Enhancement of sensitivity in Long Period Fiber Gratings with deposition of low refractive index materials

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In [Opt. Lett. **30,** 720 (2005)] it is proved that the deposition of an overlay of higher refractive index than the cladding on a Long Period Fiber Grating causes large shifts in the attenuation bands induced by the grating. The result is an enhancement of the sensitivity of the LPFG against the ambient and overlay refractive indices or the overlay thickness. In this work, the limitation of the previous design to materials with higher refractive index than the cladding of the LPFG is overcome with a five-layer model. To this purpose, a first overlay of higher refractive index than the cladding of the LPFG will enhance the sensitivity of the device to variations in the refractive index of a second overlay of lower refractive index than the cladding of the LPFG. Moreover, it is proved that if the second overlay is thick enough, its behavior resembles that of an infinite layer.

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Deposition of thin overlays on the cladding of Long Period Fiber Gratings (LPFGs),[1-4] widens the possibilities of so far analysed cases: LPFGs surrounded by an infinite medium of lower refractive index than the cladding,[5,6] and LPFGs surrounded by an infinite medium of higher refractive index than the cladding.[7-9] If the refractive index of the material deposited on the overlay of the LPFG is higher than the cladding, the overlay starts guiding one of the cladding modes if it is thick enough.[2] As a result, there is a reorganization of the effective index of the rest of cladding modes, which is confirmed by analysis of the evolution of the fields in the structure as a function of the overlay thickness.[2] 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.[3] With the hybrid mode analysis performed in this work the idea remains the same. It must be considered that in the case of no azimutal perturbation there is a correspondence between $LP_{0,j}$ modes and $HE_{1,j}$ modes. Consequently, each $HE_{1,j}$ mode will shift its effective index to that of the immediate lower order $HE_{1,j}$ mode of the LPFG without overlay. A thorough comparative between the LP and hybrid mode approximation will be offered in a next work.

This variation of the effective indices of the cladding modes has an important effect in the attenuation bands of the transmission spectrum of the LPFG because there is a close relation between the wavelengths of these bands and the modified Bragg condition:[5]

$$\beta_{11}(\lambda) + s_0\zeta_{11,11}(\lambda) - \left(\beta_{1j}(\lambda) + s_0\zeta_{1j,1j}(\lambda)\right) = \frac{2\pi}{\Lambda} \qquad (1)$$

where β_{11} and β_{1j} are the propagation constants of the core and the j cladding modes respectively, $\varsigma_{11,11}$ and $\varsigma_{1j,1j}$ are the self-coupling coefficients of the core and the j cladding modes, s_0 is the coefficient of the first Fourier component of the grating, and Λ is the period of the grating.

The immediate consequence of the shift in effective index is that it leads to a displacement in all the attenuation bands. The attenuation band corresponding with the $HE_{1,16}$ (respectively $LP_{0,9}$ mode) shifts the wavelength to that of the $HE_{1,14}$ (respectively $LP_{0,8}$ mode); the same is true for the $HE_{1,14}$ (respectively $LP_{0,8}$ mode) that shifts the wavelength to the attenuation band of the $HE_{1,12}$ (respectively $LP_{0,7}$ mode), and so forth. Langmuir Blodgett (LB) and Electrostatic-Self Assembly (ESA) methods,[1,3] have proved this fact by analyzing the consequent shift of the attenuation bands in the transmission spectrum of the LPFG as a thin overlay is deposited on the cladding. There exist overlay thickness values where the shift in wavelength as a function of ambient and overlay refractive indices, and overlay thickness, is maximum.[2] Unfortunately, these points coincide with a vanishing of the attenuation bands due to the imaginary part of the overlay refractive index,[3] the variation of the cross-coupling constant, and probably because of other causes, as for example radiation and interface between the regions with and without deposition. Anyway, even out of these points there is an enhancement of sensitivity to variations in the ambient refractive index and overlay refractive index. This last fact has been proved with spin coating of a material sensitive to chloroform on the cladding of an LPFG.[4] The overlay refractive index variation induced by the concentration of chloroform in water causes an appreciable wavelength shift, which agrees with theoretical predictions.

