Deposition of an Overlay with Electrostactic Self-Assembly Method in Long Period Fiber Gratings

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In [Opt. Lett. **27** 686 (2002)] it is proved that the deposition of an overlay material on a Long Period Fiber Grating causes important shifts in wavelength of the typical attenuation bands caused by coupling between cladding modes and the core mode. In this work, a theoretical model for analyzing the multilayer cylindrical waveguide is presented, which permits to understand and to predict the phenomenon. The overlay, of higher refractive index than the cladding, starts guiding a mode if a certain thickness value is exceeded. This causes large shifts in the resonance wavelength induced by the grating. One important application of this phenomenon in sensors field is an enhancement of the sensitivity of the LPFG against ambient conditions. Theoretical results are corroborated with experimental ones, obtained with Electrostatic Self-Assembly Method.

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Long Period Fiber Gratings (LPFGs) have found many applications during the nineties in optical communication and sensor fields [1,2]. They consist of an index modulation of the refractive index of the core of a single mode fiber (SMF), with a much longer period than Fiber Bragg Gratings

(FBGs). As a result, dips are created in the transmission spectrum at wavelengths where there is a coupling between the core and copropagating cladding modes, unlike in FBGs, where there is a coupling between contrapropagating modes. Each attenuation band presents a minimum, notated as resonance wavelength. This wavelength value is in close relation with the one that satisfies the Bragg condition between the coupled modes:

$$\beta_{01}(\lambda) - \beta_{0j}(\lambda) = \frac{2\pi}{\Lambda} \tag{1}$$

where β_{01} and β_{0j} are the propagation constants of the core and the j cladding modes respectively, and Λ is the period of the grating. However, a much better accuracy is obtained if the self-coupling coefficients are added to this formulation [3]:

$$\beta_{01}(\lambda) + s_0\zeta_{01,01}(\lambda) - \left(\beta_{0j}(\lambda) + s_0\zeta_{0j,0j}(\lambda)\right) = \frac{2\pi}{\Lambda} \tag{2}$$

where $\varsigma_{01,01}$ and $\varsigma_{0j,0j}$ are the self-coupling coefficients of the core and the j cladding modes respectively, and s_0 is the coefficient of the first Fourier component of the grating. The effective index of the cladding modes is highly sensitive to ambient conditions and henceforward this modifies the resonance wavelength of expressions (1) and (2). This particularity has been exploited in the design of refractometers or temperature sensors [4,5].

So far, two cases have been analyzed in LPFGs. In the first one, the refractive index of ambient is lower than that of the cladding, which causes that the core mode couples to cladding modes [6]. As the ambient refractive index approaches that of the cladding, the sensitivity of the resonance wavelength to variations of the ambient refractive index is higher. The second case starts when the ambient refractive index exceeds that of the cladding. The core mode couples to radiation modes [7-9], and the dependence of the resonance wavelength on the ambient refractive index is not so accused. Instead, the resonance depth is more dependent on this parameter for values close to the refractive index of the cladding [2]. In both cases, the region of highest sensitivity is located around the refractive index of fiber. A different case is proposed in Ref. 10, where a thin overlay of higher refractive index than the cladding is deposited between the cladding of the LPFG and the ambient with Langmuir Blodgett technique. Here it is confirmed[11] with Electrostatic-Self Assembly (ESA) Method [12], that the deposition of a thin overlay on the cladding of an LPFG leads to a variation of the central wavelength of the attenuation bands.

ESA method is based on the construction of molecular multilayers by the electrostatic attraction between oppositely charged polyelectrolytes in each monolayer deposited. It is used to build up coatings on a wide variety of substrates, fiber optic among them, as it is the case in this work. The thickness of the molecular layers can be controlled with some rules, which permits to deposit layers of 5 to 100 nm on the substrate. The cylindrical multilayer waveguide structure of the LPFG after deposition of the overlay is represented in Fig.1. The other major novelty in this work is that a theoretical model permits a thorough understanding of the phenomenon. The method is based on the formulation for cylindrical multilayer waveguides presented in Ref. 3. LP modes are adequate for describing the structure of Fig. 1 even though there is a high contrast between ambient and cladding refractive indices [3]. Once the LP modes are calculated, the self and cross coupling coefficients are obtained and they are introduced in the coupled-mode equations. When they are solved, the resonance wavelength and the depth of the attenuation bands can be appreciated in the transmission spectrum. If it is only necessary to analyze the shift in wavelength, expression (2) is a much better option in terms of computation efficiency, and deviation with respect to results of coupled mode equations is less than 1% [3].

