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CO_2 laser-inscribed low-cost, shortest-period long-period fibre grating in B–Ge co-doped fibre for high-sensitivity strain measurement

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Abstract. We have developed high sensitivity long-period fibre gratings (LPGs) in B–Ge co-doped fibre for strain sensing application. These LPGs are shortest grating period (180 μm) LPGs inscribed in B–Ge co-doped fibre using CO_2 laser-based grating inscription set-up. Strain sensitivity of 1.77 dB/mε has been obtained for attenuation band corresponding to the turnaround point mode. TAP operation of LPG facilitates intensity-based detection using simple optical power meter instead of wavelength-based detection.

Keywords. Fibre-optic sensors; turnaround point-long-period fibre grating; strain.

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1. Introduction

Long-period fibre gratings have been widely investigated for sensing applications [1] due to their inherent sensitivity to environmental changes such as temperature, refractive index, strain, etc. Long-period fibre gratings (LPGs) are gratings formed within an optical fibre due to periodic modulation of core refractive index. The grating period is typically in the range 100–1000 μm.

It has been previously reported that higher-order mode resonances and operation near turnaround point (TAP) of LPG offer ultrahigh sensitivity [2]. However, such investigations were done using UV-induced index changes in the core of a single-mode photosensitive fibre. The UV-based gratings are known to have refractive index changes in time, causing a significant change in central wavelength of attenuation bands and coupling strengths. Therefore, we have used CO_2 laser-based grating inscription technique to inscribe TAP-LPGs. The technique is simple and amenable to all types of fibres. Theoretical simulation of phase matching curve for selected fibres helped in the initial prediction of grating period to obtain TAP within our source wavelength band (950–1700 nm).

Sensing mechanism of the grating depends on the wavelength shift due to the change of environmental parameters and requires bulky wavelength interrogation instruments. However, for field application, intensity-based detection is preferred for simple and compact devices. Earlier, several methods have been reported for converting the wavelength shift of LPG to intensity changes, such as FBG interrogated by LPG [3] and using a core mode blocker [4]. However, using additional components in such configuration increases the cost of the set-up and the sensitivity obtained is also less. In this paper, we present CO_2 laser inscribed, intensity-based, and highly sensitive method for strain measurement using a turnaround point (TAP-LPG) in B–Ge co-doped fibre. This is the shortest grating period LPG inscribed using CO_2 laser in B–Ge-doped fibre as per our knowledge. Since boron doping increases the attenuation near 1500 nm, it is necessary to design TAP-LPG near 1400 nm. This requires grating period lower than 190 μm which is difficult to achieve with grating writing techniques such as arc-induced modulation method. This LPG can also be used as a broad bandwidth optical filter with a bandwidth of ∼100 nm.

2. Principle and theory

LPGs couple light from fundamental core mode to different co-propagating cladding modes and the resonance loss wavelength λ_{res} is determined by the phase matching condition,

$$\lambda_{\mathrm{res}} = \left[n^{\mathrm{eff}}_{\mathrm{core}} - n^{\mathrm{eff}}_{\mathrm{clad},m}\right]\Lambda, \tag{1}$$

where Λ is the grating period and $n^{\mathrm{eff}}_{\mathrm{core}}$, $n^{\mathrm{eff}}_{\mathrm{clad},m}$ are effective indices of fundamental core mode and mth-order cladding mode respectively. The smallest transmission of the attenuation bands is governed by the expression

$$T_i = 1 - \sin^2(\kappa_i L), \tag{2}$$

where L is the length of the grating and κ_i is the coupling coefficient for the ith cladding mode, which is determined by the overlap integral of the core and cladding mode and by the amplitude of the periodic modulation of the mode propagation constants.

When an optical fibre is exposed to CO_2 laser pulses, the compressive stress induced in the fibre core during fibre manufacturing process is relaxed [5]. It has been reported earlier that boron co-doping in the fibre lowers the fictive temperature of the core substantially, and so local heating of the fibre by CO_2 laser radiation causes not only stress relaxation, but also glass structure changes in the core [6]. With a low laser irradiation power, index change occurs only in the core and the resultant index distribution is axially symmetric. In this condition, the laser irradiation produces a Gaussian-shaped index perturbation profile along the axial direction (z) of the optical fibre [7]. However, due to the single-sided exposure of the fibre with CO_2 laser, index change is asymmetric across the cladding area.

