

Manufacturing of Azimuthally Symmetric Uniform Long-Period Fibre Gratings with a CO_2 Laser

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Abstract— We present a method to manufacture symmetrically written uniform long-period fibre gratings (LPGs) in germanium-doped silica single-mode optical fibre. The manufacturing process is based on the point-by-point method using a pulse-width modulated carbon-dioxide (CO_2) laser to induce index modulation in the fibre core. A uniform LPG has been manufactured exhibiting a transmission loss of several dB for coupling to the fifth cladding mode.

Index Terms— Long-period fibre gratings, Point-by-point method, Pulse-width modulated CO_2 laser.

I. INTRODUCTION

LONG-period fibre gratings contribute a great deal to the optical communications industry with their guided-to-cladding mode power exchange. Due to low insertion loss, low back-reflection, and ease of fabrication of LPGs [1], transmission grating technology finds application in band rejection filters [2], dispersion compensation [3], fibre-optic sensing [4], [5], gain equalization of erbium-doped fibre amplifiers (EDFAs) [6], and add/drop multiplexing applications [7], [8].

Recently, it has been reported that the asymmetric refractive changes in optical fibre gratings induced by using the single-side beam exposure method [1], can result in birefringence and degradation of optical system performance. In this paper, we demonstrate a method to manufacture symmetrically-written long-period fibre gratings (LPGs) in optical fibre, where a pulse-width modulated carbon-dioxide laser is used to induce a symmetrical-written index modulation in the fibre core with the use of computer controlled equipment. Numerical results is provided to illustrate the uniform LPG characteristics.

The remainder of the paper is organized as follows. In Section II fibre grating theory is briefly discussed, and Section III discusses the LPG manufacturing process. Section IV provides the theoretical and experimental results obtained, and concluding remarks are given in Section V.

II. BACKGROUND

The refractive-index modulation of a fibre grating along the optical fibre propagation axis can be written as [9]:

$$n(z) = n_{eff} + \overline{\delta n_{eff}} \left\{ v \cos \left(\frac{2\pi}{\Lambda} z + \phi(z) \right) \right\} \quad (1)$$

where n_{eff} is the effective refractive-index of the fundamental LP_{01} core mode, Λ is the grating period, v is the fringe visibility, $\phi(z)$ denotes the grating chirp, and $\overline{\delta n_{eff}}$ is the induced index change spatially averaged over the fibre grating period.

A. Long-period gratings

The coupling of light from the fundamental core mode to different cladding modes in long-period transmission gratings can be described by the simplified coupled-mode equations given as follows [9]:

$$\frac{dA}{dz} = i\hat{\sigma}A(z) + i\kappa B(z) \quad (2)$$

$$\frac{dB}{dz} = -i\hat{\sigma}B(z) + i\kappa^*A(z)$$

The phase-matching condition for LPGs is defined as [9]:

$$\delta \equiv \frac{1}{2} \left(\beta_{core} - \beta_{clad}^{\mu} \right) - \frac{\pi}{\Lambda} \quad (3)$$

where β_{core} and β_{clad}^{μ} are the propagation constants for the LP_{01} core mode and μ th cladding mode respectively. δ is the detuning parameter, $\hat{\sigma}$ is the general "dc" self-coupling coefficient, and $\lambda_R \equiv (n_{core} - n_{clad}^{\mu})\Lambda$ is the resonant wavelength for coupling to the μ th ($LP_{0\mu}$) cladding mode.

III. MANUFACTURING PROCESS FOR LONG-PERIOD FIBRE GRATINGS

The exposure of germanium-doped silica fibres to a KrF excimer laser through an amplitude mask, is the most common technique used to fabricate long-period fibre gratings [1]. This method does not produce azimuthally symmetric long-period gratings, and results in a high polarization-dependent loss of the particular grating [10]. The manufacturing of LPGs requires special equipment to realize a UV-induced index change in the fibre core, and there are several methods that can be applied that includes CO_2 laser illumination [10], [11], electric-arc discharge [12], ion implantation [13], and by mechanical deformation [14].