If the purpose is to detect variations in the refractive index of the material deposited due to some parameter, the design is limited to materials with higher refractive index than the cladding.[4] This can be solved with the multilayer structure presented in Fig.1. An LPFG is coated with a first overlay of higher refractive index than the cladding to cause a shift of the attenuation bands in the transmission spectrum. The thickness of the overlay is chosen to guarantee that the attenuation band is located at a point where there is a good sensitivity and where it does not vanish at the same time. Then, a second material is deposited on the first overlay. The refractive index of this second overlay is lower than the cladding of the LPFG and its material is sensitive to some parameter. In this way, its variation will shift the attenuation bands in the transmission spectrum more than without the first overlay.

The parameters of the LPFG are: core diameter of 5 μm, cladding diameter 125 μm, core refractive index 1.4573, cladding refractive index 1.45, period of the grating 276 μm, and length of the grating 25 mm. The modulation is considered sinusoidal with an amplitude of 2.7×10^{-4}. The first overlay material is [$PDDA^+$/PolyR-478^-].[3] A refractive index 1.62 has been estimated with the same technique used in Ref 10. The second overlay material is [PAH+Prussian $Blue^+$/PAA] with refractive index 1.37.[10] Both refractive index values have been considered constant in the range of wavelengths analysed.

Focus will be centered now on the $HE_{1,16}$ mode (fifteen cladding mode) resonance. In Fig. 2 it is appreciated the shift as a function of the overlay thickness of the resonance wavelength of the $HE_{1,16}$ mode to that of the $HE_{1,14}$. The wavelength shift is analysed for three different ambient refractive indices: 1 (air), 1.33 (water), and 1,37 ([PAH+ Prussian $Blue^+$/PAA]). The higher is the ambient refractive index, the sooner starts the transition of the resonance wavelength. In addition to this, the shift is more abrupt, which is better in terms of sensitivity. In view of the range of wavelengths where the resonance wavelength of the $HE_{1,16}$ mode shifts, a deposition thickness of 68.72 nm is selected for ambient refractive index 1.37. This is the case where an infinite second overlay of [PAH+ Prussian $Blue^+$/PAA] is deposited on the first overlay. The result is that the $HE_{1,16}$ resonance is shifted to 1450 nm, a point where no vanishing of the resonance occurs[3] and where the sensitivity has been improved if compared with the LPFG without overlay. A trade off between both factors must be obtained for an optimum design. The fact that sensitivity has been improved with this design is confirmed by comparing with the results of an LPFG without overlay. If both designs are surrounded by a medium of refractive index 1.37 (approximately that of [PAH+Prussian Blue$^+$/PAA]) and there is a variation of the ambient refractive index, we can see in Fig. 3 that the wavelength shift for the LPFG with overlay is almost double than that of the LPFG without overlay. If the thickness of the overlay is increased, a higher wavelength shift is induced at a risk of a vanishing of the resonance wavelength.

Once it has been proved that an overlay permits to improve the sensitivity to the surrounding medium of lower refractive index than the cladding of the LPFG, it will be analysed the effect of a second overlay on the cladding of the LPFG. In Fig. 4 it is represented the first overlay thickness necessary to shift the $HE_{1,16}$ resonance wavelength to 1450 nm, as a function of the thickness of the second overlay, whose refractive index is assumed to be 1.37. The ambient refractive index is 1 (air). The result is that as the second overlay is thicker, the value of the first overlay that guarantees that the resonance wavelength of the $HE_{1,16}$ mode is 1450 nm, trends to the value of the LPFG with second overlay of infinite thickness. This has been plotted in dotted line as the value the results should diverge to. From Fig. 4 it can be concluded that there is a trade off between the first overlay thickness and the second overlay thickness to obtain a specific resonance wavelength.