Shu *et al* have derived the sensitivity expressions [2] for LPG in which the general sensitivity factor γ defined by

$$\gamma = \frac{\mathrm{d}\lambda/\mathrm{d}\Lambda}{n^{\mathrm{eff}}_{\mathrm{core}} - n^{\mathrm{eff}}_{\mathrm{clad},m}} \tag{3}$$

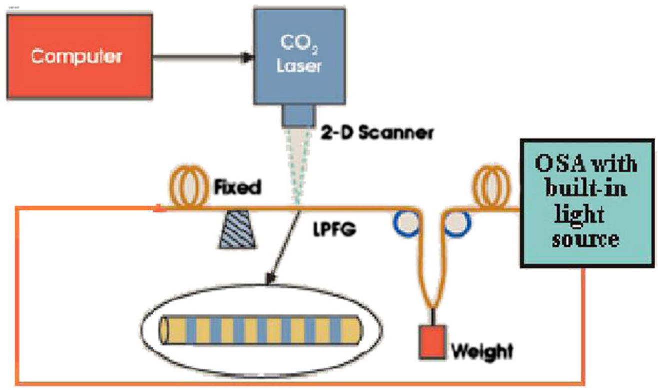

Figure 1. Schematic diagram of CO_2 laser-based LPG inscription system.

is the key factor for sensitivity determination of higher-order LPG resonances. LPG sensitivity is mainly determined by the γ factor which also describes the waveguide dispersion. For every cladding mode, $|d\lambda/d\Lambda| \rightarrow \infty$ at the turning point. Thus, from eq. (3) we find that $|\gamma| \rightarrow \infty$ and so the turning point operation of LPG determines the condition for maximum sensitivity. Fuel adulteration detection sensor based on TAP-LPGs has already been reported [8]. Here, we report TAP-LPG-based strain sensor.

3. Experiment and results

For the present work, standard photosensitive fibre (B–Ge co-doped photosensitive fibre, Fibrecore, UK) has been used. Figure 1 shows the schematic diagram of grating inscription set-up based on two-dimensional scanning of CO_2 laser beam. The sharply focussed

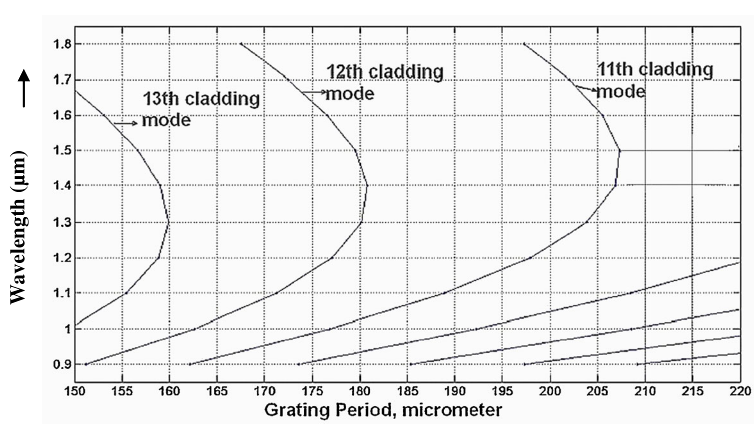

Figure 2. Phase matching curves (PMC) for core mode coupling to 11th, 12th and 13th cladding modes in B–Ge co-doped fibre (Fibrecore, UK).

