REFRACTIVE INDEX SENSITIVITY IN THINNED UV AND ARC INDUCED LONG-PERIOD GRATINGS: A COMPARATIVE STUDY

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ABSTRACT: In this work, a comparative study aimed to investigate the effects of cladding stripping on the external refractive index sensitivity in tapered and UV long period gratings is presented. Here, wet chemical etching combined with microscopic analysis allow us to identify the experimental dependence of the surrounding refractive index (SRI) sensitivity on the cladding radius for both grating types. The experimental results reveal that although in both cases a sensitivity enhancement is achieved by reducing the cladding thickness, the tapered devices offer substantially a greater sensitivity gain in respect to UV written devices.

INDEX TERMS: Long period gratings, fiber optic sensors, gratings fabrication, chemical etching of gratings.

I. INTRODUCTION.

In the last years, long period gratings (LPGs) have established themselves as versatile and effective sensor element for a range of measurements such as strain, bending measurements and chemical applications [1-3]. Comprehensive background papers focused on the creation, uses and applications of LPGs have been published [4-5]. Standard LPGs are UV based photo-induced devices which couple light from core mode to various cladding modes of single mode fiber, creating as a result, a series of attenuation bands in the fiber transmission at discrete wavelengths. The sensor principle relies with changes in the attenuation bands due to variations in the external environments, in terms of temperature, strain and surrounding refractive index. Recently, also complex structures involving cascaded and coated LPGs have been efficiently applied to enhance the sensitivity characteristics of this class of devices [6-7].

In addition, the effect of uniform fiber thinning on the spectral characteristics of UV written LPGs has been investigated. First, LPG thinning was proposed as post-fabrication resonant peak positioning mechanism in LPG spectra [8-10]. The variation of the fiber radius changes, in fact, the distribution of the field related to cladding modes and thus induces large shifts in the attenuation bands.

On the other hand, the variations in the cladding modes field distribution due to the fiber etching strongly affect the sensitivity of LPGs to SRI [11-12]. In particular, as the fiber diameter decreases the optical power related to cladding modes evanescent wave significantly grows up in the external medium. As matter of fact an enhancement of SRI sensitivity is expected as well as the fiber radius is reduced. This effect was investigated for UV written standard and D-fiber LPGs [11-13].

LPG fabrication method based on UV radiation is the most common approach for grating fabrication and thus most of the results reported in literature are referred to this type of fabrication. However, although UV-based grating fabrication is well established, it presents some shortcomings. It, in fact, requires complex and time-consuming processes, including photo-sensitization, UV fringe-pattern exposure, and different amplitude masks for different dimensions of the LPGs, and the masks needing replacement after prolonged usage. Also, UV technique needs expensive laser equipment. Recently, several non-UV methods for LPGs fabrication have been proposed. They involve periodic physical deformation of the fiber by the use of a CO_2 laser [14] or electric arcs [15]. LPGs written by periodical local heating of the fiber by electric arc discharges and by applying lateral stress on a standard fiber provides good performances as well as high thermal stability [15]. The electrical arc technique is much simpler and does not need expensive laser equipment. Moreover, it allows writing gratings on photonic crystal fibers [16]. Due to the increasing use of this technique to produce low-cost and reliable LPGs, here we focus our attention on their SRI sensitivity characteristics and how they are influenced by the fiber radius. To this aim, proper designed arc-discharge equipment was used to fabricate tapered LPGs with different periods. Wet chemical etching in hydrofluoric acid solution was selected as low cost procedure to reduce the fiber diameter. The fabricated devices were then tested to retrieve the dependence of the SRI sensitivity characteristics on the fiber radius and the obtained results have been compared with those obtained in the case of UV written devices. The obtained results allow us to identify accurately the dependence of the sensitivity characteristics on the fiber radius taking into account the SRI range, the order mode and the grating fabrication method.

II. UV and tapered Lpgs Characteristics

As well known, an LPG achieved by UV radiation combined with a proper amplitude mask consists in refractive index modulation of the core fiber, with typical modulation depth of 10^{-4}, period between 100μm – 500μm and length of 2-4 cm. In such device, the core index modulation is responsible of light coupling from the propagating core mode to co-propagating cladding modes. Because the cladding modes suffer from high attenuation, the transmission spectrum consists of a series of attenuation bands centred at resonant wavelengths depending on the effective index of the coupled modes and the grating pitch. The phase matching between the core mode and the ith forward–propagating cladding mode is achieved at resonant wavelengths given by [17]:

$$\lambda_{res} = \left(n_{eff\_co} - n^{i}_{eff\_cl}\right)\Lambda \qquad (1)$$

where λ_{res} is the resonance wavelength, and n_{eff_co} and $n^{i}_{eff\_cl}$ are, respectively, the effective refractive index of the core mode and of the i^{th} order cladding mode, while Λ is the grating period. It is worth noting that a better accurate formulation taking into account the modal self-coupling coefficients have been demonstrated [18], if compared with eq. (1). However in this paper the simplicity of the formula (1) was preferred.

