PRE-AMP EDFA ASE NOISE CHARACTERIZATION FOR OPTICAL RECEIVER TRANSMISSION PERFORMANCE OPTIMIZATION

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Abstract

Amplified Spontaneous Emission (ASE) noise mitigation from a pre-amp Erbium-Doped Fiber Amplifier (EDFA) to the Photon Detector (PD) in optical receivers can be reduced by minimizing the EDFA ASE noise at the optical receiver level to achieve optimal optical receiver transmission performance. The experimental work presented here focuses on the pre-amp EDFA noise performance characterization and analysis at the optical receiver level. This is the ultimate performance characterization method for the pre-amp EDFA, and it was performed through testing of the optical receiver transmission performance under different pre-amp operating conditions.

Introduction

The main motivation for this work was to present a set-up and a procedure that can be used to characterize pre-amp EDFA noise and to present the results obtained using such a set-up and procedure. This work adds to the current knowledge in this field by the results obtained and presented here. This study concluded that the pre-amp EDFA needs to be optimized at the same input power and the same signal-to-noise factor at which it is to operate. The input power performance was in line with the one analyzed for Figure 4, where an increase of the input signal power resulted in an improvement of the optical receiver transmission performance.

The basic design of an optical receiver consists of an EDFA, an optical band-pass filter, a photon detector, a limiting amplifier, and an electrical low-pass filter [1]. Pre-amp EDFAs are becoming an integral part of optical receivers since their performance is interrelated to the performance of the photon–detector receiver. The photon detector used in optical receivers is either a PIN diode or an Avalanche Photo Diode (APD). APDs have higher sensitivity than PIN diodes, but they exhibit excess noise that degrades the optical receiver transmission performance. On the other hand, PIN diodes have better noise characteristics than APDs; therefore, optimal optical receiver transmission performance can be achieved by using a combination of a pre-amp EDFA for good sensitivity and a PIN photon detector for low noise.

The generation of ASE noise in a pre-amp EDFA is an effect of the spontaneous de-excitation of the excited erbium electrons. Because the electrons have finite excited state lifetimes, some of the electrons return spontaneously to the ground state, emitting photons that have no coherence characteristics with respect to the incoming optical signal. These photons are different from the photons generated by stimulated emission.

The collection of spontaneously-generated photons, being multiplied by the fiber amplifier, forms background noise. This background noise is known as amplified spontaneous emission, and it is the dominant noise element in pre-amp EDFAs. ASE and its effect on the deterioration of the signal-to-noise ratio for pre-amp EDFAs can be measured in different ways [2].

Erbium Atomic Structure

Erbium atomic structure has three energy levels that are of interest for the study of its amplification characteristic for use in communications. In three-level erbium atomic structure, population inversion can be achieved using laser pumping at 980nm to excite electrons to the upper erbium atomic state. When excited to the upper state, Erbium electrons rapidly decay non-radioactively to the meta-stable state. If electrons in the meta-stable state are not stimulated within the electron lifetime in that state, electron transition to the lower states results in spontaneous emission. Spontaneous emission is a random emission that introduces noise. The behavior of the erbium-doped fiber atomic structure is described in the following level rate equations [3]

$$\frac{dN_3}{dt} = -\frac{N_3}{\tau_{32}} + (N_1 - N_3) * \sigma_P * S_P \quad (1)$$

$$\frac{dN_2}{dt} = -\frac{N_2}{\tau_{21}} + \frac{N_3}{\tau_{32}} - (N_2 - N_1) * \sigma_S * S_S \quad (2)$$

$$\frac{dN_1}{dt} = \frac{N_2}{\tau_{21}} - (N_1 - N_3) * \sigma_P * S_P + (N_2 - N_1) * \sigma_S * S_S \quad (3)$$

