Cladding-pumped erbium-doped multicore fiber amplifier

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Abstract: A cladding pumped multicore erbium-doped fiber amplifier for simultaneous amplification of 6 channels is demonstrated. Peak gain over 32 dB has been obtained at a wavelength of 1560 nm and the bandwidth measured at 20-dB gain was about 35 nm. Numerical modeling of cladding pumped multicore erbium-doped amplifier was also performed to study the properties of the amplifier. The results of experiment and simulation are found to be in good agreement.

OCIS codes: (060.2330) Fiber optics communications; (060.2320) Fiber optics amplifiers and oscillators.

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1. Introduction

Space division multiplexing (SDM) in optical fiber has attracted great interest recently due to its potential use in enhancing the capacity of transmission systems [1–5]. Optical signals from different channels can be multiplexed in the space domain using multiple cores embedded into the cladding of a fiber, or using various transverse modes of a multimode fiber. Different designs for multicore fibers have been proposed and fabricated by various research groups with an aim to reduce loss, cross-talk and optical nonlinearity [6–13]. Using such fibers transmission at unprecedented capacities beyond 100Tb/s per fiber over lengths of several tens of km has already been demonstrated experimentally [14–18]. To increase the length of the transmission links, signals in multiple cores need to be amplified in a suitable way. One approach to amplify SDM signals of a multicore fiber involves de-multiplexing into single core fibers, amplifying each of these using conventional amplifiers, and finally multiplexing the amplified signals in the space domain to re-transmit through multicore fiber [18].

It will, however, be more attractive if signals can be amplified using a single erbium doped fiber with multiple cores, rather than using separate amplifier. To this end, recently 7-core and 3-core erbium-doped fiber amplifiers have been demonstrated [19, 20]. Gain over 30 dB and noise figure smaller than 4dB were obtained [19]. In these MCF amplifiers, separate laser diodes were used to pump each of the cores.

Instead of pumping the rare earth doped fibers through the cores, pump radiation can be launched into the silica cladding [21]. A cladding pumped scheme is attractive as it allows for using multimode laser diodes, which can deliver fiber-coupled output with tens of watts and

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are much cheaper than single-mode pump sources. Cladding pumping has been widely used in high power lasers and amplifiers operating in different wavelength regions [22–27]. Cladding pumping is particularly attractive for multicore fiber amplifiers, because the cores can be pumped by a common multimode pump source. Recently, Krummrich analyzed the cost and energy requirement of EDFA having single-mode multicore and multimode single cores for different pumping schemes, such as core- and cladding-pumping [28]. The multimode laser diodes used for cladding pumping have higher electrical to optical power conversion efficiency and in most cases do not require any thermoelectric cooler, which is expected to improve the power conversion efficiency [28].

There are however, a number of important issues that need to be considered while building a multicore amplifier based on cladding pumping. Firstly, since the multiple cores share the same pump radiation guided by the cladding, any significant depletion in pump due to a signal in a particular core may affect gain experienced by the signals in the other cores, introducing unwanted spatial cross-gain modulation. The second issue is related to the noise figure of the amplifier. Since the overlap integral of the cladding-guided pump field and the doped cores is very small, a longer length of doped fiber is required that results in increased amplified spontaneous emission noise and higher noise figure when amplifying weak signals. Thirdly, in cladding pump amplifiers, the signal intensity (in W/m^2), as it gets amplified, can exceed the pump intensity over most of the amplifier. This results in a depletion of the upper state population, which affects the gain spectrum. While multicore amplifiers can be attractive from the point of view of reducing complexity of device structure and cost, proper design is, therefore, needed in order to minimize the noise figure, while achieving large gain and broad bandwidth.

In this paper, we investigated a cladding-pumped multicore fiber amplifier through numerical simulation and studied the amplification and noise properties of the amplifier. We built a 6-core erbium doped fiber amplifier that was cladding-pumped using a multimode 980 nm pump laser diode. We used specially designed tapered fiber bundle couplers that allowed us to simultaneously launch signals into 6 cores and multimode pump radiation into the cladding. A maximum gain was found to be about 32 dB at 1560 nm, and gain over 20 dB was obtained over a bandwidth that was larger than 30 nm.