Finally, in Fig. 5 the sensitivity to variations in the refractive index of the second overlay is analysed for different thickness values of this second overlay. Here it is proved that as the thickness increases the sensitivity improves. This sensitivity is related to the slope of the resonance wavelength as a function of the variation in the refractive index of the second overlay. At 1400-1600 nm of overlay thickness it stabilizes, which indicates that the second overlay resembles an infinite surrounding medium.

In summary, this is the first time a coupled mode analysis method based on hybrid modes has been applied for analyzing LPFGs with two overlays deposited on the cladding. The first overlay presents a higher refractive index than the cladding of the LPFG, whereas the second overlay presents a lower refractive index than the cladding. Under these conditions there exists a trade off between the thicknesses of both overlays to fix the resonance at a specific wavelength. The first overlay improves the sensitivity of the second overlay to variations in the refractive index of the second overlay. This widens the enhancement of sensitivity studied for overlays of higher refractive index than the cladding,[2] to deposition of materials of lower refractive index than the cladding of the LPFG. In addition to this, the thicker is the second overlay, the more sensitive is the device. Moreover, it has been proved that when the second overlay is thick enough, the sensitivity stabilizes to that of an LPFG with one overlay of finite thickness and a second overlay of infinite thickness. The consequence of this is that nanodeposition techniques can be applied to obtain artificially infinite surrounding media, with its important application in sensors field.

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Figure captions

Fig. 1: LPFG structure with two overlays deposited on the cladding.

Fig. 2: Resonance wavelength shift of $HE_{1,16}$ cladding mode resonance as a function of the thickness of the overlay. Three ambient refractive indices are analysed: 1 (air), 1.33 (water), and 1,37 ([PAH+ Prussian Blue^{+}/PAA]).

Fig. 3: Resonance wavelength of $HE_{1,16}$ cladding mode as a function of ambient refractive index for an LPFG without overlay and an LPFG with overlay of 68.72 nm and refractive index 1.62.

Fig. 4: First overlay thickness value for fixing $HE_{1,16}$ cladding mode resonance to 1450 nm as a function of second overlay thickness.

Fig. 5: Resonance wavelength of $HE_{1,16}$ cladding mode of an LPFG with two overlays as function of the refractive index of the second overlay. The refractive index of the first overlay is 1.62 and the ambient refractive index is 1 (air).

