# Modeling Long Period Fiber Grating using it's to EDFA Flatting Gain

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## ABSTRACT

In this paper we introduction a new model, which can be used to investigate the response of a Long-Period Fiber Grating to changes in ambient refractive index of value greater from refractive index cladding. The results show that even when the ambient refractive index is higher than that of the refractive index cladding, the power attenuation coefficient of the first order cladding mode being calculated over a wide range of $n_{am}$, and the power attenuation coefficient shift shows a dramatic change from a sharp increase of 0.00 dB to a sharp of 0.03788 dB. The result obtained suggest that LPFG's coated with a material of higher refractive index the cladding may be as index sensor, and flatting to parametric gain (i.e. ASE noise) in optical links.

***Key Word:*** Long Period Fiber Grating, WDM, Erbium Doped Fiber Amplifier, Fiber Bragg Grating.

# نموذج للمحزز الليفي ذو الفترة الطويلة لتسوية كسب المكبر الليفي المطعم بايونات الأربيوم

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## *الخلاصة*

في هذا البحث قدمنا نموذج جديد من المحزز الليفي ذو الفترة الطويلة، من خلال اخذ قيمة معامل الانكسار للمحيط الخارجي اكبر من معامل الانكسار لقشرة المحزز اليفي ذو الفترة الطويلة. بينت النتائج التغير ا لحاصل في قدرة معامل التوهين، حيث إن معامل التوهين يزداد مع الزيادة في معامل الانكسار للمحيط الخارجي ولكن ضمن مدى معين يتناسب مع معامل الانكسار لقشرة المحزز الليفي ذو الفترة الطويلة. أيضا بينا بعض المقترحات من ناحية استخدام مواد ذي معامل انكسار اكبر ليستخدم كمتحسس،وأيضا إمكانية استخدامه لتسوية كسب المعامل الثابت.

***1-Introduction:***

Fiber Optic Gratings or Fiber Bragg Gratings (FBG) were first reported in 1978 by Hill et al[1]. However, such devices only attracted the researcher's attention in1989, when new production techniques allowed their use with optical communication wavelengths. Several methods exist for FBG production, among them the direct phase mask writing and phase mask interferometers stand out[1].

A new class of fiber grating called Long Period Fiber Grating (LPFG) was demonstrated by Vengsarkar et al in 1996[1,2].The name is due to the refractive index change periodicity from 100µm to 700µm, about 100 times larger than the values employed for FBG formation. This difference makes possible the use of amplitude masks instead of phase masks, resulting in lower manufacturing costs when compared to the FBG production's costs. Besides this, the LPG presents other surpassing characteristics such as low insertion losses, low back reflection, relatively simple fabrication, sensibility to the surrounding medium refractive index (without etching the cladding to access the core's evanescent field), and a high sensitivity to changes in physical external parameters. These features made the LPG outstanding devices for application such as band rejection filters and gain equalizing filters in optical communication, beyond its wide applicability as a fiber optic sensor[1,2].

A long-period fiber grating, which couples light from a fundamental guided core mode into co-propagating cladding modes at various wavelengths. LPG have also been used as gain-flattening filter for EDFAs and as optical fiber polarizer's. As in the Fiber Bragg Grating (FBG),The LPG is sensitive to measured such as temperature or strain, which may alter the period of the grating or the refractive index of the core or cladding [2]. Unlike FBG the cladding mode configuration of the LPG is extremely sensitive to the refractive index of the medium surrounding the cladding, thus allowing it to be used as an ambient index sensor. An LPG is a photo-induced periodic structure written into the core of a germanium doped silica fiber by exposing it to UV light via an amplitude mask. The wavelength at which the coupling from core to cladding modes takes place is directly dependent on the difference between the core and cladding indices, the dimensions of the core and cladding and grating period. Any change in these values can shift the transmission spectral profile. The cladding mode profiles are also very sensitive to changes in the refractive index of the ambient (surrounding) environment, particularly when the value of the ambient refractive index higher then the cladding index is referred to as a leaky or hollow dielectrical wave-guide[2].

Erbium Doped Fiber Amplifiers (EDFA) are indispensable tools for providing optical amplification in wavelength-division-multiplexed (WDM) systems. However, it is difficult to transmit and amplify many WDM channels using EDFA's since the gain profile is wavelength dependent (nonuniform), while the transmission medium loss is, to first order, wavelength independent. This creates significant differences in the signal-to-noise ratios among the different amplified WDM channels which may, depended on the system power budget or dynamic rang of the receiver, cause system impairments and degrade performance[3]. Although gain-flattened EDFA's (uniform gain profile) have been fabricated, due to possible changes in operating condition and to network reconfiguration operations such as channel add/drop, variations can still exist among the power levels of the WDM channels amplifier by an EDFA. This problem will be further compounded by the fact that many EDFA's are generally used in transmission systems. It is thus of critical importance to be able equalize the power of the different WDM channels (after amplification) in a dynamic fashion in order to track the variations in the signal levels[3,4].

