Long-period fiber grating sensors fabrication at high-frequency carbon dioxide laser pulses

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Abstract. In this work, long-period fiber grating sensors are written by using a point to point technique based on the thermal shock of focused high-frequency carbon dioxide laser pulses at several kilohertz. The thermal response of each long-period fiber grating was characterized by using a Peltier module based control system. The average sensitivity of the sensor was calculated to be ~ 0.079 nm°C. The used technique facilitates to obtain compact and sturdy long-period fiber gratings, with low insertion loss and low-level back reflection.

1. Introduction
Long-period fiber gratings (LPFGs) have been widely used in optical communication systems as gain equalizers [1], bandpass and band rejection filters [2,3] and add-drop multiplexers [4]. As an optical fiber sensors LPFG, have been used for measurement of refractive index [5], axial strain [6], structural bend [7], temperature [8], concentration [9], among others. The operating principle ofLPFG’s is based on the coupling-out of light from fundamental core mode into forward-propagation cladding modes through the inscription of a permanent periodic modulation of the effective refractive index on the optical fiber core. The minima in the transmission spectrum of an LPFG could be obtained from the resonance condition giving by Equation (1) [10].

\[
\lambda_{res}^m = (n(\lambda)_{eff,co} - n(\lambda)_{eff,cl}^m)\Lambda,
\]

where \(\lambda_{res}^m\) is the resonance wavelength, \(n(\lambda)_{core}\) is the effective refractive index of fundamental core mode, \(n(\lambda)_{cl}^m\) is the effective refractive index of mth cladding mode, and \(\Lambda\) is the grating period. In the above equation, the weakly guiding condition for the optical fiber is assumed. The sensitivity of LPFGs to changes in the external parameters has strongly dependent on \(\Lambda\), and the optical properties of fundamental core mode and the mth cladding. The wavelength shift due to variations of the temperature can be described using the Equation (2) [8].

\[
\frac{d\lambda_{res}}{dT} = \frac{d\lambda_{res}}{d(\delta_{eff})} \left( \frac{dn_{eff,co}}{dT} - \frac{dn_{eff,cl}^m}{dT} \right) + \Lambda \frac{d\lambda_{res}}{d\Lambda} \frac{1}{L} \frac{dL}{dT},
\]

where \(T\) is the temperature, \(L\) is the length of the LPFG, and \(\delta_{eff} = n_{eff,co} - n_{eff,cl}^m\).
Several techniques, including UV-laser irradiation [11], CO$_2$-laser irradiation [12], electric arc discharge [13], ultrashort pulsed lasers [14], mechanical deformation [15], and chemical etching [16] have been used to write LPFG in standard optical fibers. In this work, a technique based on the thermal shock of focused high frequency CO$_2$ laser pulses at several kilohertzios (kHz) for writing the LPFG into a standard optical fiber. The thermal shock effects of modulated irradiation increase the transient laser energy density focused on the fiber, causing larger densification, residual stress relief and larger refractive index change within both the cladding and core region of the optical fiber [12]. Compared to other techniques, those based on CO$_2$ are lower in costs, use standard telecommunication fibers and can stand high temperatures [17].

2. Methodology

Figure 1 shows a schematic illustration of the experimental set-up for LPFGs inscription. The beam of CO$_2$ laser (Iradion, infinity 155) was expanded and then focused on an uncoated single-mode fiber (SMF). SMF was fixed in a rotational stage (Thorlabs RP01) to ensure the perpendicularity with the laser beam. A motorized linear translation stage with a resolution of 125 nm (Zaber XL HME) was employed to move both the fiber and the rotation stage in the inscription process. A LabView based software system was used to control and synchronize the position and velocity of the linear stage and laser pulses.

Finally, a super-luminescent light-emitting diode (SLED, Exhalos XS210048-02, central wavelength 1550 nm, bandwidth 10 nm, optical power 10 mW) and an optical spectrum analyzer (OSA, Yokogawa AQ6370B) were employed for monitoring and recording in real-time the transmission spectrum of each LPFGs during the inscription process.

3. Results

LPFGs with a period of 646 nm, a total length of 52 mm, and a resonance wavelength near 1544 nm were written by setting the laser power at 11.7 W, a frequency of 3.0 kHz, a duty cycle of 50% and an irradiation time of 200 ms on each step. By using the experimental setup shown in Figure 2, this process was replicated several times over each fiber. According to Equation (1), these LPFGs are coupling light from the LP$_{01}$ mode of the core to the LP$_{05}$ mode of cladding. Figure 3 shows the transmission spectra for several LPFGs written under different values of tension. These variations of tension modify the values of tensile stress on the fibers, leading to small shifts in the resonance wavelength associated with small changes in the residual stress.
The thermal characterization of LPFGs was conducted by using the experimental setup illustrated in Figure 4. In addition to the SLED and OSA of the experimental setup for writing the LPFGs, a Peltier module (25 mm x 25 mm, 12V-4A), a current source (Uni-t UTP 3305), and a thermocouple (K-type) were added for monitoring and controlling the variations of temperature. Characterization was carried out 3 times for testing the repeatability and sensitivity of the device.

Figure 5 shows the transmission spectra of the LPFGs at different temperatures. Further, in order to avoid errors caused by the fluctuations in the optical power of SLED, the minimum in each transmission spectrum was estimated by applying a second-order polynomial fit in the region around the resonance wavelength. Then, the mean values of obtained wavelength shifts were plotted and fitted with an $R^2$ value of 0.97, as shown in Figure 6. Moreover, a sensitivity of 0.079 nm/°C was calculated from the slope of the fit curve.
4. Conclusion
In conclusion, the point by point inscription of LPFGs using a high power CO$_2$ laser at several kHz is a technique that has proved to be easier and with a lower cost to implement when is compared to ultraviolet laser, femtosecond lasers or electric arc discharge. The response of LPFGs to temperature changes was characterized by a simple setup based on a Peltier module. Shifts in wavelength resonance were fitted by using a linear model obtaining a sensitivity of 0.079 nm/$^\circ$C and an R-squared value of 0.97. The fabricated LPFG temperature sensors have shown great sensitivity, stability, and reproducibility.

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