**, 1035 (1993).

12. Martinez A., Dubov M., Khrushchev I., Bennion I. *Electron. Lett.*, **40**, 1170 (2004).
13. Lai Y., Zhou K., Sugden K., Bennion I. *Opt. Express*, **15**, 18318 (2007).
14. Sun N.-H., Liau J.-J., Lin S.-C., Chiang J.-S., Liu W.-F. *Proc. IEEE Optoelectronics and Communication Conf.* (Hong Kong, 2009, WG6).
15. Dianov E.M., Plotnichenko V.G., Pyrkov Yu.N., Smol'nikov I.V., Koleskin S.A., Devyatyk G.G., Churbanov M.F., Snopatin G.E., Skripachev I.V., Shaposhnikov R.M. *Inorg. Mater.*, **39**, 627 (2003).
16. Tikhomirov V.K., Elliott S.R. *J. Phys.: Condens. Matter*, **7**, 1737 (1995).
17. Hill K.O., Meltz G. *J. Lightwave Technol.*, **15** (8), 1263 (1997).
18. Unger H.-G. *Planar Optical Waveguides and Fibres* (Oxford: Clarendon, 1977; Moscow: Mir, 1980).
19. Ishikawa S., Taru T., Inoue A., Shibata T., Murashima K., Tuchiya I. *SEI Tech. Rev.*, **55**, 8 (2003).
20. Nielsen M.L., Berendt M.O., Bjarklev A., Dyndgaard M.G. *Opt. Fiber Technol.*, **6**, 49 (2000).