The Effect of ambient refractive index on the action of Long Period Fiber Grating

Furat.y.Abdul-Razak

Furat_al2006@yahoo.com
Dept.of Software Eng., University of Mosul,Iraq

ABSTRACT

In this paper,we introduce a new model, of long-period fiber grating, by taking the value of ambient refractive index greater than the refractive cladding index, where the difference between them must equal(≈0.2).The results show the change in power attenuation coefficient, where it increases with the increase in refractive ambient index. The power attenuation coefficient shift shows a dramatic change of a sharp increase from 0.00 dB to 0.03788 dB.

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

تأثير معامل الانكسار للمحيط الخارجي على عمل المحزز الليفي ذو الفترة الطويلة

فرات يونس عبد الرزاق

*Furat*_al2006@yahoo.com.
جامعة الموصل قسم هندسة البرمجيات

الخلاصة

في هذا البحث قدمنا نموذجآ جديدآ من المحزز الليفي ذو الفترة الطويلة, من خلال اخذ قيمة معامل الانكسار للمحيط الخارجي اكبر من معامل الانكسار لقشرة المحزز الليفي ذو الفترة الطويلة, بحيث يكون الفرق بينهما يساوي (≈0.2). بينت النتائج التغير الحاصل في معامل توهين القدرة، حيث إن معامل التوهين يزداد مع الزيادة في معامل الانكسار للمحيط الخارجي التي تكون أعلى من معامل الانكسار للقشرة ولكن ضمن مدى معين يتناسب مع معامل الانكسار لقشرة المحزز (يزداد من 0.00 dB إلى dB 0.03788).

Received 25/2/2009

Accepted 7/9/2009

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, 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. the LPG have also been used as gain-flattening filter and as optical fiber polarizer [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. 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, and any change in these values can shift the transmission spectral profile [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, depending on the system power budget or dynamic range 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 [3].

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.

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

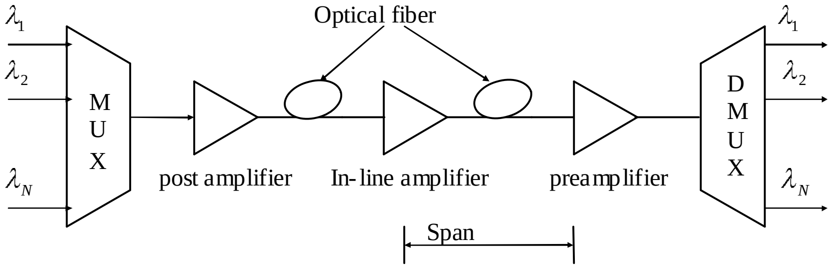


Fig.1 Implementation of a typical WDM network containing various types of optical amplifiers.

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].

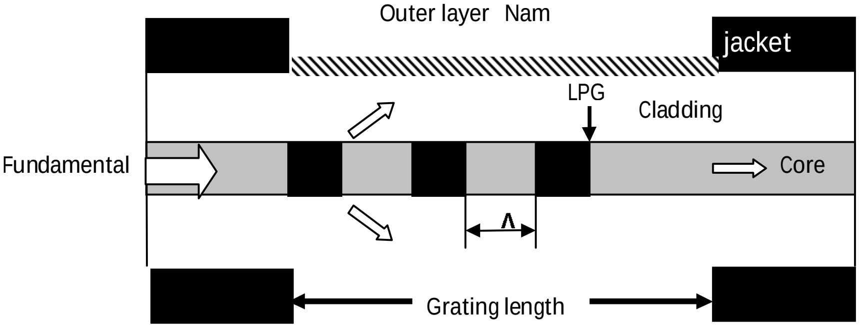


Fig.2 Long-period fiber grating

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.

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 $P = \pi$ and k is an integer describing the order of the grating and, in which the mode coupling occurs. Calculation methods of spectral characteristics of LPG's can be found in papers[12,13].Below will be considered 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 $\lambda > \lambda_C$ (where λ_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]:

$$I = \frac{\int_0^a \int_0^{2\pi} E_{core} E^*_{core} r\,dr\,d\phi}{\sqrt{\int_0^\infty \int_0^{2\pi} E_{core} E^*_{core} r\,dr\,d\phi}\sqrt{\int_0^\infty \int_0^{2\pi} E_{clad} E^*_{clad} r\,dr\,d\phi}} \qquad (3)$$

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 is 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 for some 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].

