

# Space division multiplexed multicore erbium-doped fiber amplifiers

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**Abstract** We report on the recent development of multicore fiber amplifiers suitable for amplifying space division multiplexed signals. We have constructed 7-core amplifiers, where the cores could be pumped individually or simultaneously through the cladding, and studied the amplification and noise properties of these amplifiers. In the core-pumped amplifier, the net average gain was 25 dB, and noise figure was less than 4 dB. Using side-coupled cladding pumping, gain over 25 dB was obtained in each of the cores over a 40-nm bandwidth covering the C-band. We have further studied numerically the amplification and noise properties of a few-moded single/multicore erbium doped fiber amplifier with a doped region that extends beyond the few-mode core. We show that when excited by a multimoded pump, this can provide nearly uniform gain in C-band for modes such as, LP<sub>01</sub>, LP<sub>11</sub>, LP<sub>21</sub>, and LP<sub>02</sub> over a wide range of pump power. Differential modal gain (DMG) between LP<sub>01</sub>, and LP<sub>02</sub> was ~0.5 dB for a small signal gain of 32 dB at 1550 nm signal wavelength. The dependence of modal gain on the size of the doped core has also been studied.

**Keywords** Optical fiber · Erbium-doped fiber amplifiers · Space division multiplexing · Multicore · Few-mode

## Introduction

Space division multiplexing (SDM) [1–5] has drawn immense interests lately as a potential means for enhancing the capacity

of optical transmission systems. SDM of optical signals can be achieved by parallel transmission of optical signals using multiple cores or by using multiple modes in a fiber. SDM can be combined with telecommunication technologies already matured for standard single mode fiber, such as, wavelength division multiplexing, polarization division multiplexing, multi-level modulation formats, coherent detection, to further enhance the transmission capacity and the spectral efficiency. Attenuation and cross talks among cores in multicore fibers have been reduced to as low as 0.18 dB/km (for 7-core fiber), –55 dB (over a length of 17.6 km span), respectively [6]. For few-mode fibers where strong coupling between the modes exists, MIMO digital signal processing can be adapted to decouple the modes following transmission through the fiber. SDM transmission through MCF has been demonstrated over a span as long as 76.8 km [7], over 59 km in few mode fiber [8], and 40 km of 3-core few mode fiber [9]. Optical transmission at a record-high bit rates of over 1pb/s has been demonstrated by using multicore (MC) and few-mode fibers [10, 11], and recently a spectral efficiency of 247.9 b/s/Hz has been reported by using 3-mode multicore fiber [9].

In order to further increase the span of transmission link, suitable means to amplify the SDM signals will be necessary [12–14]. Various forms of amplifiers have already been developed for this purpose, which includes few-mode (FM) [15–23], bundled [24], multi-element [25], and multicore [26–33]. In few-mode EDFA the core is designed to support a few modes that could be simultaneously amplified by using suitable pump source(s). In multicore fiber amplifier, cores are embedded in a common glass cladding, whereas in bundled and multi-element fiber, each core have individual claddings that are embedded in a common polymer coating material. EDFAs based on multicore are particularly attractive due to its simplicity, compactness, lower cost, and reduced power consumption.

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Depending on how amplifiers are being pumped, MC-EDFAs can be mainly divided into two different categories, which are core-and cladding-pumping. Pumping each core of a MC amplifier separately using individual single mode pumps, while involving higher cost, has the advantage of allowing independent control of gain in each core by adjustment of pump power. Cladding pumping, on the other hand, requires fewer optical components, and has the potential to use low-cost, energy efficient multimode diodes.

All the multicore amplifiers developed so far are based on single mode cores, and in the near future with further advancement of SDM, we would require MC-EDFA with cores configured to support multiple modes, such as LP(0,1), LP(1,1), LP(0,2), LP(2,1) and so on. For such amplifiers cladding pumping can be attractive in simultaneously amplifying all modes supported by multiple cores.

In this paper, we report on the recent development of MC-EDFAs. We have developed multicore erbium doped fibers that can be used for pumping through the cores or through the cladding. We have also made all-fiber based fan-in and fan-out devices for coupling SDM signals and also pump into the gain fiber. We will present the amplification, noise properties of such MC-EDFAs. We further show using numerical simulation a novel design of a few-mode multicore fiber that enables uniformly amplifying various modes supported by each cores of the fiber.

### Multicore erbium-doped fibers for core and cladding pumping

Figure 1a and b show the cross-sections of a 7-core EDF made for core-pumped [26] and cladding-pumped [30] amplifiers. The preforms were made from commercially available (OFS) erbium-doped core rods, where the cores are arranged in a hexagonal array with a  $\sim 41$   $\mu\text{m}$  pitch. The symmetry and structures of the cores in these fibers were the same. The core diameter and numerical aperture were equal to 3.2  $\mu\text{m}$  and 0.23, respectively. The mode field diameter at 1550 nm was estimated to be about 6  $\mu\text{m}$ . The erbium-doped core has an

absorption coefficient of  $\sim 2.3$  dB/m at 1550 nm. The multicore fiber for core pumping had a cladding diameter of 148  $\mu\text{m}$ , and for cladding pumping the fiber diameter was reduced to 100  $\mu\text{m}$  in order to increase the intensity of pump and was coated with low-index polymer coating ( $\sim \text{NA}: 0.45$ ) for guiding multi-mode pump light.

