A Study of Dynamic Characteristics of Spectral Hole Burning in Erbium-Doped Fiber Amplifiers

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Abstract: ***This paper aims to study various dynamic characteristics of Spectral Hole Burning (SHB) in Erbium Doped Fiber Amplifiers (EDFA) under different parameters. Studies showed that gain variations induced by SHB decreases with increasing temperature and the SHB effects are proportional to the elevation in signal powers. However, inhomogeneous line-width broadening of EDFA occurs at shorter wavelengths.***

Keywords: Erbium-Doped Fiber Amplifier (EDFA), Spectral Hole Burning (SHB), Amplified Spontaneous Emission (ASE)

1. Introduction

The most popular doped fiber amplifier is an Erbium-Doped Fiber Amplifier (EDFA) which is currently utilized in many long-haul lightwave systems. This amplifier is doped with rare earth ions such as Erbium (Er^{3+}) which are excited to a higher level by laser pumping, resulting in a signal gain in the 1500nm wavelength window. Since long distance communication links typically use wavelength near 1550nm, Erbium-Doped Fiber Amplifiers (EDFAs) are most useful for long distance communications applications.

Currently, most of the commercial EDFAs operate in the C-band, but the amplification bandwidth has been extended to include the L-bands and S-bands in recent years thus enhancing the transmission bandwidth [1]. An EDFA can be built using a single or dual pump lasers. A pumping signal can either co-propagate or counter-propagate with an input signal. The most efficient pump band for pre-amplifier applications is 980nm since it requires much less pump power to obtain the same noise performance compared to 860nm and 1480nm pump bands. On the other hand, for booster applications, a 1480nm pump is more efficient than 860nm and 980nm pump bands.

The use of insufficient pump power or too long fiber can lead to part of amplifier providing loss rather than gain. Alternatively, increasing pump power arbitrarily or using too short a fiber leads to insufficient use of pump power. There is, therefore, an optimum fiber length that has a strong dependence on pump power, input signal power, amount of rare-earth doping, pumping wavelength[1]. The EDFA characteristics that play a key role in determining the performance of lightwave link are gain, saturation power and spontaneous amplifier noise.

2. Optical Amplifiers

A basic optical communication link consists of a transmitter, receiver and an optical fiber cable connecting the transmitter and receiver. Although signals propagating in optical fiber suffer lesser attenuation than in other mediums, such as copper, there is still a limit of about 100km on the distance the signals can travel before becoming too noisy to be detected [2].

Before the commercialization of optical amplifiers, it was necessary to electronically regenerate the optical signals every 80km to 100km in order to achieve transmission over long distances. So an ideal optical amplifier, as given in Fig.1, is designed to directly amplify any input optical signal, without needing to transform it first to an electronic signal. It can simultaneously amplify all Wavelength Division Multiplexing channels, and is generally transparent to the number of channels, their bit-rate, modulation format and protocol[2]. Thus, a single optical amplifier can replace all the multiple components required for an electronic regeneration station. Furthermore, the transparency of the optical amplifier means that the link can be upgraded without the need to replace the amplifier.

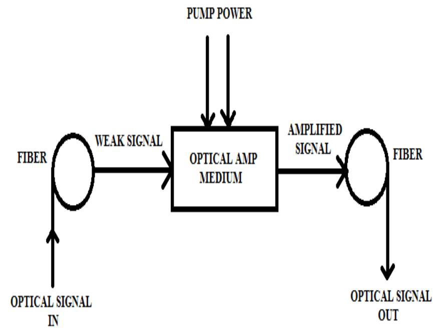

Figure 1. General Representation of an Optical Amplifier

2.1 Principle And Theory

To achieve optical amplification, the population of electrons in the upper energy level has to be greater than that of lower energy level. This condition is known as population inversion and it can be achieved by exciting electronsto higher energy level by an external source called pumping [3]. Stimulated emission occur, when incident photon having energy E= hc/λ interact with electron in upper energy state causing it return to lower state with creation of second photon, where h is Plank constant, c is velocity of light and λ is the wavelength of light. When an incident photon &an emitted photon are in phase, two more photons are released leading tolight amplification. Continuation of this process effectively creates avalanche multiplication and thereby obtaining an amplified coherent emission.

