Optical Amplifier Basic Properties And System Modeling: A Simple Tutorial

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Abstract

Erbium-doped fiber amplifiers have received much interest for CATV because of their high output power, low distortion, and low noise capability. These devices have only recently become commercially available and probably are not well understood by those who have not been involved with them from a research or applications viewpoint. This paper is intended to present a simple coverage of the principles of operation and characteristics of these amplifiers. Signal gain, saturation output power, and noise properties are discussed. Equations for optical amplifier noise figure are developed and typical data for CATV are given.

INTRODUCTION

The rapid developments in fiber-amplifier technology now enable employment of these devices for telecommunications and CATV with a substantial advancement in system capabilities. For telecommunications, optical amplifiers can easily compensate for fiber loss in very long repeatered transmission links. Experiments have shown that it is feasible to transmit at multi-Gbit/s rates in ultra-long distance amplifier cascades with losses of a few thousand dB. For CATV, although the expectations are not so astounding, erbium-doped fiber amplifiers (EDFA's) can be used as power amplifiers to boost the output of the laser source and enable a large increase in the optical loss budget. However, EDFA's are expected to have limited application, if any, as repeaters because of the high input signal power required to achieve acceptable carrier-to-noise ratios for AM CATV.

This paper begins with a simple discussion of noise in the electrical and optical domain. Next is a general discussion of the basic principles of operation and characteristics of an EDFA. The noise figure is derived and characteristics for CATV are shown.

THERMAL NOISE

Thermal noise is an electrical noise phenomena that occurs in a conductor or resistor due to the continual random scattering of free electrons with the molecules. This electron scattering of free electrons is responsible for the electrical resistance of the material. Each flight of an electron between collisions with molecules constitutes a short pulse of current. This random motion of charges results in a thermally-induced noise voltage across the terminals of the resistor. This effect, also called Johnson or Nyquist noise, was first observed by J. B. Johnson in 1927, and a theoretical treatment was given by H. Nyquist in 1928. Accordingly, for a thermal noise source the available power in a 1-Hz bandwidth is given by

$$p_{th} = kT \qquad [W/Hz] \qquad (1)$$

where k is Boltzmann's constant ($1.38 \cdot 10^{-23}$ joule/°K, and T is the absolute temperature in degrees Kelvin. At room temperature, $kT = 4.0 \cdot 10^{-21}$ W/Hz (-174 dBm/Hz). In a 75 ohm system and for a bandwidth of 4 MHz, the thermal noise voltage is -59.2 dBmV, which is the familiar number used in CATV carrier-to-noise ratio calculations. At room temperature, the power density spectrum is theoretically constant up to ~3000 Ghz and decreases rapidly for higher frequencies. At optical frequencies, quantum noise dominates, as discussed in later sections.

SHOT NOISE

Shot noise is a noise current caused by the discrete nature of electron flow. It was first observed in the anode current of vacuum-tube amplifiers and was described by W. Schottky in 1918. In a shot-noise source, electrons are generated or released randomly in time. This random flow of electrons results in a mean-square noise current in a 1-Hz bandwidth of

$$i_{sh}^2 = 2qI_{dc} \qquad [A^2/Hz] \tag{2}$$

where q is the charge of an electron ($1.6 \cdot 10^{-19}$ coulomb), and I_{dc} is the direct current through the device in amperes. Shot noise occurs in most active devices, but is not generated in linear resistive and passive networks due to current flow. Unlike thermal noise, shot noise is not a function of temperature.

OPTICAL NOISE DUE TO THE PARTICLE NATURE OF LIGHT

Light, like radio waves, is a form of electromagnetic radiation. At optical frequencies, the quantum-mechanical effects become important, and the discrete nature of light must be considered. The quantum particle of light is the photon, and the energy of each photon is $h\nu$ (joules), where h is Planck's constant ($6.624 \cdot 10^{-34}$ joule·sec) and ν is the optical frequency. The power of an optical signal is thus

$$P = Nh\nu \tag{3}$$

where N is the average number of photons emitted per second by the optical source. However, photons are not emitted at a constant rate, but, in fact, the emission times of the photons vary randomly. From Poisson's probability distribution law, it follows that the variance, or mean-square deviation in the number of photons emitted per second, is equal to the mean number of photons per second:

$$<\Delta N^2> = N. \tag{4}$$

The minimum detected number of quanta is considered to be that for which the rms fluctuation is equal to the average value. Thus,

