Optical Amplifier with 27 dB Dynamic Range in a Coherent Transmission System

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Abstract—**For applications of optical amplifiers it is important to know the range of amplifier input powers that cause no or negligible system performance degradation. This dynamic range sets limits on information capacity and amplifier cascadability. We have measured a 27 dB dynamic range for a traveling-wave optical amplifier with 10 dB fiber-to-fiber gain and 0.8 dB gain ripple. The device was used in a 150 Mb/s coherent transmission system. Our result, the widest dynamic range reported to date, indicates excellent suitability of the optical amplifier for coherent photonic networks and systems.**

Introduction

Optical amplifiers have successfully been used in direct detection and coherent systems [1]–[4]. For applications it is important to know the range of amplifier input powers that cause no or negligible system performance degradation. From radio and microwave engineering this concept is known as dynamic range [5]. It sets limits on the maximum number of channels, bit rate, and number of cascaded amplifiers. In one report [2], the dynamic range of an amplifier was measured, although it was not explicitly mentioned. In order to provide a guideline for practical application, the dynamic range of a traveling-wave optical amplifier was measured [3] and correlated to the device parameters output saturation power and spontaneous emission factor. In this experiment, we used a 150 Mb/s coherent FSK system [6].

Theory

We follow the theory as given by Olsson [1]. The dominant noise contributions in an optical heterodyne system with optical amplifier are the local oscillator shot noise N_{shot}, the thermal noise N_{th} of the receiver, and the beat noise $N_{\text{lo-sp}}$ between the local oscillator and the spontaneous emission. We find

$$N_{\text{shot}} = 2 \cdot I_{\text{lo}} \cdot B_e \cdot e \tag{1}$$

$$N_{\text{lo-sp}} = 4 \cdot I_{\text{lo}} \cdot N_{\text{sp}} \cdot (G-1) \cdot \eta_{\text{out}} \cdot L \cdot \eta \cdot B_e \cdot e \tag{2}$$

$$P_s = P_{\text{in}} \cdot \eta_{\text{in}} \cdot G \cdot \eta_{\text{out}} \cdot L \tag{3}$$

where I_{lo} is the photocurrent generated by the local oscillator, B_e is the electrical bandwidth, and e is the electron charge. The amplifier is characterized by its spontaneous emission factor N_{sp}, gain G, and coupling efficiencies η_{in} (input) and η_{out} (output). The loss between amplifier and receiver is L, the quantum efficiency of the coherent receiver is η. The signal powers in the amplifier input fiber and at the receiver are P_{in} and P_s, respectively.

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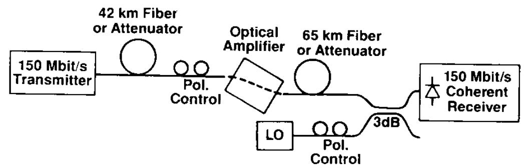

Fig. 1. Coherent transmission setup with optical amplifier.

The degradation of the signal-to-noise ratio in a coherent receiver due to spontaneous emission noise is

$$\begin{aligned}\Delta_{\text{SNR}} &= 10 \cdot \log\left[(N_{\text{shot}} + N_{\text{th}} + N_{\text{lo-sp}})/(N_{\text{shot}} + N_{\text{th}})\right] \\ &= 10 \cdot \log\left[1 + \frac{2 \cdot N_{\text{sp}} \cdot \eta \cdot P_s}{(1 + N_{\text{th}}/N_{\text{shot}}) \cdot \eta_{\text{in}} \cdot P_{\text{in}}}\right]\end{aligned} \tag{4}$$

where we have used (1)–(3) and $(G-1) \sim G$. As the low end of the dynamic range we have chosen the power P_{in} that causes $\Delta_{\text{SNR}} = 1$ dB. The SNR degradation is easily measured as the equivalent BER increase.

Four-wave mixing (third-order intermodulation) may limit the maximum permissible P_{in}. However, it strongly depends on channel spacing and will become insignificant if the channel spacing is wide enough [4]. This mechanism and crosstalk are nonexistent for single-channel systems. As the high end of the dynamic range we have therefore chosen the value of P_{in} that causes 1 dB gain compression: if the amplifier output power approaches the saturation limit the number of free carriers decreases and hence the gain is reduced. This effect starts at the amplifier output where the optical power density is highest. Given a constant loss span, gain compression decreases the signal power P_s thus increasing the BER.