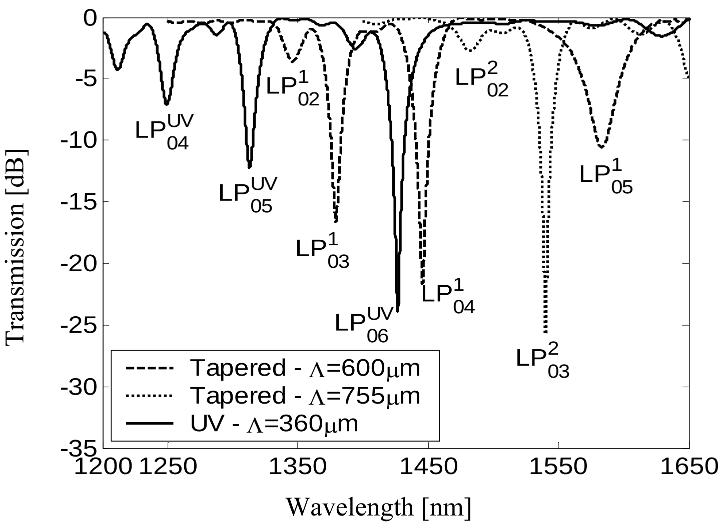

Fig. 1. Transmitted spectra of the investigated gratings.

The effective refractive indices of the cladding modes are strongly dependent on the refractive index of the surrounding environment. This means that the ith cladding mode resonant wavelength will change as the refractive index of the surrounding environment change.

The solid line in fig. 1 plot the transmitted spectrum of commercial UV-LPG written in Corning SMF-28 fiber with pitch of 360 μm and air as surrounding medium selected for our experiments. In the wavelength range 1200-1650nm, it exhibits several attenuation bands related to low order cladding modes coupling well identified in the same figure. In particular the numeric subscript identifies the cladding mode order whereas the UV apex identifies the UV-based grating. The optoelectronic set-up, involved for spectral measurements and further experiments (SRI characterization and etching monitoring), comprises two superluminescent diodes centered to 1310nm and 1550nm coupled in the same fiber by a 2x1 coupler and an optical spectrum analyzer for spectral measurements.

In addition, the tapered LPGs for our experiments were manufactured also from Single-mode Corning SMF-28 optical fibers, using a computer-assisted precision arc-discharge apparatus [19]. The method is based on periodic melting of the fiber, while a pulling weight stretches it, thus determining a periodically tapered fiber. The grating period was mainly determined by the moving step of the translation stage that was controlled by a computer and by some other factors such as arc intensity, arc duration time (τ), and pulling weight. A schematic diagram of the fabrication setup is plotted in fig. 2.a.

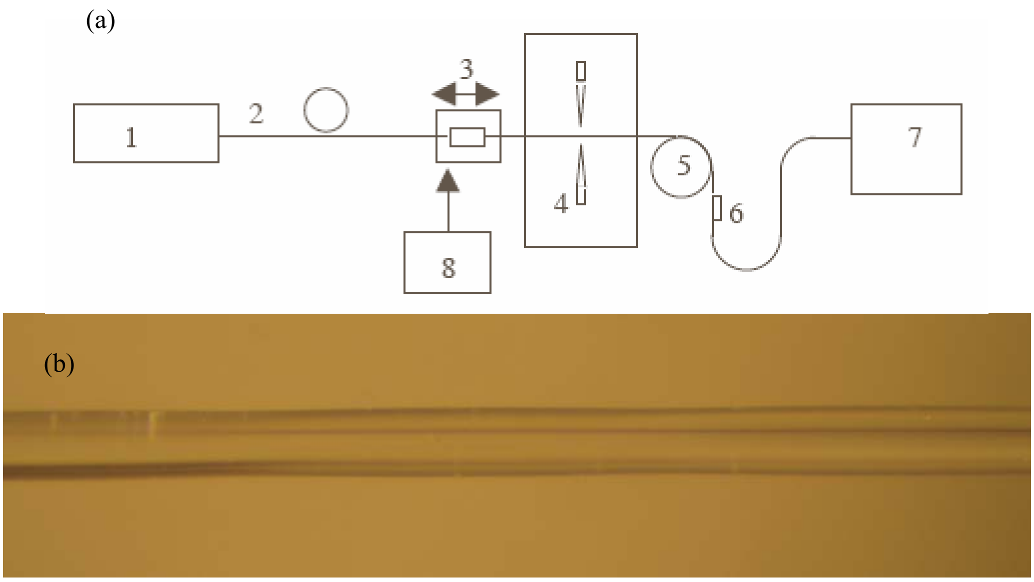

Fig. 2. (a) Computer-assisted arc-discharge apparatus for manufacturing of taperd LPG: 1 – broadband light source, 2 – Corning SMF-28 optical fiber, 3 – motorized translation stage, 4 – arc-generating electrodes, 5 – pulley, 6 – weight, 7 – optical spectrum analyzer (OSA), 8 – computer; (b) microscope image of the investigated tapered LPG with Λ=600 μm.