$$(N_{min})^{1/2} = N_{min} \tag{5}$$

for which $N = 1$. Consequently, for an ideal photon counter, the minimum detectable number of photons per second in a 1-Hz bandwidth is 1, and the minimum detectable power is [1]

$$p_{min} = h\nu \qquad [W/Hz]. \tag{6}$$

Note that in the following section it is determined that with an ideal photodetector the minimum detectable optical power is $2h\nu$. The factor of 2 difference occurs because the equivalent optical bandwidth (double-sided) is twice the baseband (single-sided) bandwidth. This quantum noise provides the fundamental limitation to performance of optical systems. Because of the high energy of a photon, the minimum detectable optical power is much higher than it is as limited by kT in the electrical domain. At a wavelength of 1550 nm, $h\nu$ = -159 dBm/Hz, whereas kT = -174 dBm/Hz at 25°C.

PHOTODETECTION PROCESS

The photodetector commonly used in CATV applications is the PIN photodiode. Incident photons are absorbed in the depletion region creating electron hole-pairs. Under the influence of the reverse bias electric field, the electrons and holes drift in opposite directions creating a displacement current in the external circuit. For an ideal photodiode, one electron is emitted for each incident photon. The efficiency of generating electrons is given by the quantum efficiency of the detector, which is defined as

$$\eta = \frac{\text{number of electrons emitted}}{\text{number of incident photons}}. \tag{7}$$

Since optical power = (number of photons/sec)·$h\nu$, and detector current = (number of electrons/sec)·q, it follows that

$$I_{dc} = P(\frac{\eta q}{h\nu}) \tag{8}$$

where P is incident optical power (W), and I_{dc} is detector current (A). Responsivity R of the detector is defined as

$$R = \frac{\eta q}{h\nu}. \tag{9}$$

Noise is inherent in the output of the photodetector. The origin of this noise can be treated in two ways. In the quantum treatment, the optical field is quantized into photons and each photon gives rise to an electron with probability η. Due to the random occurrence in time of the photons, a noise current is generated which limits the minimum detectable signal as discussed in the previous section. In the semiclassical approach, a constant electromagnetic field interacts with atoms in the photodiode and generates the photodiode current. Shot noise is generated in this process. Each electron-hole pair results in a single pulse of detector current of charge q. The total current is the superposition of these pulses occurring randomly in time. Because of this random fluctuation, shot noise results just as Schottky observed it did in vacuum-tube amplifiers. Photodetector shot noise current is

$$\begin{aligned} i_{sn}^2 &= 2qI_{dc} \\ &= 2qPR \qquad [A^2/Hz] \end{aligned} \tag{10}$$

where I_{dc} is the dc current.

The minimum detectable optical power is defined for quantum efficiency = 1 as the minimum power for which the rms value of shot noise is equal to the dc current. Thus,

$$P_{min} = 2h\nu \tag{11}$$

This is the same as given in the previous section. The question as to whether the limit to sensitivity is imposed by photodetector-generated shot noise or the fluctuations in the incident photon number is academic. The resultant photodiode current is the same in either case [1].

ERBIUM-DOPED FIBER AMPLIFIERS

Amplification occurs in an erbium-doped fiber amplifier (EDFA) due to the photoluminescent properties of the rare-earth element erbium concentrated in the core of the fiber. The atomic energy levels of erbium allow erbium to absorb energy at any of several wavelengths and release energy in the 1550-nm range. In the interaction of photons and atoms, the frequency of absorbed or emitted radiation ν is related to the difference in energy E between the higher and the lower energy states E_2 and E_1 by the expression

$$\begin{aligned} E &= E_2 - E_1 \\ &= h\nu. \end{aligned} \tag{12}$$

Discrete energy states correspond to particular energy levels of the electrons within the atom relative to the nucleus. A single electron transition between two energy levels represents a change in energy suitable for the absorption or emission of a photon.

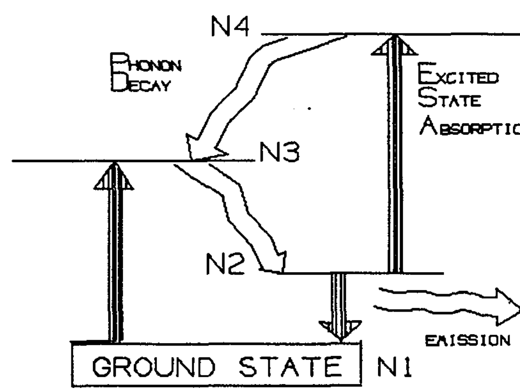

Fig. 1. Erbium three-level system with excited-state absorption.

