# First demonstration and detailed characterization of a multimode amplifier for space division multiplexed transmission systems

**Y. Jung,[1,*] S. Alam,[1] Z. Li,[1] A. Dhar,[1] D. Giles,[2] I. P. Giles,[2] J. K. Sahu,[1] F. Poletti,[1]
L. Grüner-Nielsen,[3] and D. J. Richardson[1]**

[1]*Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK*
[2]*Phoenix Photonics Ltd, 22 Carlton Road, Surrey, CR2 OBS, UK*
[3]*OFS Fitel Denmark, Priorparken 680, 2605 Brøndby, Denmark*
**ymj@orc.soton.ac.uk*

**Abstract:** We present the first demonstration of a multimode (two mode-group) erbium-doped fiber amplifier for Space Division Multiplexed (SDM) applications and demonstrate various design and performance features of such devices. In particular we experimentally demonstrate that differential modal gains can be controlled and reduced both by fiber design and control of the pump field distribution. Using a suitably designed fiber we demonstrate simultaneous modal gains of ~20dB for different pair-wise combinations of spatial and polarization modes in an EDFA supporting amplification of 6 distinct modes.

**OCIS codes:** (060.0060) Fiber optics and optical communications; (060.2320) Fiber optics amplifiers and oscillators.

---

## References and links

1. A. D. Ellis, J. Zhao, and D. Cotter, "Approaching the non-linear Shannon limit," J. Lightwave Technol. **28**(4), 423–433 (2010).
2. P. J. Winzer and G. J. Foschini, "MIMO capacities and outage probabilities in spatially multiplexed optical transport systems," Opt. Express **19**(17), 16680–16696 (2011), http://www.opticsinfobase.org/abstract.cfm?URI=oe-19-17-16680.
3. R. W. Tkach, "Scaling optical communications for the next decade and beyond," Bell Labs Tech. J. **14**(4), 3–9 (2010).
4. R.-J. Essiambre, G. Kramer, P. J. Winzer, G. J. Foschini, and B. Goebel, "Capacity Limits of Optical Fiber Networks," J. Lightwave Technol. **28**(4), 662–701 (2010).
5. R. Ryf, S. Randel, A. H. Gnauck, C. Bolle, R. Essiambre, P. Winzer, D. W. Peckham, A. McCurdy, and R. Lingle, "Space-division multiplexing over 10km of three-mode fiber using coherent 6x6 MIMO processing," in Proc. of OFC/NFOEC'11 (Optical Society of America, Washington, 2011), PDPB10.
6. J. Sakaguchi, Y. Awaji, N. Wada, A. Kanno, T. Kawanishi, T. Hayashi, T. Taru, T. Kobayashi, and M. Watanabe, "109-Tb/s (7x97x1720Gb/s SDM/WDM/PDM) QPSK transmission through 16.8-km homogeneous multi-core fiber," in Proc. of OFC/NFOEC'11 (Optical Society of America, Washington, 2011), PDPB6.
7. S. Randel, R. Ryf, A. Sierra, P. J. Winzer, A. H. Gnauck, C. A. Bolle, R. J. Essiambre, D. W. Peckham, A. McCurdy, and R. Lingle, Jr., "6×56-Gb/s mode-division multiplexed transmission over 33-km few-mode fiber enabled by 6×6 MIMO equalization," Opt. Express **19**(17), 16697–16707 (2011), http://www.opticsinfobase.org/abstract.cfm?URI=oe-19-17-16697.
8. C. Koebele, M. Salsi, D. Sperti, P. Tran, P. Brindel, H. Mardoyan, S. Bigo, A. Boutin, F. Verluise, P. Sillard, M. Astruc, L. Provost, F. Cerou, and G. Charlet, "Two mode transmission at 2×100 Gb/s, over 40 km-long prototype few-mode fiber, using LCOS-based programmable mode multiplexer and demultiplexer," Opt. Express **19**(17), 16593–16600 (2011), http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-19-17-16593.
9. E. Ip, N. Bai, Y. Huang, E. Mateo, F. Yaman, S. Bickham, H. Tam, C. Lu, M. Li, S. Ten, A. P. T. Lau, V. Tse, G. Peng, C. Montero, X. Prieto, and G. Li, "88x3x112-Gb/s WDM Transmission over 50-km of Three-Mode Fiber with Inline Multimode Fiber Amplifier," in Proc. of ECOC'11 (Optical Society of America, 2011), paper Th.13.C.2.
10. B. Zhu, T. F. Taunay, M. Fishteyn, X. Liu, S. Chandrasekhar, M. F. Yan, J. M. Fini, E. M. Monberg, and F. V. Dimarcello, "112-Tb/s space-division multiplexed DWDM transmission with 14-b/s/Hz aggregate spectral efficiency over a 76.8-km seven-core fiber," Opt. Express **19**(17), 16665–16671 (2011), http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-19-17-16665.