Fig. 2.b shows an optical microscope image of a tapered grating with period of 600 μm where it was possible to estimate a fiber cross section reduction in the taper waist of about 6%. It is worth noting that in such device it is reasonable to assume that the total fiber diameter and the core diameter stay in the same ratio along the taper [20]. In such structure, the periodic perturbation induced by arc-discharge operation forces the mode coupling between the core mode and the bounded cladding modes, where the phase matching condition between the core and the i^{th} cladding mode, expressed by eq. (1), is still valid. However, in tapered LPGs, three main reasons explaining the mode coupling can be proposed: the fiber (core and cladding) diameter change (periodical tapering), the dopant diffusion, and a change of the glass properties by the fast local heating–cooling process [15]. Between them, the dopant diffusion plays a minor role in grating formation as discussed in [15]. However, studies to identify the predominant effect are currently in progress [20].

The transmitted spectra for two 2-cm long tapered LPGs with periods of Λ=600μm and Λ=755μm, respectively, are also plotted in fig. 1 (dashed and dotted lines, respectively). It can be seen that each spectrum exhibits several attenuation bands in the wavelength range 1200 to 1650 nm. Each of them is related to low order cladding modes coupling also identified in the figure: here the 1 and 2 apexes identify the LPG with 600μm and 755μm pitch, respectively.

In both grating structure types, the effective refractive indices of the cladding modes are strongly dependent on the refractive index of the surrounding environment through the evanescent wave interaction. Also, the cladding mode distribution is dependent on the geometrical features of the fiber. This means that the fiber cladding reduction induces modifications in the distribution of the cladding modes leading to changes in the spectral characteristics. This principle has been successful used as post-fabrication tuning mechanism in standard UV-induced LPG [8-9]. At the same time, sensitivity enhancement towards the external medium refractive index is expected in light of the improved evanescent wave interaction with the external medium due to fiber cladding reduction [12].

It is worth noting that the optical field of the core mode is dominantly confined in the core region and decays quickly in the cladding. This means that residual cladding radius is not able to affect the core mode propagation in the investigated range as demonstrated in Ref. [21].

Here, we, for the first time to our best knowledge, present a comparative analysis of the sensitivity enhancements due to fiber cladding reduction in UV and tapered LPG. To this aim, in the following analysis we focus the attentions on the attenuation bands related to LP_{04} and LP_{05} cladding modes with regards the UV-induced LPG, here labelled as LP^{UV}_{04} and LP^{UV}_{05}

(see fig. 1), and on the attenuation bands related to LP_{03} and LP_{04} cladding modes with regards the tapered LPG with Λ=600µm, LP^1_{03} and LP^1_{04}, and on the attenuation band related to LP_{03} cladding mode with regards the tapered LPG with Λ=755µm, LP^2_{03}.

Before cladding removal, UV and tapered gratings have been characterized in terms of SRI sensitivity in the original state. To this aim, proper gratings packages were request, since LPGs are strongly sensitive to environmental features such strain and bending. In particular, a proper holder, able to fix the LPGs without changing its tensional state and ensuring bending and strain free operation, was designed and realized to be used during the SRI testing and etching steps. A schematic diagram of the holder is reported in fig. 3. It consists in two Teflon supports which, once closed, form a test chamber, 4.0 mm long and with a 10ml volume. The fiber with the LPG under testing is thus arranged on a proper designed V-groove and fixed as the two Teflon part are closed. Two pipes on the lateral side of the holder allow the insertion of the HF acid for the etching process and pure water for washing the holder and the LPG.

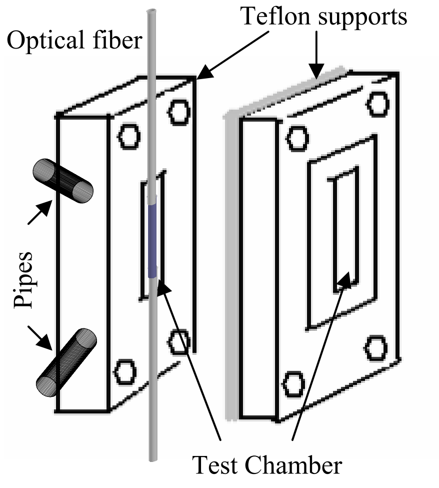

Fig. 3 Teflon holder for the etching process and for SRI testing.