Carbon-dioxide laser exposure of a fibre at $10.6 \mu m$ has been demonstrated to produce LPGs with polarization insensitivity, and with stable thermal and mechanical transmittance

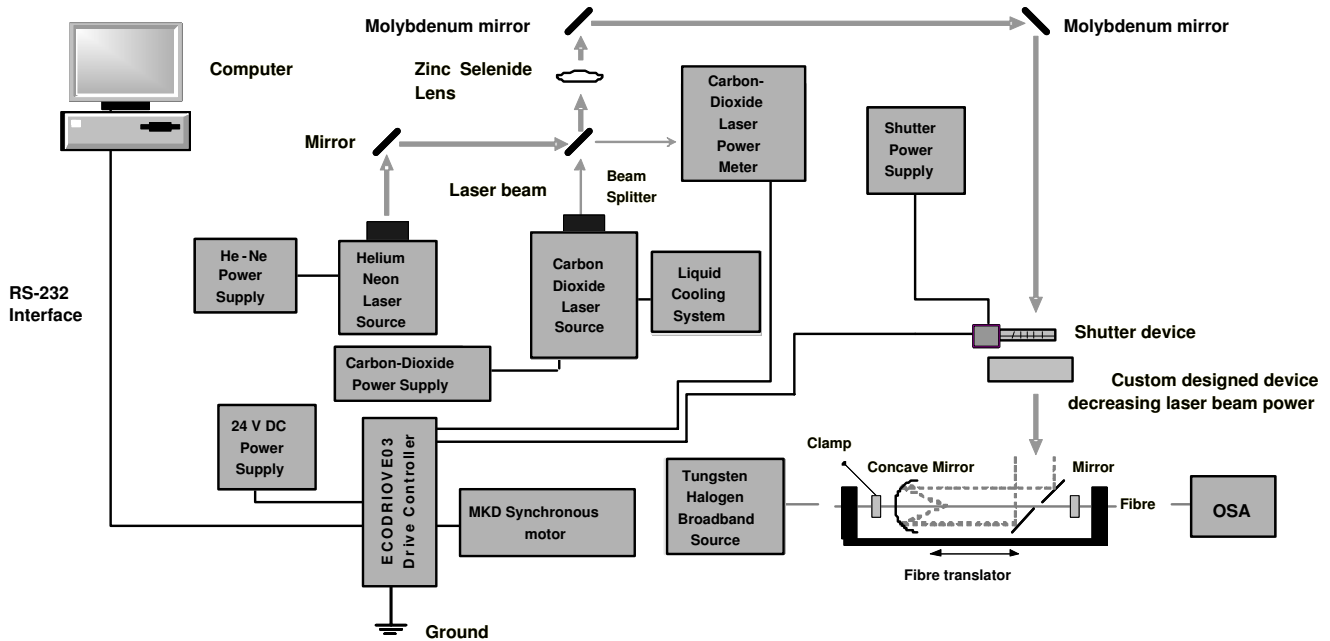


Fig. 1. Schematic configuration of the experimental setup for manufacturing azimuthally symmetric uniform long-period fibre gratings (LPGs).

properties [15]. When the fibre containing the CO_2 induced LPG was annealed at $1200^\circ C$, it was also shown that the spectral properties of the LPG remained unchanged [11].

In this paper, we will consider computer controlled manufacturing of uniform long-period gratings in germanium-doped silica optical fibre, using a pulse-width modulated 25 W CO_2 laser to produce azimuthally symmetrically-written fibre gratings, based on the point-by-point method [10].

Fig. 1 illustrates the experimental setup to manufacture the uniform long-period fibre gratings using the point-by-point method. A computer is connected via an RS-232 communications interface to a ECDRIVE03 drive controller, developed by the *Mannesmann Rexroth corporation* [16]. A computer program was written to control each device connected to this drive controller to perform the manufacturing process, and obtain the transmission spectra from the optical spectrum analyzer (OSA). An MKD synchronous motor, connected to the drive controller, is used to move the translation stage in the axial direction to predetermined positions. The movement is in synchronization with the shutter and the carbon-dioxide laser beam. The laser power meter is used to monitor the power levels of the CO_2 laser source when the LPGs are manufactured, since the power of the particular laser used fluctuated by more than 30% during grating fabrication. The Helium Neon (HeNe) laser source is used to illuminate the light path of the CO_2 laser beam, since carbon-dioxide laser beam exposure at $10.6 \mu m$ is invisible to the human eye.

