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Design Coordination of Pre-amp EDFAs and PIN Photon Detectors For Use in Telecommunications Optical Receivers

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Abstract

The pre-amp Erbium-Doped Fiber Amplifier (EDFA) is becoming an integral part of optical receivers, and, consequently, pre-amp performance is interrelated to the performance of the receiver photon detector. For optimal optical receiver transmission performance, the pre-amp EDFA design must be coordinated with the photon detector design in order to minimize amplified spontaneous emission (ASE) noise mitigation from the pre-amp EDFA to the photon detector. The pre-amp EDFA output power and laser pump power should be fine-tuned at the optical receiver level to determine the best output power/laser pump power combination to minimize ASE noise at the output of the pre-amp EDFA.

In this work, the pre-amp EDFA noise performance was characterized first at the pre-amp level through modeling using computer simulations. Then, pre-amp noise performance was characterized experimentally at the optical receiver level. This work demonstrates that simulations and experiments together provide the best optimization of the pre-amp EDFA performance. The experimental work focused 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 the optical receiver transmission performance under different pre-amp operating conditions.

Introduction

Pre-amp Erbium Doped Fiber Amplifiers (EDFAs) are becoming integral parts of long-haul telecommunication optical receivers, and pre-amp EDFA performance is becoming a main factor influencing optical receiver photon detector performance. Based on that, pre-amp EDFA design needs to be coordinated with the photon detector design and the optical receiver design in order to improve optical receiver transmission performance. Pre-amp EDFA laser pump power needs to be optimized first at the EDFA design level. This can be done using computer simulation. Then Pre-amp EDFA output power should be fine-tuned at the optical receiver level to achieve the best output power/laser pump power to minimize ASE noise at the output of the pre-amp EDFA.

Optical receiver transmission performance, commonly known as bit error rate (BER), is the gauge by which optical receivers are characterized. It is used to characterize the ability of the receiver to perform up to the transmission performance specifications when operating under the operating conditions present in the field. In this paper, the test results of pre-amp-based optical receiver transmission performance are measured at different pre-amp EDFA operating conditions. The effects of the optical amplification in the pre-amp EDFA as a function of the pre-amp input power, output power, and input signal to noise ratio on the optical receiver transmission performance were analyzed to characterize the optical receiver transmission performance as related to the EDFA operating conditions. Since the most important factor in pre-amp performance is how well it performs in the optical receiver, 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.

At the optical receiver level, several characterization experiments need to be performed to analyze the effects of changing pre-amp operating conditions on optical receiver transmission performance. Then the effects of changing the pre-amp output power setting on optical receiver transmission performance need to be analyzed in order to characterize optical receiver transmission performance.

Noise in Erbium-Doped Fiber Amplifiers

The generation of noise in doped optical pre-amplifiers is an effect of the spontaneous de-excitation of the laser ions. As the electrons have a finite excited state lifetime, some of the electrons return spontaneously to the ground state emitting a photon. This photon has no coherence characteristics with respect to the incoming light signal, as opposed to a photon generated by stimulated emission. The collection of such spontaneously generated photons, being multiplied by the fiber amplifier, forms a background noise. This background noise is known as amplified spontaneous emission. This is the dominant noise element in pre-amp EDFAs. The optical noise elements of a pre-amp EDFA at different input power, output power, and different signal wavelengths and their effects on the EDFA transmission performance can be analyzed by evaluating the contributions of the EDFA ASE noise generated in the process of signal amplification. The noise instability issues that is results from ASE was analyzed in [1]

Pre-amp EDFA operation is based on stimulated emission of optically pumped Er +3 ions in silica. Erbium atomic structure and the 3-level atomic level rate equations, for the case of a single-stage 980 nm pumped EDFA, were analyzed to help characterize the pre-amp ASE noise. The most fundamental limitation to the gain of an erbium-doped fiber amplifier is the energy conservation principle. This principle can be expressed in terms of the photon flux. The photon flux of the output signal cannot exceed the photon flux of the input signal plus the laser pump photon flux [2]. Since modern receivers use a narrow optical band pass filter at the output of their pre-amp EDFAs, the pump shot noise is filtered in this filter. So pump noise does not play a factor in the pre-amp EDFA transmission performance; however, the pump power affects transmission performance from its contribution to ASE. The most basic treatment of erbium-doped fiber amplifier noise is by analyzing a 3-level erbium atomic system. So the erbium atomic structure needs to be understood to analyze pre-amp noise.

