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Review Article

Arc-Induced Long Period Fiber Gratings

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Long period fiber gratings produced by the electric arc technique have found an increasing interest by the scientific community due to their ease to fabricate, virtually enabling the inscription in any kind of fiber, low cost, and flexibility. In 2005 we have presented the first review on this subject. Since then, important achievements have been reached such as the identification of the mechanisms responsible for gratings formation, the type of symmetry, the conditions to increase fabrication reproducibility, and their inscription in the turning points with grating periods below 200 μm. Several interesting applications in the sensing area, including those sensors working in reflection, have been demonstrated and others are expected, namely, related to the monitoring of extreme temperatures, cryogenic and high temperatures, and high sensitivity refractometric sensors resulting from combining arc-induced gratings in the turning points and the deposition of thin films in the transition region. Therefore, due to its pertinence, in this paper we review the main achievements obtained concerning arc-induced long period fiber gratings, with special focus on the past ten years.

1. Introduction

The concept of long period fiber gratings (LPFGs) was introduced in 1996 by Vengsarkar et al. in which a periodic modulation of the core refractive index was induced by UV laser radiation [1]. Since the grating periodicity is of the order of hundreds of micrometers several techniques have been used for LPFGs fabrication not only through exposure to UV, CO_2, and IR femtosecond laser radiation [1–3] but also based on ion beam implantation, etching, mechanical arrangements, acoustic waves, broadband UV light, and electric arc discharges [4, 5]. Among the different available techniques the electric arc has paved its way during the past two decades since it is a simple, flexible, and low cost technique that enables the writing of gratings in all kinds of fibers. Furthermore, as is the case for CO_2 and IR femtosecond laser radiation, the arc discharge technique also overcomes several limitations of the technique based on UV laser radiation [6] and enables the fabrication of several optical fiber components [7]. In fact, based on the number of publications, arc-induced gratings compares well with those fabricated by using laser radiation. Presently, and apart from Africa, it is a technique spread all over the world (see Figure 1; there are also some traces of research activity in Turkey and Iraq). More than two-tenths of research groups, by their own or in consortiums, have been studying LPFGs produced by the electric arc technique (in Figure 1 the flags dimensions are proportional to the number of publications in international journals and conferences) resulting in more than 250 papers. INESC TEC, in Portugal, accounts for about 40% of the publications (see Figure 2). It can be said that the fabrication of LPFGs started in 1994 by Poole et al. where they have used a two-step process involving ablation of the fiber cladding by CO_2 radiation followed by annealing through arc discharges [8]. LPFGs based solely on arc discharges are due to Dianov et al. in 1997 [9]. In the following years a scarce number of publications were registered and despite the peak in 1998, the take-off occurred in 2001 by Rego et al. [6] followed by Humbert and Malki [10] that led to an increasing interest until 2007, also with important contributions from research groups in Japan [11], UK [12], and Brazil [13]. From 2008 up to 2012 there was a decrease in the number of publications despite the contribution of research groups from Mexico [14] and Canada/Poland [15]. In the past three years we have been

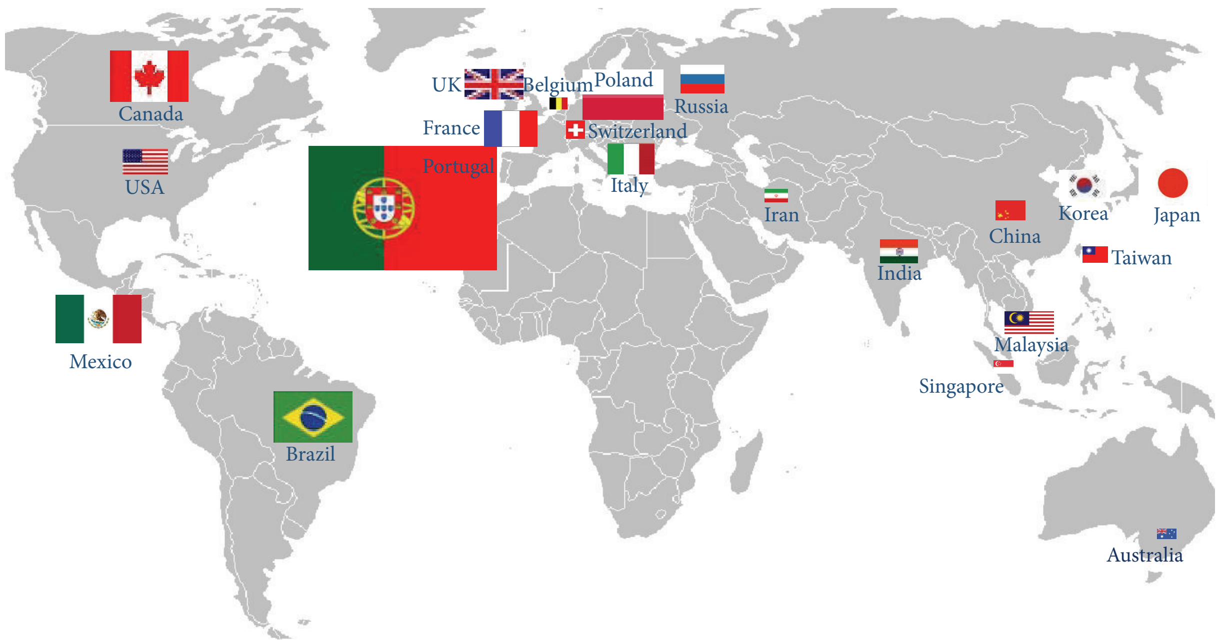

Figure 1: Worldwide research on arc-induced gratings.

