Gain cross saturation and spectral hole burning in wideband erbium-doped fiber amplifiers

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Received June 18, 1991

Cross-saturation characteristics are investigated in broadband 1.48-μm pumped and 980-nm pumped gain-shaped erbium-doped fiber amplifiers. Gain shaping is shown to give a more uniform spectral gain compression on saturation. In addition, a degree of room-temperature spectral gain hole burning is observed for what is to our knowledge the first time.

One of the major applications of erbium-doped fiber amplifiers (EDFA's) is likely to be in broadband wavelength-division multiplexed (WDM) systems.[1] In this case it is desirable to flatten and maximize the gain bandwidth of the EDFA. To date two techniques have been employed, either by the use of a pump wavength of ~1.48 μm combined with a careful choice of pump power and fiber length[2] or by gain shaping that incorporates an optical filter in the middle of the amplifier.[3] Application to aluminosilicate, germanoaluminosilicate, or fluorozirconate[4] EDFA's results in 3-dB gain bandwidths of ≈35 nm. In addition, it is important to understand and optimize the wavelength cross-saturation characteristics of the EDFA. Thus the number of WDM channels can be maximized while the gain penalty for each channel and interchannel cross-talk effects can be minimized.[5,6]

In this Letter we describe an efficient, 1.48-μm diode-pumped fiber amplifier. The use of a germanoaluminosilicate erbium-doped fiber as well as careful choice of pump power, pump wavelength, and fiber length creates an amplifier characterized by a 25-dB gain and a 35-nm 3-dB bandwidth for only 15 mW of pump power. Cross-saturation characteristics are investigated for saturating signals at various wavelengths across the gain band and different pump powers. In general, the gain spectrum decreases nonuniformly, with shorter wavelengths suffering the largest penalty. Such a characteristic is expected owing to the different emission and absorption spectra near 1.5 μm. In addition, saturation characteristics show little dependence on the saturating wavelength, and only small spectral gain hole burning is observed, which confirms the near-homogeneous nature of the erbium transition in germanoaluminosilicate glass. Comparison with similar results for a gain-shaped 980-nm pumped EDFA shows this to be a preferable technique that yields a more uniform decrease in the gain spectrum.

The amplifier consisted of 35 m of germanoaluminosilicate erbium-doped fiber that was characterized by an Er^{3+}-doping level of ~160 parts in 10^6, a N.A. of 0.2, and λ_{cutoff} at 930 nm. The signal source was an edge-emitting light-emitting diode (ELED), which permitted measurement of gain spectra between 1.52 and 1.57 μm. Its power was maintained to be less than 200 nW within the gain band of Er^{3+}, thus ensuring small-signal operation. A further signal from either a distributed-feedback laser diode or a tunable external-cavity laser diode was mixed with the probe signal through a 3-dB fiber coupler. This large signal was sufficient to saturate the amplifier and permitted the measurement of spectral gain under saturated conditions.[3] Pump light at ~1.485 μm was obtained from two diode lasers. This was combined with the two signals through a dichroic fiber coupler and injected into the amplifier fiber. All free fiber ends were angle polished to suppress optical feedback.

The amplifier output was coupled to a monochromator and detected with lock-in techniques to allow discrimination of the broadband (ELED) saturating signals (distributed-feedback or tunable laser) and amplified spontaneous emission by virtue of their different modulation frequencies. Output spectra were obtained for various pump powers, under both small-signal and saturated operation and for several wavelengths of saturating signal. At the end of the experiments, the fiber was cut back and the spectrum of the broadband (ELED) signal was measured such that the gain spectrum could be obtained.

Figure 1 shows small-signal gain spectra obtained for various pump powers. The spectra are seen to exhibit a transition from absorption to emission with increasing pump power and a corresponding increase in population inversion.[7,8] As a result, a pump power between 15.2 to 17.7 mW gives the broadest gain. In the case of a pump power of 15.2 mW, a peak gain of 25 dB and a 3-dB bandwidth of 35 nm are obtained. This corresponds to a gain efficiency of ~1.6 dB/mW.