2. Numerical simulation of gain and noise figure in a cladding pumped multicore fiber amplifier

If we consider an M-core erbium doped fiber amplifier that is cladding pumped at 980 nm (where pump emission cross-section is negligible), the population density in the upper and lower energy level, $N_{2,\mathrm{i}}$ and $N_{1,\mathrm{i}}$, respectively, in *i*-th core can be expressed as [29],

$$N_{2,i}(z)=\frac{\dfrac{\tau\sigma_s^a}{h\nu_s}\cdot I_{s,i}+\sum_j\dfrac{\tau\sigma_{\nu_j}^a}{h\nu_j}\cdot I_{A,i}(\nu_j)+\dfrac{\tau\sigma_p^a}{h\nu_p}\cdot I_p(z)}{\dfrac{\tau\left(\sigma_s^a+\sigma_s^e\right)}{h\nu_s}\cdot I_{s,i}+\sum_j\dfrac{\tau\left(\sigma_{\nu_j}^a+\sigma_{\nu_j}^e\right)}{h\nu_{\nu_j}}\cdot I_{A,i}(\nu_j)+\dfrac{\tau\sigma_p^a}{h\nu_p}\cdot I_p(z)+1}N_0 \quad (1a)$$

$$N_{1,i}(z)=N_0-N_{2,i}(z). \quad (1b)$$

Here, N_0 is the concentration of erbium ions, I_p, $I_{\mathrm{s,i}}$ and $I_{A,i}$ (ν_j) are the intensities of the pump, the signal, and ASE components at wavelength ν_j within the core. Numerical simulation of cladding pumped fiber amplifiers often uses beam propagation method (BPM) for field propagation and nonlinear rate equations for the gain medium [30]. Here, for simplicity we assume that the pump field distribution remains uniform over the cladding region. We thus express pump intensity as I_p (z) = P_p(z) $/A_{cladding}$ = P_p(z) $\Gamma_\mathrm{p}/A_{core}$, where P_p(z) is the pump power at a distance z from the input of doped fiber. A_core and A_cladding represent the

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core and the cladding area, respectively, and Γ_p is the effective overlap factor (EOF) between pump radiation and core, which equals ($A_{core}/A_{cladding}$) [31]. For single mode cores, signal intensity can be approximated as, $I_{s,i}(z) = P_{s,i}(z)\Gamma_s/A_{core}$, where Γ_s is the overlap factor between the signal and the core. Also intensity of ASE at a frequency ν_j can be expressed as $I_{A,i}(\nu_j) = P_{A,i}(\nu_j)\Gamma_{\nu j}/A_{core}$. Here, $P_A(\nu_j)$ is the sum of the forward (P_A^+) and backward (P_A^-) propagating ASE component at frequency ν_j integrated over a bandwidth of $\Delta\nu_j$. σ_s^a and σ_s^e are the absorption and emission cross sections at the signal wavelength. $\sigma_{\nu j}^a$, $\sigma_{\nu j}^e$ represent the absorption and emission cross sections at frequency ν_j. σ_p^a is the absorption cross section in the doped core region at the pump wavelength. τ is the lifetime of the upper energy level.

Neglecting fiber loss, the gain per unit length at the signal wavelength can be expressed as,

$$\frac{dP_{s,i}}{dz} = \left(N_{2,i}\sigma_s^e - N_{1,i}\sigma_s^a\right)\Gamma_s P_{s,i} \tag{2a}$$

$$\frac{dP_p}{dz} = -\sum_i N_{1,i}\sigma_p^a \Gamma_p P_p = -\sum_i N_{1,i}\sigma_p^a P_p (A_{core} / A_{cladding}). \tag{2b}$$

The summation over $N_{1,i}$ accounts for pump absorption in the multiple cores. In regions close to the input end of the amplifier, where the signal intensity is typically low ($I_s < I_p$), the upper state population becomes,

$$N_{2,i}(r,z) = \frac{\frac{\tau\sigma_p^a}{h\nu_p}\cdot I_p(z)}{\frac{\tau\sigma_p^a}{h\nu_p}\cdot I_p(z)+1}\cdot N_0 = \frac{I_p(z)/I_{po}}{I_p(z)/I_{po}+1}\cdot N_0. \tag{3}$$

Here, $I_{po} = h\nu_p / \left(\tau\sigma_p^a\right)$ represents the pump power density which results in 50% population of the upper level. Using typical values for erbium doped fiber amplifier, τ = 10 ms, $\sigma_p^a = 1.8\text{x}10^{-25}$ m^2, at 980 nm I_{po} becomes 112 MW/m^2, which will correspond to a pump power of 0.88 W for a cladding of 100μm in diameter. At such pump power level, however, amplification can be achieved only at signal wavelengths where $\sigma_s^e > \sigma_s^a$.

