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Influence of period on surrounding refractive index sensitivity of arc-induced Long Period Gratings

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Abstract

In this work, we present the assessment of our electric arc-discharge based technique in order to fabricate optical fiber Long Period Gratings (LPGs) with desired spectral features and period ranging in 410-470 μm, able to excite high order cladding modes useful in chemical sensing applications. Here, a wide experimental investigation was carried out with the aim to study the sensitivity to surrounding refractive index (SRI) changes of several LPGs as function of the grating period, in order to derive a project criterion to improve the SRI sensitivity. Moreover, in order to evaluate the goodness of the experimental results, we compare the experimental results with numerical ones based on coupled-mode theory achieving very good agreement.

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Keywords: long period gratings; arc discharge technique; sensors fabrication; refractive index sensors; chemical sensors; numerical simulations.

1. Introduction

Long Period Gratings (LPGs) are in-fiber devices that were first introduced for application in optical communication systems [1]. In parallel, they started to gain popularity for their sensitivity to strain and temperature induced effects, as well as for the possibility to develop chemical sensors by exploiting their intrinsic sensitivity to the material surrounding the cladding in the grating region [2,3]. They act by coupling the light of the fundamental core propagation mode LP_{01} to discrete forward propagating cladding modes LP_{0m}, resulting in several attenuation bands in the fiber transmission spectrum, centered at specific wavelengths and whose position is influenced by the aforementioned effects [1-3].

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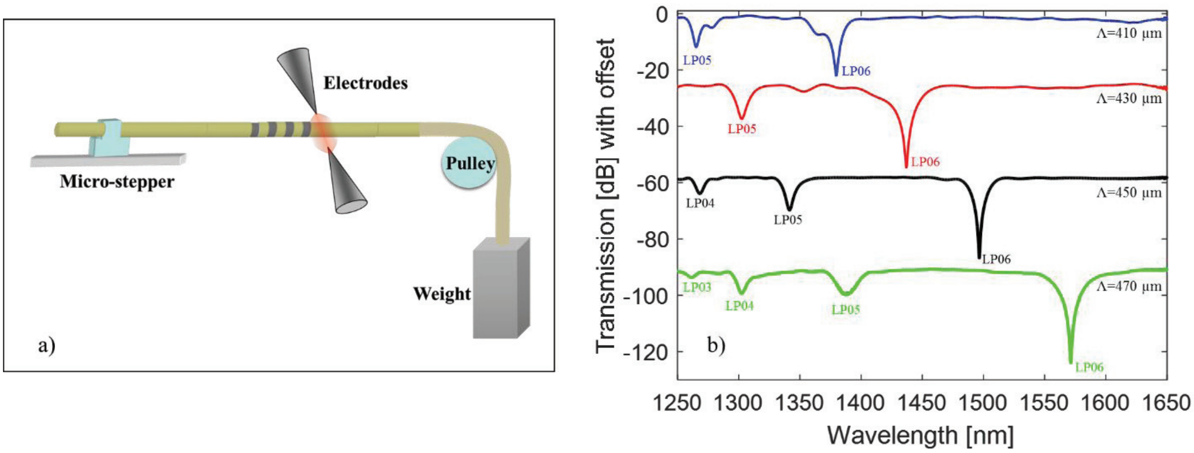

Fig. 1. a) Schematic diagram of LPGs fabrication setup; b) Transmission spectra of LPGs with different period Λ=410, 430, 450, and 470 μm.

Long Period Gratings are fabricated by inducing a period perturbation in the refractive index and/or in the geometry of the optical fiber. Among the different available techniques, the Electric Arc Discharge (EAD) has experienced wide diffusion during the last years since it is a straight, flexible and convenient procedure, which in principle could allow the fabrication in all kind of optical fibers [4-7]. During the procedure, the optical fiber is placed between two electrodes, with one end blocked on the top of a precision translation stage, and the other end kept under constant axial tension. To produce the LPG, a short portion of fiber length is hit by the arc discharge, after that the fiber is moved through the translation stage and the procedure is repeated again until the desired features are reached. The main challenge of the EAD technique is the fabrication of gratings with low period Λ. In 2011, Smietana *et al.* [8] reported on the fabrication of a LPG in standard SMF28 fiber with a period of 345 μm, whereas more recently they demonstrated that LPGs with period lower than 200 μm could be realized only in boron co-doped fibers (being more sensitive to the arc effect than the standard fiber) and with a grating length greater than 50 mm. During last year, the research group of Rego [9] also investigated the realization of LPGs with period lower than 200 μm in SMF28 fiber, but with results still not satisfactory: in fact, a weak grating was obtained even after 400 discharges, with a final length greater than 78 mm.