2.2 Types of Optical Amplifiers

Optical amplifiers were classified on the basis of device characteristics i.e., whether it is based on linear characteristics (Semiconductor optical amplifier and Rare-earth doped fiber amplifiers) or nonlinear characteristics (Raman amplifiers and Brillouin amplifiers). Optical amplifiers were also classified on the basis of structure i.e., whether semiconductor based (SOAs) or fiber based (Rare-earth doped fiber amplifiers), Raman and Brillouin scattering amplifiers.

3. Erbium-Doped Fiber Amplifiers

The Erbium-Doped Fiber Amplifier (EDFA) is the most deployed fiber amplifier as its amplification window coincides with the third transmission window of silica-based optical fiber [4]. There are two bands developed in the third transmission window – the Conventional, or C-band, from approximately 1525nm to 1565nm, and the Long, or L-band, from approximately 1570nm to 1610nm. Both of these bands can be amplified by EDFAs, but two different amplifiers are used for optimizing each of the bands. The energy levels of erbium ions in EDFA are shown in Fig.2.

The principal difference between C-band and L-band amplifiers is that a longer length of doped fiber is used in L-band amplifiers [5]. The longer length of fiber allows a lower inversion level to be used, thereby providing a useful amount of gain.

EDFAs have two commonly-used pumping bands – 980nm and 1480nm. The 980nm band has a higher absorption cross-section and is generally used where low-noise performance is required. The absorption band is relatively narrow and so wavelength stabilized laser sources are typically needed. The 1480nm band has a lower, but broader absorption cross-section and is generally used for higher power amplifiers. A combination of 980nm and 1480nm pumping is generally utilized in amplifiers.

The optical fiber amplifier was invented in the early 1980s by H. J. Shaw and Michel Digonnet at Stanford University, California. The EDFA was first demonstrated by a group including David N. Payne, R. Mears and L. Reekie, from the University of Southampton and a group from AT&T Bell Laboratories, E. Desurvire, P. Becker and J. Simpson.

3.1 Basic Principle of EDFA

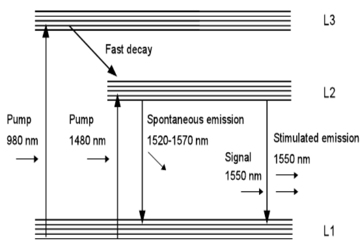

Figure 2. Energy levels of Erbium ions in EDFA [6]

Using a wavelength-selective coupler, a relatively high-powered beam of light is mixed with the input signal. The input signal and the excitation light must be at significantly different wavelengths. This mixed light is guided into a fiber whose core is doped with erbium ions. This high-powered light beam excites the erbium ions to their higher-energy state. When the photons belonging to the signal at a different wavelength from the pump light meet the excited erbium atoms, these erbium atoms give up some of their energy to the signal and return to their lower-energy state. These erbium ions give up its energy in the form of additional photons which are exactly in the same phase and direction as the signal being amplified. The signal is amplified along its direction of travel only. It is because, when an atom “lases”, it always gives up its energy in the same direction and phase as the incoming light. Thus all the additional signal power is guided in the same fiber mode as the incoming signal. Usually an isolator is placed at the output to prevent reflections returning from the attached fiber. Such reflections disrupt amplifier operation and in the extreme case can cause the amplifier to become a laser.

3.2 Advantages of using EDFA

- Available in C-band & L-band
- High gain: 20dB to 40dB
- Low noise figure: 4.5dB to 6dB
- No distortion at high bit rates
- Can simultaneously amplify Wavelength Division Multiplexing signals
- Immunity to cross-talk between wavelength multiplexed channels
- High speed electronics is not required
- Bit rate independent

4. Spectral Hole Burning in EDFA

The gain spectrum has an inhomogeneous component due to the inhomogeneous portion of the line-width broadening of the dopant ions. Thus gain saturation occurs, to a small extent, inhomogeneously. This phenomenon is known as spectral hole burning because a high power signal at one wavelength can 'burn' a hole in the gain for wavelengths close to that signal by saturation of the inhomogeneously broadened ions [1]. Spectral holes vary in width depending on the characteristics of the optical fiber in question and the power of the burning signal. In the case of C-band, they are typically less than 1nm at the short wavelength end and a few nm at the long wavelength end. The depth of the holes is very small and hence it is difficult to observe in practice.