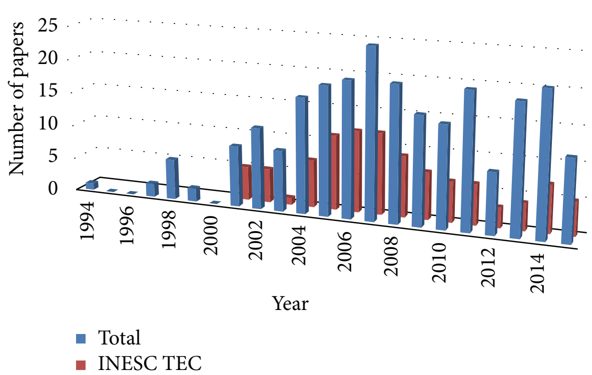

Figure 2: Publications concerning arc-induced gratings in international journals and conferences.

climbing the technique's notoriety with growing interest in Asia, namely, in Malaysia [5].

In the early days, publications were essentially related to the fabrication in different kinds of fibers, the study of the gratings properties, and the discussion of the mechanisms of formation, being those issues reviewed in 2005 [4]. In the last decade we registered the consolidation of the knowledge concerning the formation mechanisms, the improvement of the reproducibility of the technique, the implementation of several sensors, namely, for the simultaneous measurement of temperature and strain, the development of refractometric sensors based on coated LPFGs and, more recently, to the inscription of arc-induced gratings in the turning points. At these points, the slope of the phase matching curves, for each cladding mode resonance, reaches its maximum value. On the other hand, near the turning points the slope steeply increases and changes from positive to negative and, for each grating period, there are two resonance wavelengths for each cladding mode. These are the regions where LPFGs show the highest sensitivities [16]. Therefore, by properly addressing issues related to the reproducibility of the technique associated with electrodes degradation and environmental parameters that impact the optimum arc discharge conditions and also the required LPFG engineering development associated with their intrinsic cross sensitivities to other physical parameters such as temperature, strain, and bending, it is expected that arc-induced gratings continue their worldwide spreading leading, in the near future, to commercial devices in the sensing area.

In the following sections, we begin by reviewing the underlying mechanisms of arc-induced gratings formation. Afterwards, the fabrication of long period fiber gratings, in particular, in the turning points is discussed. The main properties of LPFGs, which include the thermal behavior and the dependence on the external refractive index, are also presented. Finally, we analyze three important applications in the sensing area, namely, the simultaneous measurement of temperature and strain, flow measurement, and refractometric sensors.

2. Mechanisms of Gratings Formation

A long period fiber grating is a wavelength selective filter whose transmission spectra exhibit several resonances resulting from coupling between the core mode and the different copropagating cladding modes at wavelengths that obey the resonance condition [1]: $\lambda_{\text{res}} = (n_{\text{co}}^{\text{eff}} - n_{\text{cl},m}^{\text{eff}})\Lambda$, where λ_{res} represents the resonance wavelengths, Λ represents the grating period, and $n_{\text{co}}^{\text{eff}}$ and $n_{\text{cl},m}^{\text{eff}}$ represent the effective

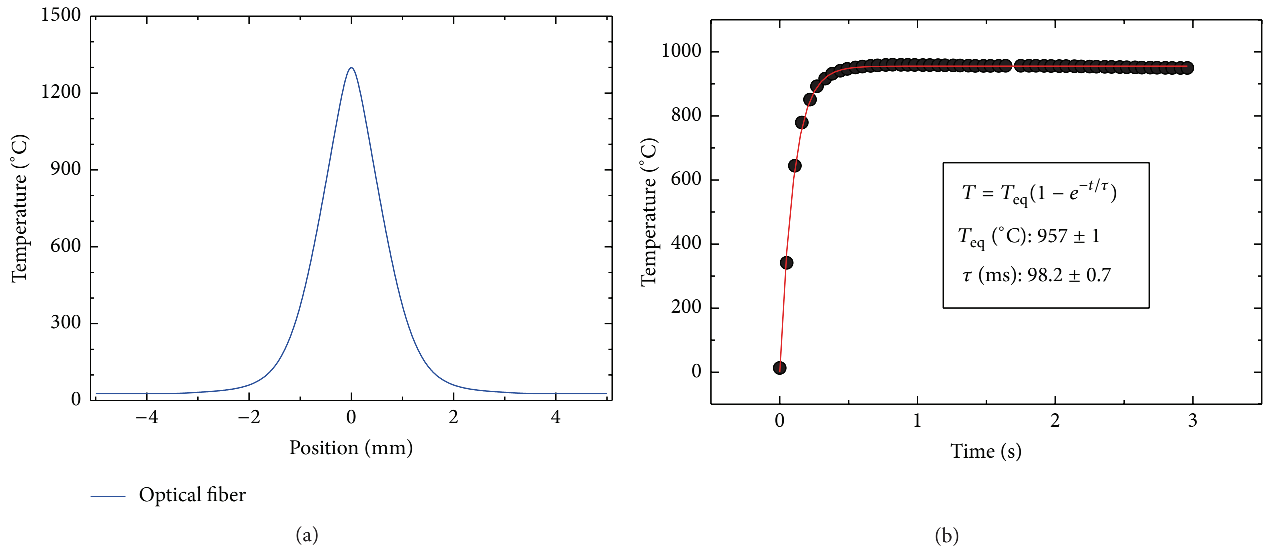

Figure 3: (a) Temperature profile in the fiber during the arc discharge and (b) and its time dependence (it corresponds to a 50 μm Pt/Rh thermocouple inserted in a 56/125 μm silica capillary) [23].

refractive index of the core mode and the effective refractive index of the cladding modes, respectively. The theoretical equations governing the intrinsic properties of LPFGs, such as, transmission loss and resonance wavelengths or their temperature and external refractive index dependence, can be found elsewhere [5, 17–20]. For almost two decades that the underlying mechanisms of arc-induced gratings are under debate and in this context the estimation of the temperature reached by the fiber during an arc discharge allowed a proper discussion on the mechanisms responsible for their formation [21–23]. Figure 3 shows that for the typical fabrication parameters used, namely, electric current and time of the arc discharge, the fiber reaches a peak temperature of about 1400°C in less than half a second (estimated from Figure 3(b)) [23]. The latter result is also important in order to limit heat diffusion along the fiber since it prevents the use of short grating periods, due to overlap of the effects caused by the adjacent arc discharges.