Here, N is the population density at the given level [1/cm3], S is the photon flux [1/cm2 * s], τ is the spontaneous lifetime [s], and σ is the transition cross section [cm^2]. The first equation describes the population change rate for the upper state, the second equation describes the population change rate for the meta-stable state, and the third equation describes the population change rate for the ground state. The steady-state atomic populations N1 and N2 are functions of the pumping rate, which represents the pump absorption rate between levels 1 and 3, and of the absorption and stimulated emission rates between levels 1 and 2. Figure 1 shows the three-level erbium atomic structure, and it shows the level transitions when erbium is used in a single-stage 980nm pumped pre-amp EDFA [4]. The sum of the population in the three states of the erbium atomic structure is equal to the total population, and that can be expressed in the equation

$$N = N1 + N2 + N3 \tag{4}$$

Under a steady-state condition, electron state transition in Erbium atoms is given by

$$\frac{dN_1}{dt} = \frac{dN_2}{dt} = \frac{dN_3}{dt} = 0 \tag{5}$$

The basic principle of signal amplification in erbium-doped fiber is based on the fact that when an optical signal passes through the erbium-doped fiber, the signal is amplified due to stimulated transition between electronic states in the presence of electromagnetic radiation at the correct wavelength to achieve population inversion. In order for signal amplification to occur [5], a frequency f12 is needed:

$$f12 = \frac{E1 - E2}{\text{h}} \tag{6}$$

where h is Plank's constant = 6.626x10E-34 [J/s]

Stimulated photons are in coherence with the input signal, and that results in signal amplification. In free space, the radiation wavelength is given by

$$\lambda 21 = hc/(E2 - E1) \tag{7}$$

When this radiation interacts with a photon in the lower energy level, the photon is transformed into the upper atomic level. If a photon in the excited state is not stimulated within the 10ms lifetime of the excited state, it will spontaneously decay to the ground state, producing ASE. When this photon travels through the erbium-doped fiber, it is amplified, resulting in amplified spontaneous emission. All of the excited electrons can spontaneously relax from the upper state to the ground state by emitting a photon that is unrelated to the signal photons. This spontaneously-emitted photon can be amplified as it travels down the fiber and stimulates the emission of more photons from excited electrons.

Amplified spontaneous emission can occur at any frequency within the fluorescence spectrum of the amplifier transitions. The dominant noise source in any EDFA is amplified spontaneous emission [6]. This spontaneous emission reduces the amplifier gain by consuming the photons that would otherwise be used for stimulated emission of the input signal.

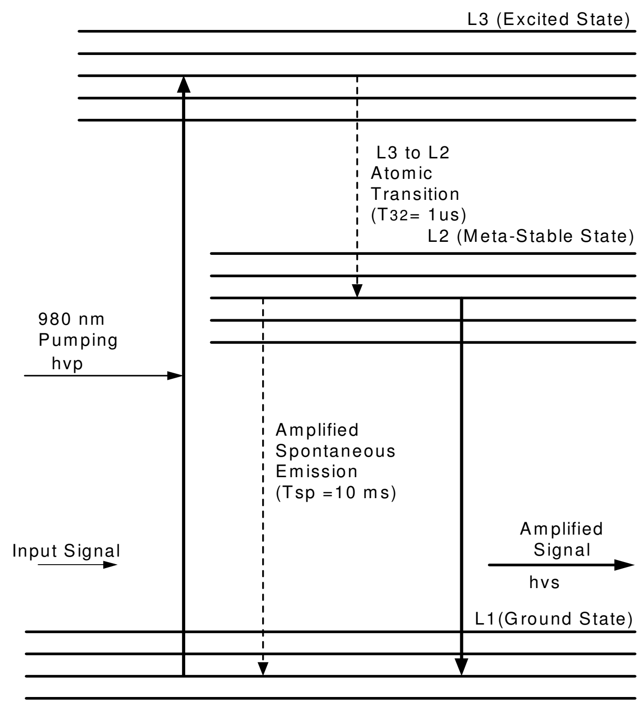

Figure 1. 980nm pumping in Erbium atomic structure

The total amplified spontaneous emission at any point in the fiber is the sum of all amplified spontaneous emission power from the previous sections in the fiber and the amplified spontaneous emission at the given fiber point. To minimize ASE noise, the pump power should be just enough to achieve population inversion. Population inversion can be achieved when the population in the excited state, N2, is greater than the population in the ground state, N1. The threshold pump power required to achieve population inversion can be obtained by setting the rate equation of level 2 to 0 and setting N1 to be equal to N2. A long meta-stable state lifetime and a large absorption cross section are needed to have a low pump threshold to achieve population inversion. A detailed analysis of EDFA and photodiode noise elements was performed by different researchers [7], [8].