In this work, we first report on the assessment of our EAD based system for the fabrication of LPGs with low period in standard fiber. The optimization of the fabrication parameters lead us to the inscription of gratings with good optical quality (e.g. trivial power losses, deep attenuation bands, total length of 20-30 mm) and with a full control of the period. Then we investigated the effect of the period on the surrounding refractive index (SRI) sensitivity of high order cladding modes, in order to derive a project criterion. To support both the phases of fabrication and characterization, a numerical model for the simulation of LPGs was also developed, achieving a very good agreement with experimental results.

2. Fabrication of Long Period Gratings by Electric Arc Discharge technique

A schematic diagram of our EAD-based technique is reported in Fig. 1a [5], where the arc discharges are provided by a commercial fusion splicer machine (model Sumitomo Type-39), modified to allow the full control of the discharge parameters, and operating in the open hood mode, in order to improve the fiber alignment between the electrodes. The proper selection of arc power, arc duration, fiber tension, and electrodes relative position make it possible the control of the core and cladding effective refractive indexes modulation and thus the selection of LPG spectral features. Typical values for the procedure parameters are: the arc power in range of 1-15 step (i.e. proprietary unit from Sumitomo) and its duration from of 200 to 1000 ms. The displacement of the fiber is done by means of a micro-stepper, with resolution better than 1 μm. In all the presented experiments, a constant force was applied to the fiber by using a weight of 12 g and a high precision pulley. The grating transmission spectra were recorded with optical

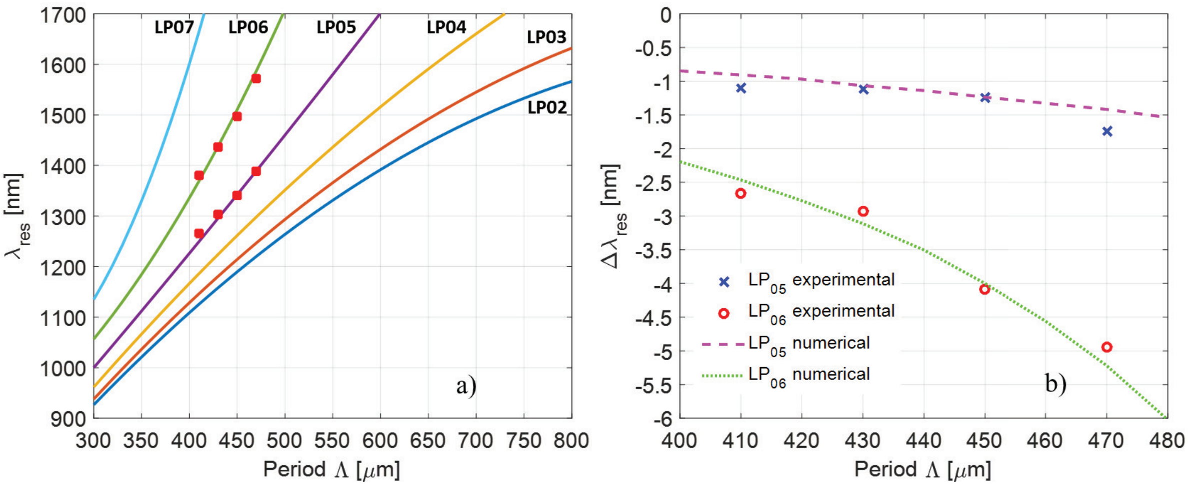

Fig. 2. a) Resonance wavelength values versus grating period: numerical results are reported as solid lines and experimental values as red dots; b) Wavelength shift of LP_{05} and LP_{06} bands towards period, in the SRI range 1-1.33 (air-water).

spectrum analyzer (OSA) model Yokogawa AQ6370B, set to a resolution of 0.1 nm, while the illumination was provided by a broadband source (SLED in range 1250-1650 nm).

