Gain Equalization of Erbium Doped Fibre Amplifiers with Tuneable Long-Period Gratings

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Abstract—This paper presents an adaptive gain equalization technique of the gain spectrum for an Erbium Doped Fibre Amplifier (EDFA) by using a tuneable Long-Period Grating (LPG). The gain spectrum of an EDFA at a wavelength of 1530nm was equalized from 5.2dB peak-to-peak to 2.3dB peak-to-peak. The LPG was fabricated by using an excimer laser and a metal mask. By means of a novel technique that enables one to tune the peak attenuation of the LPG, the gain equalizer can operate over a wide range of pump power.

Index Terms—Erbium Doped Fiber Amplifier, Long-Period Grating, Gain Equalization, Wavelength-Division Multiplexing.

I. INTRODUCTION

Gain equalization of EDFA's has been a research topic in recent years with the development of high capacity WDM optical communication systems. The EDFA has been considered to be a key device in WDM transmission systems for fiber loss compensation and for the provision of an optical network with almost unlimited coverage [1]. However, the EDFA has a non-uniform gain spectrum that restricts its usable amplifier bandwidth. The amplification of a WDM signal by a non-equalized EDFA may result in signal distortion and poor signal-to-noise ratio performance. Several methods, either intrinsic or extrinsic, have been proposed to equalize the EDFA gain spectrum. Intrinsic methods constitute changing the spectroscopic properties of the erbium-doped glass absorption and emission cross-section by co-doping with other ions, or by using different glass matrices or special fibre designs. Alumino-silicate [2] or fluoride based glass [3] are known to improve the flatness of the EDFA gain spectrum. Extrinsic methods are based on filtering devices connected in series with the EDFA. Several filters that have been demonstrated include acousto-optic tuneable filters [4], long-period gratings [5] and blazed gratings [6]. LPGs are showing promise as spectrally selective filters due to unique features such as low insertion loss, low back-reflection and excellent polarization-insensitivity [7]. When the LPG is used for gain equalization of an EDFA, the transmission spectrum of the LPG is fixed at the resonance wavelength. This is because it involves fibre parameters, and coupling between the core and the cladding modes.

II. EDFA CHARACTERIZATION

A. Optical Amplification by Erbium-Doped Fibres

The EDFA relies simply on pumping the ions within the erbium-doped fibre to high energy levels where they can relax via the process of stimulated emission, which produces amplification [8, 9]. The pumping can be either around 1480nm or 980nm as shown in Figure 1. Electrons in the lower level can absorb energy and are excited to a higher energy level. The probability of this occurring is weighted by the absorption cross-section, $\sigma_a(\lambda)$. Similarly, electrons in the upper level can be stimulated to return to the lower level, releasing a photon by stimulated emission. The probability of this process occurring is weighted by the emission cross-section, $\sigma_e(\lambda)$. Electrons in the upper level can also return to the lower level spontaneously, releasing a photon by spontaneous emission. The probability of spontaneous emission is proportional to the inverse of the lifetime in the upper state.

![Three-level energy diagram of erbium ions](image-url)

Fig. 1. The three-level energy diagram of erbium ions.
B. Gain Spectrum for the EDFA

The spectral dependence of the amplifier gain is a weighted combination of the gain and absorption cross-sections where the weighting depends on the populations of the upper and lower levels. This can be written as [9, 10]:

\[ G_{\text{sp}}(\lambda) = 4.343(\bar{N}_2 \sigma_e(\lambda) + \bar{N}_1 \sigma_a(\lambda))\Gamma_s L \]  

(1)

where \( \Gamma_s \) indicates the effective overlap factor between signal and ion population, \( \bar{N}_1 \) is the lower level population, \( \bar{N}_2 \) is the upper level population and \( L \) is the length of the erbium doped fibre. The gain can be calculated directly from the longitudinal average of the upper and lower populations. A typical gain spectrum for an EDFA obtained by using equation (1) is shown in figure 2.

C. Power Conversion Efficiency

The power conversion efficiency describes the efficiency of conversion of pump power into added optical signal power by the amplifier. Although the amplifier only uses at most a few watts of power, the pump efficiency is important because of the cost of manufacturing higher power pump lasers with good reliability. Thus high pump efficiency is always desirable. A formal definition of power conversion efficiency (PCE) is given by [8]:

\[ \text{PCE} = \frac{P_{\text{signal\_out}} - P_{\text{signal\_in}}}{P_{\text{pump}}} \]  

(2)

where \( P_{\text{signal\_out}} \) is the signal output power, \( P_{\text{signal\_in}} \) is the signal input power and \( P_{\text{pump}} \) is the pump power. The PCE will depend on the proportion of the pump photons lost to spontaneous recombination, to those used for signal amplification.