The EDFA behaves like a homogeneously broadened amplifier across a limited wavelength range. The EDFA, across its entire gain band, has significant homogeneous broadening. That is, all the signals across the EDFA gain band can equally access the stored energy responsible for gain anywhere across the band. However, measurements have revealed the presence of spectral hole-burning (SHB) with a dependency of ~0.3 dB for each dB of gain compression. Thus the accuracy of a method that uses a single high-power channel to represent the ensemble of Discrete Wavelength Division Multiplexing channels would be limited by SHB. In general, in the presence of SHB, N channels are used to represent M actual channels ($N \leq M$) across the wavelength range of the channel plan. The separation of the N channels is determined by the widths of the spectral holes. For example, a minimum of one channel per SHB hole-width should be used. Spectral hole widths vary from about 3nm to greater than 10nm across the EDFA gain region. The narrower holes tend to be around the 1530nm region which implies more saturating channels to cover this region.

SHB demonstrates more impacts at the shorter wavelength range of around 1530nm compared with that in the extended wavelengths as shown in Fig.3. A hole depth as small as 0.1dB is produced for a 4dB gain compression in the 1545nm to 1560nm wavelength domain. Some researchers have also found that the spectral hole depth and width were functions of saturating signal wavelength and power. The shape of the spectral hole is complex and thus cannot be characterized by a simple Gaussian distribution.

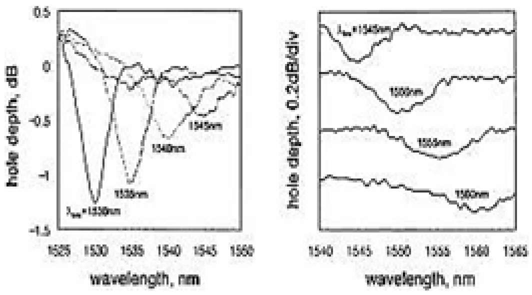

Figure 3. Spectral Hole Depths versus Wavelength
Courtesy: www.sciencedirect.com

3.3 Dependence of SHB on Temperature

Gain variations are observed in EDFA even if channels are added or dropped and typically the effect of SHB becomes clearly noticeable only in a cascade of amplifiers. Dynamic response of SHB is one of the effects that lead to these gain variations. Using pump wavelengths of around 1480nm leads to larger variations in gain and noise figure as compared to 980nm pumping.

Depending on the pump wavelength, different energy levels of the erbium ions are involved in the amplification mechanism. When using pumping light around 1480nm, only the lowest two energy levels (ground level $^4I_{15/2}$ and metastable level $^4I_{13/2}$) are of importance. However a third energy level $^4I_{11/2}$ comes into play if the pump wavelength is close to 980nm.

An experiment to show the dependence of SHB on temperature has been suggested by Joao.M.Ferreria*et al* [7] in 2012 by using one probe channel centered at 1531.1nm and one co-propagating pump in a widely used commercial EDF of 10m length. In addition, ten polarization scrambled signals are launched in the fiber. Using an oscilloscope, power variations at the output of the EDF are recorded.

The above experiment concluded that gain variations induced by SHB decreases with increasing temperature, irrespective of the number of involved energy levels of erbium ions. Also, EDFA pumped at 980nm is more sensitive to temperature variations than that pumped at 1480nm. No significant difference with respect to transition time has been observed [7].

3.4 SHB Effects in a Gain-Flattened EDFA

A.R.Sarmani*et al* [8] in their experiment demonstrated that SHB effects in a gain-flattened EDFA are significant in the presence of large signal power around 1530nm to 1532nm wavelength range. They suggested that an introduction of a new local population variable into the laser equation is required to support the original inversion ratio that is determined by the pump lasers. Spectroscopic parameters and high signal powers are considered to be other contributing parameters to the change in gain characteristics. Thus, they have implemented a mathematical modeling to validate similarities between the gain shapes of simulation to that obtained in the experiment.