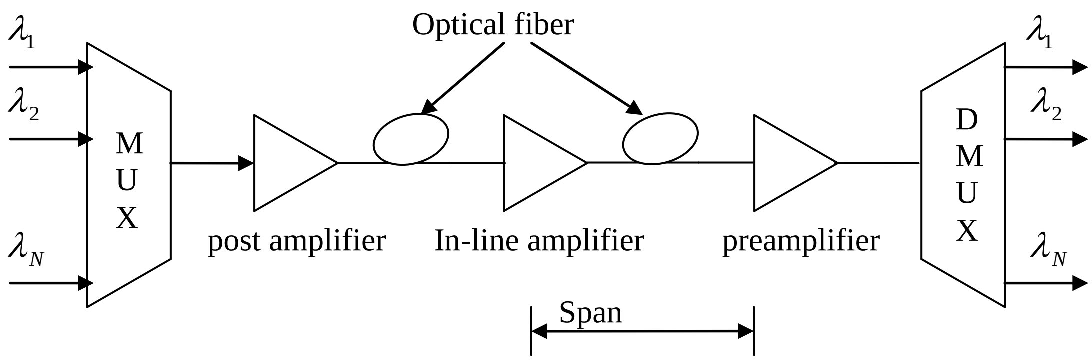
## *2-Wavelength Division Multiplexer (WDM):*

A powerful aspect of an optical communication link is that many different wavelengths can be sent along a single fiber simultaneously in the 1300nm-to-1600nm spectral band. The technology of combining number of wavelength onto the same fiber is known as wavelength-division-multiplexing or WDM.

Conceptually, the WDM scheme is the same as frequency-division-multiplexing (FDM) used in microwave radio and satellite systems. Just as in FDM, the wavelengths (or optical frequencies) in WDM must be properly spaced to avoid interchannel interference. The key system features of WDM are as follows[4,5]:

- Capacity upgrade: The classical application of WDM has been to upgrade the capacity of existing point-to-point fiber optic transmission links. If each wavelength supports an independent network signal of perhaps a few gigabits per second, then WDM can increase the capacity of a fiber network dramatically.
- Transparency: An important aspect of WDM is that each optical channel can carry any transmission format. Thus, using different wavelength, fast or slow asynchronous and synchronous digital data and analog information can be sent simultaneously, and independently, over the same fiber, without the need for a common signal structure.
- Wavelength Switching: Whereas wavelength-routed networks are based on a rigid fiber infrastructure, wavelength-switched architectures allow reconfiguration of the optical layer. Key components for implementing these networks include optical add/drop multiplexers, optical cross connects, and wavelength converters.
- Wavelength Routing: In addition to using multiple wavelengths to increase link capacity and flexibility, the use of wavelength-sensitive optical routing devices makes it possible to use wavelength as another dimension, in addition to time and apace, in designing communication networks and switches. Wavelength-routed networks use the actual wavelength of a signal as the intermediate or final address.

Figure (1) shows the use of such components in a typical WDM link containing various types of optical amplifiers[5].




Figure(1) Implementation of a typical WDM network containing various types of optical amplifiers.

### *3-Long-Period Fiber Grating Theory:*

Long period gratings are fiber optics based devices made up of periodic changes in core's refractive index. Photo induced long-period fiber gratings (LPG) with periods $L_{LPG} = 10^2 - 10^3 \mu m$. LPG are transmission grating in which the coupling is between forward propagation core and cladding modes, propagation in the same direction.

Typically in a single mode fiber(see figure 2) an LPG couples the fundamental guided core mode to a co-propagating cladding mode at a coupling (or resonance) wavelength[2].