Amplified and Stimulated Emission Analysis at the Erbium Atomic level

Erbium atomic structure has three energy levels that are of interest for the study of its amplification characteristic for communication use. 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, 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 this erbium-doped fiber atomic structure is described in the following level rate equations [3]:

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

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

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

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. When laser 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 gets amplified resulting in amplified spontaneous emission. All 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 ASE. This spontaneous emission reduces the amplifier gain by consuming the photons that would otherwise be used for stimulated emission of the input signal. In order 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.

EDFA Design Optimization Using Computer Simulations

Testing and computer simulation were used to characterize a 980 nm pumped single-stage C-Band pre-amp EDFA for optimization, and the total ASE and optical noise figure (NF) were used for the pre-amp noise characterization. The modeling of amplified spontaneous emission for the computer simulation here is done by treating amplified spontaneous emission as an extra signal with a bandwidth corresponding to an effective bandwidth of the entire transition. Bray has experimentally used this method to test for noise figure spectra using ASE sources [4]&[5]. The noise figure defined here is the optical noise figure, and it is calculated by adding an ASE wave at the signal wavelength. So the optical noise figure at the signal wavelength calculated in these simulations is:

$$NF(dB) = 10 Log_{10}\left[\left(\frac{P_{ASE}}{h\nu\Delta\nu} + 1\right)\left(\frac{P_{sig-out}}{P_{sig-in}}\right)\right] \tag{4}$$

Where Psig-out is the output power in mw in the ASE wave, Psig-in is the amplifier input optical powers in mw, Psig-out is the amplifier output optical powers in mw, ν is the frequency of the signal and its ASE wave, Δν is the spectral band width represented by the ASE wave. At the pre-amp level optimization of pre-amp EDFA performance, 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 which helps minimize the amplified spontaneous emission at the output of the pre-amp EDFA.

In modeling pre-amp performance, one needs to analyze the pre-amp noise characteristics. Zhang presented an erbium-doped fiber amplifier model [6]. The parameters of the main components, affecting the pre-amp performance were given by Desurvire [2]. These parameters are the erbium concentration and the doped fiber length, the pump wavelength and absorption band, the input signal power and wavelength, and the wave guide characteristics.

Computer simulations of the pre-amp noise figure and ASE at different pump power levels are given in figures1 and 2. The pre-amp EDFA gain progress through the erbium-doped fiber is characterized by analyzing the gain of both the pump power and the signal power through the fiber. The small signal gain through the erbium-doped fiber can be analyzed using the erbium atomic structure rate equations. Becker has derived the equations for the signal and pump intensities through the erbium-doped fiber [4].