It is to be noted that, in cladding pumped amplifiers, as the signal grows, its intensity can become comparable with or even larger than the pump intensity I_p. This in effect, decrease the population inversion, making it harder to achieve amplification at shorter wavelengths, where $\sigma_s^a > \sigma_s^e$. Higher population inversion and thus pump intensities much larger than I_{po} are required to achieve gain at shorter wavelengths. Krummrich [28] estimated that for cladding-pumped amplifiers, pump intensity about 10 times larger than I_{po} (~1 GW/m^2) will be needed to achieve over 90% population intensity.

To estimate the gain, we performed numerical integration based on Eq. (1) and (2) for a multicore erbium doped amplifier having 7 cores. We have chosen MP980 core rods (manufactured by OFS) to form cores with 3.2 μm diameter (NA: 0.23) and a cladding diameter of 100 μm. We assumed that the multi-mode pump is uniformly distributed over the cladding. The lifetime of the upper energy level τ is 10 ms, and erbium concentration was chosen as $7.1\text{x}10^{24}$ /m^3. The ASE was considered by introducing 181 wavelength components with 1-nm-seperation over a wavelength range of 1450 to 1630 nm. The overlap factor Γ_s (Γ_A) between the signal (ASE) field and the doped core was numerically calculated from their respective mode field diameters (MFDs) using the equation $\Gamma = 1\text{-}\exp(-2a^2/\omega_o^2)$, where a is the radius of doped core and ω_o = MFD/2. It was found to vary linearly from 0.539 to 0.436 over the range 1450-1630nm.

Figure 1 shows the gain and noise figure (NF) calculated at different signal wavelength for a constant input power level of 7.6 W and for different lengths of the doped fiber. Gain over

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40 dB can be obtained at wavelength of 1560 nm for input signal power level of −20 dBm. It is found that as we increase the length, the bandwidth of amplification becomes narrower and a shift in the gain peak shifts towards the longer wavelength. For a length of 50 m, the NF remained below 6.4 dB when the signal wavelength was longer than 1560 nm.

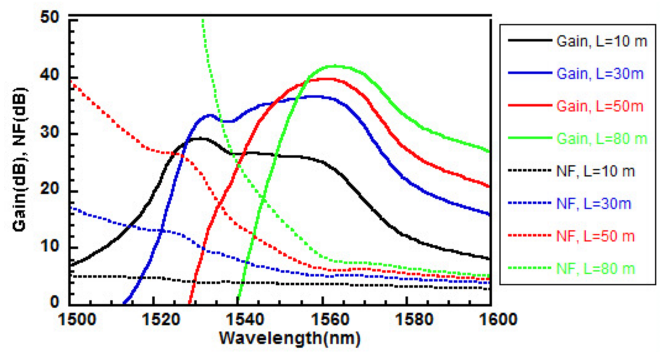

Fig. 1. Gain and noise figure plotted as a function of wavelength for different lengths of doped multicore fiber. Pump power was 7.6 W and input signal power was held at −20 dBm.

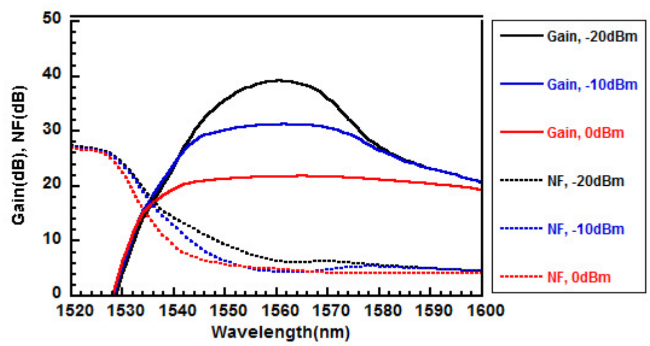

Fig. 2. Gain plotted as a function of wavelength for different signal power level. The pump power was 7.6 W and the length of the fiber was 50 m.