Several works have been published focused on stress and refractive index profile measurements [24–28]. The main conclusions are that the arc discharge (considering typical fabrication parameters) relaxes intrinsic stresses in the fiber core and cladding but in regions that are larger than the grating period being, therefore, the refractive index modulation not enough to explain the grating formation. On the other hand, an increase of the refractive index of the cladding and a decrease of the core-cladding difference were observed which impacts the position of the resonance wavelengths. The conclusions concerning the core region are not so straightforward and results may depend on the fiber and also on the fabrication conditions. In 2006, it was demonstrated through simulation and by measuring the near field intensity distributions that depending on the fiber, LPFGs could couple to cladding modes of different symmetries [29]. Further studies revealed that the arc discharge is directional, possessing a temperature gradient that induces asymmetric microdeformations in the fiber [30]. These microdeformations can account for the formation of the gratings and, simultaneously, the average reduction of the fiber cross section also leads to a displacement towards shorter wavelengths of the resonances (see Figure 4(a)). It should be stressed that five years earlier the periodic modulation of the fiber was already pointed out as a potential origin of LPFGs formation [31, 32], although in the case of a symmetric perturbation it would require a severe deformation of the fiber cross section (~17%) in order to obtain strong gratings [17]. Therefore, both changes, the geometrical and the refractive indices, caused by the arc, need to be taken into account for the correct simulation of arc-induced gratings (see Figure 4(b)).

In the case of the B/Ge codoped fibers typical cladding modes are symmetric (Figure 5(a)), unless the fiber is placed under tension in a region of the arc with lower average temperature and higher temperature gradient (which is also an optimum point to increase the reproducibility of the technique) where, with optimized fabrication parameters, gratings with different symmetries are written simultaneously [33]. In Figure 5(b), the resonances at shorter wavelengths belong to asymmetric cladding modes whilst the others are due to coupling to symmetric cladding modes, in accordance with the simulations. Moreover, the latter modes vanish at higher temperatures, so they are not a consequence of permanent geometrical changes. These superimposed gratings showing a dual set of resonances results from two different mechanisms: microdeformations and densification [34].

In the case of pure silica-core fibers it was also demonstrated that microdeformations can be responsible for the formation of the gratings [35]. During these investigations the knowledge regarding mechanically induced LPFGs was very important for the sake of comparison between both types of gratings [36]. Figure 6 shows the dispersion curves for symmetric and asymmetric modes being the latter at shorter wavelengths in accordance with the theory. For our particular

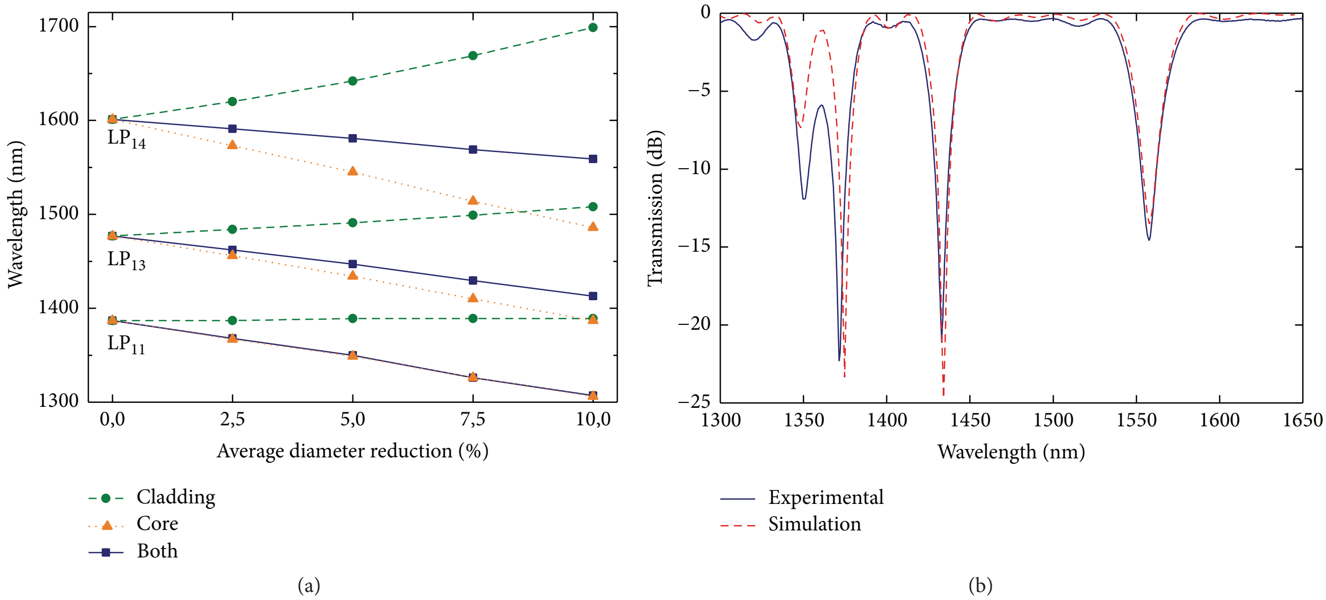

Figure 4: (a) Resonance wavelengths as a function of the geometric modulation and (b) transmission spectrum of an asymmetric 540 μm LPFG induced in the SMF28 fiber: experimental (solid line) and simulation (dashed line) [32].