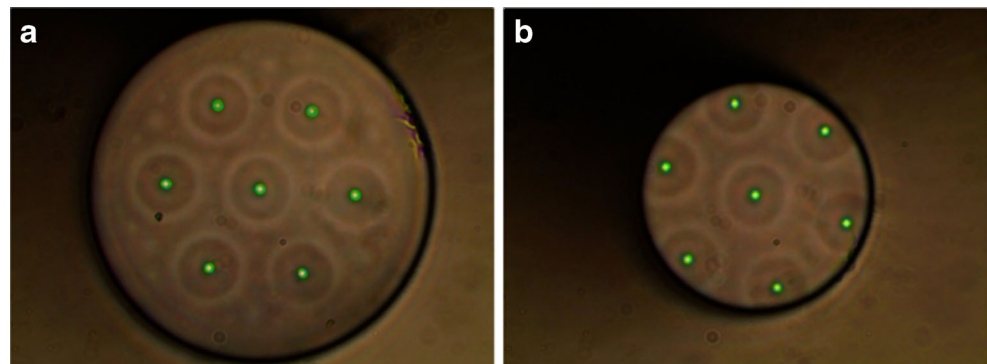
### Couplers for multicore erbium doped fibers

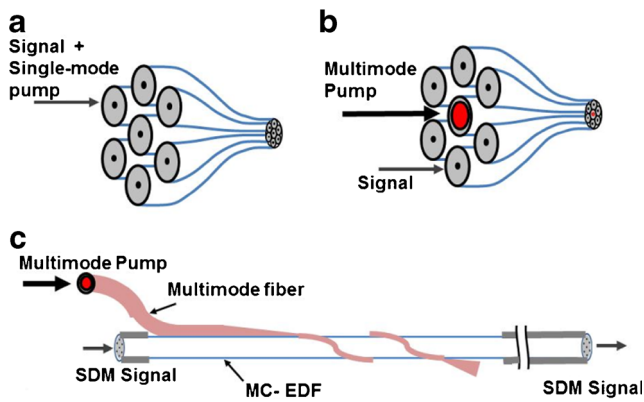
One critical consideration for MC-EDFA is implementing a suitable means for launching SDM signal and pump into the gain fiber. In core pump amplifiers, where each core needs to be provided with single mode pump radiation, fan-in/fan-out devices can be used. So far, a number of such devices have been proposed, which includes bulk-optics collimators [27, 29], reduced-cladding bundled coupler [28], and all-fiber based tapered fiber bundled (TFB) coupler [7, 26, 30].

Figure 2a shows, TFB coupler we used as a fan-in/out device for core pumping that was created by tapering adiabatically a bundle of specially designed fibers by a predetermined ratio so that the core-to-core pitch at the tapered end matches with that of the MC-EDF. The 7-input fibers (at the un-tapered end) of TFBs, could be spliced to SMF fibers with low loss. At the tapered end the MFD was  $\sim 6$   $\mu\text{m}$  that matched well with the MFD of the MC-EDF.

In cladding pump multicore amplifiers, while SDM signals are launched into the multiple cores, the multimode pump is launched through the cladding. This can be achieved in a number of ways, such as bulk-optic coupler based on multicore collimators and miniature WDM filter [33], modified TFB pump-signal combiner [30], and also side-coupled pump coupler [32]. Figure 2b shows a schematic of modified TFB pump-signal combiner we had developed by tapering a bundle of 7 fibers, consisting of a central multimode fiber (NA of 0.22, and core/cladding diameter of 105/125  $\mu\text{m}$ ) surrounded by six single mode fibers. This allowed launching of signals into the outer six cores, multimode pump into the cladding through the central fiber.

**Fig. 1** Cross section of the 7-core EDFA, used in (a) core pump, and (b) cladding pump amplifier





**Fig. 2** All-fiber fan-in/fan-out and pump/signal combiners used for (a) core-pumped, (b) end-coupled cladding pump, (c) side-coupled cladding pump amplifier

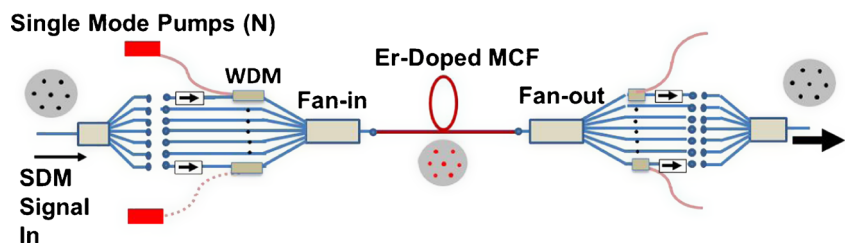
One problem associated with using fan-in and fan-out devices at the amplifier ends is that the throughput loss results in attenuation of the signal. Such device also prevents direct coupling of signals from an input SDM fiber into the amplifier, posing a bottle neck for the realization of a simple and compact amplifiers. We can overcome this problem, by coupling the multimode pump through the side of the gain fiber, without interruption of the core waveguide. Side-coupling with high efficiency has been demonstrated in single core double-clad fibers in various bulk forms, such as V-groove side-coupling combiners [34], embedded-mirror combiners [35], direct fusion of tapered multimode fiber [36, 37], and also in the form of distributed coupling using GT-wave fiber assembly [38–40].