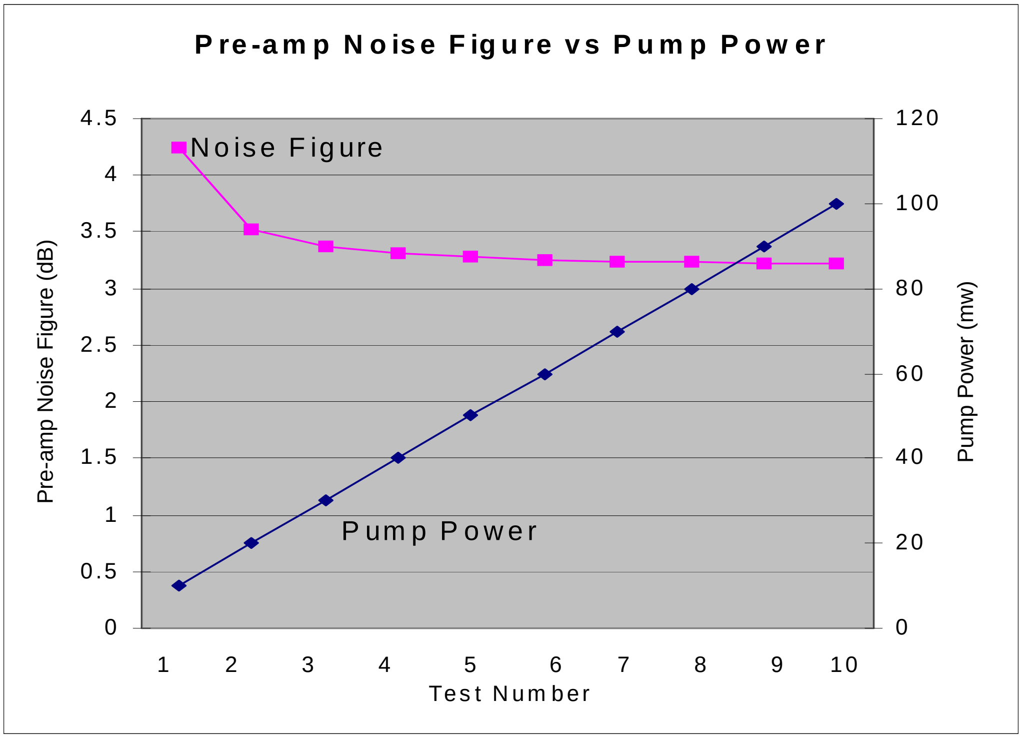

Figure1: Pre-amp noise figure as a function of the pump power

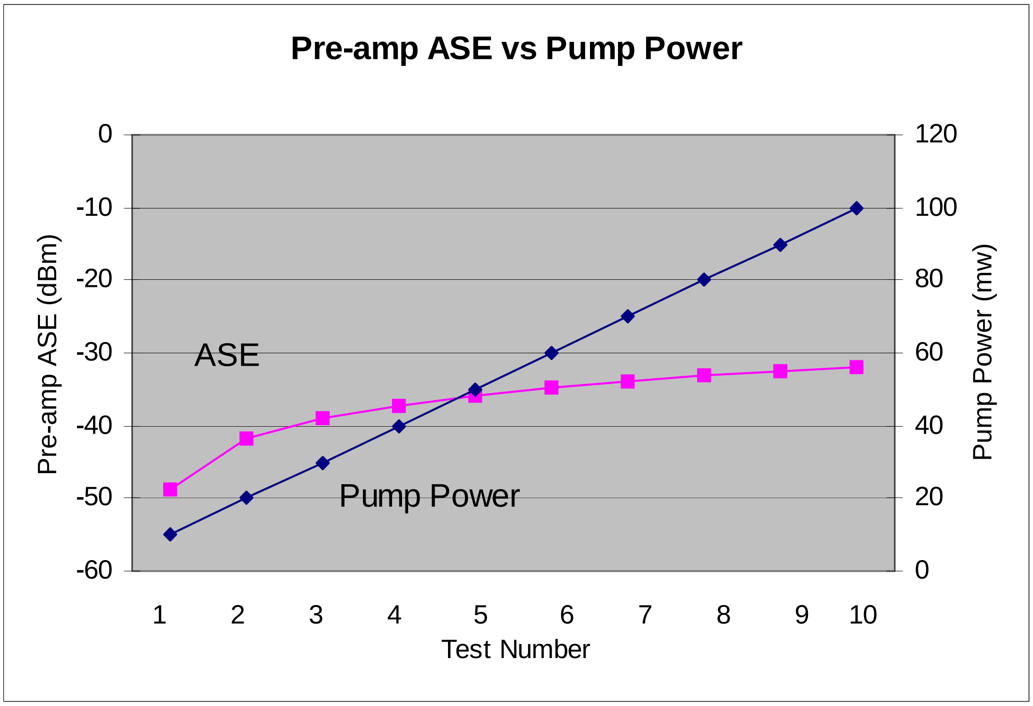

Figure2: Pre-amp ASE as a function of the pump power

The change in the signal flux through the erbium-doped fiber, meta-stable state rate equation is given by:

$$\frac{d\ \varphi s}{dz} = (N_2 - N_1) * \sigma s * \varphi s \qquad (5)$$

From the last above equation, we can obtain the signal and the pump intensity through the erbium-doped fiber. Computer simulation uses these equations to calculate noise figure through the erbium-doped fiber. This helps in optimizing the erbium-doped fiber length to obtain the best design that minimizes the amplified spontaneous emission at the end of the erbium-doped fiber.

Since the most important performance factor in the pre-amp performance is how well it performs in the optical receiver, the optical receiver Optimal Transmission Performance analysis under different operating conditions is the ultimate method for characterizing the pre-amp noise performance. The pre-amp EDFA design needs to be optimized at the two levels analyzed here, and the pre-amp performance should be determined by how well the pre-amp performs in the optical receiver.

Pre-Amp EDFA-PIN Photon Detector Design Coordination

Several studies were performed to improve the transmission performance of long haul optical receivers [7-9]. Since optical receiver transmission performance is the gauge by which optical receivers are characterized, BER was used in the experimental work presented here to characterize the ability of optical receivers to perform up to the transmission performance specifications under the same test conditions as those where the receiver operates in the field [5]. The setup of figure 3 was used to perform the optical receiver tests analyzed in this paper. This setup has the ability and flexibility to perform optical receiver transmission performance measurement, optical input and output measurements, optical signal and noise control, and optical input SNR control [5]. Since the most important factor in the pre-amp performance is how well it performs in the optical receiver, the optical receiver 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. Also, for optimal optical receiver transmission performance, the pre-amp EDFA design must be coordinated with the photon detector design in order 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 during those tests. This allows designers to choose the right erbium-doped fiber length and pump power combination, and it also helps in minimizing amplified spontaneous emission at the output of the pre-amp EDFA.