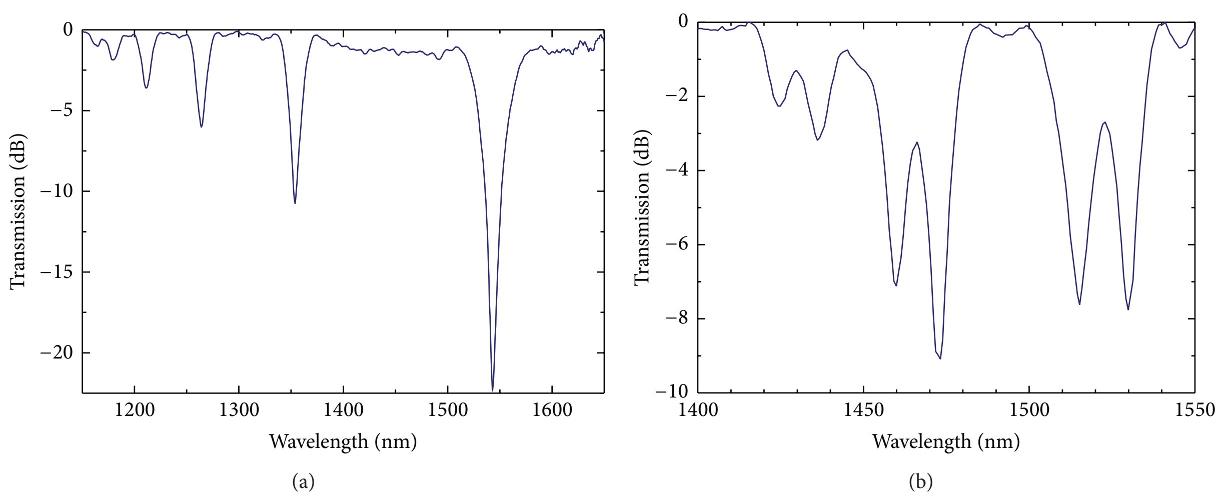

Figure 5: (a) Spectrum of a symmetric 415 μm LPFG induced in the B/Ge codoped fiber using an external tension of 5.1 g and 60 discharges with 8.5 mA and 0.5 s; (b) spectrum of a 540 μm grating with a dual set of resonances inscribed simultaneously in the B/Ge codoped fiber after downshifting ~20 μm the fiber relatively to the arc and using an external tension of 23 g and 60 discharges of 9 mA and 0.5 s [33].

setup, where the arc discharge is directional, and considering Ge-doped fibers such as the SMF28 from Corning, coupling occurs for asymmetric cladding modes. The comparison between arc-induced and mechanical-induced gratings (MLPFGs) is presented in Figure 7. It can be observed that the resonances of arc-induced gratings are located at shorter wavelengths, which can be attributed to the changes caused by the arc in terms of a reduction of the average core diameter and also due to annealing of intrinsic stresses that lead to a change of the refractive index of the core and cladding regions, as discussed previously. As far as the inscription of LPFGs in photonic crystal fibers is concerned this topic is discussed, for instance, in [11, 37].

3. Fabrication and Characterization of Arc-Induced LPFGs

Generally speaking, arc-induced gratings are fabricated by placing an uncoated fiber, under tension, between the electrodes of a splicing machine [6], being it then submitted to an arc discharge with an electric current of 7 to 15 mA and a duration ranging from 200 ms up to 2 s. Afterwards the fiber is displaced by the grating period, typically from 400 μm to 700 μm, and the whole process arc discharge/fiber displacement is repeated 20 to 50 times. Along the years several modifications to the set-up were implemented, in part, to increase the reproducibility [17, 30]. Other improvements

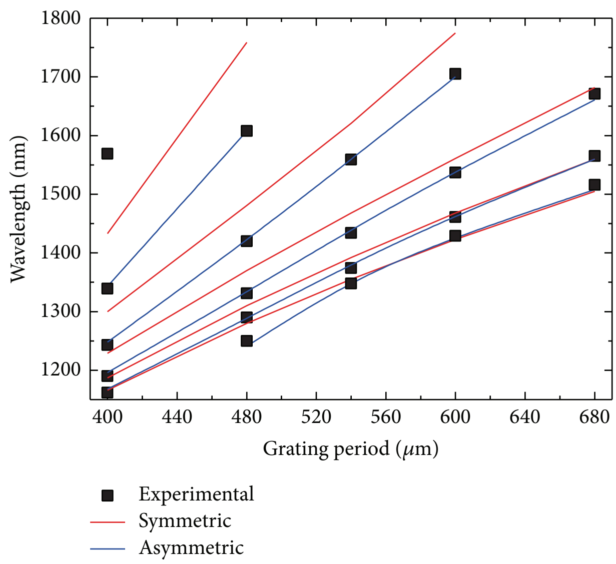

Figure 6: Resonant wavelength versus grating period for the lowest cladding modes. The experimental data was fitted considering both types of perturbations: symmetric and asymmetric [17].

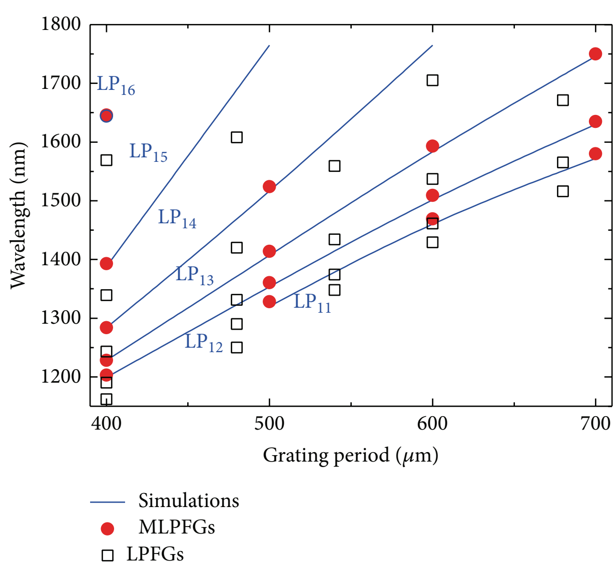

Figure 7: Resonance wavelengths, corresponding to coupling to asymmetric cladding modes, as a function of the grating period [36].