It is affected by the doping concentration, host material, fibre length, and pump configuration. The PCE is lower for a 980nm pump source than for a 1480nm pump source because one photon at 980nm has more energy than one photon at 1480nm: either pump will produce one signal photon for one pump photon. Thus a 100mW 1480nm pump will produce 50% more power than a 100mW 980nm pump. A fairer comparison is the quantum conversion efficiency (QCE) which is defined as [9]:

\[ \text{QCE} = \left( \frac{P_{\text{signal\_out}} - P_{\text{signal\_in}}}{P_{\text{pump}}} \right) \frac{\lambda_{\text{signal}}}{\lambda_{\text{pump}}} \]  

(3)

Optimizing the conversion efficiency of the erbium-doped fibre has resulted primarily from the proper choice of erbium concentration and host material [10]. Thus, too high concentrations of erbium will reduce the conversion efficiency.

D. Noise Characteristics

All amplifiers will generate noise during the amplification process, given that the net gain of any internal losses is greater than unity. The noise power due to ASE \( (P_{\text{ASE}}) \) within a measurement bandwidth \( B_M \) (in both polarizations of an optical amplifier with negligible internal losses) can be related to its gain, G, [8]

\[ P_{\text{ASE}} = 2n_{sp}(G - 1)h\nu B_M \]  

(4)

where \( n_{sp} \) is the population inversion parameter, \( \hbar \) is Planck’s constant and \( \nu \) is the optical frequency of the noise. For the erbium doped fibre amplifier the population inversion parameters are related to the absorption and emission cross-sections, \( \sigma_e \) and \( \sigma_a \), that are strongly wavelength dependent, and the population in the upper and lower levels, \( N_2 \) and \( N_1 \), by [8]

\[ n_{sp} = \frac{\sigma_e(\lambda)N_2}{\sigma_e(\lambda)N_2 - \sigma_a(\lambda)N_1} \]  

(5)

Equation (5) suggests that a very strong pump will reduce \( n_{sp} \) close to unity, as ions will be transferred from the lower to the upper level. The population inversion depends on the signal and noise power at a particular point along the amplifier, so the ASE has to be integrated along the amplifier length. If the fibre amplifier has a very low gain (such as occurs in lightly doped fibre), the population inversion parameter will be modified to be [9]:

\[ n_{sp} = \frac{\sigma_e(\lambda)N_2}{\sigma_e(\lambda)N_2 - \sigma_a(\lambda)N_1\left(\frac{g}{g - \alpha}\right)} \]  

(6)
where \( g \) is the gain coefficient and \( \alpha \) is the loss coefficient of the erbium fibre. The loss coefficient dominates the noise figure for fibre and the gain coefficient compensates the gain of the amplifier. The noise figure of an amplifier is a measure of the degradation of the signal-to-noise ratio for a signal passing through the amplifier. The noise figure is expressed as [8]:

\[
NF (dB) = 10 \log_{10} \left( \frac{P_{ASE}}{h\nu B_m G} + \frac{1}{G} \right)
\]

(7)

It is important to realize that equation (7) assumes that no noise is rejected at the input to the amplifier (i.e., a shot-noise-limited input signal). In reality, noise figure measurements are useful in the process of evaluating optical amplifier performance for analog modulation applications. Noise figure is commonly used to measure the signal-to-noise (SNR) of the amplifier and is defined by

\[
NF (dB) = \frac{SNR_{in}}{SNR_{out}}
\]

(8)

where \( SNR_{in} \) and \( SNR_{out} \) are signal-to-noise ratios at the input and output of the amplifier.

III. LPG MODELLING

LPGs consist of a refractive index modulation in the core of optical fibers. Operation of the LPG is based on the coupling of the fundamental guided mode and forward cladding leaky modes. Coupling occurs when the matching condition satisfies [7]:

\[
\beta_{co} - \beta_{cl}^m = \frac{2\pi}{\Lambda}
\]

(9)

where \( \beta_{co} \) and \( \beta_{cl}^m \) are the propagation constants of the fundamental and \( m \)th cladding modes, \( \Lambda \) is the grating period and the superscript \( m \) defines the order of the mode. Using the relation \( \beta = \frac{2\pi n_{eff}}{\lambda} \), where \( n_{eff} \) is the effective index of the mode, we can rewrite the phase matching condition as [11]

\[
\lambda_{res} = \left( n_{co}(\lambda) - n_{cl}^m(\lambda) \right) \Lambda
\]

(10)

where \( \lambda_{res} \) is the resonance wavelength, \( n_{co} \) is the effective refractive index of the core mode and \( n_{cl}^m \) is the effective index of the \( m \)th cladding mode. The wavelength dependence of the effective indices is due to material and waveguide dispersion. Material dispersion can be assumed to have the same overall effect on \( n_{co}(\lambda) \) and \( n_{cl}^m(\lambda) \). Thus when the difference is taken, it is the waveguide dispersion which is the dominant contributor to the grating spectrum [12].