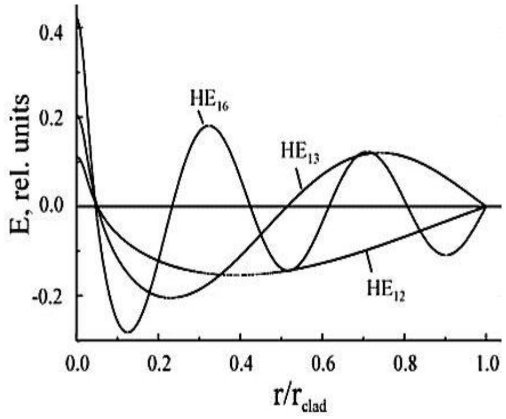


Fig.3 Radial distributions of the electric field

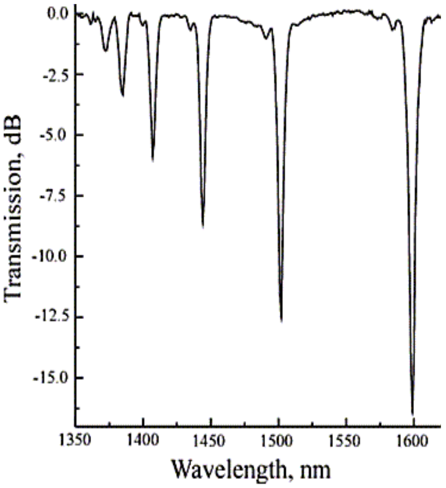


Fig.4.A typical transmission spectrum of a LPG.

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 $R(0)=1$, $S(0)=0$)[9,10,11]:

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

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

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). The normalized frequency d is:

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

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

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

Dn_{mod} is the induced index modulation amplitude of the fiber core, related with the total induced index change Dn_{ind} via relation $Dn_{\text{mod}} = Dn_{ind}/2$,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, $C = 4\sin(px/L_{LPG})/p$, where $p = \pi$ and x is the size of the irradiated part of the fiber within one grating period[12,13].

4-Results and discussion:

Here, we use matlab program version 6.5 to simulate and design the transmission characteristics of an LPFG coupler. 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:

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

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

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 changes. 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 signal).

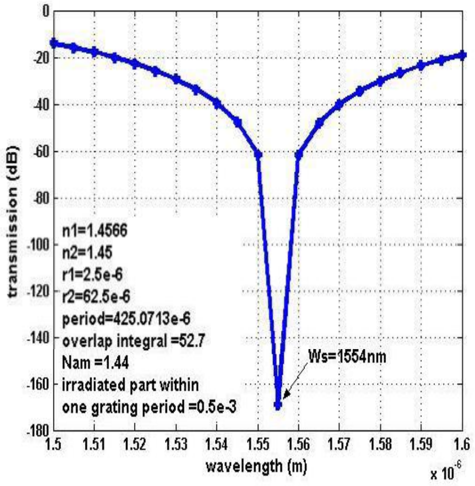


Fig.(5) Transmission spectrum of LPFG vs. wavelength at input signal (1554).

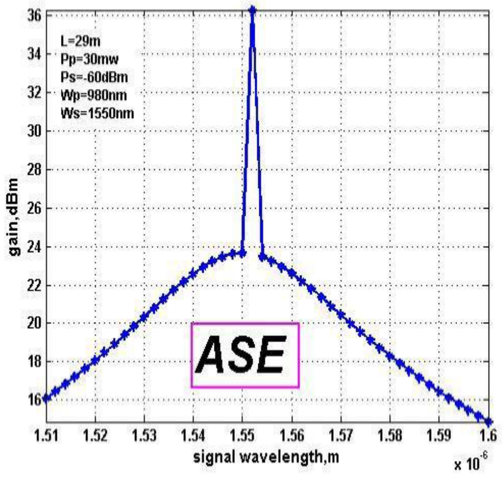
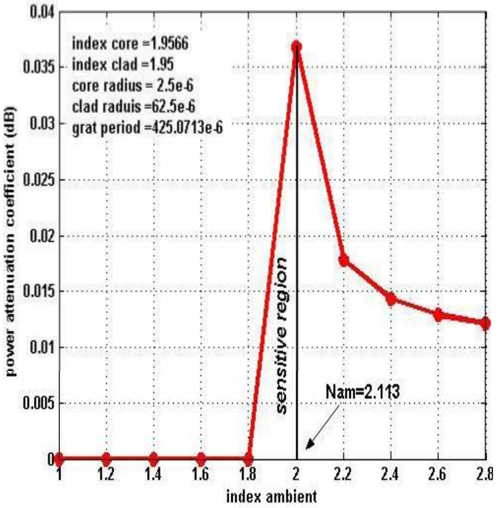