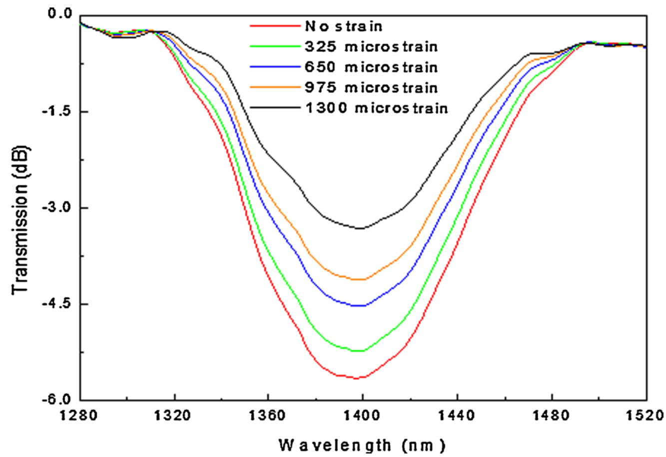

Figure 3. Transmission spectrum of the grating corresponding to TAP mode (12th) at different applied longitudinal strain.

CO_2 laser pulses are scanned across the fibre by means of a two-dimensional automated scanner and the transmitted LPG spectrum in the wavelength range 950–1700 nm is monitored online using an optical spectrum analyser (OSA model Agilent 86146B) with a wavelength resolution of 0.1 nm. The line speed of the scanning laser is 60 mm/s, pulse repetition rate is 2 kHz and the average output power is about 1 W. The scanning process is repeated until the LPG with sufficient strength is formed. Phase matching curves (PMC) for fundamental core mode and LP_{01} to LP_{013} cladding modes were calculated (figure 2) for B–Ge co-doped single-mode fibre using fibre parameters provided by the supplier in the standard brochure ($r_{cl} = 62.5$ μm, MFD at $\lambda_{op} = 6$ μm, numerical aperture = 0.13–0.14, cladding pure silica). Simulations showed that ∼180 μm grating period LPG

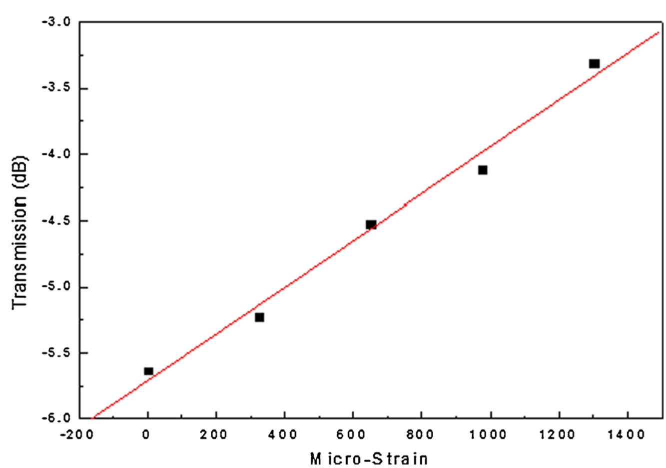

Figure 4. Decrease in transmission loss at 1400 nm with increase in longitudinal strain for strain in the range 0–1300 $\mu\varepsilon$.

operates at turn around point having broadband loss centred at 1400 nm. Accordingly, experimental set-up was used to inscribe an 180 μm grating period, 20 mm length LPG in B–Ge-doped fibre (Fibrecore, UK) to achieve TAP-LPG for the 12th-order cladding mode.

The insertion loss was <0.5 dB for this LPG. Figure 3 shows the changes in transmission spectrum of TAP-LPG when it was fixed over two translation stages and strain was applied gradually by pulling one of the stages. Figure 4 shows the linear fit of the values obtained for different strain applied to the LPG. Strain sensitivity of 1.77 dB/mε was obtained. These observations show that a TAP-LPG in B–Ge co-doped single-mode fibre can form an excellent intensity detection-based strain sensor without requiring any wavelength-based demodulation instrument.

4. Conclusion

We have designed highly sensitive intensity-based TAP-LPG strain sensor with 1.77 dB/mε sensitivity which is at least five times greater compared to the earlier reported values [4,9]. Intensity-based detection opens up new areas for simple, fibre-based and sensitive strain sensing devices. This LPG can also be used as broadband loss filter in the wavelength range 1300–1500 nm with strain tunable transmission.

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