Figures

Fig. 1

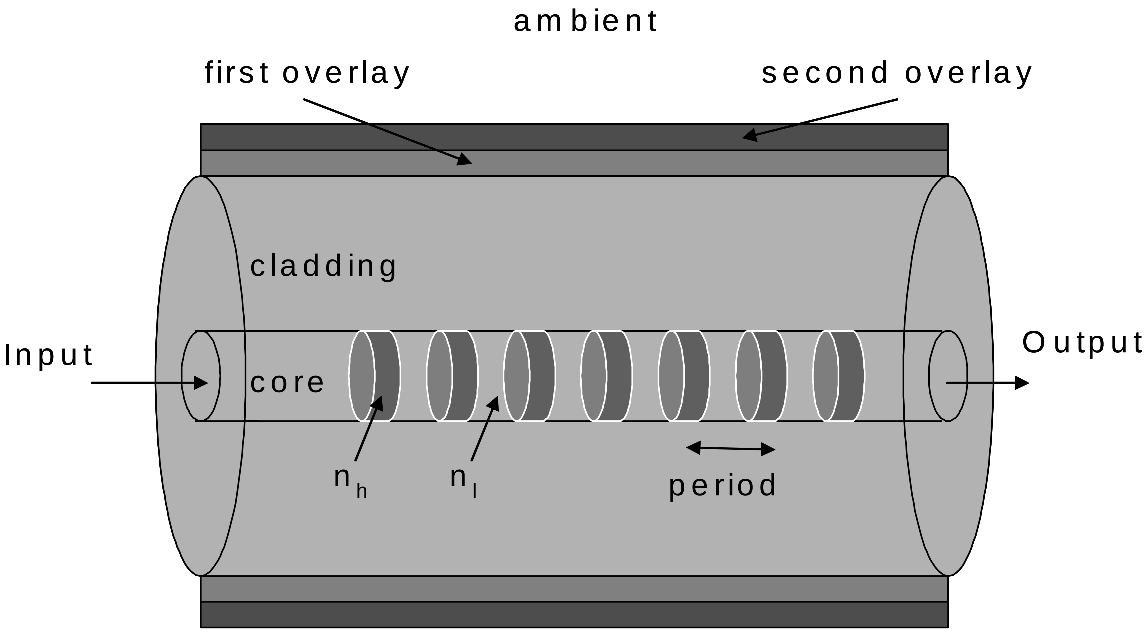


Fig. 2

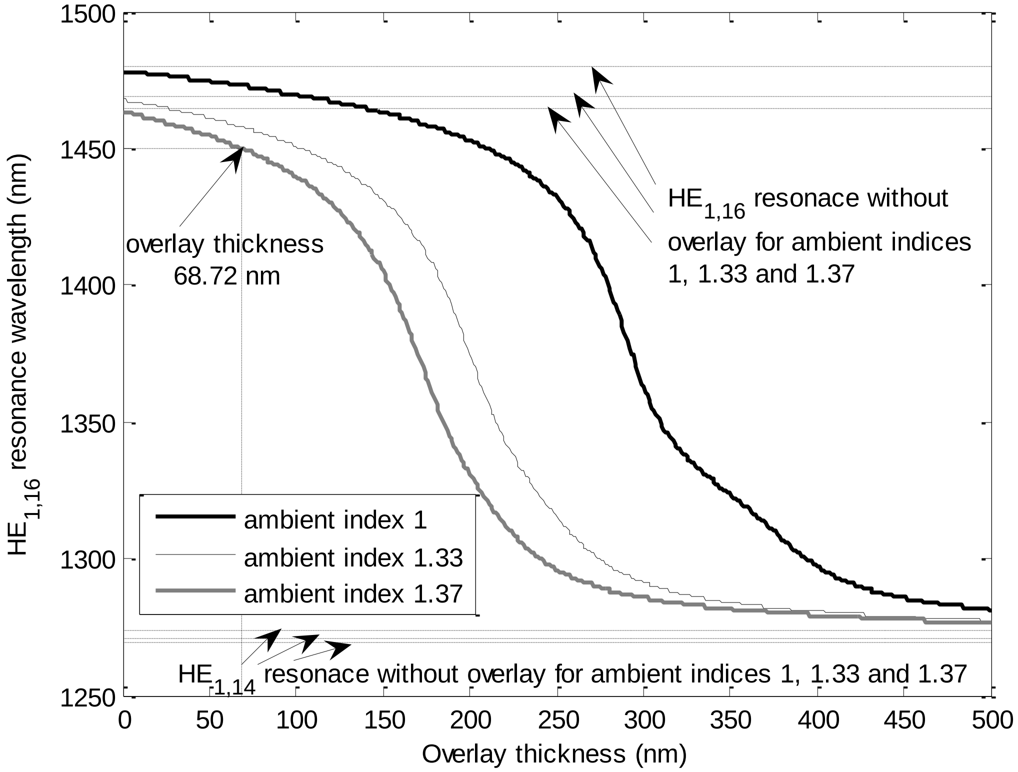

1500
1450
1400
1350
1300
1250
0
50
100
150
200
250
300
350
400
450
500
Overlay thickness (nm)
$HE_{1,16}$ resonance wavelength (nm)
ambient index 1
ambient index 1.33
ambient index 1.37
overlay thickness 68.72 nm
$HE_{1,16}$ resonace without overlay for ambient indices 1, 1.33 and 1.37
$HE_{1,14}$ resonace without overlay for ambient indices 1, 1.33 and 1.37