In Fig. 2 we have plotted the gain in a 50 m long fiber as a function of input signal power, while the pump was held constant at 7.6 W. We found a region centered near 1560 nm, where the gain decreased with an increase in the input signal power, which indicates saturation of the gain of the amplifier. On both sides of the region the gain remains almost independent of the input signal power. For an amplifier length of 50 m and 0 dBm input signals, the calculated NF was below 5 dB for wavelengths longer than 1560 nm.

To investigate further the behavior of gain saturation, we calculated the gain as a function of input pump power level for a fiber length of 50 m and pump power of 7.6 W. Figure 3 shows the curves plotted for two different signal wavelengths, 1530 nm and at 1560 nm, where gain peaks. At 1560 nm, we found a linear dependence between gain (dB) and input power (dBm). The slope was ~-0.9 dB/dBm, indicating that the output of the amplified signal remained almost constant over a dynamic range as large as 20 dB.

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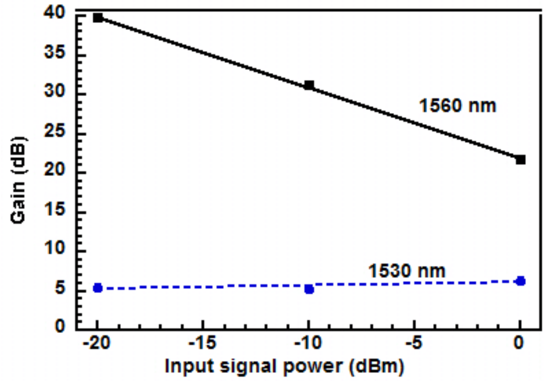

Fig. 3. Gain plotted as a function of input signal power level. The pump power is 7.6 W, and the length of gain fiber is 50 m.

3. Experimental demonstration

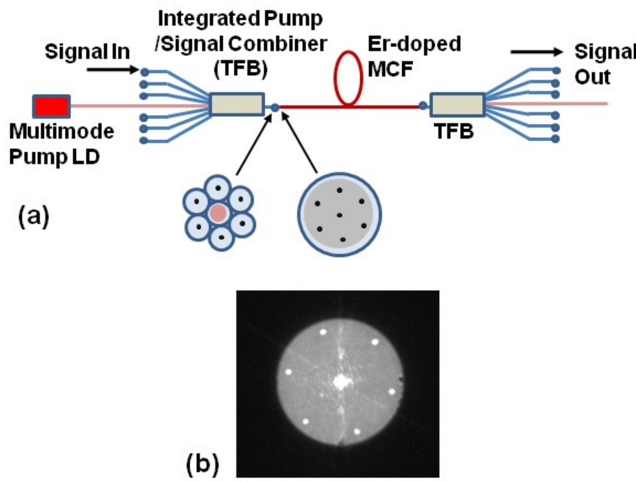

Fig. 4. Schematic of multicore fiber amplifier (a). Photograph of the cross section (with coating removed) of the multicore erbium-doped fiber (b).

Based on our simulation results, we built a cladding pump multicore fiber amplifier, the schematic diagram of which is shown in Fig. 4(a). The multicore erbium doped fiber has 7 identical cores that are arranged in a hexagonal array with a pitch of about 41 μm. Out of 7 cores, the outer 6 cores were used to make a 6-core EDFA. For the current demonstration of EDFA with 6 cores, the central core has no role besides absorbing some pump radiation.

The MC-EDF was drawn from a preform similar to what we used to make core-pumped MC-EDFA [19]. However, we etched the preform slightly in order to reduce the cladding size which would result in an increase in pump intensity I_p.

A photograph of the multicore fiber cross section taken using 980 nm illumination is shown in Fig. 4(b). The outer six cores were configured for launching signals with an all-fiber coupler as shown in Fig. 4(a). The diameter of the cores and the numerical aperture were 3.2 um and 0.23, respectively. The fiber had a cladding diameter of 100 μm and was coated with low index polymer providing a numerical aperture of 0.45. The absorption of the erbium-doped core for core-guided light at 1530 nm was ~6 dB/m. We measured the background losses at 1305nm, for the central and outer cores using an OTDR and found them to be about the same, ~41dB/km.