For the purpose of this work, several LPGs were written in standard Ge-doped SMF28e supplied by OZ Optics Ltd, by using the arc power of 12 step and duration of 600 ms. Grating period Λ was selected from 410 to 470 μm (with a step of 20 μm), in order to have LP_{05} and LP_{06} attenuation bands always visible in the wavelength range of 1250-1650 nm, as illustrated in Fig. 1b. In particular, for the period of 410 μm the resonant band LP_{05} is positioned at 1265.1 nm and LP_{06} at 1379.6 nm, for 430 μm LP_{05} is visible at 1302.6 nm and LP_{06} at 1437.1 nm, for 450 μm LP_{05} is at 1341.5 nm and LP_{06} at 1496.6 nm, finally for 470 μm LP_{05} is positioned at 1387.6 nm and LP_{06} is at 1571.4 nm. According to theory, attenuation bands exhibit red shifts with period increasing, justifying the necessity of smaller periods in order to excite higher order cladding modes [1-3].

A numerical model for the simulation of LPGs was also developed, following the coupled-mode theory (CMT) based approach proposed by Anemogiannis *et al.* [10] and further investigated by Del Villar *et al.* [11], in order to validate the experimental results. The model fitting parameters for our EAD based technique were identified, and the outcomes are illustrated in the dispersion plot of Fig. 2a, reporting: i) as red dots the experimental values for the resonance wavelengths (LP_{05} and LP_{06}) concerning the gratings under investigation; ii) the numerical values (as solid lines) for different attenuation bands (LP_{02}-LP_{07}) over a wider period range (Λ=300-800 μm). As it is possible to see, there is a good agreement between experimental and numerical values confirming the repeatability performance of our procedure.

3. Sensitivity to Surrounding Refractive Index and period influence

The SRI sensitivity is one of the most appealing feature of LPGs, exploited to develop chemical sensors. Such response arises from the dependence of the phase matching condition, upon the effective refractive index of the cladding modes, which in turn depends on the external medium refractive index [3].

On this line of argument, after the fabrication we investigated the sensitivity of LPGs reported in Fig.1b to surrounding refractive index changes, by placing them in liquids with refractive indexes in range 1.33-1.44. In order to focus the attention on the influence of grating period on the SRI sensitivity, we have reported in Fig. 2b the wavelength shifts of LP_{05} and LP_{06} bands towards the grating period, due to a change in SRI from air to water (1-1.33). Starting from basic things, according to theoretical behavior [2,3] the attenuation bands exhibit a blue shift with SRI increasing, with the magnitude of shift increasing with the order of the cladding mode. The same stands for the sensitivity, as it can be seen from values reported in Table1. Numerical simulations are also reported (as lines) in order to validate experimental results and confirming the good agreement between the two results, concerning the SRI sensitivity too.

Moreover, another important information that can be highlighted from Fig. 2b is that shift and sensitivity also increase with grating period Λ, following a sublinear behavior. For example, it can be seen that sensitivity almost doubles passing from a period of 410 μm to a period of 470 μm. Hence, from another point of view, this means that in the project of LPG after that a period is selected in order to excite a certain cladding mode, the SRI sensitivity can be further improved by tuning the period value according to the presented analysis.

Table 1. LPGs sensitivity in SRI range 1-1.33 (air-water).

Period Λ [μm]	LP_{05} [nm/RIU]	LP_{06} [nm/RIU]
410	-3.3	-8.0
430	-3.4	-8.8
450	-3.7	-12.2
470	-5.2	-14.8

4. Conclusions

In this work, we have first presented the assessment of our electric arc-discharge based technique for the fabrication of LPGs with low period in standard fiber. The optimization of the fabrication parameters lead us to the inscription of gratings with good optical quality (e.g. trivial power losses, deep attenuation bands, total length of 20-30 mm) and with a full control of the period. Several LPGs were written in standard SMF28e fiber, with grating period Λ from 410 to 470 μm, a wide experimental investigation was carried out with the aim to study the sensitivity to SRI changes as function of the grating period, and a project criterion was given in order to improve such sensitivity. Furthermore, a numerical model for the simulation of LPGs was developed, to support both the phases of fabrication and characterization, achieving a very good agreement with experimental results.

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