From (9), it can be shown that [7]:

\[
\frac{d\lambda_{res}}{d\Lambda} = \left( \frac{n_{co}(\lambda)-n_{cl}^m(\lambda)}{1 - \frac{dn_{co}(\lambda)}{d\lambda} \frac{dn_{cl}^m(\lambda)}{d\lambda}} \right)
\]

(11)

A particular grating period can cause the mode-coupling at the wavelength that would be predicted. The first step is the calculation of effective indices of the fundamental core mode and the various resonant cladding modes of the fibre at a specific wavelength. A set of periodicities of \( \Lambda^m \) is obtained that will meet the matching condition given by equation (9). This step is repeated for several wavelengths and the resulting plot of coupling wavelength versus grating period is shown in figure 3. The graphs in figure 3 describe the process of mode coupling to azimuthally symmetric modes with uniform index perturbations perpendicular to the direction of propagation. It is clear from the graph that as the higher order cladding modes are encountered (moving from right to left on the graph), the slope of the resonant line changes from a positive value to a negative value at a particular mode. The transmission loss for each mode depends on the strength of the coupling coefficient defined as [13]:

\[
\kappa(\lambda) = \frac{\pi \Delta n_{mod} \overline{\mathcal{I}}}{\lambda}
\]

(12)

where \( \Delta n_{mod} \) is the refractive index modulation of the grating and \( \overline{\mathcal{I}} \) is the overlap integral between the core and cladding modes.

![Fig.3 Theoretical determination of the relationship between grating periodicity and wavelength where guided-to-cladding mode coupling takes place](attachment:fig3.png)
The overlap integral is defined as a measure of coupling strength between the guided LP_{01} and LP_{mn} modes:
\[ S = \frac{2\pi}{L} \int_0^\infty \int_0^\infty \psi_{01}(r,\varphi) \psi_{mn}(r,\varphi) r dr d\varphi \]  
(13)
where \( \psi_{01}(r,\varphi) \) and \( \psi_{mn}(r,\varphi) \) are the normalized optical field distribution of the LP_{01} and LP_{mn} modes respectively. The transmission spectrum of the uniform LPG can be calculated by using [14]:
\[ T(\lambda) = \cos^2 \left( \sqrt{\kappa^2(\lambda) + \delta^2(\lambda)L} \right) + \frac{\delta^2(\lambda)}{\delta^2(\lambda) + \kappa^2(\lambda)} \sin^2 \left( \sqrt{\kappa^2(\lambda) + \delta^2(\lambda)L} \right) \]  
(14)

IV. EXPERIMENTAL RESULTS

A KrF excimer laser operating at 248nm was used as UV source. The length of fibre exposed to the excimer laser was 2.5cm. The LPG was made using an amplitude mask and the transmission spectrum was monitored with a computer. Figure 5 shows the experimental setup to observe gain equalization of an EDFA using a tuneable LPG. The EDFA is composed of a 16-m long erbium-doped fibre (EDF), WDM couplers and an optical isolator. The EDFA is co-directionally pumped by a 980-nm laser diode with power up to 80mW. The optical isolator is used to block the reflected light into the tuneable laser. The WDM coupler on the right in figure 5 is used to dump the residual pump power while simultaneously allowing the 1550nm signal to pass. The equalized gain spectrum of the EDFA was achieved at 150mA pump current by adjusting the tuneable long period grating appropriately.
The measured non-equalized gain spectrum of the EDFA pumped at 980nm, 150mA (60mW) is shown in figure 6. There is a primary gain peak at 1531nm of 25.7 dB and a secondary gain peak at 1547nm of 21.6dB. The LPG was placed inside a 55% Glycerin and water for wavelength shifting and we used a proprietary technique to change the attenuation of the LPG to match the gain peak of the EDFA. Figure 7 shows the wavelength shifting of the grating spectrum by using the external liquid. The transmission spectrum of the LPG to match the primary gain peak of the EDFA is shown in figure 8. This spectrum was found by measuring the spectrum of the LPG using the broadband source of about 1500-1600nm.

Figure 9 shows the measured relative attenuation of the tuneable equalization filter over the wavelength range from 1480 nm to 1580 nm as obtained with a broadband optical source. The gain spectrum of the EDFA with the implemented tuneable LPG is shown figure 10. From the spectrum it is seen that the tuneable LPG greatly improves the gain flatness of the EDFA gain spectrum. The EDFA was pumped with a current of 150mA and the signal input of –30dBm wavelength tuneable range was used as the input to the EDFA. The EDFA spectrum shows that it amplifies the input signal by 100, which means that we have a gain of about 20dB for the input of –30dBm. Thus, this type of EDFA is an ideal choice for WDM applications as a pre-amplifier. The tuneable filter also serves as an ideal adaptive gain equalizer as shown in figure 10.
V. CONCLUSION

Gain equalization of an EDFA with tuneable LPG was successfully demonstrated. This gain equalization technique could be used in long-distance amplified lightwave communication systems to prevent the accumulation of relative gain differences among channels in WDM transmission.

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