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We chose a length of 50 m for the MC-EDF to obtain sufficiently high gain and also a broad bandwidth. Our numerical simulation shows that further increase in length will result in narrower gain-bandwidth and also a further shift in the peak gain towards longer wavelength.

A tapered fiber bundled coupler was used to simultaneously couple optical signals from single mode fibers and the multimode pump radiation into the multicore erbium doped fiber. The TFB couplers were fabricated by tapering a bundle of 7 fibers, consisting of a central multimode fiber (NA of 0.22, and core/cladding diameter of 105/125μm) surrounded by six single mode fibers. The bundle was tapered adiabatically to match the core-to-core spacing and MFD at the tapered end of the bundle to those of the multicore EDF. The diameter of the cladding after tapering was about 115 μm. Inside the TFB coupler, as the multimode fiber gets tapered, the numerical aperture of the pump field increases and the pump starts to penetrate into the surrounding fibers. Since the double clad EDF has a higher NA (0.45), the pump radiation can be effectively guided.

The central multimode fiber at the input of the TFB coupler was spliced to the multimode fiber pigtail (NA: 0.22, 105/125μm) of a 980 nm multimode pump laser diode. The amplified output signals were extracted by using a second TFB coupler connected to the output end of the doped fiber. At the output end of the MC-EDF, near to the output TFB coupler, a short segment (~4cm) was stripped of its low-index coating, and covered with thermally conductive paste to remove the residual pump and prevent it from entering the output single mode fibers.

Single-frequency laser radiation from an external cavity laser diode tunable in the range of 1530-1600 nm was used as a signal. In order to avoid unwanted reflection and suppress ASE noise, isolators (not shown in Fig. 4(a)) were connected at both the input and output ports, and pump radiation was launched into the multimode fiber port of the input TFB coupler.

We launched a maximum pump power of about 10.9 W, of which about 7.6 W was estimated to be coupled into the cladding of the MC-EDF. The unabsorbed pump, measured at the output of the 50-m EDF before it was spliced to the output TFB coupler was 6W and it was removed through the coating-stripped section of the doped fiber. The absorption coefficient of the pump radiation in the MC-EDF was also measured in a 15 m long fiber by cutback method, and was found to be 0.033 dB/m. If the pump absorption were uniform along the length of the 50-m long EDFA, this total pump absorption would have been 1.65 dB. The measured value was lower (about 1.03 dB), which can be due to insufficient scrambling of the modes due to the cylindrical geometry.

4. Experimental results

Figure 5 shows the net (external) gain versus wavelength plotted for the six cores, when the pump power was 7.3 W and input signal power levels of −20 dBm, −10 dBm, and 0 dBm. For small signals (−20dBm), a maximum gain of 32 dB could be obtained from the amplifier (for core #1). Considering the total passive loss (two TFBs and splice loss, which was ~7.0 dB) the net gross gain in the amplifier was about 39 dB, reasonably close to the calculated gain. We observed some variation in the gain in different cores, due to differences in the passive losses, which can be suppressed through further optimization of the TFB fabrication.

We did experiments to see if there was any cross gain effect. We measured the gain in a core with and without signal in another neighboring core, but did not observe any change in the gain. This is expected due to relatively small absorption of the pump over 50 m long EDF.