A *Zinc Selenide* (ZnSe) convex lens (with focal length=130 mm) is used to change the beam waist of the CO_2 laser beam (with a diameter of approximately 3.5 mm) to fill the spherical mirror. The carbon-dioxide laser beam is deflected from three 50 mm diameter flat molybdenum mirrors

($< 1/40$ th wave) and a 50 mm concave spherical mirror (protected gold coated) with focal length of approximately 25 mm, whereby the CO_2 laser beam is then focussed on the the optical fibre with the required spot size. The last molybdenum planar mirror that deflects the laser beam, is tilted at a 45° angle, reflecting the laser beam to the concave spherical mirror. molybdenum's intrinsically hard surface makes it an ideal choice for dirty industrial applications (where frequent cleaning is necessary) and CO_2 laser applications.

The planar flat molybdenum and concave spherical mirrors have been modified in such a way that the fibre passes through it horizontally, and the fibre is supported by clamps. These last mentioned mirrors are mounted separate from the translation stage, and remains in one position the whole time during the grating manufacturing process. The only thing that moves along with the translation stage is the optical fibre. A custom-made device has been produced to attenuate the CO_2 laser power by removing a small circular inner area ($\approx 1.13 \times 10^{-4} m^2$) of the laser beam (having a 22 mm diameter at special device) illustrated in Fig. 1. This device reduced the laser beam power in such a way that the necessary index perturbation in the fibre core could be created.

IV. THEORETICAL RESULTS

The theoretical relationship between the the coupled wavelengths, and the LPG period Λ is used to obtain the specified LPG resonant wavelength. Fig. 2 indicates the variation of resonant wavelength with grating period for the coupling to different cladding modes. The parameters used to simulate Fig. 2 are similar to those of *PS1500 FiberCore* single-mode fibre, where $NA = 0.12$, core radius $a_1 = 4.1 \mu m$, and cladding radius $a_2 = 62.5 \mu m$.

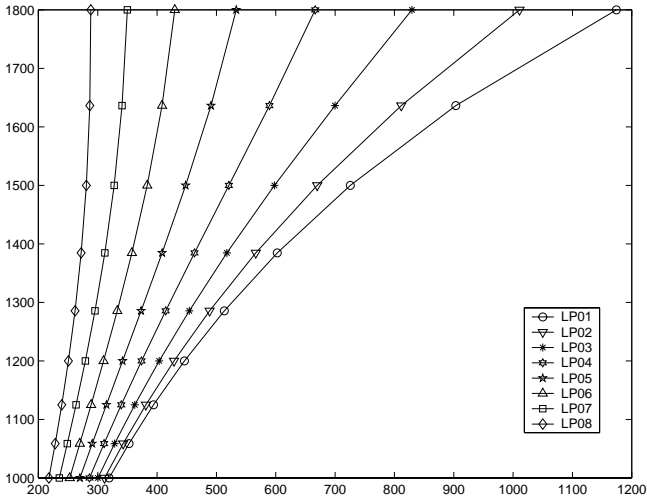


Fig. 2. Theoretical relationship between resonant wavelengths λ_R and grating period Λ in the case of core-to-cladding mode coupling.

To obtain the characteristics of LPGs, it is required to plot these curves for a specific optical fibre, since the properties of the core/cladding refractive indexes and core/cladding sizes, differ from fibre to fibre. Fig. 3 illustrates the theoretically obtained transmission spectra of an LPG of 25 mm length, induced index change $\Delta n_{eff} = 0.85 \times 10^{-3}$, simulated for coupling to the first few of the cladding modes using the transfer-matrix method [9]. The fibre parameters are the same as those used in Fig. 2.