Fig. 3

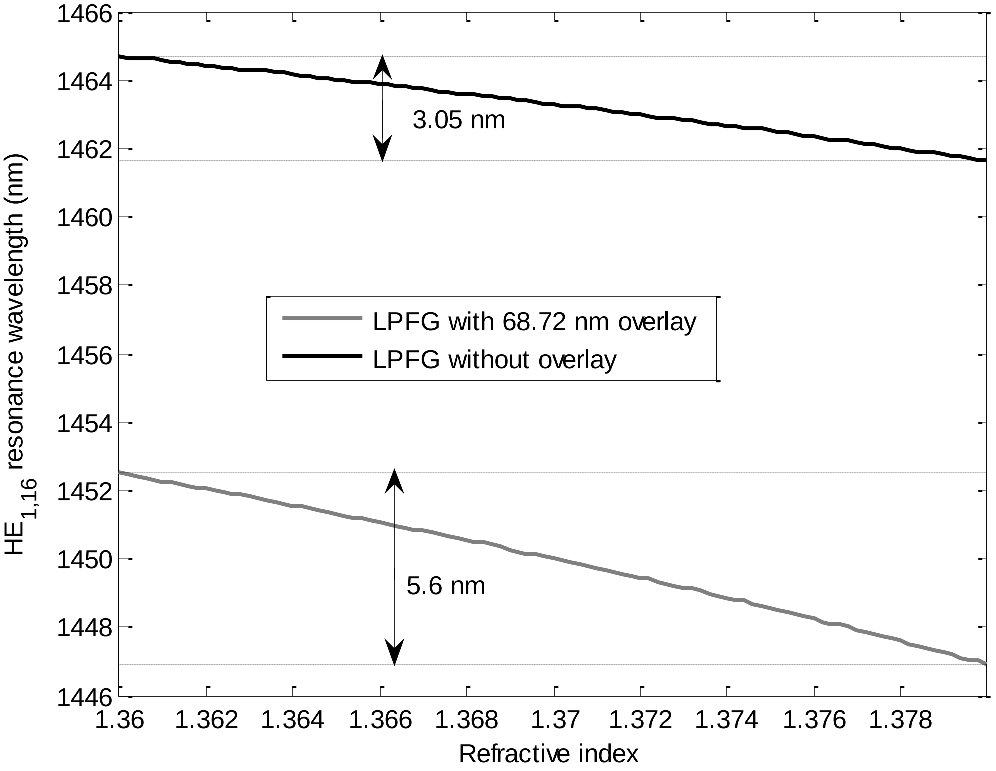

1466
1464
1462
1460
1458
1456
1454
1452
1450
1448
1446
1.36
1.362
1.364
1.366
1.368
1.37
1.372
1.374
1.376
1.378
Refractive index
HE$_{1,16}$ resonance wavelength (nm)
3.05 nm
5.6 nm
LPFG with 68.72 nm overlay
LPFG without overlay