Such a device is shown in Fig. 2c, where a short section of the gain fiber (~8 cm long) near the input end was stripped of its low-index coating, and the exposed section was brought into optical-contact with a tapered multimode pump fiber [32]. The pump coupling efficiency was ~67 %. This pumping geometry made the two ends of the gain fiber available for splicing directly to passive multicore fibers.

### Core-pumped 7-core EDFA

The schematic of the core-pumped multicore fiber amplifier using TFB couplers as fan-in and fan-out devices [26] is shown in Fig. 3 Here SDM signal from passive MCF is split

**Fig. 3** Structure of a core-pumped-MC- EDFA



into individual channels using a TFB coupler, and combined with pump radiation using WDM couplers, and then launched into MC-EDF using another TFB coupler.

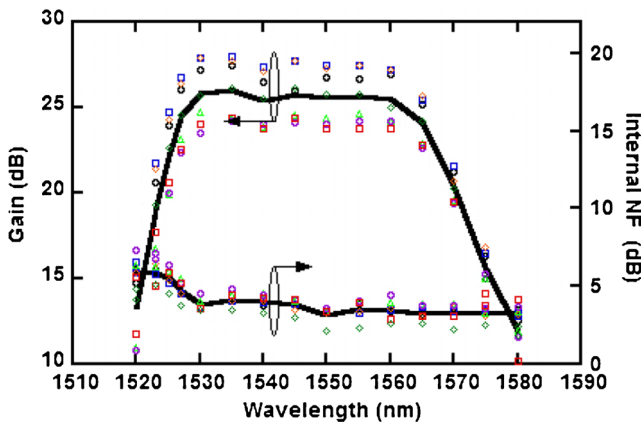
Figure 4 shows net gain and internal NF measured in the C-band for the seven cores. For an input signal power of -15 dBm and a pump power of 146 mW (at 980 nm), an average net gain of 25 dB was obtained from the amplifier. From the passive losses (maximum of 5 dB) in the TFBs and splices, the internal gain was estimated to be 30 dB and the internal NF over the whole C-band was found to be ~4 dB. Assuming a passive loss of 2.5 dB for the coupler at the input side, the external NF thus can be higher by 2.5 dB than that plotted in Fig. 4.

In a core pumped amplifier, due to the short length (15 m) and high NA (0.23), the cross-talk between the cores caused by bending is not significant. Cross-talk originates primarily from the fan-in and fan-out devices used at the input and output, because of the mismatch in mode-field size and core-to-core pitch between the TFB and the MCF. The cross-talk averaged over six cores for TFB-MCEDF-TFB module was found to vary between 30.2 and 36.6 dB for the seven channels [26].

### Cladding pumped 7-Core EDFA

The schematic of a cladding pump 7-core fiber amplifier employing the multimode pump and SDM signal combiner (Fig. 2c) is shown in Fig. 5.

Here, signal can be launched through the MC input end of the pump signal combiner and multimode pump is incident through the multimode pump port. At the output end of the gain fiber, to remove the unabsorbed pump, a short section of the gain fiber was stripped of its low index coating, and covered with thermally conductive light absorbing material. In a cladding pumped amplifier, as the signal gets amplified along the gain fiber, the intensity can become large when compared with the pump intensity. This can deplete the upper state population, which makes it harder to achieve gain in the C-band with low noise figure (especially below 1560 nm). To extend the gain spectrum to C-band, a relatively short length of erbium-doped fiber (34 m) was used. Both ends of the gain fiber was angled cleaved for suppressing Fresnel reflection. Gain and noise figure of the amplifier were measured by



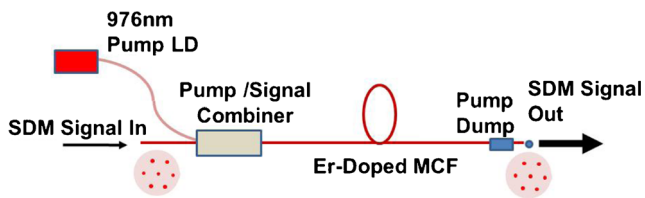
**Fig. 4** Net gain and internal NF measured for the 7 different cores of the MC-EDFA. The length of the MC-EDFA was 15 m. *Solid line* represents average

coupling light into and out of the cores using anti-reflection-coated tapered lensed fibers. The pump power coupled to the gain fiber was 4.7 W. Since we used a pump dump, we could not experimentally measure the throughput power. However, for a launch pump of 4.7 W, we estimated from numerical simulation a throughput pump power of ~4 W.

