Dual-stage erbium-doped, erbium/ytterbium-codoped fiber amplifier with up to +26-dBm output power and a 17-nm flat spectrum

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By concatenating an aluminum-codoped erbium-doped fiber with an efficient erbium/ytterbium-codoped fiber, we produce a gain spectrum that is flat within 0.5 dB for 17 nm from 1544 to 1561 nm. By using energy transfer between erbium and ytterbium ions, we are able to pump the second stage with a high-power 1064-nm source to achieve an output power as high as +26 dBm. Using 980-nm pumping of the first stage, we produce an overall noise figure below 5 dB.

When erbium-doped fiber amplifiers (EDFA's) are used in multiple-wavelength wavelength-division multiplexed (WDM) systems and analog CATV systems, high output powers, low noise figures (NF's), and spectral gain flatness are required. One can achieve high power levels by increasing the available pump power or by using ytterbium codoping. In phosphorus-containing fibers, ytterbium can absorb pump power from available sources near 1064 nm and efficiently transfer energy to erbium ions for power amplification near 1550 nm. Unfortunately, such fibers do not readily produce flat gain spectra or low NF's. Gain flatness has been achieved with fluoride-based host fibers, which have not yet produced a very high output and can only be effectively pumped near 1480 nm (producing a higher NF than 980-nm pumping). Flatness is also attainable with optical filtering or by combination of fibers of differing host composition. In this Letter we describe an unfiltered EDFA with up to +26-dBm output power, 38-dB gain, flatness to within 0.5 dB in a 17-nm bandwidth, and a low (<5-dB) NF.

In an EDFA all possible spectra are predicted by fractional combinations of the gain spectrum measured when all ions are inverted with the loss spectrum measured when all ions are uninverted. Some possible gain spectra predicted with these parameters are shown in Fig. 1(a) for a typical aluminum-codoped EDFA and in Fig. 1(b) for a phosphorus-codoped erbium/ytterbium-doped fiber amplifier (EYDFA). These are the fibers used throughout this Letter. Unfortunately, the EYDFA does not produce spectra as flat as those of the EDFA, which, in turn, does not produce a very high output. Fortunately, some of the spectra for these fibers can be combined for certain length choices to produce flat spectra. Some computed combined flat gain spectra for 15 m of erbium-doped fiber (EDF) and 6 m of erbium/ytterbium-doped fiber (EYDF) inverted to various levels are shown in Fig. 2. The inversion of the EYDF was adjusted in each case to produce the flattest spectrum when combined with the EDF inverted to the indicated level. Clearly, a loss of inversion in the EDF can be partially compensated by an inversion increase in the EYDF. Because erbium is considered mostly homogeneously broadening in a silicate host at room temperature, it does not matter what power levels produce these inversion levels. The spectrum is determined solely by the average inversion of the ions.

To produce the flattest spectrum from 1544 to 1561 nm, one should combine a 100%-inverted EDF combined with a nearly 50%-inverted EYDF. These inversion levels can be reached in a typical dual-stage...
amplifier. A first-stage EDF can be highly pumped at 980 nm so that, as long as the signal is moderate, nearly 100% inversion (and a corresponding low NF) is possible. The input power to a second-stage EYDF is high enough to reduce the inversion to less than 50%. A diagram of the dual-stage hybrid design is shown in Fig. 3. An isolator was used between stages to prevent backward-traveling amplified spontaneous emission from reducing the EDF inversion. A pump reflector was also used in the first stage to reflect extra pump power. The EYDF pump power was adjusted until the flattest spectrum was observed. As signal power increased, the EYDF pump power was increased to bring the net gain back to the design point and achieve flatness.

The lengths of the EDF and the EYDF are easily chosen by modeling and computation of spectra like those of Fig. 2. In the design tested here, the first stage consisted of 15 m of EDF (6% alumina, N.A. = 0.28) copumped with 100 mW at 980 nm. The second stage consisted of 9 m of an efficient EYDF (phosphorus codoped, N.A. = 0.2) copumped at 1064 nm. A shorter length of EYDF would produce a flatter combined spectrum, but 9 m produces greater efficiency. The loss before the EDFA (from the isolator, WDM, and splices) was 1 dB. The interstage loss (from the isolator, WDM, pump reflector, a connector, and the splices) was 3.2 dB, and the postamplifier loss (from the isolator, WDM to reject excess pump, and splices) was 1.8 dB. Unless noted, all values reported below include component losses.

