An Effectiveness Investigation of Erbium-Doped Fiber Amplifiers for Cable TV Networks in presence of Noise

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Abstract – **Recent growth of modern CATV networks is accompanied by the necessity of ensuring large areas of reception. This brings about to replacement of conventional coaxial cable trunks with optical rings. Despite its major advantages, optical equipment also has its peculiarities and shortcomings. This article makes observations of the impact of various noise components within Erbium-Doped Fiber Amplifiers (EDFAs) and will estimate the carrier-to-noise ratio (*CNR*) in this particular type of amplifiers in transmitting analogue amplitude modulated (AM) video signals.**

Keywords – **Erbium-Doped Fiber Amplifier, Amplifier Spontaneous Emission, Signal-Spontaneous Beat Noise, Spontaneous-Spontaneous Beat Noise, Noise Factor, Carrier-to-Noise Ratio.**

I. INTRODUCTION

Understanding noise generation in optical amplifiers and its negative impact on amplifier performance is a critical issue in optical communication networks. Optical amplifiers serve to amplify TV video signal which are distributed over the network. They are in-line amplifiers, power booster amplifiers (to the laser transmitter), or preamplifiers (to the receiver).

In order to determine the signal *CNR* in optical communication systems it is necessary to analyze noise components in optical amplifiers first. Such analysis would involve the following assumptions:

1) It is assumed a single-stage optical amplifier with gain so that the output power is related to the input power by $P_{out} = GP_{in}$, where P_{out} is the output power, and P_{in} – the input power;
2) It is assumed that there is a 100% coupling efficiency between the amplifier and photodetector;
3) The optical communication network is based on single mode fibers (SMF).

II. OPTICAL FIBER AMPLIFIER NOISE

The photocurrent at the receiver due to the amplifier spontaneous emission (ASE), according to [1], can be expressed as

$$I_{ASE} = RP_{ASE} = 2Rn_{sp}h\nu(G-1)\Delta\nu \ , \qquad (1)$$

where P_{ASE} is the amplified spontaneous emission powering the amplifier; R – the load resistor of photodetector; n_{sp} – the spontaneous emission factor; h – the Plank constant; ν – the photon energy; $\Delta\nu$ – the amplifier optical bandwidth.

From Eq. (1), the current variance in the photodetector due to the ASE shot noise can be written as:

$$\sigma^2_{ASE} = \left\langle i^2_{ASE} \right\rangle = 2qI_{ASE} = 4q^2\eta n_{sp}(G-1)\Delta\nu \ . \qquad (2)$$

where q is the electronic charge; η – the quantum efficiency of the photodetector.

There is also a shot-noise component due to the photocurrent I_R. Let define a related quantity to the ASE power called the single-sided spectral density of the ASE, which is nearly constant and can be written as:

$$S_{sp(\nu)} = \frac{P_{ASE}}{2\Delta\nu} = n_{sp}(G-1)h\nu \ . \qquad (3)$$

The effect of the ASE is to add noise fluctuations to the amplified power, which are converted to current fluctuations during the photodetection process. The primary contributions to the optical receiver noise come from the beating of the spontaneous emission with the signal, which is called a signal-spontaneous beat noise (S-ASE beat noise), and with itself, which is called a spontaneous-spontaneous beat noise (ASE-ASE beat noise) [2].

Using Eq. (3), the variance of the photocurrent due to the S-ASE beat noise can be given by

$$\sigma^2_{S-ASE} = \left\langle i^2_{S-ASE} \right\rangle = 4I_R(RS_{ASE}) = 4\frac{(q\eta)^2}{h\nu}n_{sp}G(G-1)P_{in} \ , \qquad (4)$$

where a factor of 4 in Eq. (4) is used because needs to consider a double-sided ASE spectral density, and to include both light polarizations. Notice that the S-ASE beat noise is independent of the amplifier optical bandwidth ($\Delta\nu$). Consequently, the negative impact of ASE cannot be removed without eliminating the desired signal at the same time. In contrast, the ASE-ASE beat noise is proportional to the amplifier bandwidth. This means that a narrow bandpass optical filter can be used to remove this ASE beat noise. The variance of the ASE-ASE beat noise can be given by

$$\sigma^2_{ASE-ASE} = \left\langle i^2_{ASE-ASE} \right\rangle = 4(RS_{ASE})^2\Delta\nu = 4\left[q\eta n_{sp}(G-1)\right]^2\Delta\nu \ , \qquad (5)$$

where the factor of 4 in Eq. (5) is used for the same considerations as in Eq. (4). When the amplifier gain G is high (i.e., small input power levels), the current variance of both the S-ASE and ASE-ASE beat noise is proportional to G^2, while the ASE shot noise is only proportional to G. Consequently, the ASE shot noise contributions can be neglected