Fig.(6) Transmission spectrum of EDFA vs. wavelengths

The two-layer model, The power attenuation coefficient of the first order cladding mode being calculated over a wide range of n_{am} . Figure (7) shows 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. $\Delta n \approx 0.2$).



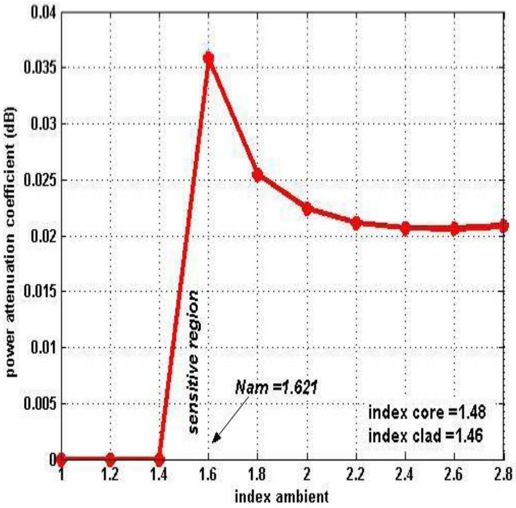


Fig.(7) Effect the surrounding medium

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(i.e. work region of our LPFG model will be only in sensitive region).

Fig.(8) shows the same effect result but with change to the core refractive index, cladding refractive index and surrounding refractive index ($n_{am}>n_{clad}$).From the above equations(from 1 to 9), we can derive the equation that shows the relationship between input signal wavelength and index ambient (i.e. choose the input signals wavelength that is flatting):-

$$\lambda_{wavelength} = A\pi L_{LPG} N_{am} N_{clad} \qquad (10)$$

Where A is fiber core area(1-10)µm^2. From the above equation we can design our the LPFG modeling in order to use it in flatting gain to EDFA when there are multi signals amplified on the link. Our model consists of a range from (1.4 to 1.48) to index ambient, that is larger than cladding index (i.e. $\Delta n \approx 0.2$). Figs(9,10,11,12) show our model, where this figs show effective index ambient on power attenuation coefficient, we notice a dramatic change and sensitive region and power attenuation coefficient value at $N_{amb}^{eff} \approx 1.61$.