Fig. 4

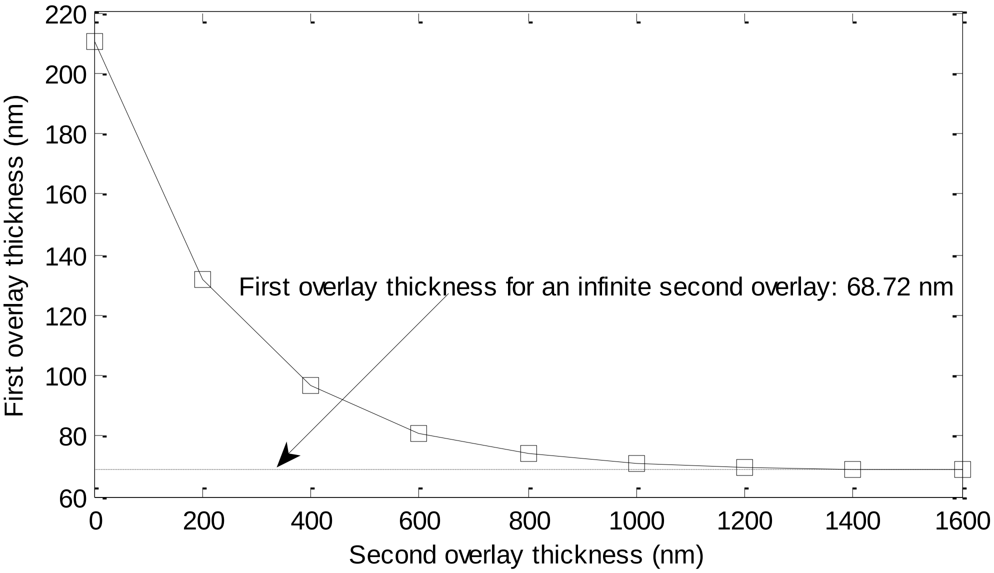
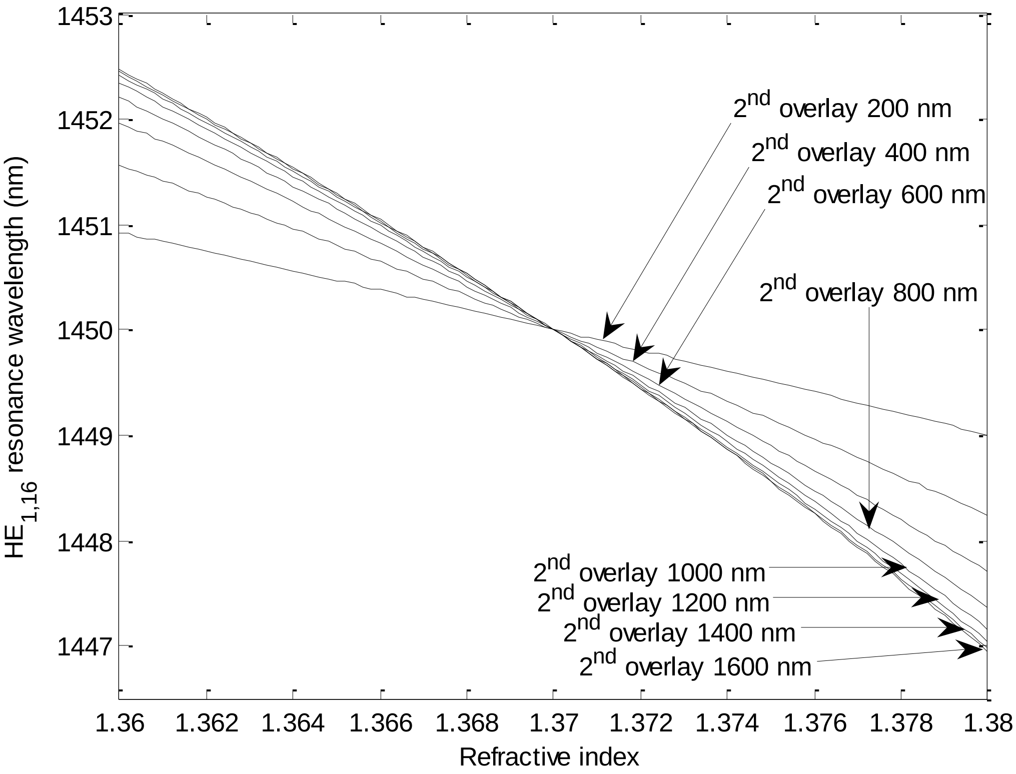

220
200
180
160
140
120
100
80
60
0
200
400
600
800
1000
1200
1400
1600
First overlay thickness (nm)
Second overlay thickness (nm)
First overlay thickness for an infinite second overlay: 68.72 nm

Fig. 5


1453
1452
1451
1450
1449
1448
1447
HE$_{1,16}$ resonance wavelength (nm)
1.36
1.362
1.364
1.366
1.368
1.37
1.372
1.374
1.376
1.378
1.38
Refractive index
2nd overlay 200 nm
2nd overlay 400 nm
2nd overlay 600 nm
2nd overlay 800 nm
2nd overlay 1000 nm
2nd overlay 1200 nm
2nd overlay 1400 nm
2nd overlay 1600 nm