Fig. 4 plots the wavelength shift (referred to air as external medium) versus the SRI for the LP^{UV}_{04}, LP^{UV}_{05}, LP^1_{03}, LP^1_{04}, and LP^2_{03} attenuation bands. To this aim, as in previous works [7,12,21], aqueous glycerine solutions at different concentrations were used to produce reference liquids with refractive index varying in the range 1.33-1.45. A commercial Abbe refractometer with a resolution of 10^{-4} was used as reference for liquid refractive index measurements. As evident, all the attenuation bands exhibit a blue-shift as the SRI grows up whereas the sensitivity increases for higher order cladding modes and SRI approaching the cladding refractive index value. The total blue-shifts (as SRI changes from 1 to 1.445) for

LP^{UV}_{04}, LP^{UV}_{05}, LP^{1}_{03}, LP^{1}_{04}, and LP^{2}_{03} have been estimated to be 1.44, 4.34, 1.87, 5.33 and 3.78 nm, respectively. It is worth noting that the wavelength shift ratio of LP^{2}_{03} and LP^{1}_{03} is 2.02 whereas the ratio of the gratings periods is 1.26. This means that for a fixed cladding mode, the grating period is not the unique parameter responsible for the SRI sensitivity enhancement; in fact the waveguide wavelength dispersion plays a fundamental role in the grating sensitivity [17]. A similar comparison can be conducted between LP^{1}_{04} and LP^{UV}_{04}. Here the wavelength shift ratio was estimated to be 3.70 vs grating period ratio of 1.67. On the other side, the total blue-shift of LP^{1}_{04} is greater than the LP^{UV}_{05} one.

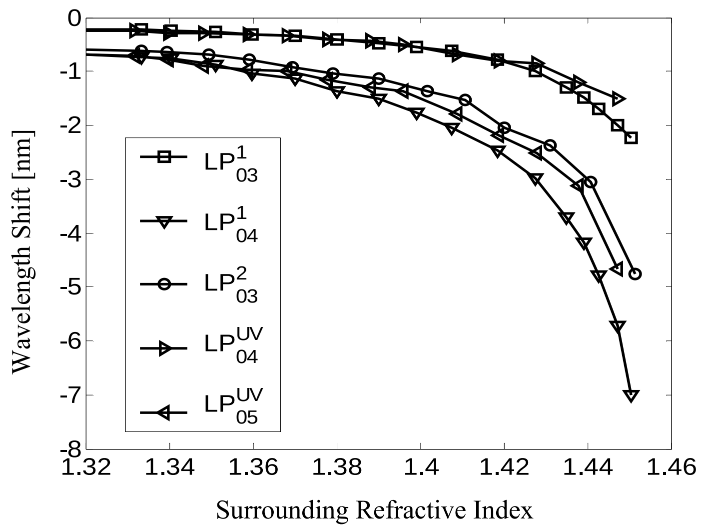

Fig. 4. Resonant wavelength shifts versus SRI of the LP^{UV}_{04}, LP^{UV}_{05}, LP^{1}_{03}, LP^{1}_{04} and LP^{1}_{03} cladding modes.

III. FIBER CLADDING LAYER ETCHING

The cladding removal was implemented by a low-cost approach based on wet chemical etching in 12% hydrofluoric (HF) acid solution [21]. The relatively low HF concentration was selected in order to achieve a slow etching rate leading to a fine control of the residual fiber diameter. In our experiments, an etching rate of approximately 20μm/min was estimated for UV and tapered LPGs at room temperature.

To characterize the sensitivity dependence on the fiber diameter, for each grating the etching process was implemented in several steps. After each step, the residual fiber diameter was estimated by optical microscope images +/- 2 μm and successively the spectral response to several SRI was explored.