Regarding the experimental setup, the signal of a white-light source was coupled into SMF-28 optical fiber where the Long Period Grating (LPG) had been written with a laser ExciStar S-200.

The output was monitored with an Agilent 86140B OSA. The parameters of the LPFG are: core diameter of 8.3 um, cladding diameter 125 um, core refractive index 1.47, cladding refractive index 1.4647, period of the grating 276 µm, and length of the grating 25 mm. The modulation is considered sinusoidal with an amplitude of 2.85×10^{-4}. The overlay material is [PDDA^{+}/PolyR-47^{-}]. A refractive index 1.62 has been estimated with the same technique used in Ref 13. The range of measurement was 1000–1500 nm, and a resolution of 0.5nm was recorded after each layer was deposited.

In Fig. 2 experimental results of the shift in resonance wavelength of the attenuation bands corresponding to coupling of the core mode to the seventh and eight modes are contrasted with theoretical values obtained with expression (2). As the overlay thickness is deposited on the cladding of the LPFG, cladding modes shift their effective index to higher values. When the overlay is thick enough, one of the cladding modes is guided by the overlay. This causes a reorganization of the effective index of the rest of modes. Cladding modes with lower effective index than the one that is guided by the overlay will shift their effective index value towards the effective index of the immediate higher effective index mode. As more material is deposited, the effective index distribution before deposition is recovered. The effective index of the eight cladding mode will be now that of the seventh one, the effective index of the seventh cladding mode will be that of the sixth mode, and so forth. The same is true for the resonance wavelength values. The attenuation band corresponding with the eighth mode shifts the wavelength to that of the seventh mode and the same is true for the seventh mode that shifts the wavelength to the attenuation band of the sixth mode. The same explanation is valid for the rest of attenuation bands.

In the transition towards the guiding of a mode in the deposited region, there is a fast variation of the effective index of the cladding modes. This causes a fast shift of the resonance wavelength of each attenuation band. The shift is maximum when the effective index of the mode is half way between its original effective index before deposition and the original effective index before deposition of the next lower cladding mode. The sensitivity of LPFG could be improved by more than one order of magnitude if deposition was stopped at this point.

However, there is an additional phenomenon. In Fig. 2 no experimental points are shown around the highest variation of the resonance wavelength. The reason is that the attenuation bands disappear at this region because the refractive index of the overlay material presents a high imaginary part. This causes a negligible change in terms of wavelength shift compared with results where the refractive index is considered purely real; and that is why results in Fig. 2 continue to be valid. Nonetheless, the imaginary part of the refractive index of the overlay must be included in coupled mode equations for obtaining the transmission spectra. The imaginary part of the overlay refractive index was estimated to be 0.004, which is caused by losses of the material and the high scattering of light through a region of molecular multilayers.

In Fig. 3, the transmission spectra before deposition of the overlay and for two overlay thickness values (266 nm and 364 nm) are presented both experimentally and theoretically. Results differ in quantity mainly because of the modulation of the grating. It has been considered in the theory as sinusoidal, which is the more adequate shape for reproducing the effects of UV irradiation; the fabrication method used for writing the LPG on fiber. The important point is that theory and experiments coincide qualitatively. As the thickness of the overlay increases, at 266 nm, the seventh cladding mode resonance vanishes. The eighth cladding mode resonance has already reduced its depth and it will vanish. At 364 nm the seventh cladding mode resonance has reappeared close to the resonance wavelength of the sixth cladding mode before deposition of the overlay. The same is true for the eighth cladding mode. In Fig. 3 the eighth cladding mode resonance has been marked with numbers 8, 8’ and 8’’ for the three overlay thickness values analyzed: 0, 266 and 364 nm, to show the shift of the resonance towards the original value of the seventh cladding mode resonance. The same is done for the seventh cladding mode. All cladding mode resonances have experienced the same phenomenon around not very different overlay thickness values. The vanishing of the resonance occurs when the overlay starts guiding a mode. The explanation of this phenomenon will be presented in a future work. This phenomenon of vanishing of modes is also present in Ref. 10, which indicates that the material used in the Langmuir Blodgett deposition presents also a high imaginary refractive index.