To test the hybrid EDFA, we provided a saturating tone at 1548 nm and adjusted its power to various levels. A small probe signal was added and swept across the spectrum to measure its shape. Because erbium is a mostly homogeneous medium, the spectrum measured by this technique has the same shape as the spectrum produced by use of multiple saturating tones to produce the same ion inversion level (except for a very small amount of spectral hole burning). For each saturating tone level, the pump power of the second stage was adjusted until the flattest spectrum was achieved. The resultant best spectra are shown in Fig. 4 for some useful saturating tone levels. These levels might, for example, represent the power in a single analog signal or the total power for all channels in an eight-channel WDM system. The measured results are fitted theoretically by using modeling parameters, known component losses, and inversion levels predicted by modeling this design. The fit is good, but some discrepancy is observed near 1551 nm. This may be the result of inaccurate modeling parameters, measurement errors, or spectral hole-burning near the 1548-nm saturating tone. Because the pump in the EYDF was adjusted to reach flatness, a hole centered at 1548 nm would be compensated by an increase in the inversion of the second stage. Calculations show that this would leave a remnant hole near 1551 nm for typical spectral hole depths and widths. A multichannel saturating tone of equal total power would burn multiple smaller holes more uniformly across the spectrum and therefore would not leave a dip at 1551 nm.

All four spectra of Fig. 4 achieve an > 17-nm bandwidth with as little as 0.5 dB variation. The 1064-nm pump power levels for these cases were 307, 425, 645, and 1024 mW for −15, −11, −7, and −3 dBm signal inputs, respectively. The measured output power levels at 1548 nm were 14.53, 18.01, 21.06, and 23.61 dBm for −15, −11, −7, and −3 dBm signals, respectively. The penalty produced by the component losses mentioned above is significant. Because the spectrum was forced to flatness by
pump power, all component losses directly reduce the output. If total component losses were 3 dB, the output power would be 3 dB higher when the flattest gain was reached. Of course, the pump power required for a higher output power would be greater as well. To assess the required pump for a given output, output power was measured versus 1064-nm pump power. The measured result at 1548 nm is shown in Fig. 5 for two signal levels straddling the four signal powers used above. The output power varies little with signal input. The slope of these plots is \( \sim 27\% \). The internal efficiency is 1.8 dB higher (owing to output loss), or \( \sim 41\% \). Figure 5 can be used to predict the pump power needed to produce the projected output power levels described above. For example, to produce 26.61-dBm output at \(-3\) dBm input, assuming a 27% slope efficiency, would require \(-1.85\) W of 1064-nm pump power.

To confirm that this hybrid amplifier can achieve flatness with \(+25\)-dBm output, we lengthened the second stage to 12 m. The 6-dB component losses were left intact. When optimized, the output power increased by 5.4 dB for all signal levels to 19.93, 23.41, and 26.46 dBm for \(-15\), \(-11\), and \(-7\) dBm signals, respectively. Adequate pump power was not available to reach \(+29\) dBm for the \(-3\)-dBm signal. In all cases, the flatness was slightly worse than shown in Fig. 4, with the variation increasing by \(-0.3\) dB across the 17-nm width. The NF of the hybrid amplifier is determined almost completely by the NF of the first-stage EDF. Because this stage is a standard aluminum-codoped EDF pumped at 980 nm, a low NF is possible. The measured external NF at 1548 nm was below 5 dB for all tested cases with a minimum of \(-4.2\) dB for the smallest-signal case. This corresponds to an internal NF (not including pre-EDFA loss) of \(-3.2\) dB. This measurement was made with polarization nulling with an estimated accuracy of \(-0.2\) dB.

The hybrid EDFA described here produces high output power, high gain, a low NF, and a flat spectrum \(~17\) nm wide. The design can easily be scaled to different gain levels by scaling the lengths of the two stages equally or by altering the second stage, at the possible expense of flatness. Counterpumping the second stage could also produce greater output power. The greatest limitation on the hybrid design is set by the need to invert the EDF to a high level to produce the flattest spectrum and the lowest NF. This limits the input power for a given 980-nm pump power and also limits the maximum length of the EDF. However, typical WDM and analog applications require levels similar to those used here.

References