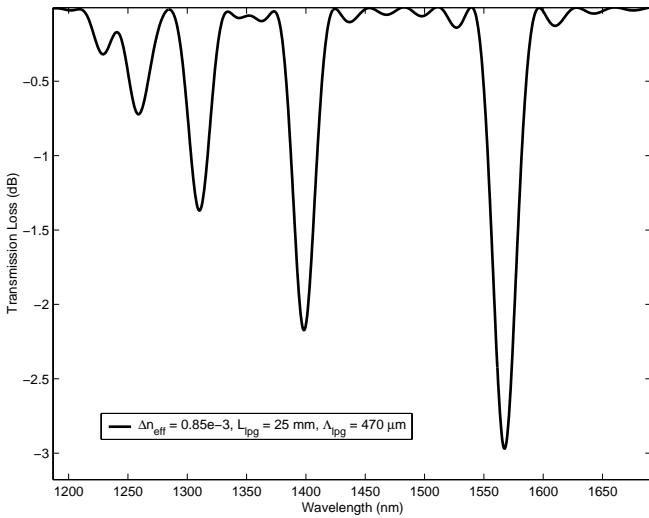


Fig. 3. Transmission spectrum of a uniform LPG for coupling to the first three odd cladding modes.

V. EXPERIMENTAL RESULTS

Fig. 4 show the transmission spectrum obtained after manufacturing a 25 mm uniform azimuthally symmetric long-period fibre grating in *PS1500 FiberCore* single-mode fibre having a period of 470 μm . The LPG was manufactured to exhibit a

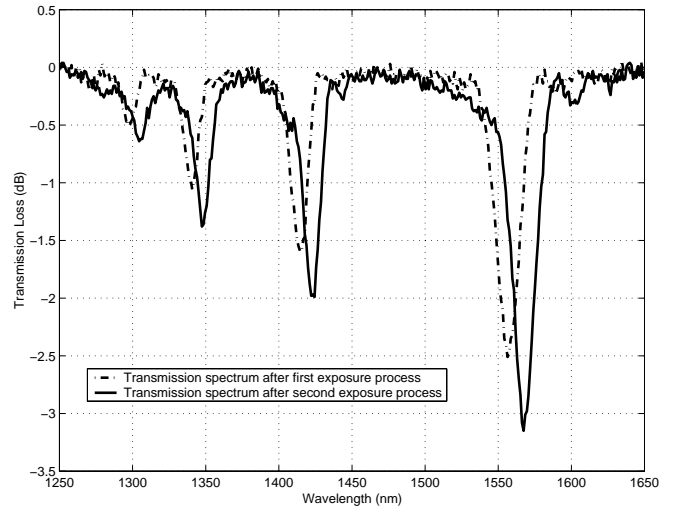


Fig. 4. Measured transmission spectrum of a uniform azimuthally symmetric long-period fibre grating.

3 dB transmission loss for coupling to the fifth cladding mode. A carbon dioxide laser ($\lambda = 10.6 \mu\text{m}$) was used to induce the refractive index change in the fibre core. The exposure time of the optical fibre was 130 ms at a CO_2 laser power calculated to be approximately 0.7 W (Note: This is the laser power after it propagated through the special device illustrated in Fig. 1). The CO_2 laser power before it travelled through the device depicted in Fig. 1 was 1.3 W.

A tungsten-halogen broadband source was used to measure the spectrum at the fibre output. From Fig. 4 the transmission loss is approximately -3.15 dB for coupling to the fifth cladding mode at $\lambda_R \approx 1567.40$ nm. The LPG transmission loss is small, indicating that core-mode-cladding-mode coupling is not strong (resulting in a low coupling coefficient κ). From the experimental results obtained, the transmission loss peaks correspond well with the theoretical results. There are only small differences, but the reason for this is that the theoretical results was simulated for a specific refractive index change, and this particular index change was not implemented when the uniform LPG was manufactured. This was because the refractive index change induced by the CO_2 laser source was not measured beforehand.

Knowledge regarding the exact refractive index change induced using a specific laser source when manufacturing fibre gratings is important to produce long-period gratings with special transfer functions. At present there are a few sensitive measurement techniques available to obtain information on small refractive index changes induced by IR light. It has been demonstrated that an in-fibre Mach-Zehnder interferometer incorporating a pair of long-period fibre gratings can be used to measure refractive index changes accurately in a optical fibre induced by a CO_2 laser [17].

VI. CONCLUSION

A method to manufacture symmetrically-written uniform LPGs based on the point-by-point method using a CO_2 laser source has been demonstrated, and successful experimental results were obtained from the uniform LPG manufactured. The LPG experimental results obtained from the manufacturing method used was satisfactory, and it shows great promise to develop future long-period gratings for several applications.

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