Erbium has a three level system, the ground level (N_1), the metastable level (N_2), and a higher level (N_3) as shown in Fig. 1. In an EDFA the absorbed energy comes from a pump laser. The optimum pump wavelengths for EDFA's are those for which there is no excited state absorption (ESA). These wavelengths are 980 nm, 1480 nm, or 1047 nm. ESA creates a fourth level (N_4) by the process of exciting or pumping the electrons from N_2 to N_4. This depletes the number of electrons or population at the N_2 level creating a need for increased pump power, which will increase the pumping rate allowing the system to maintain the same degree of population inversion. Population inversion occurs when the pumped electrons transition from N_1 to N_3 and then rapidly decay to the N_2 level. The amount of time they spend at the N_2 level is controlled by the erbium ion fluorescence lifetime which is approximately 10 ms. Therefore, for complete population inversion to occur, the rate at which the electrons are transitioning from N_1 to N_2 and then held in the N_2 level must exceed the number of electrons transitioning from N_2 to N_1 at any given time. Ideally, the total number of electrons associated with the erbium atoms available per length of fiber, must remain in the N_2 level, and just as quickly as one decays to the lower N_1 level another one must already be at the N_2 level. Their decay from N_2 to N_1 can occur in two ways:

(a) by spontaneous emission in which the atoms return to N_1 in an entirely random manner, creating optical noise from ~1530 nm to ~1560 nm, and:

(b) by stimulated emission in which an incident photon causes the release of a second photon of the same energy. Stimulated emission produces coherent amplification or gain.

By this process the optical input signal and noise generated by spontaneous emission are amplified. At the amplifier output there are two optical components: the desired amplified input signal and amplified spontaneous emission (ASE), which is optical noise.

For the uniform inversion model, which means that the pumping rate throughout the entire length of erbium-doped fiber is sufficient to keep N_2 completely populated, the following equations apply:

$$\begin{aligned} p_{ase} &= 2\eta_{sp}(G-1+X)h\nu \\ &\approx 2\eta_{sp}(G-1)h\nu \quad \text{for } (G-1) \gg X \\ \eta_{sp} &= \frac{N_2}{N_2 - N_1}. \end{aligned} \tag{13}$$

X is the excess noise parameter of the EDFA. p_{ase} is the ASE noise power in both polarization modes emitted by the EDFA. Eqn. 13 gives the optical noise spectral density (W/Hz) at the output of the erbium-doped fiber. This noise field has all of the statistical properties of thermal noise; it is additive and Gaussian with respect to the amplified input field [2]. η_{sp} is the inversion parameter, and with complete population inversion its value is equal to one. To obtain complete population inversion everywhere along the fiber, the pump power into the fiber must be at least twenty times greater than the pump power threshold at which population inversion begins [3]. Qualifying this further, the product of the pumping rate and the fluorescence lifetime of the N_2 level must be much greater than one, which will occur with sufficient remnant pump power. Without complete population inversion, η_{sp} increases due to the decrease in number of electrons in level N_2. This causes an increase in the amplifier noise figure as given by the equation NF = $2\eta_{sp}$ as derived later.

EDFA IMPLEMENTATION

The amplifier gain medium is the erbium-doped fiber, whose length varies from a few meters to about 100 meters. The length can be optimized for either gain or noise characteristics. Also, the optimum length increases with pump power and decreases with the signal power [4]. The fibers used typically have a codopant such as germanium, aluminum, ytterbium, or phosphorus to change various fiber characteristics. The fiber is designed to utilize pump power as efficiently as possible, and has a mode-field diameter much smaller than that of standard single-mode fiber. This results in relatively high splice loss, typically about 1 dB.

A general block diagram of an EDFA is shown in Fig. 2. Two pump lasers are shown, although a single pump laser can be used either at the erbium fiber input (co-propagating pump) or at the erbium fiber output (counter-propagating pump). In either configuration, the pump power should be greater than approximately 100 mW to eliminate the effect of absorption allowing complete population inversion and identical ASE powers in the forward and reverse directions. This is important particularly in a system that utilizes a double pump configuration because if one fails, without sufficient pump power available to the Er-doped fiber, the EDFA noise and gain characteristics will change drastically.