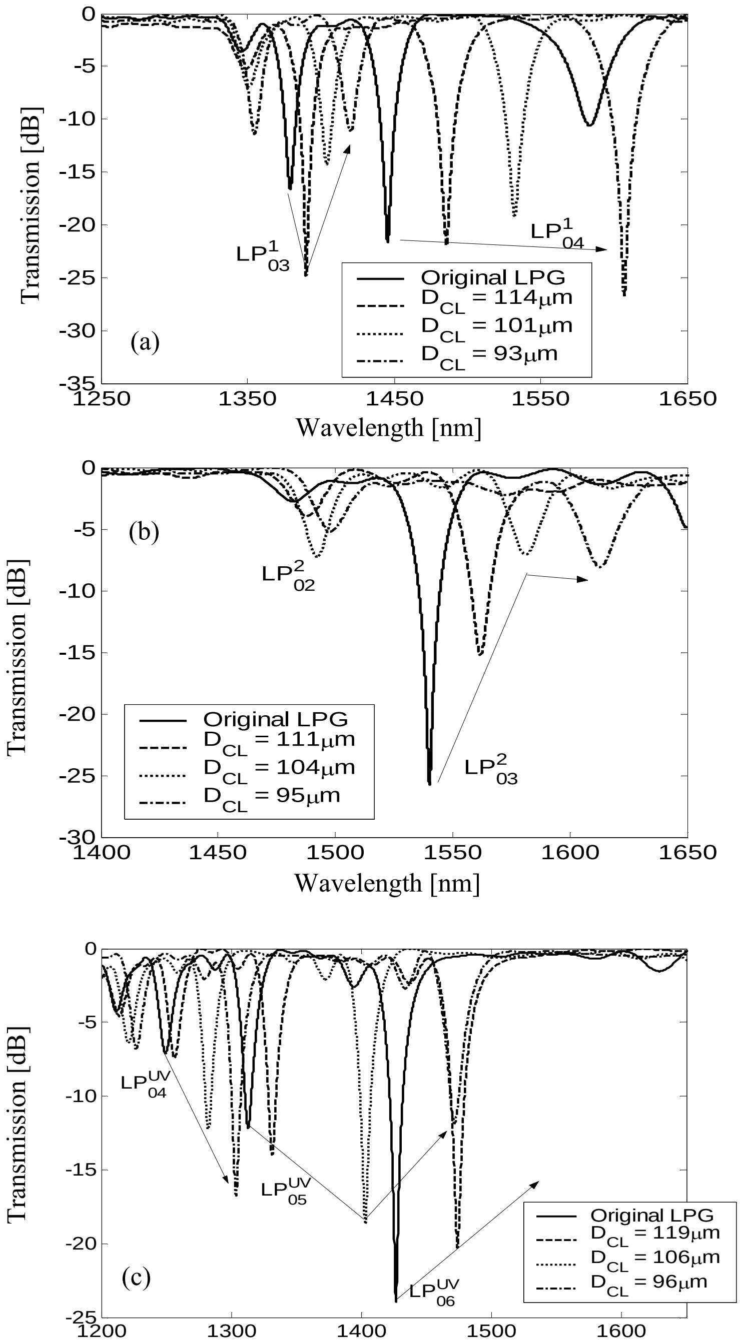

Fig. 5. Grating spectra with SRI=1 at several etching steps: (a) Tapered LPG with Λ=600 μm; (b) Tapered LPG with Λ=755 μm; (c) UV-induced LPG with Λ=360 μm.

Fig. 5.a, 5.b and 5.c shows the transmitted spectra of the tapered LPG with Λ=600 μm, tapered LPG with Λ=755 μm and UV-induced LPG, respectively, during several etching steps, where D_{CL} indicates the residual fiber diameter after each step. As predicted from theoretical analysis and experimentally demonstrated in previous works [8-10, 17], referring

to the UV based LPG, the fiber diameter decreasing induces a lowering of the effective refractive index of the cladding modes and thus a red shift of all the attenuation bands. On the other side, since the cladding stripping affects the cladding mode content within the optical fiber, also the coupling strength between core mode and cladding modes is strongly influenced, as evident in figures 5 [9].

Fig. 6 reports in detail the wavelength shifts of the investigated attenuation bands as function of the fiber diameter, obtained by a centroid analysis for the central wavelength identification. It can be clearly observed that all resonance wavelengths exhibit a shift to longer wavelengths as well as the cladding layer is removed. Also, the red-shift amount increases with the mode order. As the fiber diameter is reduced from 125µm to approx. 96µm, the wavelength shift for the LP^1_{03}, LP^1_{04} attenuation bands was 35nm and 132nm, respectively. For comparison, the effects of the fiber diameter thinning have been investigated also on UV-writing LPG. The investigated bands, LP^{UV}_{04}, LP^{UV}_{05}, exhibit red-shift of 54nm and 159 nm, respectively. By observing the attenuation bands related to the same cladding mode in tapered and UV LPGs, a higher sensitivity to the fiber diameter was found for the tapered device. A detailed comparison is reported in Table I, where the wavelength shift of the investigated attenuation bands is reported for a cladding reduction from 125µm to 96µm.

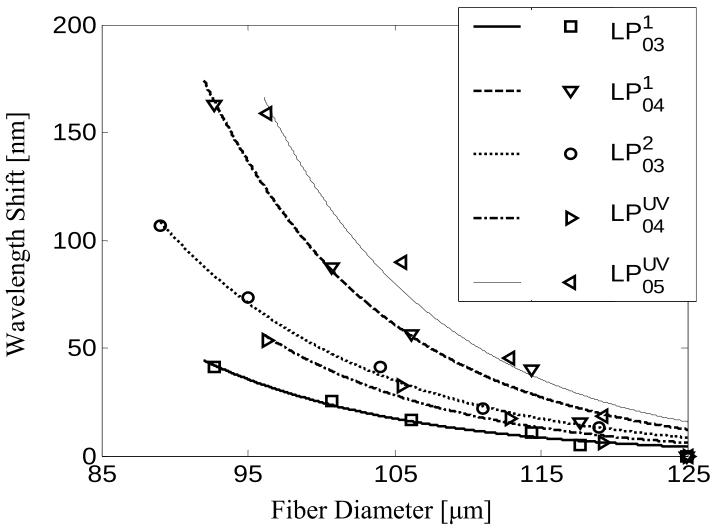

Fig. 6. Wavelength shift for the LP^{UV}_{04}, LP^{UV}_{05}, LP^1_{03}, LP^1_{04} and LP^1_{03} versus the fiber diameter with SRI=1: markers indicate experimental data and curves trend lines.