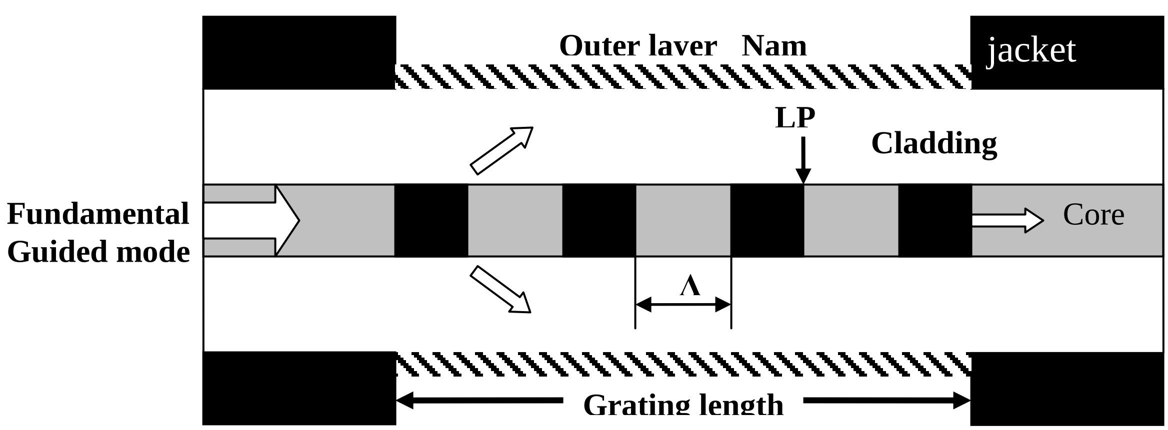



Figure (2) Long-period fiber grating

The excited cladding mode attenuates in the coated fiber part after the grating, which results in the appearance of resonance loss in the transmission spectrum. In contrast to Bragg grating, LPG does not produce reflected light and can serve as spectrally selective absorber[6].

The interaction of one mode of a fiber with other modes is commonly described with the help of coupled-mode theory in which only two modes are supposed to be nearly phase-matched and capable of resonant coupling. Based on this theory, quantitative information about the coupling coefficients and spectral properties of fiber grating can be obtained [10,11]. Two modes are coupled by a grating with period L, if their propagation constants $b_1$ and $b_2$ satisfy the phase matching condition[6]:

$$b_2 - b_1 = 2pk / L \qquad (1)$$

where k is an integer describing the order of the grating, in which the mode coupling occurs. Calculation methods of spectral characteristics of LPG's can be found in papers[12,13]. Below we will consider the most important relation describing the grating properties. Equation (1) for the resonant coupling of the fundamental mode and one of the cladding modes can be rewritten as[6]:

$$\left(n_{eff}^{core} - n_{eff}^{clad}\right) L_{LPG} = I_{LPG} \qquad (2)$$

where $n_{eff}^{core}$ and $n_{eff}^{clad}$ are effective refractive indexes of the core and cladding modes, respectively, and $I_{LPG}$ is the resonance coupling wavelength.

In order to get a complete set of modes $HE_{IM}$ and $EH_{IM}$ ( I and M are azimuthally and radial orders of the mode, respectively ), the wave equation for a dielectric cylinder with a certain radial index distribution should be solved. In single-mode fiber, only $HE_{11}$ mode is guided by the fiber core at $1 > 1_C$ ( where $1_C$ is the cutoff wavelength)[6,7].

Normally, a large quantity of modes ( $N \sim 10^4$ at $n_{ext} = 1$) can be guided by the cladding (stripped fiber with 125μm cladding diameter). Nevertheless, only some of them have a significant overlap integral *I* with the fundamental core mode. The integral should be taken in the fiber cross-section region, where modulation of the refractive index has been induced (for photo induced gratings, the integration region usually coincides with fiber core)[6,7]:

$$I = \frac{\int_0^A \int_0^{2\pi} E_{core} E^*_{core} r dr d\phi}{\sqrt{\int_0^\infty \int_0^{2\pi} E_{core} E^*_{core} r dr d\phi} \sqrt{\int_0^{\infty\infty} \int_0^{2\pi} E_{clad} E^*_{clad} r dr d\phi}} \tag{3}$$

where a is the core radius $E_{core}$ and $E_{clad}$ are the amplitude of the electrical field of the core and cladding modes, respectively, r and j are radial and azimuthal coordinates.

The overlap integral $I$ defines the efficiency of inter-modal conversion. Its value is large only for $HE_{1m}$ $(m>1)$ cladding modes, because only these modes have a sufficiently great electric field component in the fiber core. Fig. (3) shows the energy-normalized radial distribution of the electric field some of $HE_{1m}$ cladding modes. These modes are linearly polarized, their intensity distributions are axially symmetric, and the number of zeroes in the radial direction is $m$-1[6,7].

The overlap integral increases with increasing the radial mode number up to $m$~10, which is accompanied by an increase in the inter-modal coupling intensity. The latter can be seen from the transmission spectra of LPGs (Fig.4).Starting with a certain value of $m$, the overlap integral decreases to zero and thereafter oscillates with $m$, the amplitude of the oscillation tending to zero[6,7,8].