Isolators are used to prevent reflected signals from being re-amplified. The reflections would induce intensity noise and intermodulation distortion by distorting the shape of the ASE spectra. At high pump powers, such as with a double-pump configuration, the reflections can cause laser oscillation or cause the higher ASE powers to self-saturate the amplifier and reduce the pump efficiency [5].

The general input-output signal characteristic of

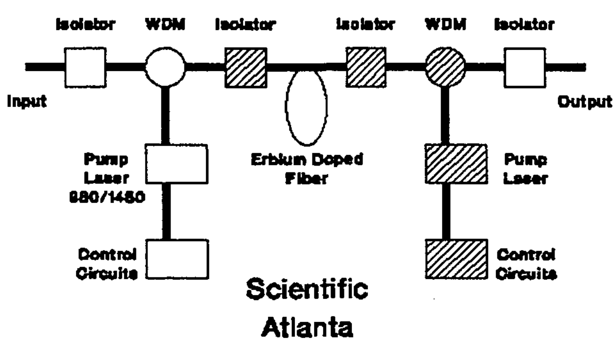

Fig. 2. Block diagram of EDFA with double pump.

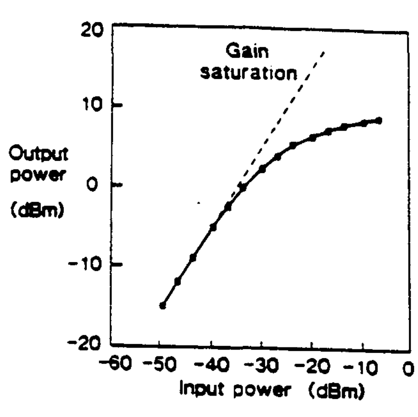

Fig. 3. Amplifier input-output characteristics using a 980-nm pump laser [8].

an EDFA is shown in Fig. 3. As the input signal increases the gain decreases as the amplifier goes into saturation or gain compression. When an EDFA is driven sufficiently hard into saturation the output power tends toward a limiting value (P_{sat}) which is the maximum output power [6]. Saturated output increases approximately linearly with pump power. As the EDFA goes deeper into saturation, more and more of the pump light is converted into signal. As booster or power amplifiers, EDFA's are operated deeply in saturation in order to deliver high output power. The saturated output power of commercially-available amplifiers for use as booster amplifiers is in the range of about 10 dBm to a little over 20 dBm. High differential pump-to-signal quantum efficiencies have been obtained. There exists a performance tradeoff for an EDFA to have low noise amplification and high pumping efficiency. To obtain both, the use of short pump wavelengths are preferred in order to lower the ASE power and obtain high efficiencies by strongly saturating the amplifier. At the 980-nm pump wavelength, 47-mW saturation power (16.7 dBm) has been obtained with 100 mW of pump power [7].

Due to the temporal properties of the erbium fiber, the signal may experience intermodulation distortion in a single channel system or saturation induced crosstalk in a multiple channel system. These transient effects are produced when operating in gain saturation. One effect of signal induced gain saturation is to increase the pump attenuation thus reducing the population inversion toward the output of the EDFA which changes the gain spectrum and creates noise. The gain spectra will shift under nonuniform gain saturation conditions depending on such factors as fiber type, fiber length, pump power, pump wavelength, and signal wavelength [6]. For CATV application, these transient gain effects are dampened by the long fluorescent lifetime in erbium which sets a lower frequency limit of approximately 100 kHz by filtering out any high frequency modulation of the EDFA's gain. Fluctuations in the gain spectra are inversely proportional to the pumping rate. Therefore, the stronger the pump power, the smaller the fluctuation or the smaller the gain-recovery time constant which minimizes crosstalk and distortion. The slow gain response combined with the third-order susceptibility of the erbium fiber also prevents the occurrence of intermodulation distortion in multichannel systems [9]. Other techniques useful in eliminating the transient gain effects are by utilizing filters at the erbium fiber to equalize the gain spectrum and by utilizing an all-optical feedback loop to the EDFA [4].

The output spectrum of an EDFA is given in Fig. 4 with no input signal, and in Fig. 5 for a high input signal level (5 dBm). In Fig. 5, the amplifier is operating 20 dB into saturation (small signal gain reduced 20 dB).