Some important ideas can be extracted from the results obtained. In Fig. 2 it is observed that the shift of the resonance is maximum for a specific overlay thickness. This value is in close relation to the transition to guidance of the mode that is guided by the overlay. Consequently, the sensitivity of the LPFG to ambient conditions is maximum. Furthermore, the shift in wavelength is higher for higher order cladding modes, as it could be expected from the higher separation between the effective indices of higher order modes. As a result, the goal is to build LPFGs with overlays that guarantee a maximum shift in resonance wavelength that correspond with higher order modes. It is also important to remark that the shift in resonance wavelength of each cladding mode does not start at the same thickness. Higher cladding mode resonances experiment the shift with thicker overlays than lower modes. This is the reason why the overlay thickness will be designed for the optimum shift of a specific attenuation band. Fortunately, the optimum thickness is not very different for each cladding mode resonance, and all cladding mode resonances will present improved sensitivities. As an example, in Fig. 2 it was theoretically calculated that the optimum thickness values for the sixth, seventh and eighth cladding mode resonances are: 263 nm, 280 nm and 308 nm.

This idea of the optimum overlay thickness is restricted by the phenomenon studied in Fig. 3. The fact that the refractive index of the overlay material is not purely real causes a vanishing of the attenuation bands around the maximum shift of the resonance wavelength. Nonetheless, even out of the region of maximum shift of the resonance wavelength, sensitivity against ambient refractive index is much higher than if no overlay was deposited. Furthermore, if materials with lower imaginary part are deposited, the region of vanishing of attenuation bands will be reduced. This will allow improving the field of LPFG sensors in an important way.

In summary Electrostatic Self-Assembly (ESA) Method has been applied to the deposition of a thin overlay on the cladding of an LPFG. In this way a new case is explored. A theoretical model for multilayer cylindrical waveguides based on coupled mode theory has been used to understand and predict the phenomenon. The guidance of one of the cladding modes causes a shift of the effective index values of the cladding modes. There is a large wavelength shift of the attenuation bands, which will permit to improve the sensitivity of LPFG sensors. The phenomenon of vanishing of attenuation bands as well as the material is deposited is also explained by introducing an imaginary part in the refractive index of the overlay. To our knowledge, this is the first time the shift of modes in a dynamical structure (a structure where one of regions varies in size) is analyzed both theoretically and experimentally.

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Figure captions

Fig. 1: Transversal and longitudinal section of LPFG structure deposition of an overlay on the cladding.

Fig. 2: Resonance wavelength shift originated by coupling between core mode and seventh (LP_{07}) and eighth (LP_{08}) cladding modes, as a function of the thickness of the overlay. Square points: experimental values. Straight line: theoretical values.

Fig. 3: Transmission spectra of an LPFG as a function of three overlay thickness values: 0, 266, and 364 nm. a) Experimental plots b) Theoretical plots. Three overlay thickness values analyzed: 0, 266 and 364 nm