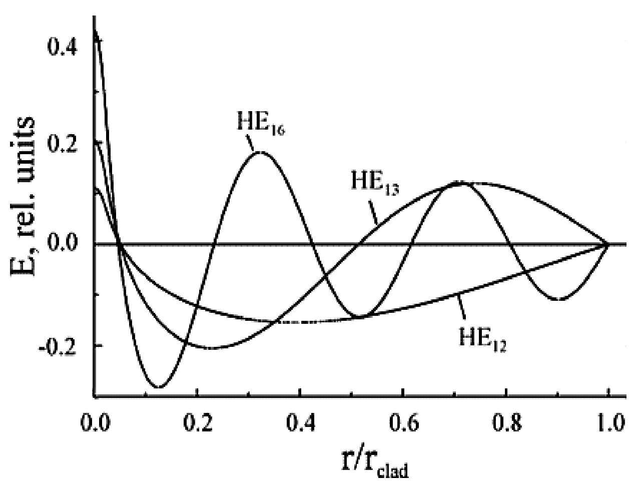



*Fig.3 Radial distributions of the electric field amplitude of the cladding modes $HE_{12}$, $HE_{13}$, $HE_{16}$*

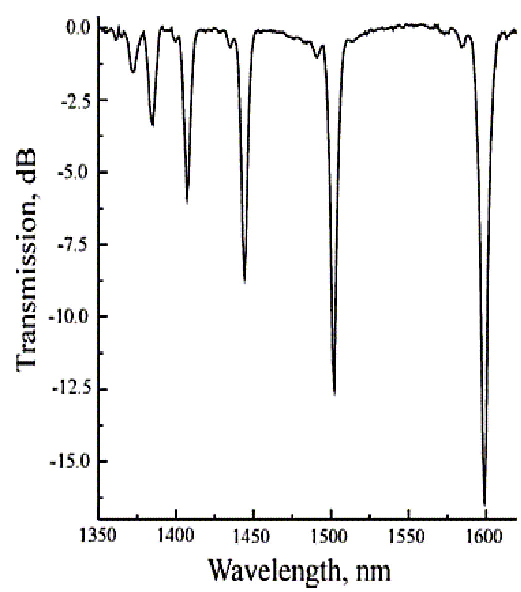



*Fig.4. A typical transmission spectrum of a LPG.*

The solution of coupled mode equations in the approximation of two interaction modes traveling in the same direction and in the assumption of small amplitude of induced index modulation in comparison with the silica glass index, gives the following energy exchange law ( for initial condition $R(0)=1$, $S(0)=0$)[7,8,9]:

$$R(z) = \cos^2(z(h^2 + d^2)^{1/2}) + d^2 \sin^2(z(h^2 + d^2)^{1/2})/(h^2 + d^2) \qquad (4)$$

$$S(z) = h^2 \sin^2(z(h^2 + d^2)^{1/2})/(h^2 + d^2) \qquad (5)$$

where $R(z)$ and $S(z)$ are the normalized energies of the core and cladding modes, respectively, considered as a function of z-coordinate along the fiber axis (the beginning of the grating corresponds to z=0):

$$d = pDn_{eff} D1/(I_{LPG}^2) = (P/L)(D1/I_{LPG}) \qquad (6)$$

is the normalized frequency, which describes the deviation from the exact synchronism; h is the coupling coefficient defined by a relation:

$$h = CpDn_{\mathrm{mod}} I / I_{LPG} \qquad (7)$$

$Dn_{\mathrm{mod}}$ is the induced index modulation amplitude of the fiber core, related with the total induced index change $Dn_{ind}$ via relation $Dn_{\mathrm{mod}} = Dn_{ind}/2$ ,C is a constant equal to the first coefficient in the Fourier transform of the grating pitch shape. If the index profile is sinusoidal, this constant is equal to unity. For a rectangular profile, which is more typical for LPG, $C = 4\sin(pd/L)/p$, where $d$ is the size of the irradiated part of the fiber within one grating period[١٢,١٣].

## *4-Results and discussion:*

Here, we using matlab programming(version 6.5) to simulation the transmission characteristics of an LPFG coupler and design it's. At the exact resonance (d=0), equations (4,5) gives a sinusoidal law of the energy exchange, showing a possibility of mutual energy transfer from one mode to another:

$$R(z) = \cos^2(hz) \qquad (8)$$

$$S(z) = \sin^2(hz) \qquad (9)$$

with the help of equations (4,5,6) it is possible to determine the total spectral width, which follows from the first zero of the grating spectrum:

$$\Delta\lambda_0 = \frac{2\lambda_{LPG}^2\sqrt{\pi^2-(\eta L)^2}}{\pi L \Delta n_{eff}} = \frac{2\lambda_{LPG}\Lambda\sqrt{\pi^2-(\eta L)^2}}{\pi L} \qquad (10)$$

Equation (10) allows one to obtain $DI_0$ in the assumption of a constant $Dn_{eff}$ within the grating bandwidth. However, the presence of dispersion of $Dn_{eff}$ in some cases can give a significant discrepancy between the experimental bandwidth and the calculated one. As mentioned above, the standard diameter of silica cladding is large enough and the cladding can guide plenty of modes. An LPG allows selective excitation of an individual cladding mode. This fact makes it possible to investigate the field distribution of the cladding mode excited by the grating.