were also claimed by other researchers through modification of commercial fiber splicers [15, 38–43] or by developing their own high voltage power supply [31, 32, 44–46]. All advancements led us to a compactness, flexible and reproducible technique that enables the fabrication, virtually in all kinds of fibers, of low loss LPFGs with considerable short grating periods. However, as far as high sensitivity LPFGs based sensors are concerned, it was necessary to inscribe LPFGs in the turning points and this goal was reached in the last couple of years, first by Smietana et al. [47, 48] by writing LPFGs below 200 μm in B/Ge codoped fibers and later by Colaço et al. [49] that were able to inscribe LPFGs below 200 μm in the SMF28e fiber and below 150 μm in the 1250/1550 B/Ge codoped fiber, establishing a new record for the shortest grating period achieved for arc-induced gratings. This goal resulted from the development of a dedicated high voltage power supply (see Figure 8).

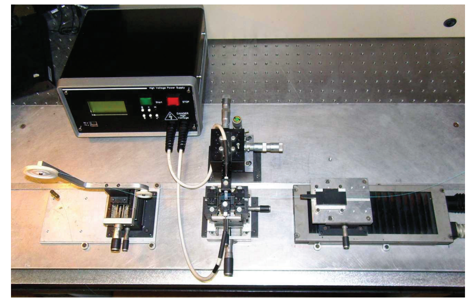

Figure 8: Experimental set-up (mechanical arrangement and high voltage power supply) used to fabricate arc-induced gratings in the turning points.

Figure 9 shows the spectra of gratings arc-induced in the SMF28e fiber and also in the B/Ge codoped fiber. The fabrication parameters were set as electric current of 12.7 mA, 600 ms arc duration, 2 g pulling weight, and 400 arc discharges, for the SMF28e fiber. It should be stressed that we are working in the limits of the electric arc technique since it was only possible to write a week grating even after 400 arc discharges. Even so, this result is quite impressive since previously in this fiber the shortest period was larger than 300 μm [15]. For the grating inscribed in the Fibercore fiber we used the following fabrication parameters: electric current of 13.8 mA, 308 ms arc duration, 2 g pulling weight, and 142 arc discharges. Note, however, that we have also produced gratings (Λ = 180 μm) in this fiber with resonance strength of about 20 dB by applying only 122 arc discharges (see Figure 10).

LPFGs have been arc-induced in different types of fibers including Ge-free fibers [24, 50, 51], photonic crystal fibers [52–58], flat cladding fibers [59], and cladding-etched fibers [14, 60, 61] and in adiabatic tapers [62]. Modifications to the technique include applying no tension, applying compression, or even pressurizing the hollow core fibers during the arc discharges [5, 19, 55, 63]. LPFGs have been produced with random period [64], superimposed with different periods [65] or with phase-shifts resulting from changing the fabrication parameters during their inscription [66]. In B/Ge codoped fibers the choice of the fabrication parameters also allowed fabricating simultaneously LPFGs with different symmetry [33].

Arc-induced LPFGs have been characterized as a function of the variation of physical parameters such as strain and temperature [40, 66–72], bending and torsion [73], pressure [74, 75], and external refractive index [76–86]. They were also exposed to gamma radiation [51]. The polarization dependence loss was also investigated [87] and the results demonstrate why they have a minute success in optical communications. As far as sensing is concerned three important characterizations were performed. First, one of the major potential applications of arc-induced gratings

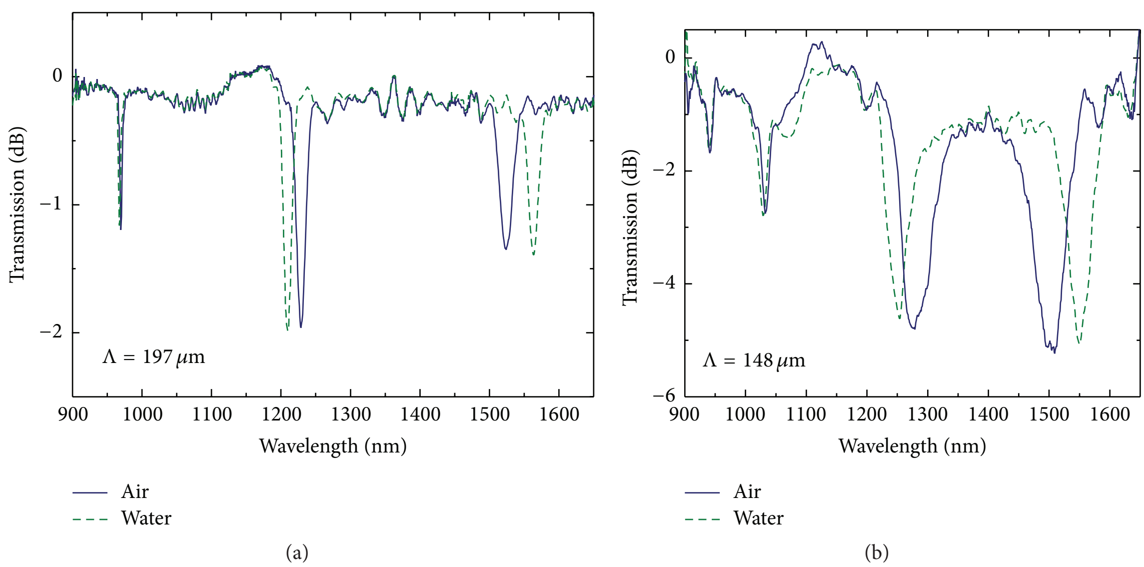

FIGURE 9: Transmission spectra of LPFGs near the turning points, inscribed in the (a) SMF28 fiber, (b) B/Ge codoped fiber [49].