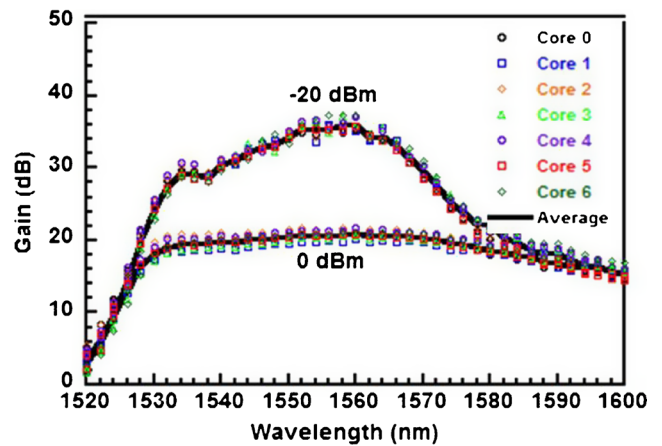
Figure 6 shows the gross gain versus wavelength measured in the seven cores for input signal powers of -20 and 0 dBm (measured at the output of the lensed fiber). The gross gain is the gain that signals from a multicore transmission fiber will experience, when spliced directly to the multicore gain fiber. The maximum gross gain was about 36 dB near 1560 nm, and gain over 25 dB was obtained over a bandwidth of ~40 nm.

The internal NF for different cores as a function of wavelength is shown in Fig. 7 for input signal powers of 0 dBm. As shown in the figure, the NF becomes high for wavelength shorter than 1540 nm, while it tends to decrease for longer wavelengths. The NF was ~5 and 8 dB for the signal wavelength of 1560 and 1530 nm, respectively.

Pump-depletion induced crosstalk may occur when the gain fiber is too long. The length of the gain fiber in our MC-EDFA is 34 m. If we had instead chosen much longer gain fiber (for enhancing the pump conversion efficiency), signal launched in just one core could deplete the pump enough to affect the signal gain (and thus the intensity) in another core. Since a large fraction of pump (~4.0 W) remains unabsorbed in the amplifier, there is negligible pump-depletion induced crosstalk among the cores.



**Fig. 5** Schematic diagram of a 7-core EDFA with side-coupled cladding pumping. The length of MC-EDFA was 34 m

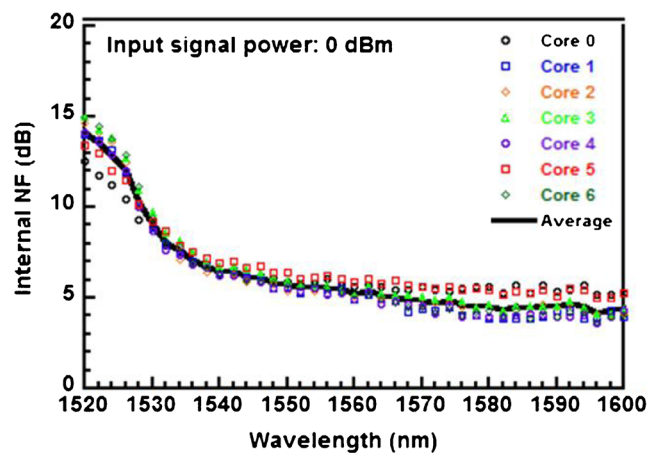


**Fig. 6** Gain measured for the 7 different cores of the MC-EDFA, for input signal powers of 0 and -20 dBm. The launched pump power was 4.7 W. The central core is represented by core 0

For cladding pumped amplifier, where the pump intensity is much lower than core-pump, the gain saturation occurs when the signal power is increased, or equivalently, when the number of channels for wavelength division multiplexed signals is increased.

### Cladding-pumped multicore amplifiers supporting few modes: Design

Rare-earth doped fibers that are used in single mode optical amplifiers have a core with step-like refractive-index profile and a rare-earth doped region that has a radius the same as the core or slightly smaller. When the core size is made larger to support higher order modes, the overlap integral of modal intensity profile over the rare-earth doped region becomes different for different modes. For the higher order modes, a greater fraction of light remains outside the doped region which results in a smaller overlap integral and thus a smaller gain.



**Fig. 7** Internal NF plotted as a function of wavelength for different cores of the multicore EDF amplifier. The coupled pump power was 4.7 W and the input signal power was 0 dBm

To reduce the differential modal gain, a number of solutions have been proposed recently, which include, i) using reconfigurable few mode pump field [15, 16], ii) inclusion of a ring-like doped region [17–21]. In the first scheme (i), the gains of the modes are controlled through adjustment of the modal content of the pump radiation used to excite the doped fiber. Controlling the power of different pump mode, however, can add complexity to amplifier design, raising the cost. Few-mode fiber amplifier based on ring-like doped fiber design (ii) can equalize the modal gain while using single mode pump radiation ( $LP_{01}$ ), which simplifies the amplifier construction. The doped ring can enhance the overlap integral between the higher order mode and the doped region, thus minimizing the differential modal gain. Also fine-tailoring of doping of the core region has been proposed for equalization of modal gain of even higher order modes, e.g.,  $LP_{31}$  [22]. Recently, few mode fiber amplifiers have been demonstrated by pumping through the cladding using a multimode pump laser diode in a counter propagating configuration. Simultaneous amplification of four modes  $LP_{01}$ ,  $LP_{11}$ ,  $LP_{02}$ ,  $LP_{21}$  was achieved with gain over 25 dB, where the modal differential gain was about 4 dB [23]. Cladding-pumping of few mode fiber using multimode pump diode will have potential application in the realization of few mode multicore fiber amplifiers.