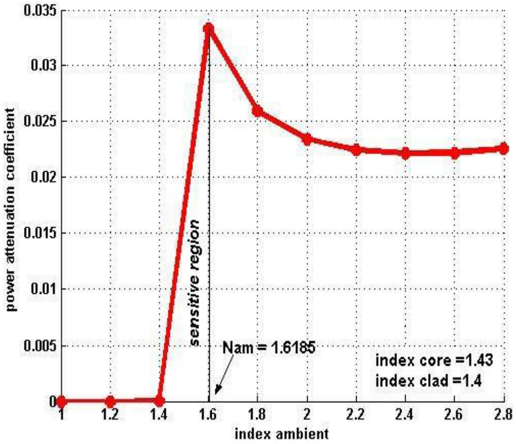


Fig.(9) Modeling index ambient

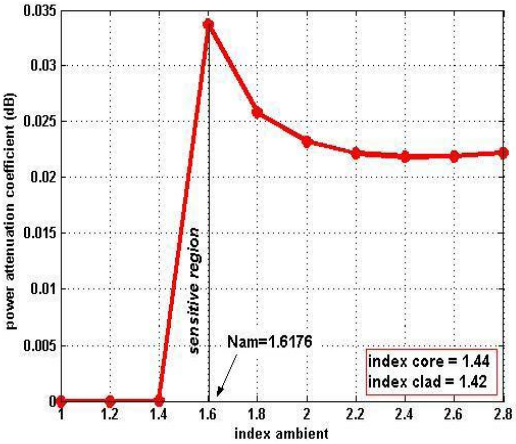


Fig.(10) Modeling index ambient

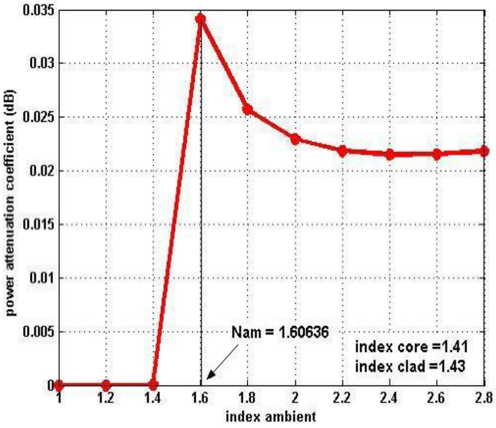


Fig.(11) Modeling index ambient

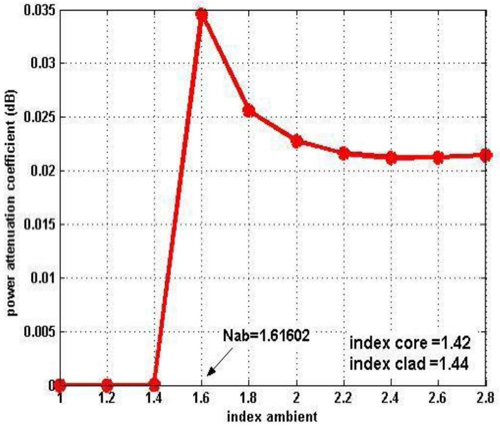


Fig.(12) Modeling index ambient

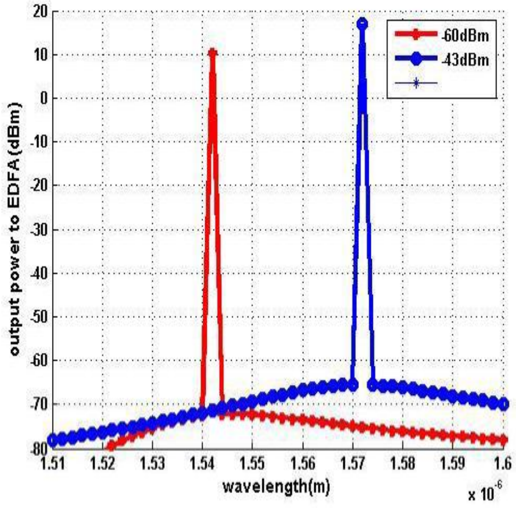


Fig.(13) Output power to EDFA vs. wavelength with two signals.

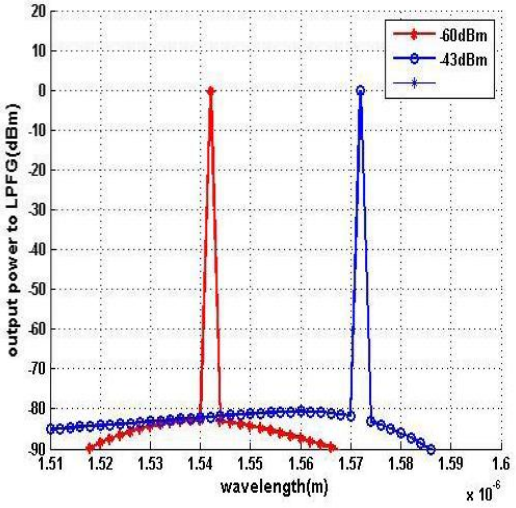


Fig.(14) Output power to LPFG vs. wavelength with two input signals

Table (1) Wavelength(flatting) used in modeling

λ_{eff} (nm)	N_{clad}	$N_{amb}rang$	$N_{clad} > N_{amb}^{eff}$	$\Delta n \cong$
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

From the figs and the table above notice the difference between cladding refractive index and surrounding refractive index must be $\Delta n \approx 0.2$, i.e. working region will be in sensitive region ($N_{amb}^{eff} > N_{clad}$). we will use our model in gain flatting to output signals for EDFA.