Table I. Wavelength shifts of the LP^{1}_{03}, LP^{1}_{04}, LP^{2}_{03}, LP^{UV}_{04} and LP^{UV}_{05} resonances for a cladding removal up to 96µm.

	LP^{1}_{03}	LP^{1}_{04}	LP^{2}_{03}	LP^{UV}_{04}	LP^{UV}_{05}
Fiber diameter 96µm	35 nm	132 nm	70 nm	54 nm	159 nm

IV. SRI SENSITIVITY ENHANCEMENT IN THINNED LPG

In this section, we investigate the SRI sensitivity of both grating types in order to provide a comparison of the performances improvement due to fiber etching. With regards the tapered grating with Λ=600µm, figures 7.a and 7.b plot the SRI induced blue-shifts for the LP^{1}_{03} and LP^{1}_{04} resonances against SRI and as function of the fiber diameters.

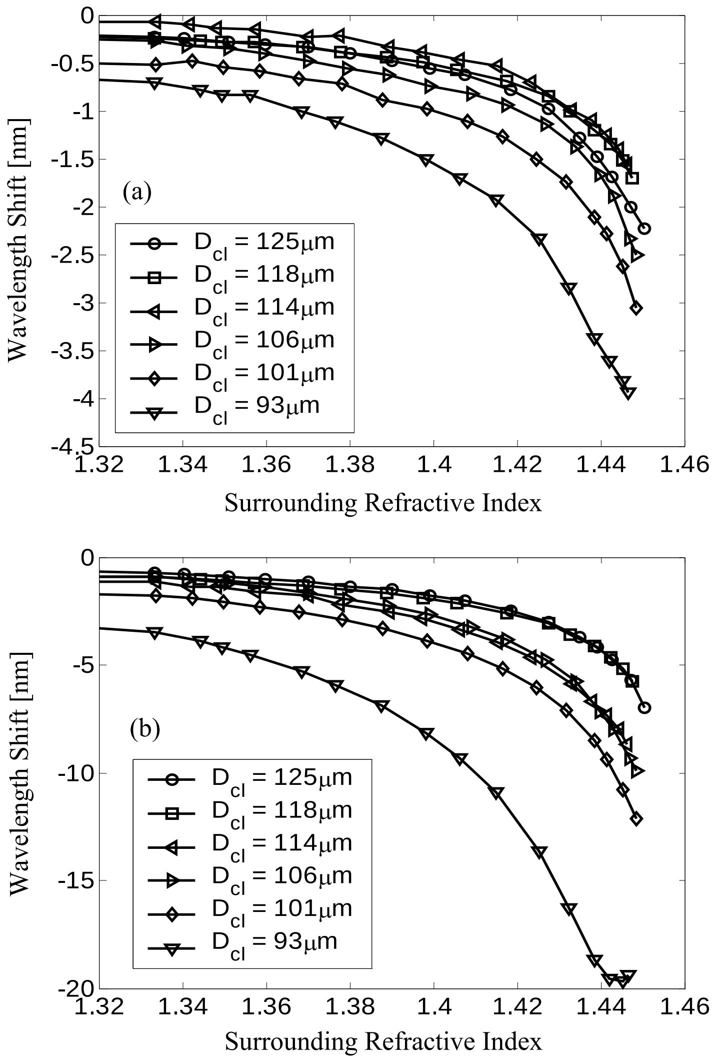

Fig. 7. Resonant wavelength shifts versus the surrounding refractive index as function of the fiber diameter for (a) LP^{1}_{03} and (b) LP^{1}_{04} resonances.

The blue shift can be explained considering that the effective index of the cladding modes increases as well as the SRI, leading to a shift to lower wavelengths in the phase matching condition (eq. (1)). In addition the shift in the attenuation bands increases as well the cladding modes order and it reaches its maximum as the SRI approaches the refractive index of the cladding. Moreover, in the SRI range 1-1.445, the blue-shift changes from 1.9 to 3.8 nm and from 5.3 to 19.6 nm for the LP^1_{03} and LP^1_{04} resonances, respectively, when the fiber diameter is reduced from 125μm to 93μm. For the LP^2_{03} resonance (tapered LPG with Λ=755μm), in the same conditions, the wavelength shift against the SRI is plotted in fig. 8. Here, in the same SRI range, it was estimated total blue-shift of 3.8nm and 12.5nm for fiber diameters of 125μm and 93μm, respectively, demonstrating a sensitivity enhancement of about 1.64 times in respect to the LP^1_{03} resonance.