Figure (5) shows the work style of LPFG. We can notice that transmission spectrum of this device when there is one input signal whose wavelength is 1554nm, The effective indices of the cladding modes are dependent on the cladding index and the index of the surrounding (outer) ambient environment ($n_{am}$)(see fig.2). This mean that the *n*th cladding mode coupling wavelength will change as the index of the surrounding environment change. Cladding modes are most accurately calculated using three-layer modes for case of $n_{am} < n_{eff}^{clad} < n_{clad}$ and irradiated part within one grating period =0.5e$^{-3}$. In this paper we focus on modeling of the leaky configuration (i.e. when $n_{am} > n_{clad}$).

The output signal whose of Erbium Amplifier, as shown in fig.(6),consists of two parts (the activated emission signal and the spontaneous emission signal). This device removes part of this signal when the resonance condition is realized (the resonance condition is 1557nm for this signal) so as to equalizer (flatting) the gain when the gain is changed in accordance with using several input signal to be amplified simultaneously (when there is a variety in the input power of this signals).

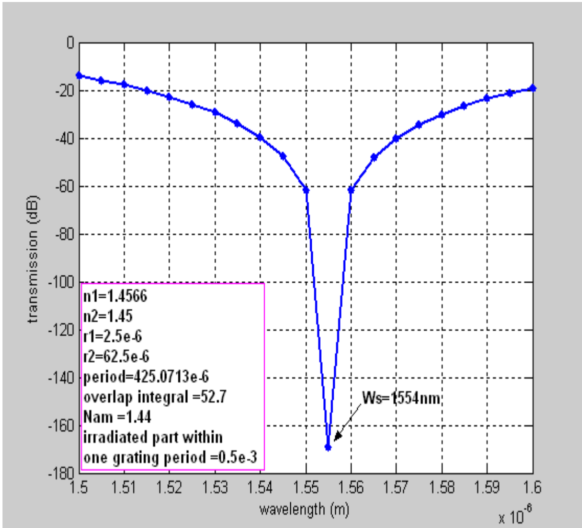



Fig.(5) Transmission spectrum of LPFG vs. wavelength at input signal (1554).

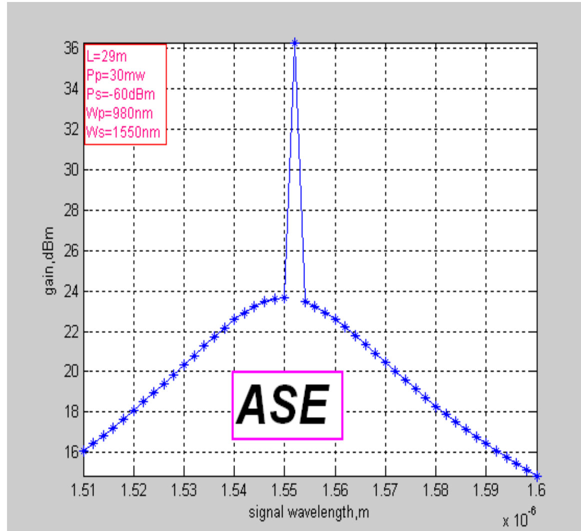



Fig.(6) Tran. Spectrum of EDFA vs. wavelengths

The two-layer model, equations (1) to (10), was used to create figures (7,8), the power attenuation coefficient of the first order cladding mode being calculated over a wide range of $n_{am}$ .The figure (7) show that the most sensitive regions are when $n_{am}$ is close to $n_{clad}$ and when $n_{am}$ changes from 1.889 to 2.113 (i.e. $\Delta n \approx 0.2$).