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compared with the ASE-ASE and S-ASE beat noise contributions in the photodetector. This approximation will also be used in the calculation of the *CNR* in the next section.

III. ESTIMATION OF *CNR* AND NOISE FIGURE OF OPTICAL FIBER AMPLIFIER

Here will be made analysis of the *CNR* of fiber-optics communication system, particularly for cable TV applications. It is assumed a communication system with an in-line single-stage optical amplifier, with modulation index m per RF channel, and DC photocurrent of I_R. Then, using the *CNR* definition in [3], the *CNR* can be written as

$$CNR = \frac{\langle i_R^2 \rangle}{\left(\sigma_{shot}^2 + \sigma_{th}^2 + \sigma_{S-ASE}^2 + \sigma_{ASE-ASE}^2\right)B}, \quad (6)$$

where $\langle i_R^2 \rangle = \left(mI_R^2\right)/2$ is the mean-square signal photocurrent, σ_{shot}^2, σ_{th}^2 – the variance of the photocurrent due to the shot noise and thermal noise; B – the photodetector electrical bandwidth. The photodetector shot-noise variance can be given by the following equation:

$$\sigma_{shot}^2 = \langle i_{shot}^2 \rangle = 2q\left(I_R + I_{ASE}\right) = 2q^2\eta\left[\frac{GP_{in}}{h\nu} + 2n_{sp}(G-1)\Delta\nu\right]. \quad (7)$$

From a practical aspect, it is convenient to express the *CNR* given by Eq. (6) in terms of the amplifier noise figure. The amplifier noise figure is defined as [4]

$$F = \frac{SNR_{in}}{SNR_{out}} = \frac{CNR_{in}}{CNR_{out}}, \quad (8)$$

where "*in*" and "*out*" refer to the *SNR* or the *CNR* measured at the output of the photodetector with and without the optical amplifier, respectively). Without the optical amplifier, the photodetector is essentially shot-noise limited. Consequently, the *CNR* can be written as:

$$CNR_{in} = \frac{\left(mI_R\right)^2}{4qI_R} = \frac{m^2\eta P_{in}}{4h\nu}. \quad (9)$$

In the presence of the optical amplifier, the photodetector is primarily limited by the shot noise and the S-ASE beat noise. The ASE-ASE beat noise and the ASE shot noise contributions can be neglected compared with the S-ASE beat noise contribution. The contribution to the inverse *CNR* caused by the S-ASE beat noise can be written as:

$$CNR_{S-ASE}^{-1} = \frac{8h\nu n_{sp}}{m^2 P_{in}}\left(1 - \frac{1}{G}\right). \quad (10)$$

The resultant CNR^{-1} at the photodetector with the optical amplifier can be calculated according to:

$$CNR_{OUT}^{-1} = CNR_{Shot}^{-1} + CNR_{S-ASE}^{-1} = \frac{4h\nu}{m^2 P_{in} G}\left[1 + 2n_{sp}(G-1)\right]. \quad (11)$$

Substituting Eqs. (9) and (11) into Eq. (8):

$$F = 2n_{sp}\left(1 - \frac{1}{G}\right) + \frac{1}{G}. \quad (12)$$

For a high-gain operation ($G >> 1$), the amplifier noise figure can be approximated by $2n_{sp}$. If the further assume an ideal optical amplifier with a complete population inversion, then $n_{sp} = 1$. This means that in the quantum noise limit, the amplifier has a noise figure of $F = 3dB$ (since $F = 10\log_{10}2$). Neglecting the right-hand side term $1/G$ from Eq. (12), the optical amplifier noise figure can be written as:

$$F = 2n_{sp}\left(1 - \frac{1}{G}\right). \quad (13)$$

Substituting the noise figure expression given by Eq. (13) in Eq. (6) for the *CNR*, we will finally obtain

$$CNR = \frac{m^2}{2B\left[RIN + \frac{2q}{I_R} + \left(\frac{N_R}{I_R}\right)^2 + 2h\nu + \Delta\nu\left(\frac{Fh\nu}{P_{in}}\right)^2\right]}, \quad (14)$$

where *RIN* is the overall communication system *RIN* and N_R is the photodectector noise equivalent current.