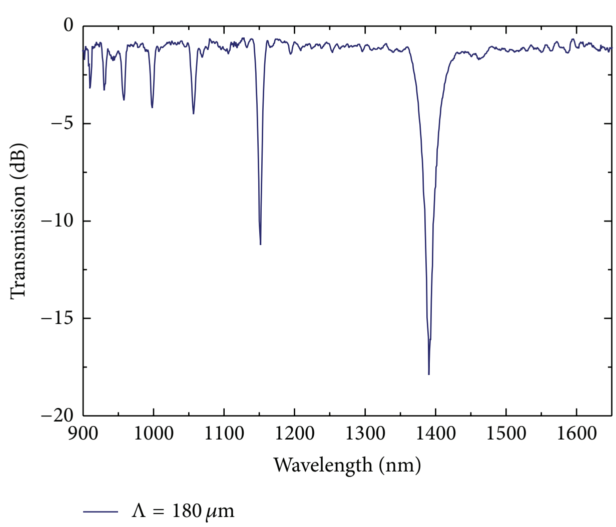

FIGURE 10: Transmission spectra of a 180 μm-LPFGs inscribed in the B/Ge codoped fiber.

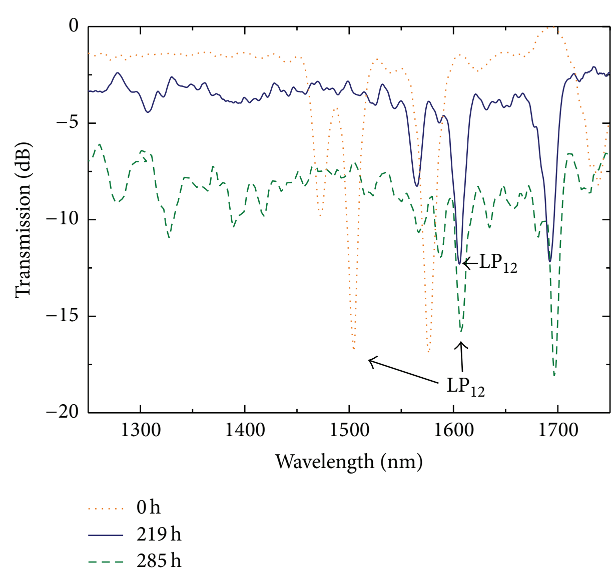

FIGURE 11: Evolution of the grating spectrum during the heat treatment at 1000°C for 12 days [68].

results from their ability to resist to high temperatures as was demonstrated by the fact that they survived at temperatures of 1000°C for about two weeks (see Figure 11). Further improvements are nevertheless expected by isolating the grating from external environment (to prevent in-diffusion of oxygen at high temperatures) and avoiding the use of unwanted external pulling tensions. This can be reached by inserting the grating into a silica capillary [68].

On the other hand, it was recently demonstrated that arc-induced gratings are also good candidates to perform at cryogenic temperatures [72]. A phase-shifted LPFG, working in reflection, was produced by polishing the fiber after cutting it at a distance from the grating of about a quarter of the period (Figure 12(a)). As can be observed in Figure 12(b), the temperature sensitivity obtained in the 4 K–30 K range is considerably higher than for other approaches such as embedded FBGs. Currently, further research is ongoing in order to improve their sensitivity and reproducibility.

Another intrinsic property of LPFGs is their dependence on the external refractive index which affects the effective refractive index of the cladding modes and, therefore, in particular, changes their resonance wavelengths [18]. The gratings sensitivity depends on the order of the cladding modes and reaches its maximum close to the so-called turning points. In these regions the slope of the phase matching curves changes from positive to negative, and for each grating period, there are two resonance wavelengths for each cladding mode. This is due to the dependence on wavelength of the core and cladding effective refractive indices. For