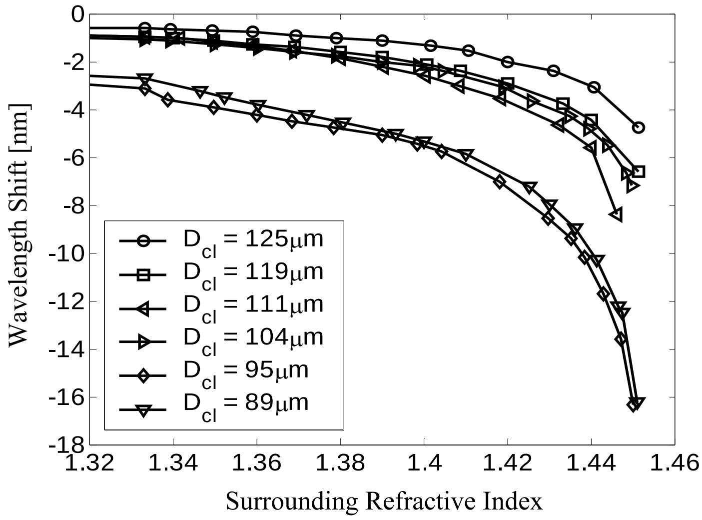

Fig. 8. Resonant wavelength shifts versus the surrounding refractive index as function of the fiber diameter for LP^2_{03} resonance.

A similar investigation was repeated for the UV-induced LPG and plotted in fig. 9.a and 9.b with regards the LP^{UV}_{04} and LP^{UV}_{05} resonances, respectively. In this case, for SRI ranging within 1 - 1.445, the blue-shift changes from 2.3 to 6.4 and from 5.3 to 23.1 for the LP^{UV}_{04} and LP^{UV}_{05} resonances, respectively, if the fiber diameter is reduced from 125μm to 96μm.

Figures 7, 8 and 9 clearly show that both grating types exhibit SRI sensitivity enhancement due to the fiber cladding etching. To better identify the SRI sensitivity enhancement and its dependence on the fiber diameter, a best fitting was applied to the resonant wavelength shift curves (figs. 7, 8 an 9) in order to perform accurate numerical manipulation to obtain the SRI sensitivity characteristics. In particular, here SRI sensitivity defined as the absolute value of the wavelength derivative in respect to the SRI, was taken into account.

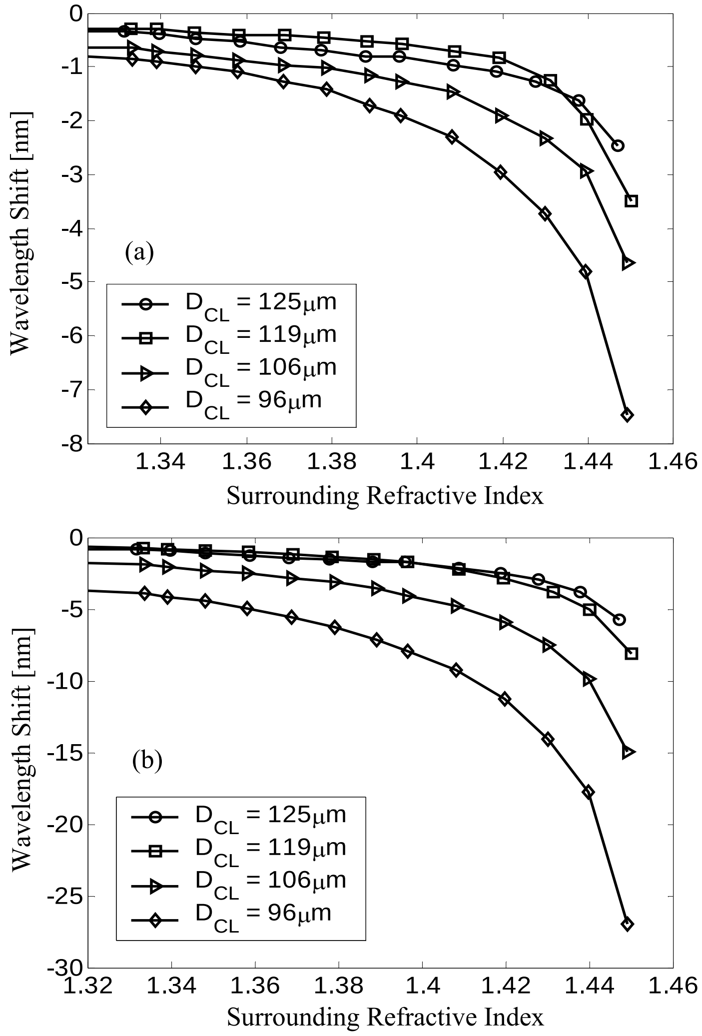

Fig. 9 Resonant wavelength shifts versus the surrounding refractive index as function of the fiber diameter for (a) LP^{UV}_{04} and (b) LP^{UV}_{05} resonances.

This simple data manipulation allows retrieving a clear comparison of the sensitivity behavior against the fiber diameter for the investigated grating types. Figures 10.a and 10.b show the SRI sensitivity related to LP^{UV}_{04}, LP^{UV}_{05}, LP^{1}_{03}, LP^{1}_{04}, and LP^{2}_{03} resonance wavelengths versus the fiber diameter and in case of SRI=1.42 and SRI=1.33 (water refractive index), respectively. In all investigated cases, the SRI sensitivity increases as the fiber diameter is reduced. Also, the sensitivity increases as well as the mode order for both tapered and UV written LPGs. In addition, figures 10 plot also the trend lines for each resonance to better identify the SRI sensitivity behavior against the fiber diameter. As evident, each attenuation band exhibits a monotone sensitivity increase as well as the fiber diameter is reduced.