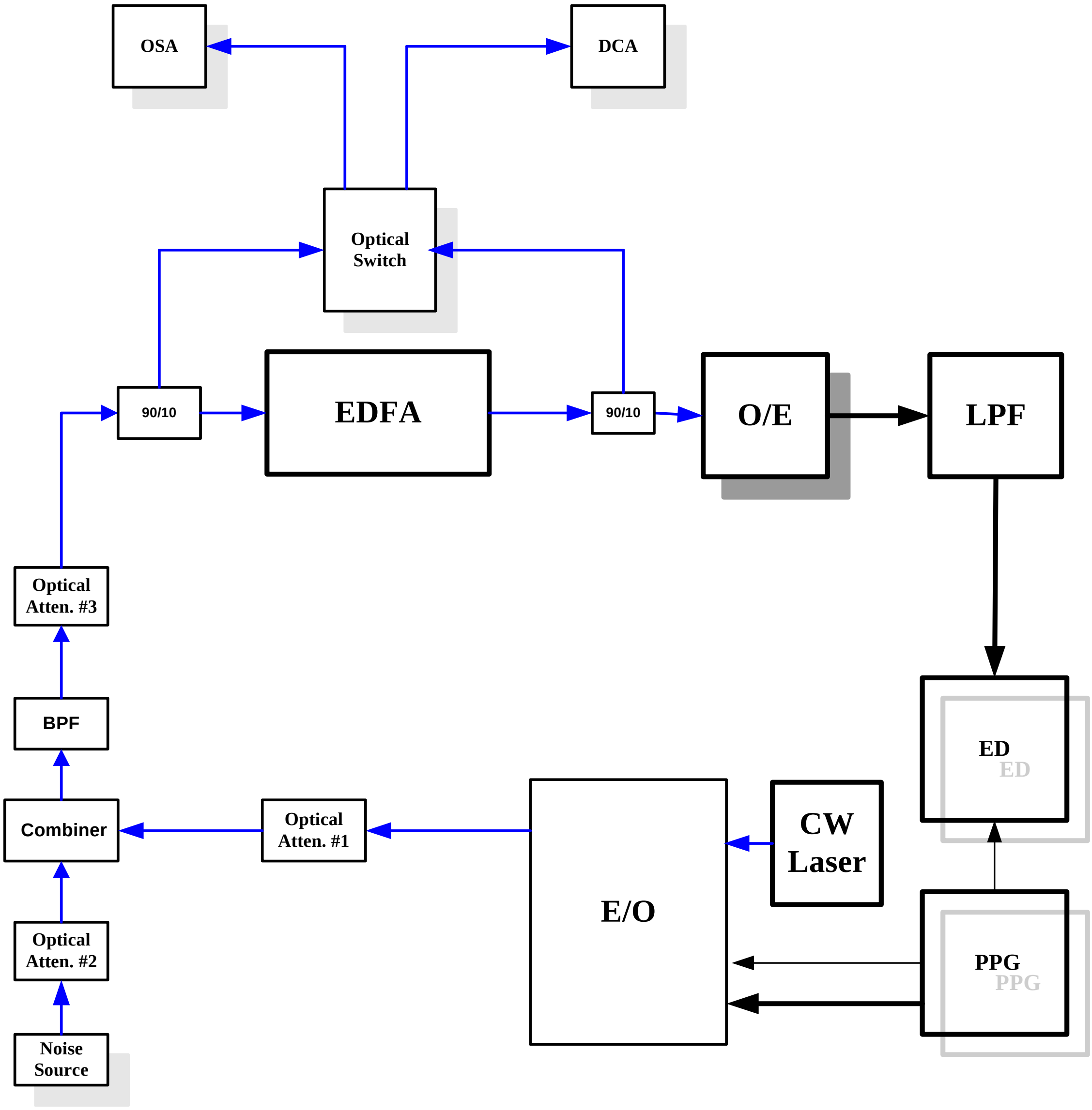

Figure 3: Optical receiver transmission performance test set-up

Since the most important factor in pre-amp performance is how well it performs in the optical receiver, 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 at 1550 nm, the transmission performance was recorded at different input/output combinations.

A graphical representation of the optical system transmission performance results, after normalizing BER, is given in Figure 4.