Here, we have investigated few mode multicore fiber amplifier with extended doped region pumped through a highly multimoded cladding that can inherently provide

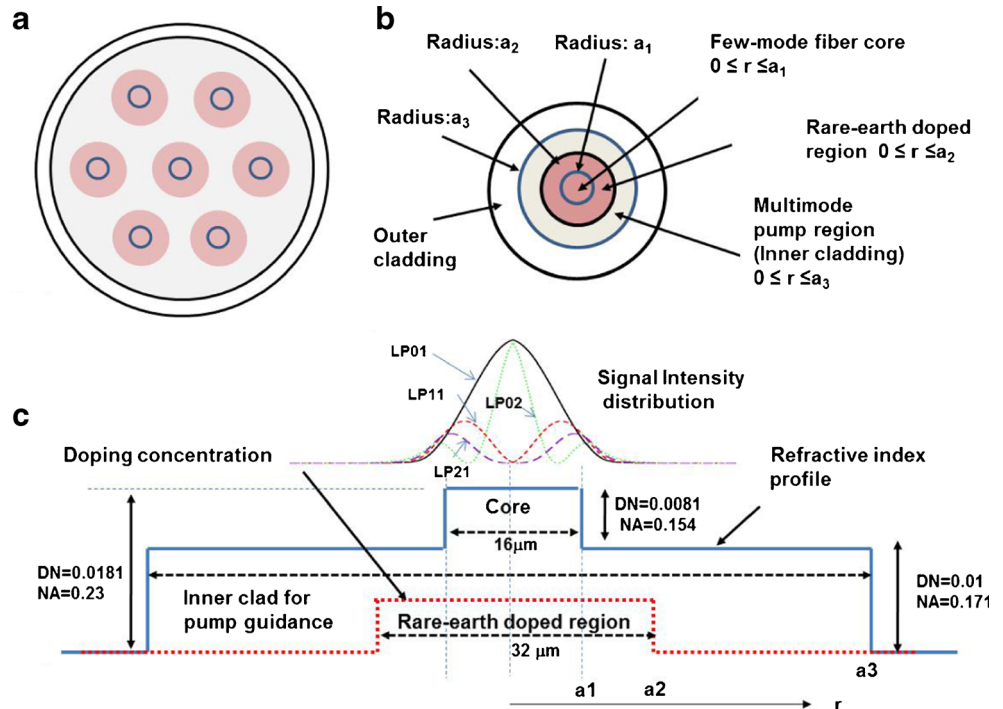
equal gain to all the modes supported by the core. The proposed few mode fiber has a core supporting few higher-order modes and a rare-earth doped region, which consists of the whole core region and a region that sufficiently extends beyond the core in order to encompass the optical field of the few-order modes supported by the core. When such a fiber is pumped through the cladding, a uniform population inversion can be achieved across the doped region, achieving equal gain for different signal modes. The fiber design has the advantage that the differential modal gain can be minimized among a larger number of modes, and over a broader range of input pump power.

A schematic diagram of the structure of the core, rare-earth doped region, and the pump region of the proposed few-mode rare earth fiber is shown in Fig. 8. The core has a radius  $a_1$  which is large enough to support four fiber modes, e.g.,  $LP_{01}$ ,  $LP_{11}$ ,  $LP_{21}$ , and  $LP_{02}$ . The region doped with rare-earth ions has a radius  $a_2$ , sufficiently large to fully encompass the field of each of the modes  $LP_{mn}$ . The rare earth doped region is uniformly pumped through an inner cladding which is larger than the size of the doped region, i.e.,  $a_3 \geq a_2$ .

Note that although the rare-earth doping is shown uniform within the region  $0 \leq r \leq a_2$ , the refractive index in the part of the doped region, which extends beyond the core ( $a_1 \leq r \leq a_2$ ), is lowered in comparison to that of the core region  $0 \leq r \leq a_1$ .

The region through which the pump is guided has a core radius  $a_3$ , which fully encompasses the doped region. The pump guiding region is sufficiently multi-moded so that power distribution can be considered uniform throughout the pump region, including the region doped with rare earth ion.