Optical Receiver Transmission Performance Testing and Analysis

Optical receiver transmission performance, commonly known as bit error rate (BER) performance, is the gauge by which optical receivers are characterized. It characterizes the ability of the receiver to perform up to the transmission performance specifications under the same test conditions as those where the receiver operates in the field [9]; therefore, transmission performance will be used to analyze the pre-amp EDFA noise characterizations under different operating conditions.

Optical receiver optimal transmission performance analysis under different operating conditions is the ultimate method for characterizing pre-amp EDFA noise performance. The pre-amp EDFA design needs to be optimized at the pre-amp level and the EDFA level. Then, the pre-amp EDFA performance is determined by how well it performs in the optical receiver. The set-up of Figure 2 was used to perform the transmission performance tests for this study using the following definitions:

DCA	Digital Communications Analyzer
OSA	Optical Spectrum Analyzer
PPG	Pulse Pattern Generator
LPF	Low Pass Filter
BPF	Band Pass Filter
O/E	Optical to Electrical
E/O	Electrical to Optical
CW	Continuous Wave
ED	Error Detector

For optimal optical receiver transmission performance, the pre-amp EDFA design must be coordinated with the photon detector design to minimize amplified spontaneous-emission noise mitigation from the pre-amp EDFA to the photon detector and the photon detector signal-spontaneous beat noise. The pre-amp input power, output power, and operating wavelength should be taken into account. This allows designers to choose the right erbium-doped fiber length and pump power combination, and it helps minimize amplified spontaneous emission at the output of the EDFA.

Optical receiver optimal transmission performance analysis under different operating conditions is the ultimate method for optimizing pre-amp EDFA performance in the optical receiver. The pre-amp EDFA design needs to be optimized at two levels: the pre-amp/photon detector subsystem level and the optical receiver level. Several characterization experiments were performed to analyze the effects of changing the pre-amp operating conditions on the optical receiver transmission performance. Testing the pre-amp-based optical receiver at a fixed signal-to-noise ratio of 9 dB at 1550 nm, the transmission performance was recorded at different input/output combinations. A graphical representation of its transmission performance, after normalizing BER, is given in Figure 3.