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) presents 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 flat the out coming power as is made clear by Fig.(13),(we can compensate for the power loss by way of fixing another 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). It can be noticed 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.

5- Conclusions:

In this paper, We have presented the LPFG model by changing the ambient refractive index higher than cladding refractive index ($n_{am} > n_{clad}$). The results may come up with many points:

1. The model works over a wide range (1.4-1.6).i.e. many inputs at the same time are flatting it (i.e. we have flat gain for the output power of EDFA over a wide range (1520-1565)*nm*).
2. is presented effective ambient index to LPFG working where the difference between cladding refractive index and surrounding refractive index in our modeling must be equal to $\Delta n \approx 0.2$.
3. The model may be used as an index sensor (when coated with a suitable material such as water).
4. In this modeling, the best working point, is when power attenuation coefficient is of a higher value ≈ 0.03788 dB (see fig.9,10,11,12).
5. 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 present a correlation between the in-phase and quadrature components. For the above reasons, LPFG's were suggested to reduce this effect(i.e. to avoid gain saturation in EDFA's that introduced by ASE noise in optical links. therefore, put LPFG's in link to flat ASE noise to reduced effect PG).

6-Referance:

1- Rosane Falate, Jose Luis Fabris, Marcia Muller and Hypolito Jose Kalinowski **"Long Period Grating Sensor to monitor Fuel Quality".** Asian Journal of Physics.Av.Sete de Setembro,3165-80230-901. Curitiba,Brazil 2002.

2- Jinho Bae, Jun Kye Base,Joohwan Chun, " **Analysis for long period fiber gratings using thermal kernel function",** Optical Society of America 2004.

3-Lawrence R. Chen, David J.F. Cooper, and Pwtwr W. E. Smith, " **Transmission Edge Filters For Power Equalization of EDFAs",** IEEE PHOTONICS TECHNOLOGY LETTERS.VOL.12,NO. 7, JULY 2000.

4-Jean-Pierre Laude," **DWDM fundamentals, components, and applications"** ,685 Canton Street Norwood,MA 020682, Artech House Boston. London 2002. www.artechhouse.com.

5-Gerd Keiser," **Optical Fiber Communications",** McGraw-Hill Higher Education,International Editions 2000,www.mhhe.com.

6-A.M. Vengsarkar, P.J.Lemaire," **Long-period grating theory",**Glass photosensitivity and Fiber Gratings, Fiber Research Center GPI RAN,2002.

7-O.Frazao,G.Rego,M.Lima,A.Teixeira.el," **EDFA Gain Flattening Using Long- Period Fiber Gratings Based on the Electric Arc Technique",** Electronics and Telecommunications Dept.,University of Averiro,3810-193 Aveiro,Portugal.2002.

8-Omer Mermer," **EDFA Gain Flattening by Using Optical Fiber Grating Techniques",** Department of Electrical and Electronics Engineering, Ege University, Bornova, Izmir, Thesis Advisor: Asst. Prof. Gokalp Kahraman.2003.

9-Kin Seng Chiang, " **Analysis of Two Parallel Long-Period Fiber Gratings",** Journal of Lightwave Technology, VOL.22,NO.5, MAY 2004.

10-T.Tamir,ed.," **Integrated Optical",** Vol.7 of Topics in Applied physics, Springer-Verlag,1975.

11-T.Erdogan, "**Fiber grating spectra",**J.Lightwave Technol., Vol 15,pp. 1277-1294,1997.

12-S.A.Vasiliev,E.M.Dianov,A.S.Kurkov,O.I.Medvedkov,V.N.protopopov, "**photoinduced in-fiber refractive-index gratings for core-cladding mode coupling",**Quantum Electron., Vol 27,pp.146-149,1997.

13-T.Erdogan,"**Cladding-mode resonances in short-and long-period fiber grating filters",**J.Opt.Soc.Am.A, Vol 14, pp. 1760-1773, 1997.

The work was carried out at the college of Engg. University of Mosul