In designing Wavelength Division Multiplexing devices for long-haul communication, maintaining the gain uniformity of the amplifier is difficult. To resolve this, optical filters have been developed to ensure consistency in the gain operation. SHB degrades the amplifier performance with the onset of unnecessary nonlinear effects.

The experiment layout consists of four amplifier stages, a dispersion compensating module (DCM), a variable optical attenuator (VOA) and a gain equalization filter (GEF). This experiment is carried out both at small signal power and at higher powers to study the SHB at different wavelengths. A slight gain distortion of around 0.6dB is observed for wavelengths that are less than 1532nm. The gain increment observed at a shorter wavelength region ($\lambda_s \leq 1532$nm) is more significant and different with respect to the signal powers. This effect is assumed to occur because of SHB.

Inversion ratio at population *i* can be expressed as:

$$\tilde{n}_2^{(i)} = n_{ave}(\lambda_p, z) + \Delta n_{SHB}(\lambda_s, z) \quad (1)$$

where, $n_{ave}(\lambda_p, z)$ is the average population inversion ratio at position z that is influenced by pump wavelength λ_p and $\Delta n_{SHB}(\lambda_s, z)$ is the inversion ratio induced by the SHB effect [8].

For signal wavelengths that are longer than 1532nm, $\Delta n_{SHB}(\lambda_s, z)$ is 0 and so:

$$\tilde{n}_2^{(i)} = n_{ave}(\lambda_p, z) \quad (2)$$

Gain dynamics is strongly influenced by the intensity of the optical powers where the SHB effect is proportional to the elevation in signal powers. At the extended wavelengths ($\lambda_s \geq 1532$nm), stable gain pattern is observed[8].

3.5 SHB in the ASE Spectrum of EDFs

The saturation characteristics of EDFA depend strongly on the relative amounts of homogeneous and inhomogeneous broadening of the erbium transition. Amount of homogeneous broadening is experimentally determined by SHB. An effect characteristic of homogeneously broadened transitions is SHB. W.A.Arellano*etal*[9] showed that using differential method as given in Fig.4, SHB can be observed directly in the ASE spectrum with the help of an experimental setup. They suggested that revealing holes in the ASE spectrum, rather than in gain spectrum, is a much simpler and faster measurement.

Two ASE spectra were recorded in the experiment, the first using a saturating wavelength of 1532nm and the second at 1552nm. The subtracted spectrum (in log-scale) directly shows the SHB effect.

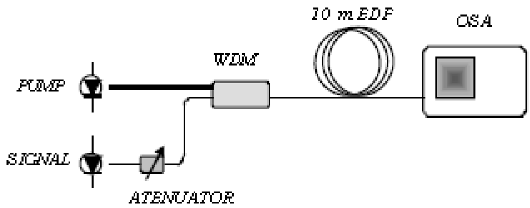

Figure 4. Experimental setup for SHB observation directly in the subtracted ASE spectrum [9]

A saturating signal at 1532nm from a tunable laser and 1480nm pump laser are coupled in EDF through Wavelength Division Multiplexing coupler. This ASE spectrum is stored in the memory of the OSA (trace A). The laser is then tuned to 1552nm, thus measuring a new ASE spectrum (trace B). The subtracted spectrum (B-A) is directly displayed in the OSA screen. It appears form the output that the homogeneous line-width is larger at longer wavelengths[9].

4. Conclusion

In this paper, we investigated the characteristics of Spectral Hole Burning (SHB) on various parameters. It is concluded that gain variations induced by SHB decreases with increasing temperature, irrespective of the number of involved energy levels of erbium ions. The gain dynamics is strongly influenced by the intensity of the optical powers where the SHB effect is proportional to the elevation in signal powers. Furthermore, at shorter wavelengths, inhomogeneous line-width broadening of EDFA occurs.

Currently, there is no efficient mitigation technique known for SHB. In future, better gain flatness can be achieved with doping modifications or filters.

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