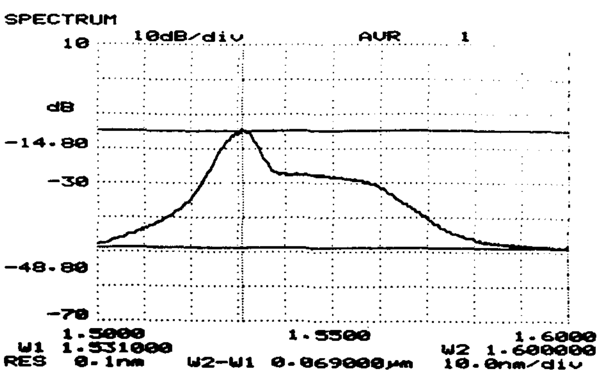

Fig. 4. EDFA output spectrum with no input signal.

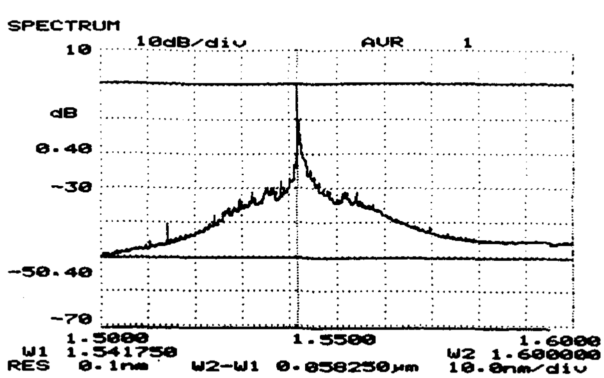

Fig. 5. EDFA output spectrum with 5-dBm input signal power.

SIGNAL AND NOISE CHARACTERISTICS

In direct-detection of an optical signal, the output current of the photodetector is directly proportional to optical power. However, optical power is proportional to the square of the magnitude of the E field and the detector responds to the square of the E field. The detector is in reality a square-law detector, and the fact that the output of a photodetector changes 2 dB per dB change in input power is very familiar. In a system with an optical amplifier, this square-law characteristic causes additional noise currents to be produced at the output of the photodetector: these are called signal-spontaneous (s-sp) beat noise, and spontaneous-spontaneous (sp-sp) beat noise.

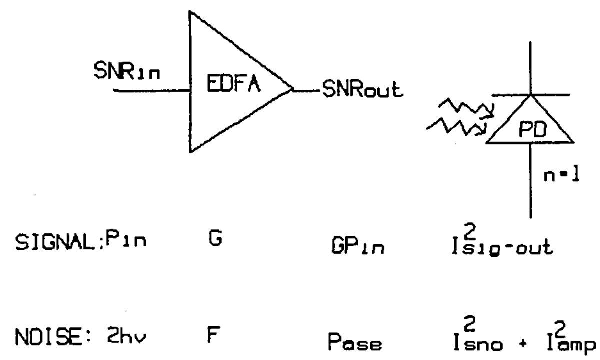

Fig. 6. Diagram for noise figure calculations.

Consider an optical amplifier directly connected to a photodetector as illustrated in Fig. 6. P_{in} is the input signal power and G is amplifier gain. There are two components at the output of the amplifier: amplified signal GP_{in} and amplified spontaneous emission noise p_{ase}. Since the photodetector is a square-law detector, heterodyning and mixing occur. The optical noise heterodynes with the signal causing the noise spectrum to be translated to dc. This noise is signal-spontaneous beat noise. In an EDFA, the spontaneous emission is randomly polarized and only the noise that is co-polarized with the signal, $\frac{1}{2}p_{ase}$, is heterodyned. Likewise, components of the spontaneous emission mix with each other in the square-law detection process to produce spontaneous-spontaneous beat-noise currents.

The signal-spontaneous beat-noise current is [10]

$$i^2_{s\_sp} = 2P_{in}Gp_{ase}(\frac{\eta q}{h\nu})^2. \tag{14}$$

Assuming the amplified spontaneous emission noise p_{ase} is constant over an optical bandwidth B_o, the spontaneous-spontaneous beat-noise current is [10]

$$i^2_{sp\_sp} = p^2_{ase}B_o(\frac{\eta q}{h\nu})^2. \tag{15}$$

Amplifier Noise Figure

The amplifier noise figure as defined and developed herein follows that presented in reference [11] and is the same as in [12]. The noise factor F of an amplifier is defined as

$$F \triangleq \frac{\mathrm{SNR}_{in}}{\mathrm{SNR}_{out}} \tag{16}$$

where SNR_{in} and SNR_{out} are the signal-to-noise ratios at the input and output of the amplifier. The input noise, by definition, is that from an ideal source. At optical frequencies, the input noise is quantum noise ($2h\nu$), whereas in the electrical domain it is KT. For the optical amplifier, the SNR's are defined as electrical quantities measured at the output of a ideal photodetector ($\eta = 1$). Signal currents are expressed in A^2, and noise currents are in A^2/Hz.