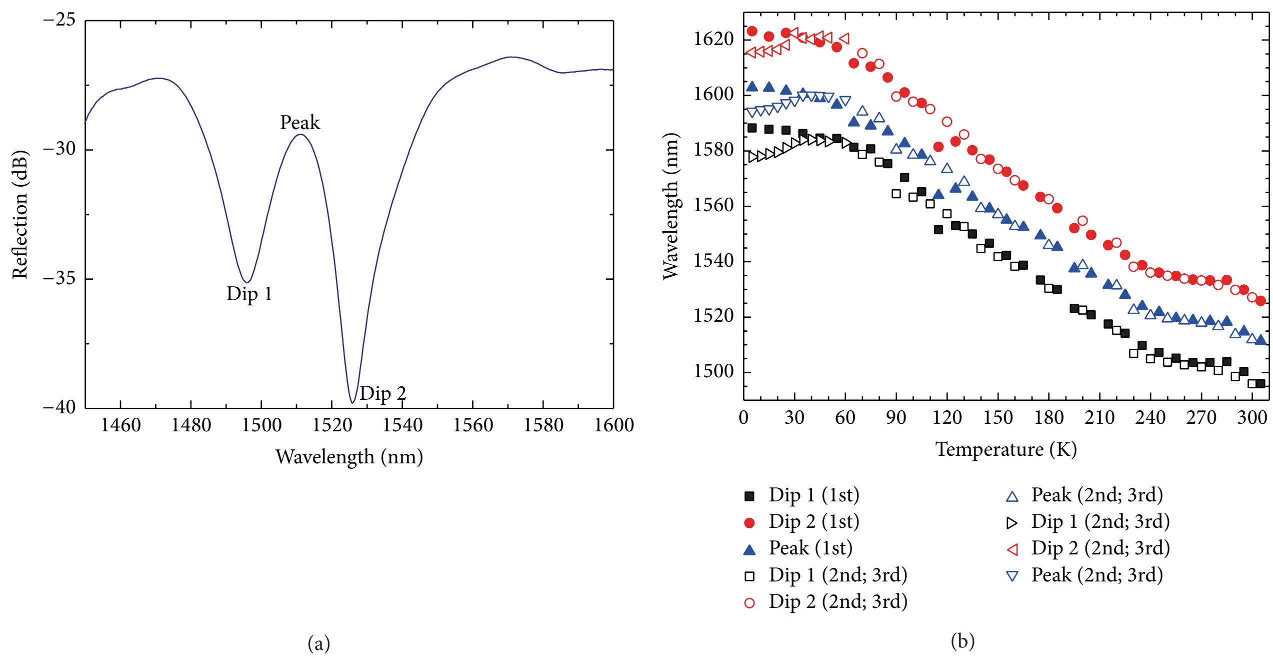

Figure 12: (a) Reflection spectrum of the phase-shifted LPFG at room temperature; (b) wavelength of the two Dips and the Peak of the phase-shifted LPFG working in reflection, inscribed in the B/Ge codoped fiber, as a function of temperature [72].

a particular grating period, the phase matching condition can be satisfied for more than one resonance wavelength since as the wavelength increases the effective refractive index of the cladding mode decreases faster than that of the core [88]. An arc-induced inscribed in the B/Ge codoped fiber in the turning points was characterized as a function of water-glycol mixtures and a sensitivity of about 1000 nm/RIU was obtained by considering the shift of the resonance at shorter wavelengths (Figure 13). Further improvements are expected as will be discussed in the next section.

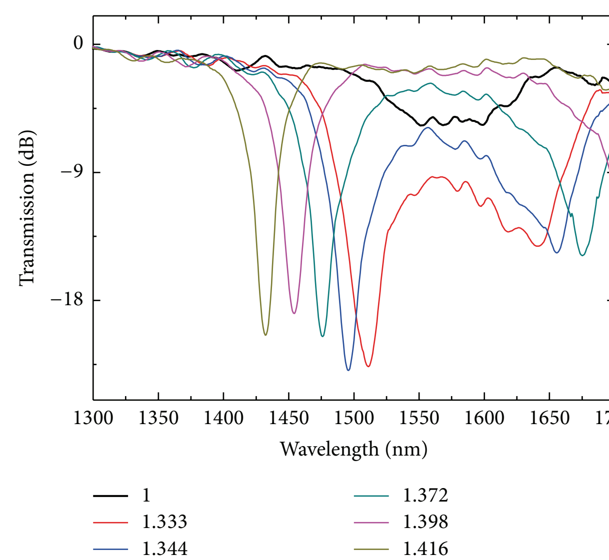

Figure 13: Transmission spectra as a function of the external refractive index for a LPFGs in the turning points, inscribed in the B/Ge codoped fiber ($\Lambda = 192\,\mu$m) [49].

4. Applications of Arc-Induced Gratings

LPFGs find application in optical communications and sensing areas. However, as far as arc-induced gratings are concerned only few works related to optical communications have been published, namely, those related to their performance as filters in optical sources and in the equalization of optical fiber amplifiers [39, 89–92]. The reason may lay in the fact they are intrinsically polarization dependent [87], therefore, impacting negatively in communication systems. A way to mitigate this issue would be the fabrication of helical arc-induced gratings, since, as demonstrated for LPFGs fabricated by CO_2 laser radiation, they exhibit low polarization dependent loss (PDL) [93–95]. Clearly this topic requires further study and, therefore, in this section we shall present only applications in the sensing area. In this field a diversity of applications have been published, namely, related to the measurement of physical parameters, such as temperature and strain [66, 96, 97], displacement [98], bending [99–102], torsion [73], or pressure [103, 104]. An important achievement related to arc-induced gratings is concerned with the demonstration that by changing the fabrication parameters not only the resonance wavelengths change but also their sensitivity to physical parameters are modified. Based on that, a sensor for the simultaneous measurement of temperature and strain was implemented by changing the fabrication parameters during the grating inscription, that is, for the first 15 discharges, an external tension of 22.8 g and a current of 9 mA during 1 s were used followed by 40 discharges using an external tension of 1.2 g

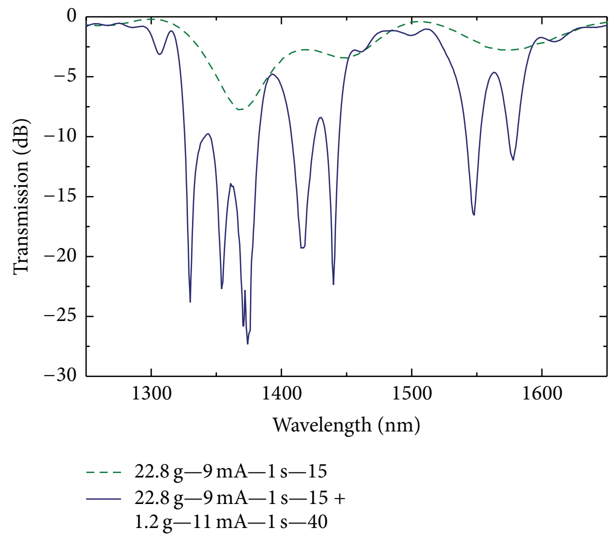

Figure 14: Evolution of the grating spectrum during the fabrication process: (dash line) normal grating spectrum obtained after 15 arc discharges; (solid line) phase-sifted grating obtained after 40 more arc discharges but with different fabrication parameters [66].