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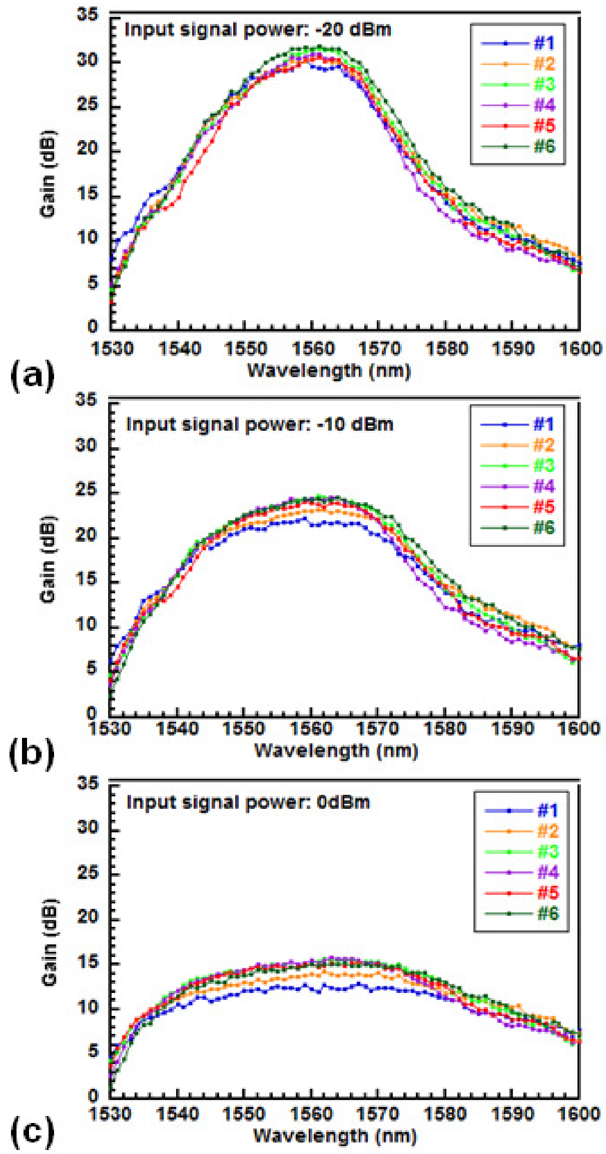

Fig. 5. Net gain measured for different cores of the MC-EDFA. The input power was (a) −20 dBm (b) −10 dBm, (c) 0 dBm. Power of pump launched in to the MCF-EDF was ~7.6 W.

Figure 6(a) shows the measured gain at 1560 nm as a function of input signal power plotted for different pump power level. Gain was seen to vary linearly with input signal over a large dynamic range. The slope of the curves were close to −0.83 dB/dBm, which resulted in a relatively constant output power level for a wide range of input power levels, as shown in Fig. 6(b). On the other hand, at a wavelength of 1530 nm, we see that output power varied with input signal to maintain a constant gain, which was in agreement with our numerical simulation. At 1560 nm, if we take 15 dBm as the net output power per core, the overall amplifier efficiency will be 2.5% with respect to the multimode launched pump power, and 12% with respect to absorbed pump power.

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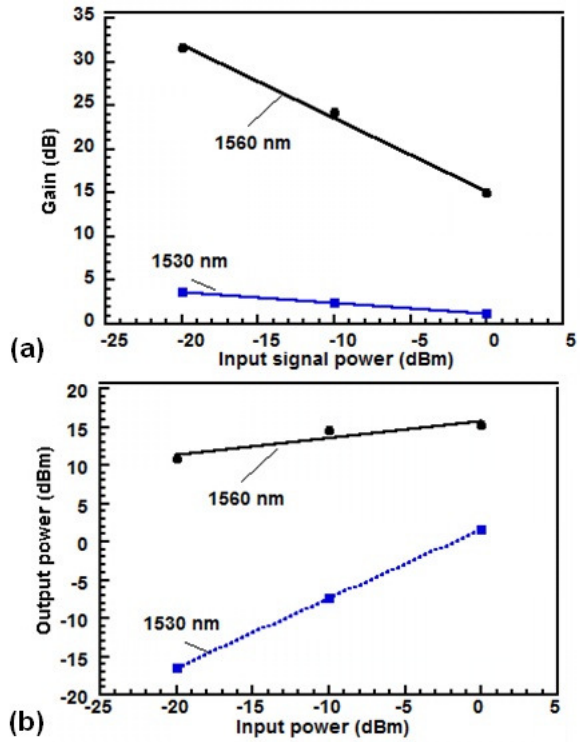

Fig. 6. (a) Measured gain at 1530 and 1560 nm (core #6) plotted as a function of input signal power. (b) Output power plotted as a function of input signal power. The launched pump power was 7.6 W.