SNR_{in} is given with the optical source directly connected to the photodetector. The signal measured at the output of the photodetector is

$$I^2_{s\_in} = [P_{in}\frac{q}{h\nu}]^2. \tag{17}$$

The photodetector output noise is shot noise

$$2q[P_{in}\frac{q}{h\nu}] \tag{18}$$

and

$$\mathrm{SNR}_{in} = \frac{P_{in}}{2h\nu}. \tag{19}$$

This result is the same as for SNR_{in} in the optical domain. With the amplifier connected directly to the photodetector, the output noise currents consist of two components: shot noise due to the amplified input signal, and total noise current due to the optical amplifier. The output signal is

$$I^2_{s\_out} = [GP_{in}\frac{q}{h\nu}]^2 \tag{20}$$

and the output noise currents are

$$i^2_{sno} + i^2_{amp} = 2q[P_{in}\frac{q}{h\nu}] + i^2_{amp} \tag{21}$$

where i^2_{sno} is shot noise due to the amplified signal and i^2_{amp} is optical amplifier noise. From the preceding equations, amplifier noise factor is

$$\begin{aligned} F &= \frac{P_{in}}{2h\nu}\frac{i^2_{sno} + i^2_{amp}}{(GP_{in}\frac{q}{h\nu})^2} \\ &= \frac{1}{G}[1 + \frac{i^2_{amp}}{i^2_{sno}}] \\ &\approx \frac{1}{G}\frac{i^2_{amp}}{i^2_{sno}} \qquad \text{for } G \gg 1. \end{aligned} \tag{22}$$

Noise figure is noise factor expressed in dB:

$$\mathrm{NF} = 10\log_{10}F. \tag{23}$$

For most practical CATV applications, signal-spontaneous beat noise dominates and the noise factor is then

$$\begin{aligned} F &\approx \frac{1}{G}\frac{4P_{in}G\eta_{sp}(G-1)\frac{q^2}{h\nu}}{2q(GP_{in}\frac{q}{h\nu})} \\ &\approx 2\eta_{sp}(\frac{G-1}{G}) \\ &\approx 2\eta_{sp} \qquad \text{for } G \gg 1. \end{aligned} \tag{24}$$

The last expression is the definition that is commonly used for EDFA noise factor. The minimum value for η_{sp} is one, for which the quantum-limit noise figure is 3 dB. Measured values approaching 3 dB have been achieved with 980-nm pumping, but the minimum achievable value for 1480-nm pumping is about 4 dB. The higher noise figure in the 1480-nm pump band is due to its proximity to the 1550-nm signal emission band, which causes the erbium three-level system to behave differently [13]. This creates a finite thermal population (N_3) at the pump level which restricts the fiber from being uniformly inverted. Coupling losses in the amplifier unit increase the amplifier noise figure. External noise figures of 5 to 7 dB appear to be readily achievable.

Measurement of Noise Figure

According to the definition of noise factor given in the preceding section, F is given by currents at the output of an ideal detector with quantum efficiency $\eta = 1$. For practical measurements, particularly when operating at high saturated output power, loss has to be inserted between the amplifier and detector. For simplicity, assume that the amplifier noise i^2_{amp} consists of signal-spontaneous and spontaneous-spontaneous beat-noise currents $i^2_{s\text{-}sp}$ and $i^2_{sp\text{-}sp}$. The noise currents measured at the output of the detector are then

$$\begin{aligned} i^2_{amp\_measured} &= \eta^2_{eff}\, i^2_{amp} \\ i^2_{sno\_measured} &= \eta_{eff}\, i^2_{sno} \end{aligned} \quad (25)$$

where

$$\eta_{eff} = \frac{I_{dc}}{GP_{in}} \frac{h\nu}{q} . \quad (26)$$

η_{eff} is the total loss factor from the amplifier output to the detector including the detector quantum efficiency. I_{dc} is the photodiode dc current due to amplified signal power (assumption is that residual pump power is negligible. The noise factor of the amplifier is then given by

$$\begin{aligned} F &= \frac{1}{G} + \frac{1}{G\eta_{eff}} \frac{i^2_{amp\_measured}}{i^2_{sno\_measured}} \\ &= \frac{1}{G} + \mathrm{SNR}_{in} \frac{i^2_{amp\_measured}}{I^2_{dc}} \\ &\approx \mathrm{SNR}_{in} \frac{i^2_{amp\_measured}}{I^2_{dc}} \quad \text{for } G \gg 1. \end{aligned} \quad (27)$$