Figure 2 shows gain spectra and corresponding gain compression obtained with a pump power of 17.7 mW and increasing signal input power at wavelengths of 1529, 1532, 1538, and 1556 nm. These wavelengths were selected to correspond to either a peak or dip in the homogeneous line shape[9] for such a fiber type and thus to maximize any inhomogeneous effects observed. From the figure it is clear

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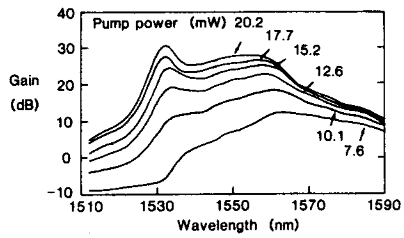

Fig. 1. Gain spectra of EDFA in small-signal operation for different pump powers at 1485 nm.

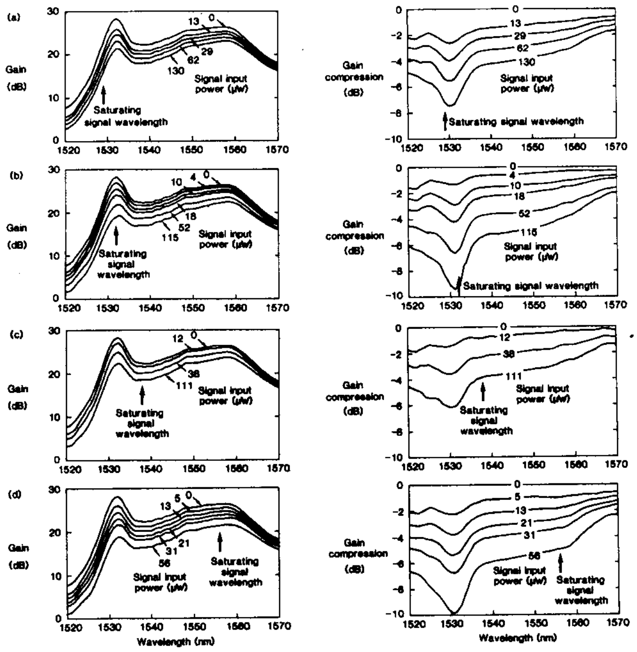

Fig. 2. Gain spectra and corresponding gain compression obtained with a pump power of 17.7 mW and increasing saturating signal power at wavelengths of (a) 1529 nm, (b) 1532 nm, (c) 1538 nm, and (d) 1556 nm.

that for all signal wavelengths the gain spectrum distorts on saturation, with the shorter signal wavelengths near 1.532 μm incurring the largest gain compression. This is undesirable for WDM systems. From the figure it can also be seen that the gain compression curves for different signal wavelengths are similar, thus confirming the homogeneous character of erbium in germanoaluminosilicate glass.

Figure 3 plots similar data for a gain-shaped, 980-nm pumped amplifier[3] in which an optical notch filter is incorporated in the middle of the amplifier to modify its gain spectrum. In this case the gain spectrum saturates more uniformly, which makes it a preferable technique. The difference in spectral saturation characteristics results from a differing degree of population inversion for the two techniques. In the case of the 1490-nm pumped amplifier an incomplete population inversion is obtained owing to the finite emission cross section at the pump wavelength. At this inversion the gain spectrum changes relatively rapidly with incremental changes in population inversion, whereas in the case of the 980-nm pumped, gain-shaped amplifier the population inversion is high, and thus the sensitivity of the gain spectrum to incremental changes in population inversion is minimal. In addition, it may be possible to optimize the performance further by exact location of the gain-shaping filter.

Figure 4 compares in more detail gain compression data of Fig. 2. Data are selected for the four saturating wavelengths and at the same degree of saturation. The differences are subtle, with

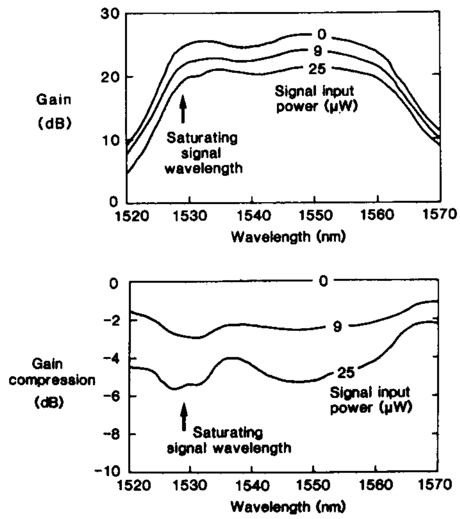

Fig. 3. Gain spectra and corresponding gain compression for a gain-shaped amplifier[3] and with saturating signal at a wavelength of 1529 nm.