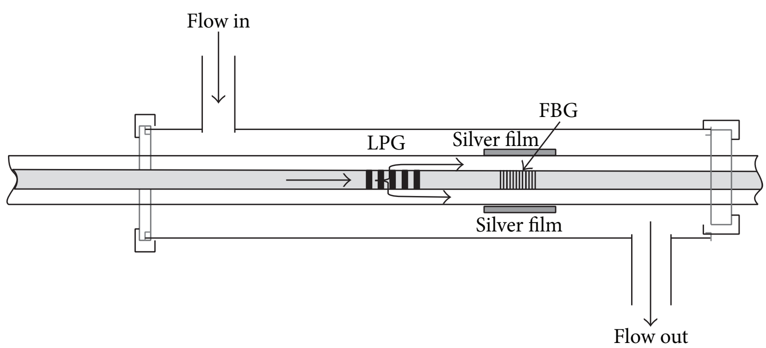

Figure 15: Sensor head used for air flow measurement [106].

and an electric current of 11 mA during 1 s. This resulted in a phase-shifted grating in which two neighbor resonances, in the third telecommunication window, exhibited different sensitivities to temperature and strain [66]. Figure 14 shows the evolution of the grating spectrum during the fabrication process, where the fabrication parameters used are also presented.

Other more unusual applications include sensors performing as inclinometers [105] and flowmeters [106]; they have been used for the determination of metal thermal conductivity [107] and oxidation [108] and also to follow reactive ion etching processes [109]. The optical flowmeter [106] is a particular interesting application that comprises the use of an LPFG, a FBG, and a metallic thin film. Figure 15 shows the sensing head used to measure the air flow. The LPFG couples light to the cladding at a wavelength that is absorbed by the metallic film in which, being in the FBG region, its resonance shifts towards longer wavelengths due to the heating process. Afterwards, the air flow removes the heat from the film at a rate that depends on the air velocity and that translates into the movement of the FBG signature. Topics concerning interrogation techniques are discussed in [110–115].

LPFGs are intrinsically sensitive to changes of the external refractive index and, therefore, they are used as refractometers [14, 18, 47, 48, 61, 65, 81, 116–151]. As discussed in [18] standard arc-induced LPFGs are limited to resolutions of about 10^{-3} in changes of the refractive index and, therefore, several techniques such as tapering, etching, and bending or by implementing interferometric configurations have been applied in order to improve their resolution. Another limitation is related to the value of the ambient refractive index to be monitored since the sensitivity increases as it approaches the cladding refractive index but, in general, one works with aqueous solutions with a refractive index around 1.33. Moreover, the resonance wavelengths do not change for external medium with a refractive index above that of the cladding. These constraints can be overcome by using thin films and recently several applications based on coated arc-induced LPFGs have been proposed [123–134]. Some examples include monitoring the quality of fried oils [125] and olive oil [126], measure humidity [127], CO_2 [131], or detect the presence of *E. coli* [132]. Figure 16 exemplifies the use of titanium dioxide coatings in order to be able to detect changes in olive oil which possesses a refractive index above that of the cladding.

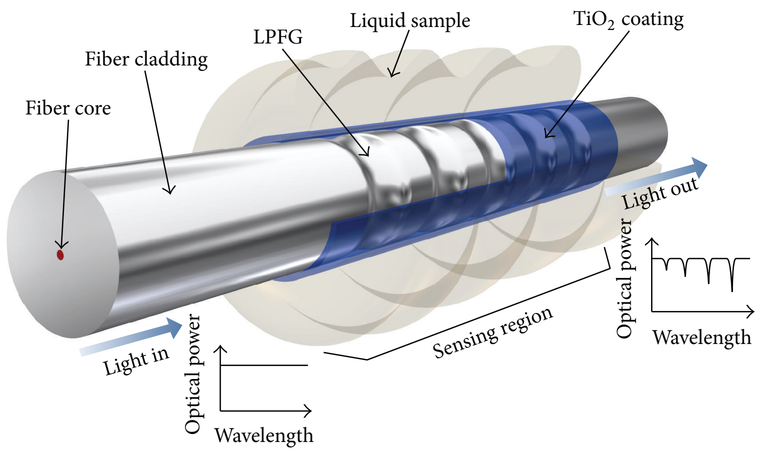

FIGURE 16: LPFG coated with a TiO_2 thin film [126].

Another recent milestone was the possibility to arc-induce gratings in the turning points [47, 48] with periods as short as 148 μm [49]. Therefore, and despite the fact that cross sensitivity issues need to be properly addressed, the combination of strong arc-induced gratings in the vicinity of the turning points coated with thin films in the transition region opens the possibility of reaching resolutions of the order of 10^{-6} [135]. Furthermore, it was demonstrated that the initial coupling strength of the grating is determinant in order to avoid the fading out of the resonance in the transition region [136]. Recently, Del Villar also demonstrated that additionally to the previous methods, the etching of the fiber cladding can be used to further increase the sensitivity of the gratings reaching potential sensitivities of the order of 1.4×10^5 nm/RIU [137]. Smietana et al. demonstrated the possibility of tuning the characteristics of LPFGs coated with diamond-like carbon nano-layers by using reactive ion etching [138, 139]. Finally, it should be stressed that these gratings can work in reflection configuration [72]. Thus, we have now all means to produce high sensitivity optical refractometers based on coated arc-induced gratings.

5. Conclusions

In this paper we review the issues related to arc-induced gratings, addressing both the research groups that are working worldwide with the technology and their main achievements. In particular, we highlighted the issues concerning the reproducibility of the technique, the mechanisms of gratings formation, and the possibility of inscribing LPFGs in the turning points. We are now in the presence of a technology with a degree of development that enables the fabrication, at a reduced cost, of high sensitivity refractometric sensors and also temperature sensors for extreme environments, namely, to perform at cryogenic and high temperatures. On the other hand, the mass production of sensors based on arc-induced gratings will require the control of the environment where the discharges occur, in order to prevent or mitigate electrodes degradation, and the intrinsic gratings cross sensitivity to other physical parameters also demands for some product engineering attention.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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