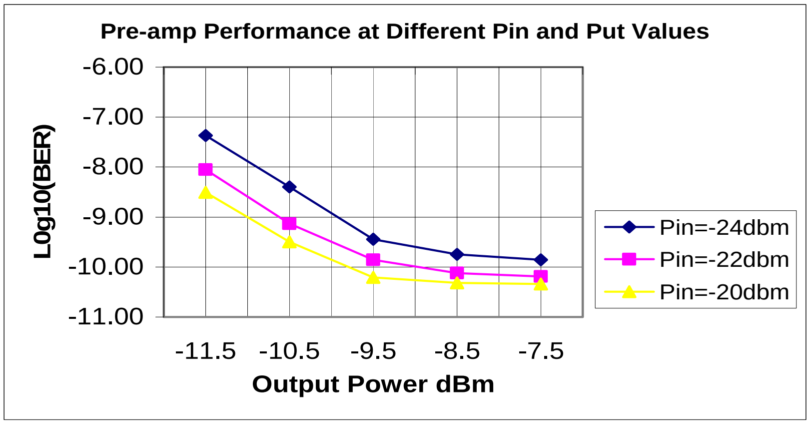

Figure 4: Optical receiver performance change at different input and output power levels

From the results in figure 4, we see 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 will result in the population inversion that is needed for the amplification process.

Testing the pre-amp-based optical receiver at different input powers and at different signal to noise ratios at fixed output power, the transmission performance changes due to the changes in the operating conditions were monitored. A graphical representation of the system transmission performance, after normalizing BER, is given in Figure 5.

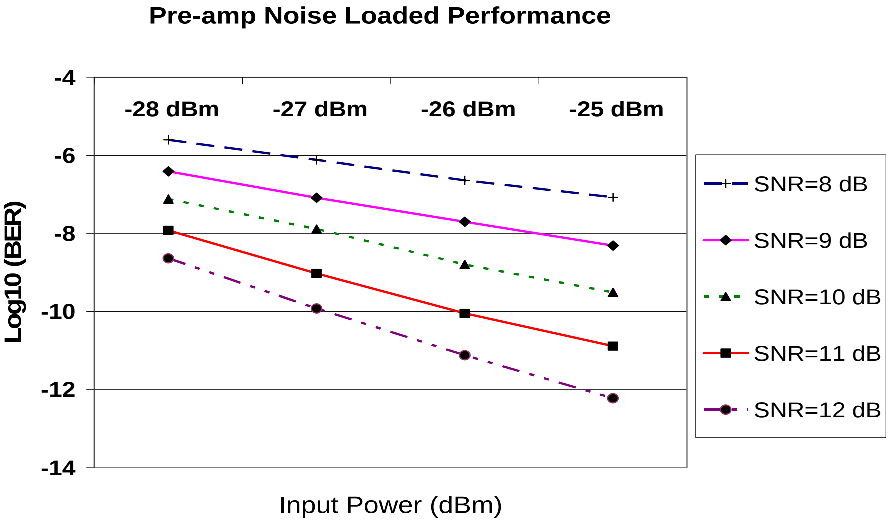

Figure 5: Receiver performance change at different input powers and different input SNR

At the atomic structure level, an increase in the input power causes more stimulated emission of the excited electrons. This leaves fewer electrons to move to the ground state spontaneously which means that the pre-amp is generating less amplified spontaneous emission, and that reduces the signal spontaneous noise in the photon detector.

Conclusion

The results of this work show a need for designing the pre-amp EDFA and photon detector as one subsystem and demonstrate that simulations and experiments together are needed for the optimization of pre-amp EDFA performance. Then the pre-amp EDFA needs to be fine-tuned at the optical receiver level. This was done by minimizing pre-amp EDFA noise performance at the pre-amp EDFA level using computer simulations and experimentally at the optical receiver level. The optical receiver transmission performance experimental test results are consistent with the pre-amp simulations. So, the optical receiver transmission performance can be used to characterize the pre-amp performance at different operating conditions. Since the most important performance factor in the pre-amp performance is how well it performs in the optical receiver, optical receiver optimal transmission performance analysis under different operating conditions is the ultimate method for characterizing pre-amp EDFAs noise performance.

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Biography

AKRAM ABU-AISHEH is an Assistant Professor in Electrical Engineering at the University of Hartford. He is currently the assistant chair of the electrical and computer engineering department and director of the electronic and computer engineering technology program. Dr. Abu-aisheh has a Ph.D. in Optical Communications from the Florida Institute of Technology and MS. and B.S. degrees in Electrical Engineering from the University of Florida.

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