Figures

Fig. 1

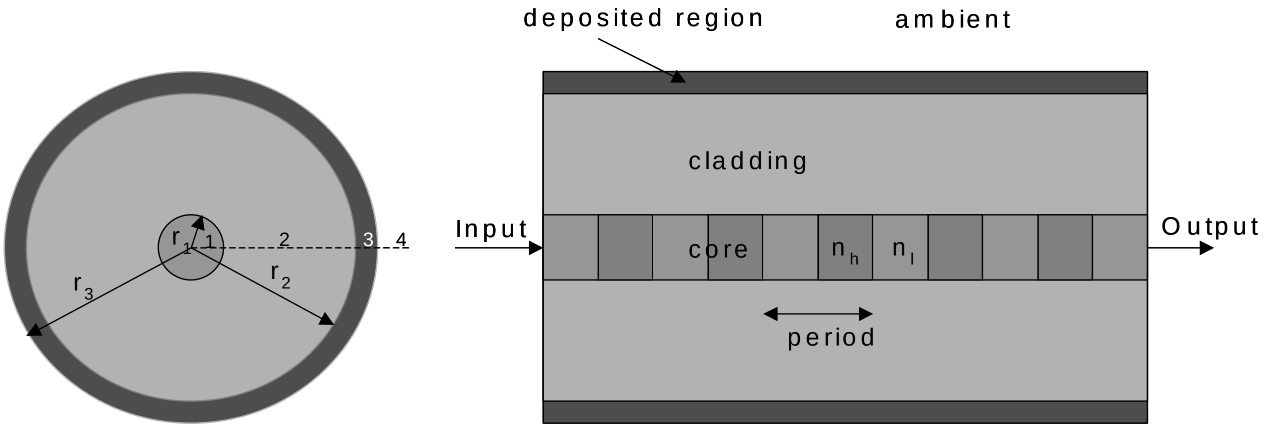


Fig. 2

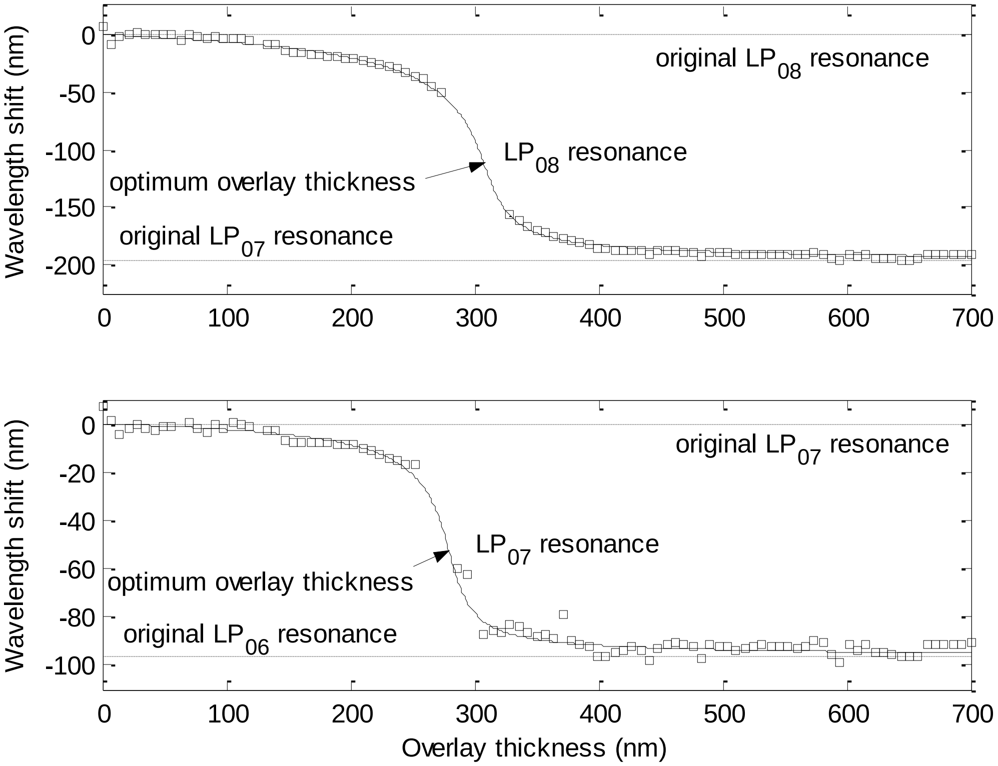

Wavelength shift (nm)
0
-50
-100
-150
-200
original LP08 resonance
LP08 resonance
optimum overlay thickness
original LP07 resonance
0
100
200
300
400
500
600
700
Wavelength shift (nm)
0
-20
-40
-60
-80
-100
original LP07 resonance
LP07 resonance
optimum overlay thickness
original LP06 resonance
0
100
200
300
400
500
600
700
Overlay thickness (nm)