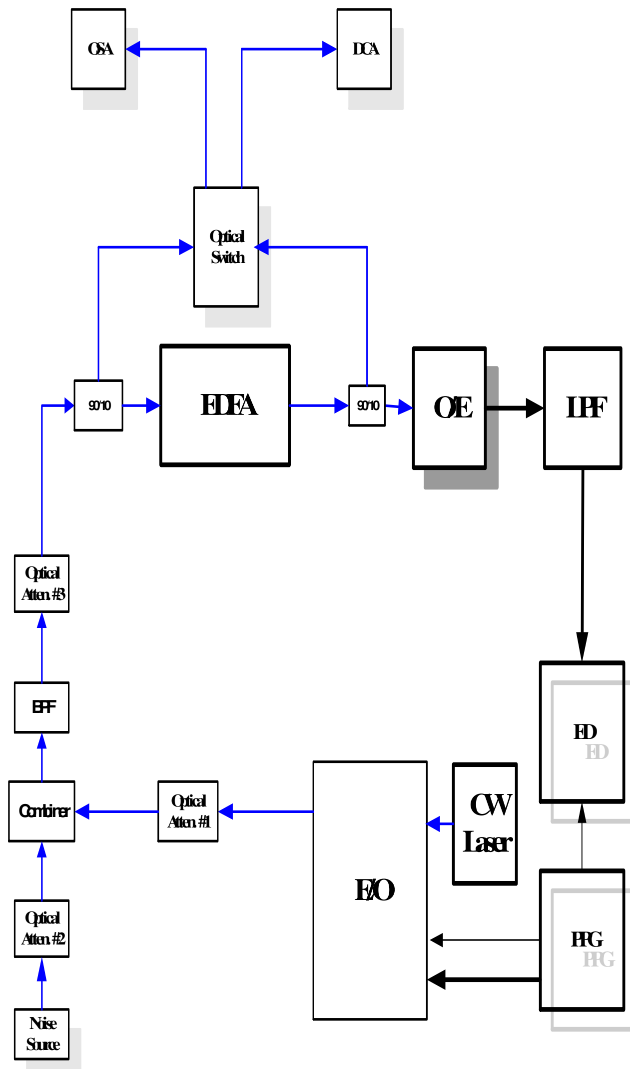

Figure 2. Optical receiver transmission performance test set-up

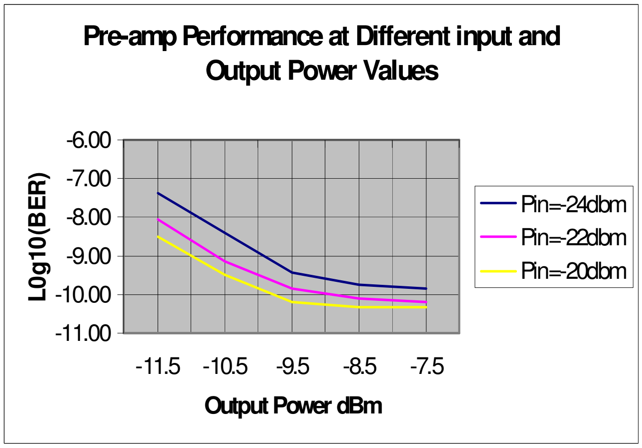

Figure 3. Optical receiver performance change at different input and output power levels

From the results in Figure 3, it can be seen that the optical receiver transmission performance improves as the pre-amp output power is increased. This improvement is due to the fact that more output power requires more pump output, and more output power excites more electrons to the upper state. This excitation results in the population inversion that is needed for the amplification process. When testing the pre-amp-based optical receiver at different input powers and at different signal to noise ratios at fixed output power and input signal wavelength, the transmission performance changes due to the changes in the operating conditions were monitored, and the results are given in Figure 4. A graphical representation of the system transmission performance is given in Figure 4, which shows that the optical receiver transmission performance improves as the pre-amp input signal power is increased.

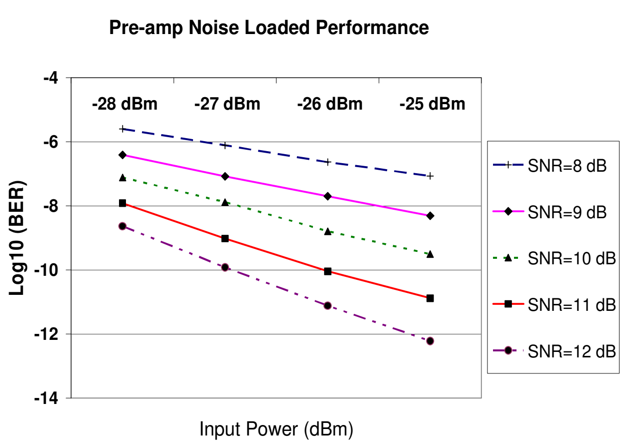

Figure 4. Optical receiver performance at different input powers and different input signal to noise ratios

The results obtained in Figure 4 can be explained at the atomic-structure level since an increase in the input optical power causes a more stimulated emission of the excited electrons. This stimulated emission of electrons, in a form of photons, leaves fewer electrons to move to the ground state spontaneously. This means that the pre-amp is generating less amplified spontaneous emission, which reduces the signal spontaneous noise in the optical receiver photon detector, and that decrease in spontaneous emission results in improved optical receiver transmission performance.

Conclusion

The results of the tests presented here show a need for fine-tuning pre-amp EDFAs at the optical receiver level in order to achieve optimal optical receiver transmission performance. Optical telecommunication engineers can benefit greatly from this work since it presents new test results that are clear indicators of the behavior of pre-amp EDFAs in long-haul optical telecommunication systems. For optimal optical receiver transmission performance, the pre-amp EDFA design must be coordinated with the photon detector design to minimize amplified spontaneous emission noise mitigation from the pre-amp EDFA to the photon detector. This will minimize the photon detector signal-spontaneous beat noise.

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