CATV CARRIER-TO-NOISE RATIO

For CATV system modeling, the carrier-to-noise ratio (CNR) due to the optical amplifier can be calculated based on the noise factor given in Eqn. 27. In multichannel AM operation, the carrier currents at the output of the photodetector are given by

$$\frac{mI_{dc}^2}{2} \qquad [\mathrm{A}^2] \quad (28)$$

where m is the modulation index per channel. Thus, from Eqn. 27 and $G \gg 1$, the CNR due to the optical amplifier is given by

$$\begin{aligned} \mathrm{CNR} &= \frac{\mathrm{SNR}_{in}}{F} \frac{m^2}{2} \qquad [/\mathrm{Hz}] \\ &= \frac{\mathrm{SNR}_{in}}{F} \frac{m^2}{8 \cdot 10^6} \quad [/4\,\mathrm{MHz}] . \end{aligned} \quad (29)$$

These expressions are also valid for amplifier noise from other causes (excluding ASE shot noise) such as interferometric -interference noise. $i_{amp\_measured}$ includes noise currents from all other sources of noise within the amplifier. Also note that F as given herein is the external noise factor of the amplifier (except for Eqn. 24 which does not take into account input and output coupling losses). CNR expressed in dB for 4-MHz electrical bandwidth is

$$\mathrm{CNR}_{dB} = 89.9 - \mathrm{NF} + P_{in\_dBm} + 20\log(m) . \quad (30)$$

An equivalent RIN can also be given:

$$\mathrm{RIN}_{dB} = -155.9 + \mathrm{NF} - P_{in\_dBm} . \quad (31)$$

As an example, if P_{in} = 0 dBm, m = .04, and NF = 5 dB, then the CNR is 56.9 dB and the amplifier RIN is -150.9 dB/Hz. As is evident here, amplifier input power should be in the range of about 0 dbm or greater to prevent excessive degradation of system CNR. The effect of amplifier RIN is to reduce the system CNR for short fiber spans, but the high output power of the amplifier results in a higher CNR for long fiber spans than is possible with today's DFB lasers only. This characteristic CNR performance is shown in Fig. 7.

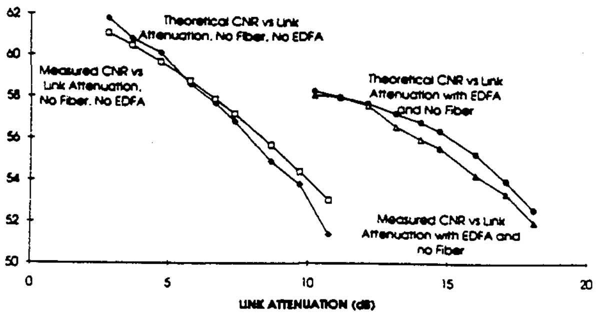

Fig. 7. CNR vs. link attenuation with and without EDFA. 4-dBm input power and 980-nm pumping. 1543-nm DFB source laser with 5.9% modulation index.

CONCLUSIONS

Erbium-doped fiber amplifiers (EDFA's) have desirable properties for use as power amplifiers for AM CATV. Output power for commercially-available amplifiers is over 10 dBm and as high as about 20 dBm. A realistic noise figure for this type amplifier is about 5 - 7 dB. In this paper amplifier noise figure equations were developed and the relationship of CATV CNR to amplifier noise figure was given. Noise figure is given based on electrical measurements at the output of a photodetector.

In spite of the advantages of 1550-nm operation with erbium-doped fiber amplifiers, because of other factors and limitations of EDFA's not discussed in this paper, the current 1310-nm technology may continue to be the dominant technology for some time. Development of 1550-nm lasers continues to lag that of their 1310-nm counterparts. Dispersion at 1550-nm with standard single-mode fiber causes serious CSO distortion, and although solutions are available, the viability and acceptability of these solutions remains to be seen. However, the EDFA technology has matured and products are now available for AM CATV applications.

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