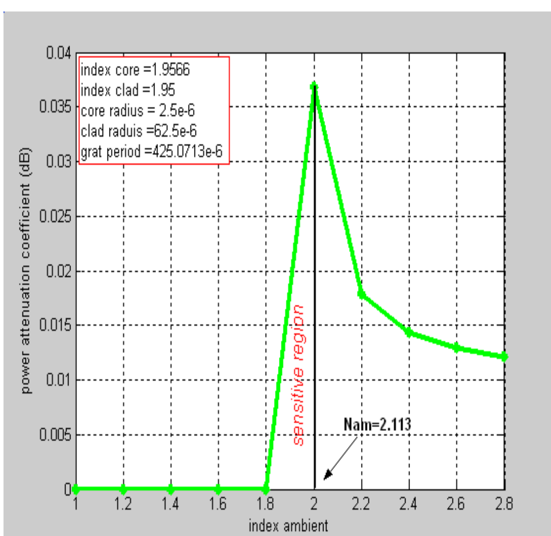



Fig.(7) effect the surrounding medium

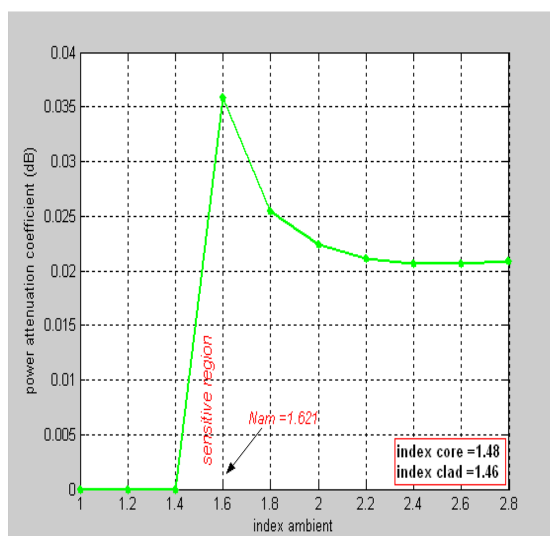



Fig.(8) effect the surrounding medium

The power attenuation coefficient shift shows a dramatic change from a sharp increase of 0.00 dB to a sharp of 0.03788 dB. This " switching property ", in this sensitive region, has a potential application in optical communications and optical sensors. Figs.(8) show the same effect result but with change to the core refractive index, cladding refractive index and surrounding refractive index ($n_{am}$>$n_{clad}$ ).From above equation with figures (7,8), we can to drive the equation that it's show the relationship between signal wavelength and index ambient (i.e. choose the signal wavelength that it's flatting).:

$$\lambda_{wavelength} = \mathrm{A}\pi L N_{am} N_{clad} \tag{11}$$

our model consists of rang from (1.4 to 1.48) to index ambient, that its large from cladding index (i.e. $\Delta n \approx 0.2$ ). Figs(9,10,11,12) shows effective index ambient on power attenuation coefficient, where we notice a dramatic change and sensitive region.