Drawing from Eq. (14) and assuming the exemplary operating system parameters given in Table I, it is possible to determine the dependency $F = f(P_{in})$ – Fig. 1 or the dependency $CNR_{AM} = f(P_{in})$ – Fig. 2.

TABLE I
SYSTEM PARAMETERS FOR *CNR* CALCULATION

Parameter	**Specification**
Modulation index per channel	*3,2%*
Electrical noise bandwidth of AM channel	*4MHz*
Optical bandwidth of the EDFA	*40nm*
Receiver Photocurrent	*0,85mA*
Receiver noise equivalent current	$7\ pA/\sqrt{Hz}$
RIN	*-164dBc/Hz*

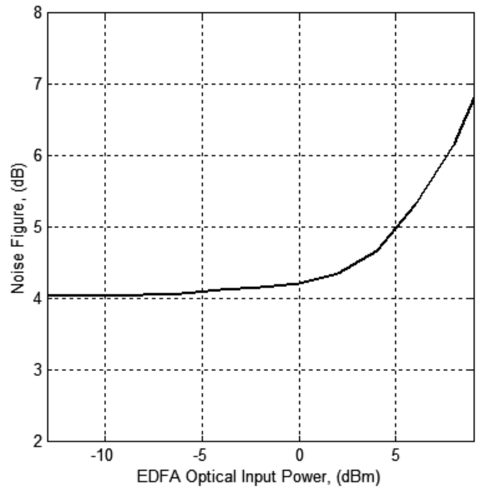

Fig. 1. Calculated noise figure F versus the EDFA optical input power level P_{in}

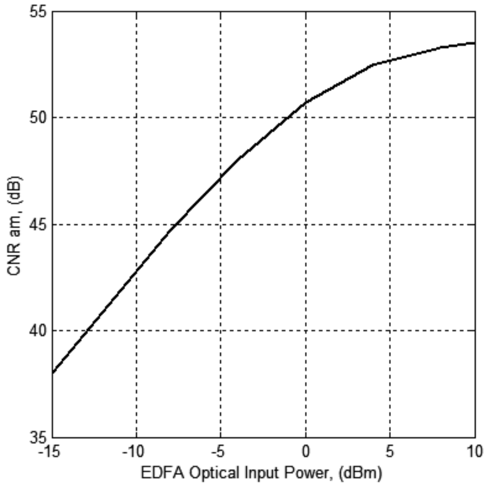

Fig. 2. Calculated AM CNR versus the EDFA optical input power level P_{in}

IV. CONCLUSION

The obtained Eq. (14) is very convenient to use since it describes the *CNR* dependence in terms of two primary measurable parameters, namely, the amplifier noise figure (*F*) and its optical input power. Furthermore, Eq. (14) suggest that the transmitted *CNR* of the RF channel after the in-line EDFA is primarily governed by the S-ASE and ASE-ASE beat noise at low optical input levels (< *-10dBm*). In this input power regime, the amplifier noise figure approaches the quantum noise limit of *3dB*). If the noise figure is nearly unchanged when the EDFA is operating in saturation (optical input power ≥ *0dBm*), the AM *CNR* becomes limited by the receiver's thermal and shot noise at a given detected optical power). However, if the amplifier noise figure increases monotonically with the optical input power, then it sets the upper limit on the AM *CNR* as seen from Eq. (14) and Fig. 2. Therefore, robust transmission of AM video channels often requires the EDFAs to operate in saturation. The result in Fig. 1 suggests that an in-line amplifier with a noise figure of *5dB* or less is needed to achieve *CNR* greater or equal to 50dB (according to the requirements for video signals transmission).

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