From the estimated sensitivity values reported in figures 10, the sensitivity gain, defined as the ratio between the sensitivity in the bare and the thinned case, can be easily computed. In particular, the sensitivity gain increases as well as the mode order and for a fiber diameter of 93μm it can be seen that its value for the LP^1_{04} (LP^1_{03}) resonance is 4.88 (2.96) and 4.55 (2.06) for SRI=1.33 and SRI=1.42, respectively.

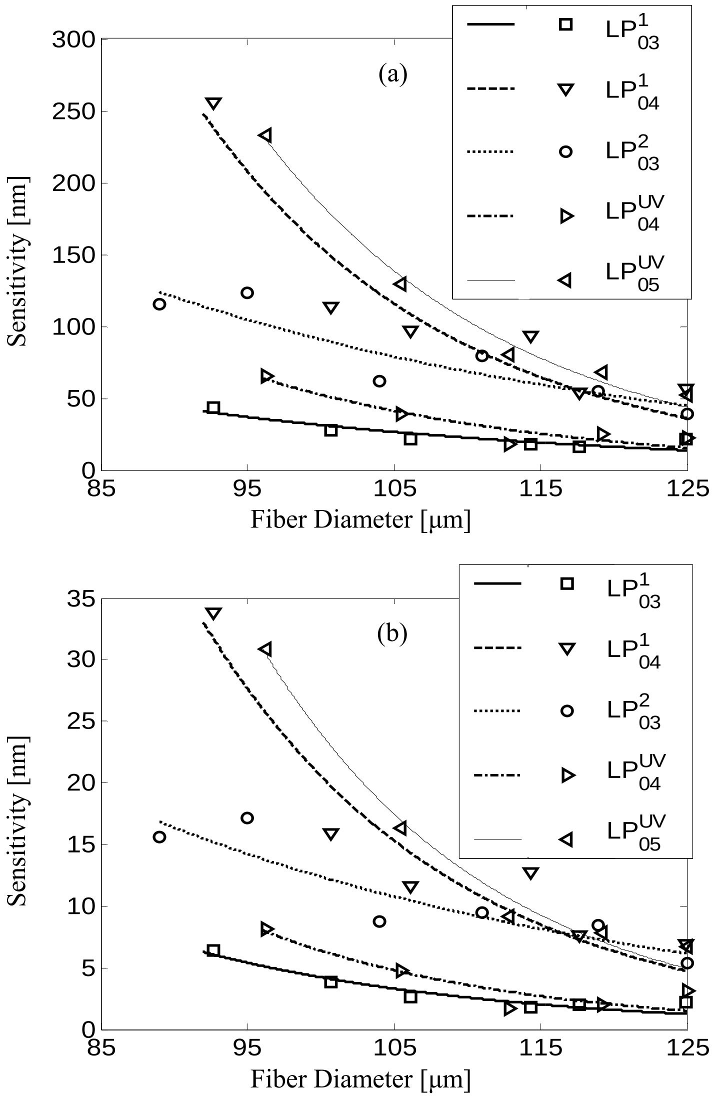

Fig. 10. Sensitivity versus the fiber diameter for LP^1_{03}, LP^1_{04}, LP^2_{03}, LP^{UV}_{04} and LP^{UV}_{05} resonances in case of (a) SRI=1.42 and (b) SRI=1.33. Here markers identify the experimental data and curves identify the trend lines.

Also, the sensitivity gain for the LP^2_{03} resonance is slightly higher than the LP^1_{03} one. In particular, the sensitivity gain for the same fiber diameter (93μm) is approx. 3.2 practically independent on the SRI value. Finally, by examining the same cladding mode order (LP_{04}) for tapered and UV written LPGs, a higher sensitivity was estimated in the case of tapered devices. For example, for a fiber diameter of 96μm, the LP^{UV}_{04} (LP^{1}_{04}) resonance exhibits a sensitivity gain of 2.61 (3.81) and 2.87 (3.51) for SRI 1.33 and 1.42 respectively. On the other side, the sensitivity for the LP^{UV}_{05} resonance results slightly higher than the LP^{1}_{04} case in the tapered device.

V. CONCLUSION

Based on the reported results, we can conclude that in both LPGs types, tapered and UV written, the fiber thinning induces a sensitivity enhancement towards the external refractive index. This enhancement increases as well as the external refractive index value and the mode order. In addition, the sensitivity gain observed in tapered devices for a given cladding mode, is higher if compared with the UV case. This approach can be efficiently used if sensitivity enhancement is required especially in the case water acts as surrounding medium.

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