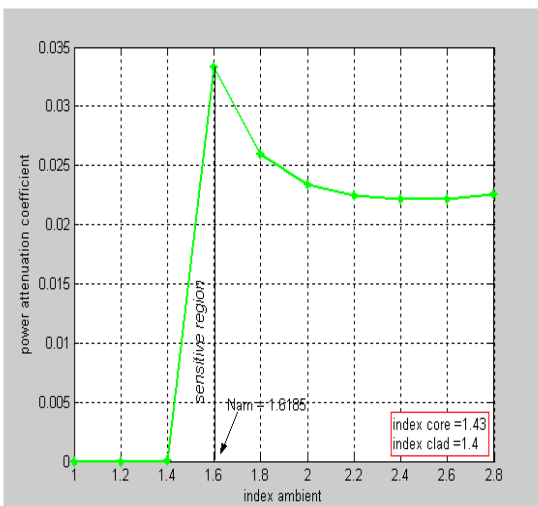



**Fig.(9) modeling index ambient**

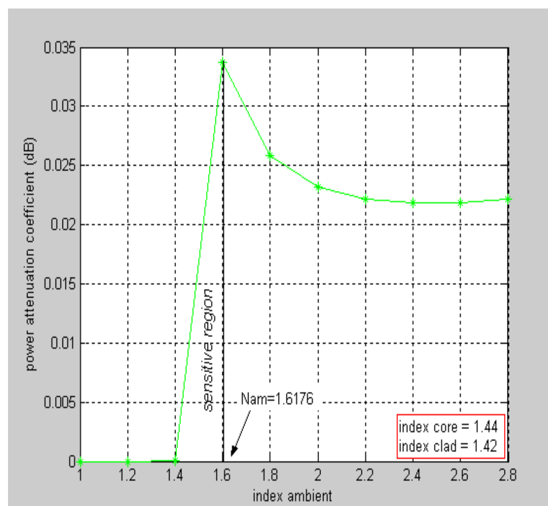



**Fig.(10) modeling index ambient**

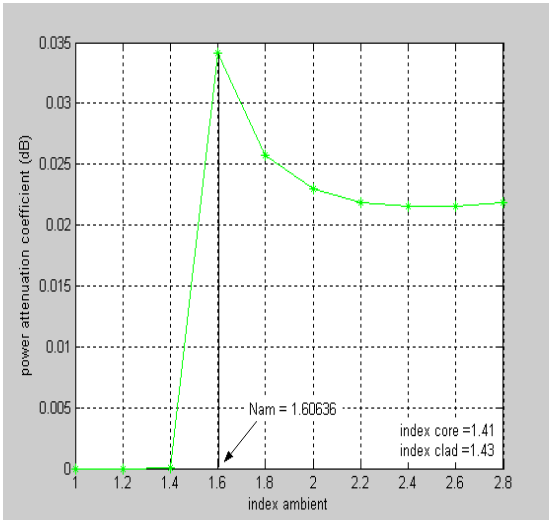



**Fig.(11) modeling index ambient**

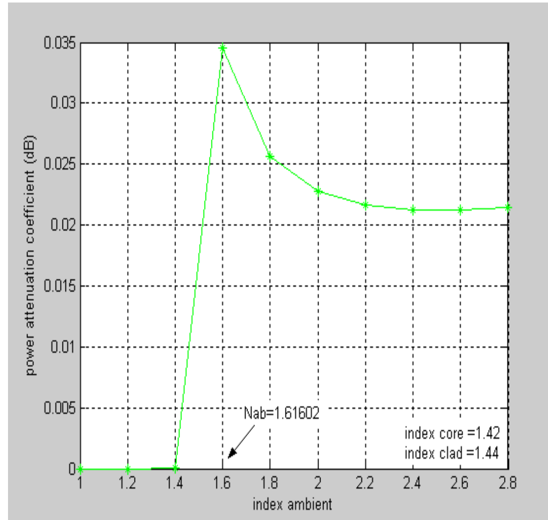



**Fig.(12) modeling index ambient**

**Table (1) wavelength(flatting) used in modeling**

| $\lambda_{eff}$ (nm) | $N_{clad}$ | $N_{amb} rang$ | $N_{amb}^{eff}$ | $\Delta n \cong$ |
|---|---|---|---|---|
| 1523 | 1.4 | 1.4213-1.61852 | 1.618524689 | 0.2185246 |
| 1533 | 1.42 | 1.4365-1.61767 | 1.617679101 | 0.1976791 |
| 1543 | 1.43 | 1.4472-1.60636 | 1.606366659 | 0.1763666 |
| 1553 | 1.44 | 1.4568-1.61602 | 1.616022964 | 0.1760229 |

Fig.(13) illustrates the output power of the EDFA with the wavelength when using two input signals to be amplified simultaneously( the value of the first one is -60dBm, and the value of the second -43dBm). We can detect the change that takes place in the amplifier output power with every input signal ( that means there is a change in the amplifier's gain when using more than one input signal with various powers to be amplified simultaneously(i.e. WDM technique )).

Fig.(14) present the flatting process for the change in the output power of the amplifier as was shown in Fig.(13). The LPFG was fixed behind the amplifier so as to flatting the out coming power as is made clear by Fig.(13),( we can compensate for the power loss by way of fixing an other amplifier just behind the LPFG).

Fig.(15) illustrates the output power of the EDFA with the wavelength when using five input signals to be amplified simultaneously (wavelength used in modeling). We can notice a change in the amplifier's output power at every input signal.

Fig.(16) shows the flatting process of the change in the output power in the amplifier's to that which is shown in Fig.(15) using our modeling.

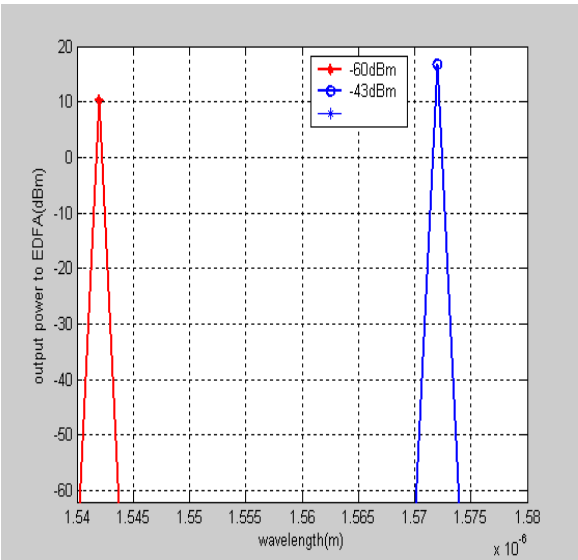



Fig.(13) output power to EDFA vs. wavelength with two signals.