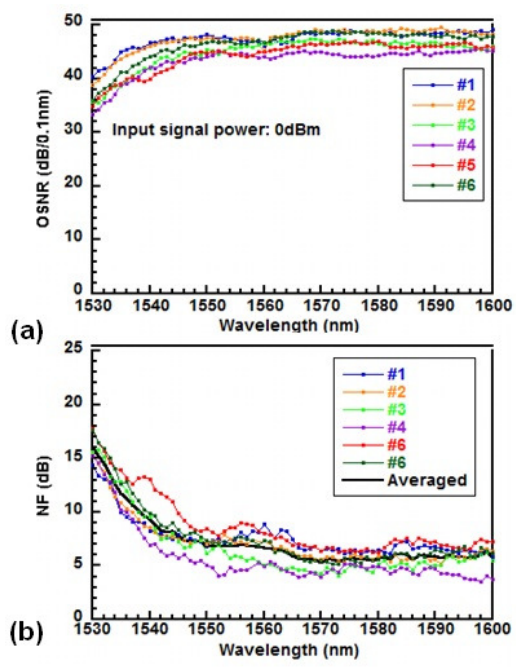

Fig. 7. The measured OSNR (a) and calculated NF (b) plotted a function of wavelength for different cores of the multicore EDF amplifier. The launched pump power was 7.6 W and the input signal power was 0 dBm.

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We also estimated the OSNR of the cladding pump multicore fiber amplifier from the measured ASE noise. Figure 7(a) shows OSNR/0.1nm bandwidth plotted as a function of wavelength. The internal NF was calculated from the gross gain (net gain plus passive losses) and the ASE noise estimated at the output of each cores following the treatment as described in Ref. 19. The internal NF for different cores as a function of wavelength is shown in Fig. 7(b). There was some inaccuracy in estimating $P_{ASE\text{-}Q}$, which was about ± 1dB, which resulted from any inaccuracy in the measurement of TFB coupler loss and ASE noise floor. This could result in an error in NF, also approximately ± 1dB. We thus took the average of NFs measured for all the cores, which is also shown in the figure. As shown in Fig. 7(b), NF becomes significantly large for wavelength shorter than 1540 nm, while it tends to decrease at longer wavelengths. Average NF was about 6 dB for wavelength longer than 1560 nm.

In the course of amplification in a cladding pumped amplifier, the signal intensity can become significantly larger compared with the pump intensity. This can deplete the upper state population, which makes it difficult to achieve gain in the C-band with low noise figure, especially below 1530 nm, where the absorption cross section is larger than the emission cross section. In our cladding pumped EDFA, the gain was below 5dB at wavelengths shorter than 1530 nm. Our numerical simulation shows that the gain spectrum can be extended to C-band by choosing a shorter length of the erbium-doped fiber. The decrease in peak gain and saturation power of the amplifier that would result from such length reduction can be compensated for by increasing the size of the cores (which increases the overlap integral Γ_s) and also by increasing the pump intensity through further reducing the cladding diameter (possible through decreasing the core-to-core spacing). The cores of the MC-EDF used in this demonstration have a diameter of 3.2 μm (NA = 0.23) can be increased to a diameter of 5.2 μm, while maintaining single mode propagation in the 1550 nm region. Further increase in the core diameter will also be possible by decreasing the numerical aperture of the doped cores, resulting in an increased output power from multicore amplifier.

MC-EDF with larger core size would also be beneficial for reducing the loss associated with input and output coupling. Due to small diameter (3.2 μm) of the cores in the MC-EDF used in this demonstration, coupling loss at the TFB fanout depended strongly on deviation of position from hexagonal arrangement. The tolerance to deviation can be increased if the cores are made to have larger MFDs. Currently the lowest loss we could achieve in the TFB-MCEDF-TFB amplifier module was about 6.2 dB. We expect that this can be reduced to 1 dB by further optimization of manufacturing of the TFB coupler and using MCF with larger core size.

5. Conclusion

In conclusion, we have demonstrated for the first time to our knowledge, an erbium-doped multicore fiber amplifier for amplifying independent signals carried by 6 cores, which were cladding pumped. Signals and pump were coupled to the individual cores of the doped fiber using an integrated all-fiber tapered fiber coupler. A peak net gain of about 32 dB was obtained at 1560 nm, with a NF of ~6 dB. Gain over 20 dB was observed over a bandwidth of about 35 nm centered around 1560 nm.

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