**Fig. 8** Schematic diagram of the few-moded doped fiber to equalize gain. (a) with multiple cores, (b) single core. (c) the refractive index profile and doping distribution of the few-moded gain fiber

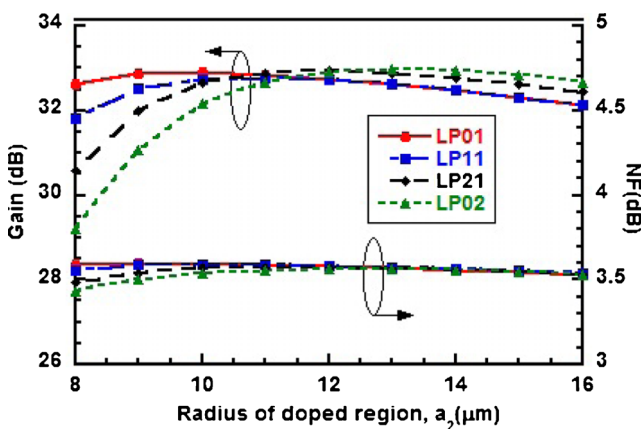


## Results of numerical simulations

We have studied the optical properties of this amplifier based on numerical modelling described in Ref. [41]. In our numerical simulation, we have considered a few-mode fiber with refractive index and doping profile as shown in Fig. 8c. The fiber is assumed to have uniform erbium doping with a concentration of  $6.89 \times 10^{24}/\text{m}^3$ . To estimate the gain and NF, we performed numerical integration. We assumed that the multi-mode pump is uniformly distributed over the cladding. The lifetime of the upper energy level  $\tau$  is 10 ms. The ASE was considered by introducing 51 wavelength components with 1-nm-separation over a wavelength range of 1525 to 1575 nm.

For 980 nm pump, launched into the 16- $\mu\text{m}$ -radius inner-cladding, the corresponding V-number is 17.5 and the number of modes supported by the pump guiding region is  $\sim 153$ . Pump radiation with such a large number of modes can make the field distribution essentially uniform. For larger cladding size, the mode number for pump wave will vary in proportion to the square of the radius  $a_3$ .

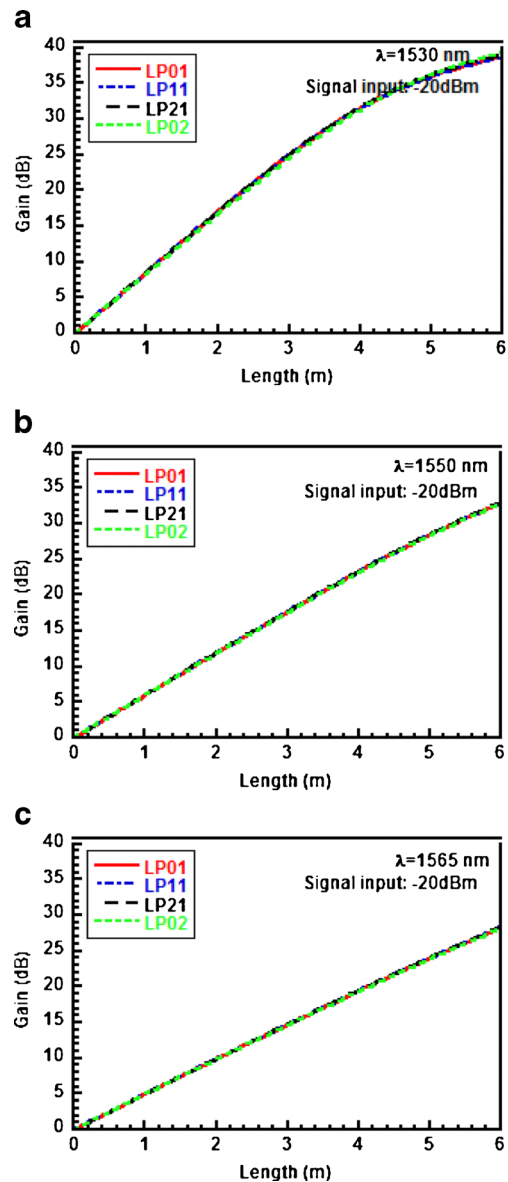
Figure 9 shows the gain and NF of four modes LP<sub>01</sub>, LP<sub>11</sub>, LP<sub>21</sub>, and LP<sub>02</sub> separately calculated for different radii of the doped region varied between 8 and 16  $\mu\text{m}$ . The length of the gain fiber is 6 m. In each case, the input signal power for each is chosen to be the same as -20 dBm. The pump power is held constant at  $1.24 \text{ mW}/\mu\text{m}^2$ , which corresponds to 1 W for an inner-cladding radius of 16  $\mu\text{m}$ . When the rare earth doped region assumes a size of 8  $\mu\text{m}$ , i.e., same as the core, the differential small-signal modal gain between LP<sub>01</sub> and LP<sub>02</sub> is around 3 dB and decreases with an increase in the size of the rare earth doped region. The differential gain can be kept below 1 dB when radius of rare earth doped region is increased, anywhere in the range from 10 to 16  $\mu\text{m}$ , i.e., 25 to 100 % larger than the core size. Differential modal gain reaches a minimum value of 0.2 dB when  $a_2$  is  $\sim 11.5 \mu\text{m}$