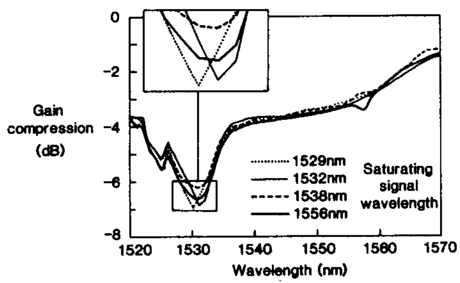

Fig. 4. Gain compression for different wavelengths of saturating signal but with the same degree of saturation. Small spectral hole burning can be observed.

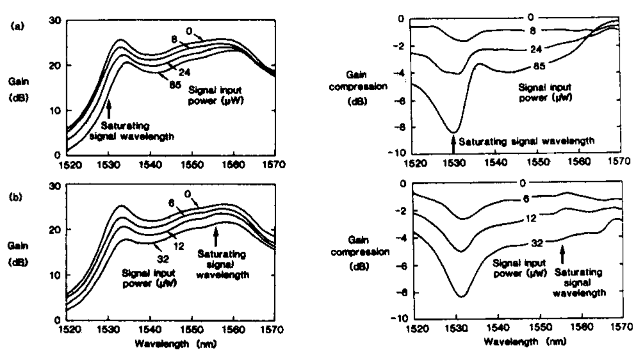

Fig. 5. Gain spectra and corresponding gain compression obtained with a pump power of 15.2 mW and increasing saturating signal power at wavelengths of (a) 1530 nm and (b) 1555 nm. A shift in the wavelength of maximum gain compression is observed in (a) owing to spectral hole burning.

the saturating signals at 1529, 1532, and 1556 nm creating a spectral hole at each of their respective wavelengths, while the signal at 1538 nm results in a reduced gain compression at 1532 nm. This is to our knowledge the first observation of room-temperature spectral hole burning in alumina codoped EDFA's. However, the effect is small, resulting in a less than 1-dB change in gain compression across the gain band, and will thus be of little consequence in future WDM systems.

Figure 5 shows additional data obtained for a reduced pump power of 15.2 mW. In this case the saturating signal wavelengths were 1530 nm [Fig. 5(a)] and 1556 nm [Fig. 5(b)]. For the saturating signal at 1556 nm we note that the compression data are similar to those presented in Fig. 2(d). The wavelength of maximum gain compression, 1532 nm, is seen to correspond to both the peak emission and the absorption wavelength. However, for the saturating signal at 1530 nm, we note that for small gain compression the peak compression occurs at 1532 nm, while at deeper compression a spectral hole occurs and the peak gain compression occurs at the signal wavelength. Gain compression is relieved near 1538 nm, a wavelength corresponding to a midpoint between Stark components.[9]

In conclusion, either gain-shaping and 980-nm pumping or 1.48-μm pumping can be used to give a broad spectral gain. Both types of EDFA exhibit gain spectra that change when saturated. However, a 980-nm gain-shaped amplifier exhibits a lower cross-saturation effect than does a 1.48-μm pumped amplifier. For example, for 1.48-μm pumping a large signal at 1556 nm sufficient to cause 5 dB of gain compression at that wavelength causes 10 dB of gain compression at 1530 nm. On the other hand, for a gain-shaped, 980-nm pumped amplifier, a 5-dB compression at 1556 nm gives only a 5.5-dB compression at 1530 nm.

In addition, we have made what are to our knowledge the first observations of room-temperature spectral gain hole burning in EDFA's pumped by broad-linewidth (~10-nm) pump sources. The effect is small and gives rise to a less than 1-dB change in gain compression across the gain band and confirms the near-homogeneous nature of the erbium transition in germanoaluminosilicate glass. This effect will be of little consequence to future WDM systems.

This research was supported by Societa Cavi Pirelli. M. Tachibana thanks Seiko Instruments Inc., for financial support, and R. I. Laming thanks The Royal Society for provision of a Research Fellowship. The authors thank J. E. Townsend for fabricating the fiber and J. D. Minelly for supplying the fiber couplers.

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