Transmission System

We used a 150 Mb/s single-filter FSK heterodyne system operating at 1.3 μm wavelength [6] (Fig. 1). Alternate mark inversion (AMI) coding was applied to overcome the nonuniform frequency response of the transmitter laser. The signal was transmitted through attenuators or 42 km of fiber to the GaInAsP/InP optical amplifier [7]. The waveguide was oriented 7° away from the [011] direction of the wafer, to

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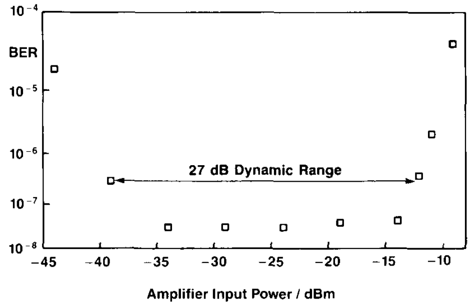

Fig. 2. Bit error ratio BER versus amplifier input fiber power P_{in} with constant total attenuation.

reduce reflections from the cleaved facets. A simple anti-reflection coating with 1-5% reflectivity improved coupling and reduced the effective facet reflectivity to $5\text{-}8 \cdot 10^{-4}$. Lensed fiber pigtails were oriented at 22° incidence angle, to obtain coupling efficiencies of -5 to -6 dB. Attenuators or 65 km of fiber were inserted between the amplifier and the coherent receiver. Polarization was controlled manually in front of the amplifier and the receiver. No optical filter or isolator was needed for the optical amplifier.

Results

The amplifier was biased at 97 mA, giving a fiber-to-fiber gain of about 10 dB for TE polarization, and 7 dB for TM polarization. The gain ripple was only 0.8 dB, at an internal gain of 20 dB. The signal was transmitted with a bit error ratio (BER) of $< 10^{-9}$ for a $2^{23} - 1$ bit pattern through a total fiber length of 107 km, including 15 biconic connectors. The usable loss span was 54 dB. A -52 dB (1 mW) receiver sensitivity was reached with or without the amplifier.

After replacing most of the fiber by attenuators, we measured bit error ratios as a function of P_{in}. For very high powers the gain was reduced due to saturation. Since the loss was kept constant, this decreased P_s in the receiver. The situation was different for very low P_{in}. In this case, we observed increased noise and the system did not reach low BER even if P_s was very high.

In order to determine the dynamic range accurately, we set the error ratio at $2 \cdot 10^{-8}$. This allowed us to measure the BER versus P_{in} in a time short enough to maintain stable coupling. The total loss was kept constant by adjusting the attenuators preceding and following the amplifier. The detected signal power in the receiver was $P_s \cdot \eta = -52.3$ dB (1 mW) except for $P_{in} > -14$ dB (1 mW) where gain compression occurred. The BER stayed practically constant over a 20 dB range (Fig. 2). A BER increase to $2.5 \cdot 10^{-7}$ corresponded to about 1 dB SNR decrease in our receiver. It was observed at -12 dB (1 mW) due to gain compression and at -39 dB (1 mW) due to spontaneous emission noise, giving a dynamic range of 27 dB. To our knowledge, this is the widest dynamic range reported so far.

Discussion

A gain reduction of 1 dB was measured at $P_{in} = -12$ dB (1 mW), i.e., -3 dB (1 mW) in the output fiber. This value is consistent with 5 dB (1 mW) saturation output power [7] at 97 mA bias current.

The ratio N_{th}/N_{shot} in the coherent receiver was 0.86, corresponding to a thermal noise penalty of $10 \cdot \log(1 + N_{th}/N_{shot}) = 2.7$ dB [6]. With $P_{in} = -39$ dB (1 mW), $\eta_{in} = 0.3$, $P_s \cdot \eta = -52.3$ dB (1 mW) and $\Delta_{SNR} = 1$ dB, we used (4) to calculate the spontaneous emission factor. The result $N_{sp} = 1.6$ is a comparatively good value [1]. However, we expect about 1 dB measurement uncertainty.

The wide dynamic range is attributed to high saturation power and low spontaneous emission factor of the amplifier, and to the coherent receiver acting like an extremely narrow optical filter. Leaving 4 dB margin, a 23 dB range could be used to increase the bit rate in this amplifier 200-fold (if a suitable transmission system were available), or increase the number of channels to 200 (unless four-wave mixing limits this number [2], [4]). Alternatively, one 150 Mb/s channel could be transmitted through a substantial number of cascaded amplifiers. Furthermore, the system designer will use the knowledge of the dynamic range to determine permissible signal power variations, whether they stem from variations in splice and connector losses, laser power, gain of preceeding amplifiers, or coupling efficiencies.

Conclusions

We operated a near traveling wave optical amplifier in a 150 Mb/s single-filter FSK heterodyne system. The fiber-to-fiber gain was ~10 dB with a ripple of only 0.8 dB. The range of amplifier input powers over which <1 dB degradation of signal-to-noise ratio in the receiver occurred was 27 dB. This is, to our knowledge, the widest dynamic range reported to date.

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