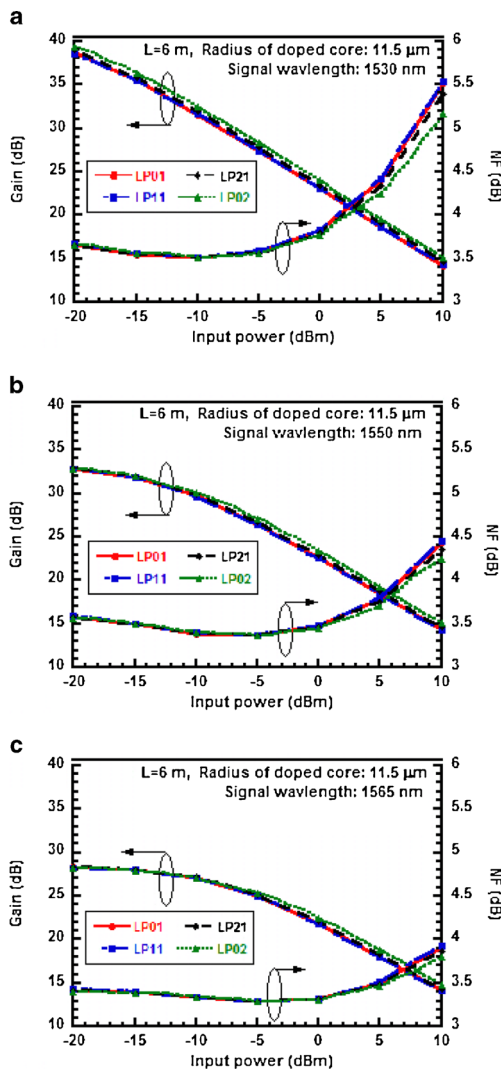
**Fig. 9** Gain for different signal modes calculated as a function of radius of rare-earth doped region. Core radius is 8  $\mu\text{m}$  ( $V=5.0$ ). The input signal power is -20 dBm (at 1550 nm) and pump intensity is  $1.24 \text{ mW}/\mu\text{m}^2$  ( $a_3=16 \mu\text{m}$ )

(44 % larger than the core). The NFs for all the signal modes are around 3.5 dB.

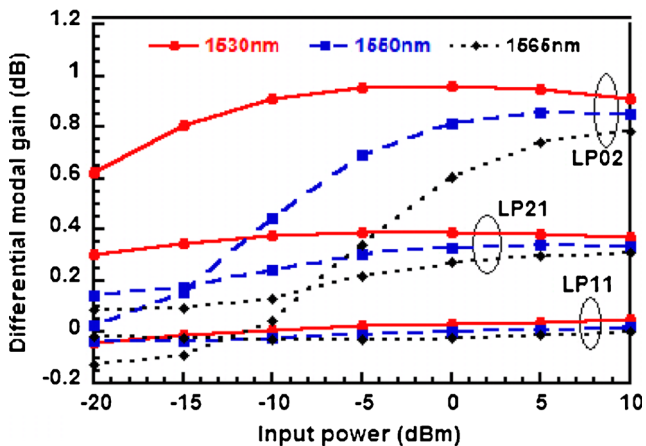
We further investigated the performance of the amplifier under different signal input conditions and different length of the gain fiber. The radius of the erbium-doped region was chosen as 11.5  $\mu\text{m}$ , which corresponds to smallest differential modal gain according to Fig. 9. Figure 10 shows the calculated gain for four different modes LP<sub>01</sub>, LP<sub>11</sub>, LP<sub>21</sub>, LP<sub>02</sub> and signal wavelengths 1530, 1550 and 1565 nm, as a function of the fiber length. The input signal power was assumed as -20 dBm, and input pump power was again 1 W. The curves indicate small differences in gain experienced by various modes.



**Fig. 10** Gain versus fiber length for different signal modes. Results are shown for three different signal wavelength within the C-band. 1530 nm (a), 1550 nm (b), and 1565 nm (c). Signal power is -20 dBm and pump intensity is  $1.24 \text{ mW}/\mu\text{m}^2$



**Fig. 11** Gain and NF versus input signal power calculated for LP<sub>01</sub>, LP<sub>11</sub>, LP<sub>21</sub> and LP<sub>02</sub> signal modes. Signal wavelength is 1530 in (a), 1550 nm in (b) and 1565 nm in (c)