Fig. 3a

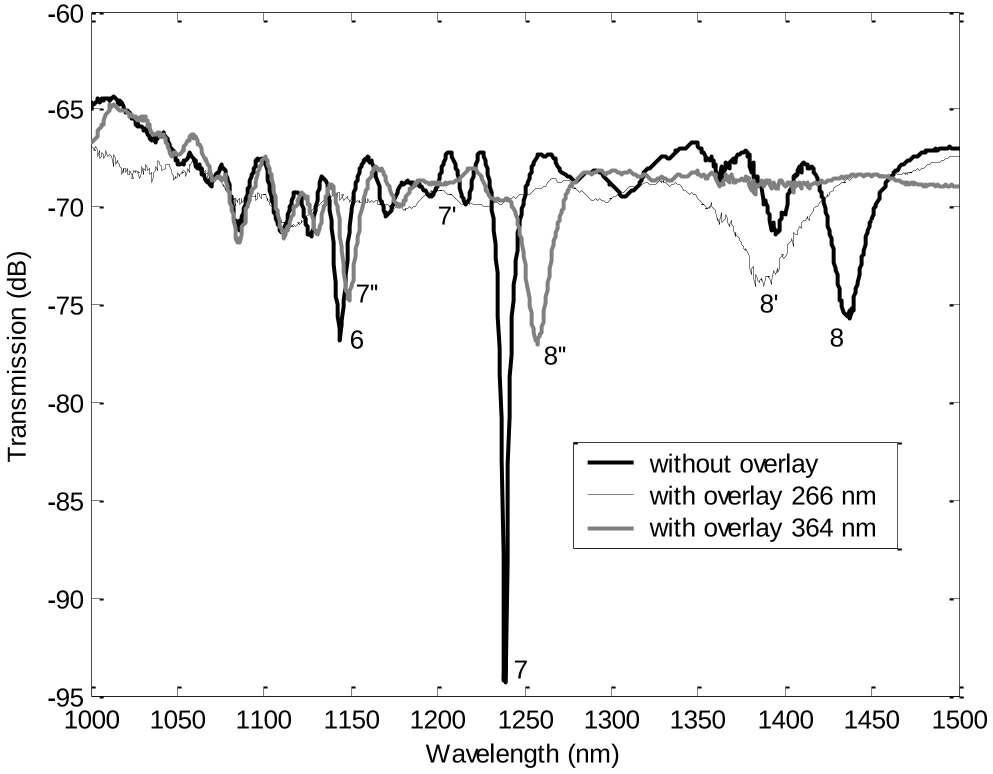
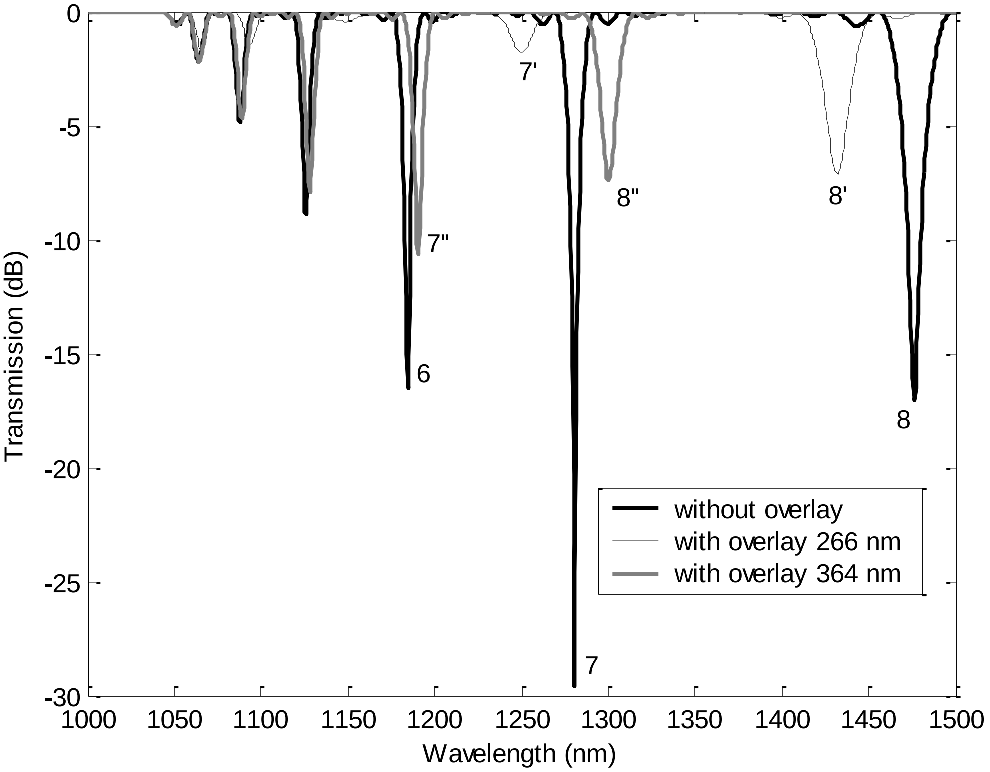

-60
-65
-70
-75
-80
-85
-90
-95
Transmission (dB)
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
Wavelength (nm)
7'
7"
6
8"
7
8'
8
without overlay
with overlay 266 nm
with overlay 364 nm

Fig. 3b


0
-5
-10
-15
-20
-25
-30
Transmission (dB)
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
Wavelength (nm)
7'
8"
8'
7"
6
8
7
without overlay
with overlay 266 nm
with overlay 364 nm