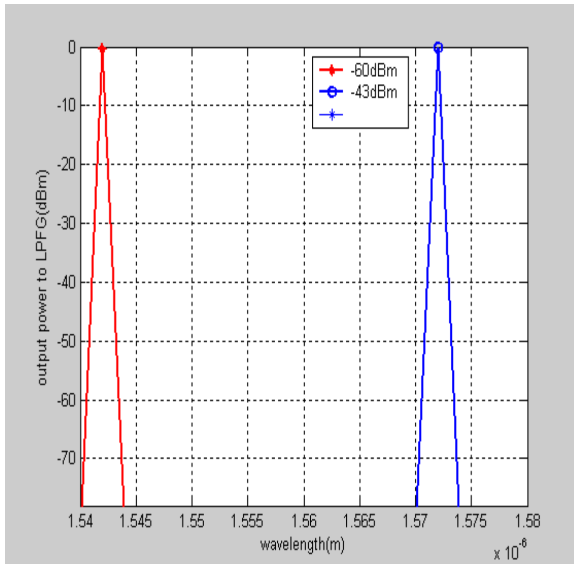



Fig.(14) output power to LPFG vs. wavelength with two input signals

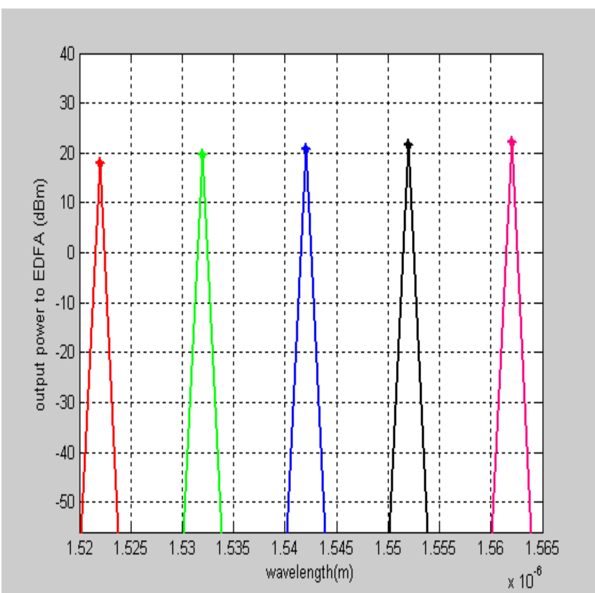



Fig.(15) output power to LPFG vs. wavelength with many input signals

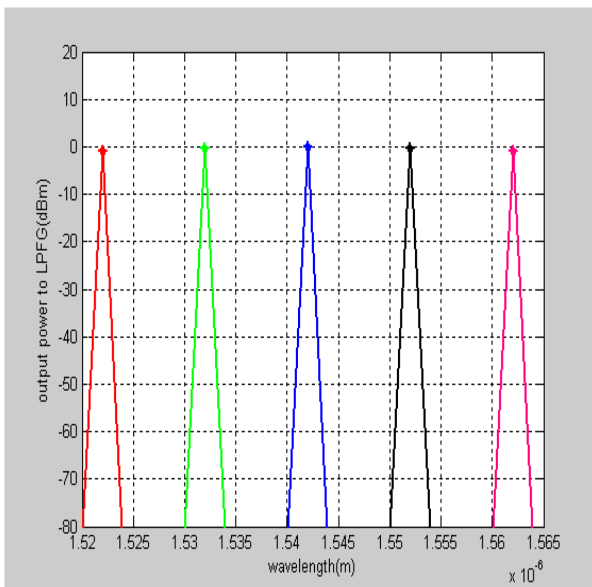



Fig.(16) output power to EDFA vs. wavelength with many input signals

## *5- Conclusions:*

In this paper we have presented to the LPFG model by changing the ambient refractive index over a wide range (1.4-1.6). these results reveal that when the ambient refractive index is higher than that of the cladding the coupling wavelength experiences a noticeable shift, which can easily be measured using a high resolution optical spectrum analyzer. And we have flatting gain to the output power to EDFA over a wide range (1520-1565)*nm*. These results suggest that the LPG may be used as an index sensor (when coated with a suitable material such as water). In long-haul amplified WDM optical links, the characteristics of the amplified spontaneous emission (ASE) noise introduced by the in-line Erbium Doped Fiber Amplifiers (EDFA's) may be modified by fiber nonlinear phenomena such as parametric gain (PG). therefore, the ASE noise affecting the signal at the receiver may be a non-white random process, and may be present a correlation between the in-phase and quadrature components. I suggest using LPFG's to reduced this effect( i.e. to avoid gain saturation in EDFA's that introduced by ASE noise in optical links. therefore, we put LPFG's in link to flatting ASE noise to reduced effect PG ).

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