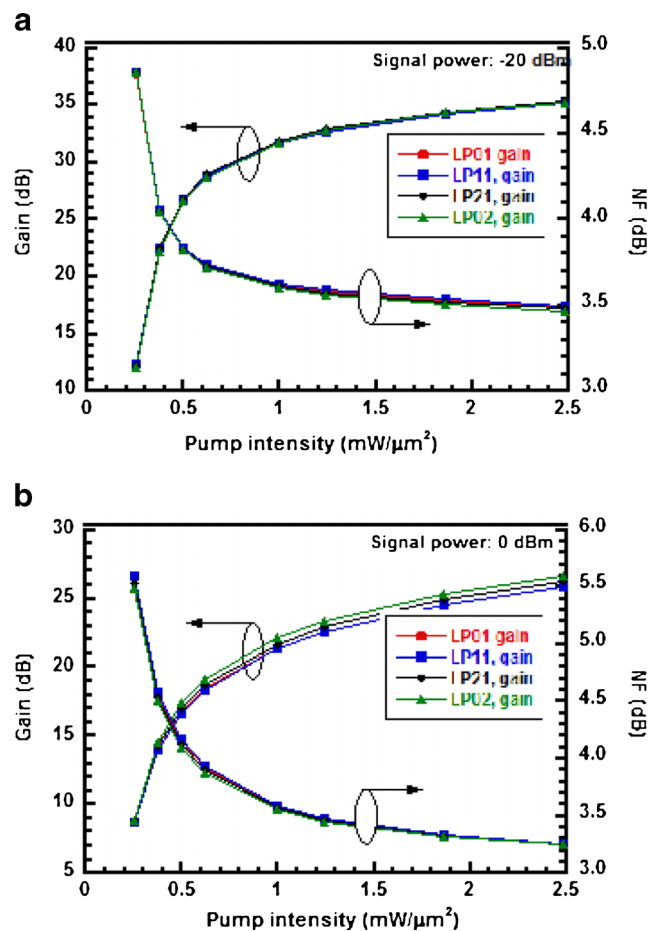


**Fig. 12** Differential modal gain (compared with LP<sub>01</sub> gain) plotted against input signal power at three different wavelength

Figure 11 shows the gain and noise figure plotted as a function of input signal power for different modes and signal wavelengths. The length of the gain fiber is 6 m, and intensity of 980 nm pump input is 1.24 mW/μm<sup>2</sup>, which is equivalent to 1 W of multi-moded pump guided through the 16 μm-radius inner cladding. Small signal gain varied over 38, 33 and 28 dB for signal wavelengths of 1530, 1550 and 1565 nm, respectively. NF was less than 3.8 dB for input signal with powers up to 1 mW.

In Fig. 12, we plot the differential modal gain with respect to LP<sub>01</sub> mode, as a function of the input signal power for wavelengths of 1530, 1550 and 1565 nm. Pump intensity is kept constant at 1.24 mW/μm<sup>2</sup>. Differential modal gain is the smallest for low intensity signals and gets higher with power. It however remains smaller than 1 dB for input signal power up to 10 dBm. Note that higher order modes spreads out over a larger area than a lower order mode, and thus gain saturation (under multimode pumping) occurs less slowly along the length, resulting in a slightly higher gain.

Figure 13 shows the gain and NF figure plotted as a function of launched pump power. The signal power at 1550 nm is



**Fig. 13** Gain and NF calculated for four modes as a function of pump power. Input signal power is -20dBm in (a) and 0dBm in (b). Length of gain fiber is 6 m. Radius of the erbium-doped region is 11.5 μm

assumed to be  $-20$  dBm in (a) and  $0$  dBm in (b). For weak input signal the gain observed by different modes are almost the same. For stronger input signal,  $0$  dBm, when the gain saturation occurs, the differential gain increases to about  $2$  dB as the pump intensity is raised to  $1.5$  mW/ $\mu\text{m}^2$ .

A pump intensity of  $1.24$  mW/ $\mu\text{m}^2$  corresponds to a pump power of  $1$  W when the inner cladding radius is chosen to be  $16$   $\mu\text{m}$  for a single core fiber amplifier. For a smaller inner cladding diameter, e.g.,  $24$   $\mu\text{m}$ , a pump power of  $\sim 700$  mW will be required to maintain the same amount of pump intensity. By using commercially available  $750$  mW,  $980$  nm pump source with single mode fiber pigtail ( $\sim$  NA of  $0.15$ ) and splicing this to a piece of multimode fiber with core size  $24$   $\mu\text{m}$ , NA of  $0.171$ , multimode pump source as required for the few mode amplifier can be readily realized.

While making multicore fiber using this core structures, the cladding size needs to be increased accordingly so as to include multiple cores. Also, the rare earth-doped region which is outside of the respective few-moded core needs to be index-matched with the cladding. If we can incorporate  $7$  such cores in a cladding diameter of  $110$   $\mu\text{m}$ , a pump power of  $\sim 12$  W will be required to maintain the same amount of pump intensity.

## Conclusion

We have reviewed recent development of core- and cladding-pumped multicore EDFAs for amplifying SDM signals. Core-pumping, while involving higher cost, has the advantage of allowing independent control of gain in each core by adjustment of pump power. Cladding pumping, on the other hand, requires fewer optical components, and has the potential to use low-cost, energy efficient multimode diodes. By employing side-coupled pumping technique, small-signal gain  $>20$  dB could be achieved throughout the C-band and gain over  $25$  dB was observed over a bandwidth of about  $40$  nm centered around  $1560$  nm. We have also shown that by extending the doped region beyond the core of few-moded doped fiber, and pumping with a multi-moded pump, we can realize few-mode MC-EDFA with minimal modal differential gain.

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