#157482 - $15.00 USD
Received 2 Nov 2011; accepted 6 Dec 2011; published 12 Dec 2011

11. A. Al Amin, A. Li, S. Chen, X. Chen, G. Gao, and W. Shieh, "Dual-$LP_{11}$ mode 4×4 MIMO-OFDM transmission over a two-mode fiber," Opt. Express **19**(17), 16672–16679 (2011), http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-19-17-16672.
12. A. Al Amin, A. Li, X. Chen, and W. Shieh, "LP01/LP11 dual-mode and dual-polarisation CO-OFDM transmission on two-mode fibre," Electron. Lett. **47**(10), 606–608 (2011).
13. P. M. Krummrich, "Optical amplification and optical filter based signal processing for cost and energy efficient spatial multiplexing," Opt. Express **19**(17), 16636–16652 (2011), http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-19-17-16636.
14. K. S. Abedin, T. F. Taunay, M. Fishteyn, M. F. Yan, B. Zhu, J. M. Fini, E. M. Monberg, F. V. Dimarcello, and P. W. Wisk, "Amplification and noise properties of an erbium-doped multicore fiber amplifier," Opt. Express **19**(17), 16715–16721 (2011), http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-19-17-16715.
15. N. Bai, E. Ip, T. Wang, and G. Li, "Multimode fiber amplifier with tunable modal gain using a reconfigurable multimode pump," Opt. Express **19**(17), 16601–16611 (2011), http://www.opticsinfobase.org/abstract.cfm?URI=oe-19-17-16601.
16. Y. Jung, S. Alam, Z. Li, A. Dhar, D. Giles, I. Giles, J. Sahu, L. Gruner-Nielsen, F. Poletti, and D. J. Richardson, "First demonstration of multimode amplifier for spatial division multiplexed transmission systems," in Proc. of ECOC'11, (Optical Society of America, 2011), paper Th.13.K.4.
17. R. C. Youngquist, J. L. Brooks, and H. J. Shaw, "Two-mode fiber modal coupler," Opt. Lett. **9**(5), 177–179 (1984).
18. J. N. Blake, B. Y. Kim, and H. J. Shaw, "Fiber-optic modal coupler using periodic microbending," Opt. Lett. **11**(3), 177–179 (1986).

---

## 1. Introduction

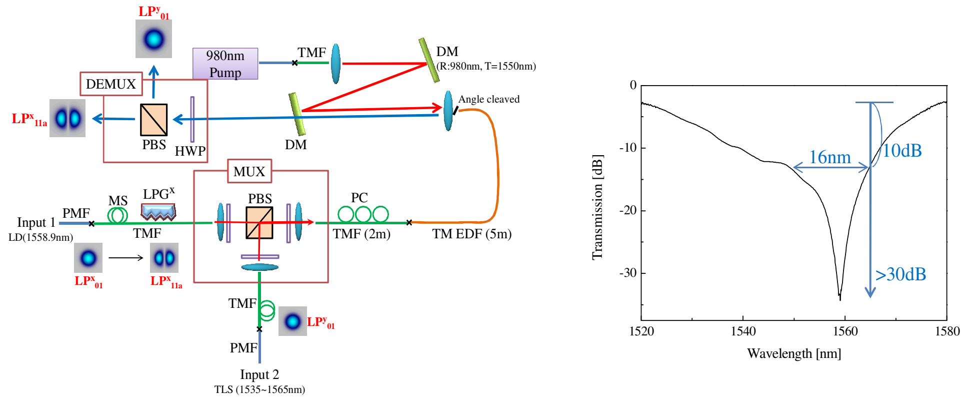
The exponential growth of internet traffic [1–4] requires improvements in the existing backbone network technology to increase drastically its transmission capacity. It is envisaged that the information carrying capacity of single-core, single-mode fiber is reaching its fundamental limits and radically new fiber designs and network architectures may soon be needed. To address this issue, space division multiplexing (SDM) schemes employing either multi-core fibers (MCFs) or multi-mode fibers (MMFs) have been recently proposed and successfully demonstrated in single-span unamplified systems [5–12]. SDM in principle allows upscaling of the capacity per fiber by a factor proportional to the number of cores or modes. However, operation of such schemes in existing long haul networks requires the development of suitable high performance in-line optical amplifiers [13]. Recently a multicore erbium doped fiber (MC-EDF) amplifier has been demonstrated with 4dB of gain variation between the cores at a net signal gain of 25dB [14].

Use of MMF is another attractive option, where each guided mode can in principle be used as an independent information channel. Neng et al. [15] has recently studied numerically the performance of a two-moded amplifier based on a uniformly doped step-index EDF. They have shown that controlling the modal shape of the pump provides a means of tailoring the overall inter-modal gain. We very recently reported the demonstration of a multimode fiber amplifier for use in SDM systems [16]. In these first experiments we demonstrated the simultaneous amplification of two signals propagating on two separate modes of different order and with orthogonal polarization (namely the $LP^x_{01}$ and $LP^y_{11a}$ modes). Gains of > 22dB were obtained for both modes using a fiber with an optimized refractive index/erbium ion distribution profile and suitable pump profile [16]. However, in order to exploit the full potential of such an amplifier it is essential to be able to simultaneously amplify signals in all spatial and polarization modes supported by the amplifier, i.e. 6 modes altogether in our particular fiber (which supported two transverse mode groups). In this paper, as well as summarizing the initial key results presented in the original postdeadline submission, we also report subsequent experiments demonstrating the simultaneous amplification of $LP^x_{11a}$ and $LP^y_{11b}$ (different polarization, different high-order transverse mode), as well as $LP^x_{01}$ and $LP^x_{11a}$ (same polarization, different transverse mode group), achieving similar gains and differential modal gains for these different pairwise combinations of modes. Our results highlight the potential for simultaneously achieving well matched gains for all 6 guided modes through fiber design and suitable pump excitation.

#157482 - $15.00 USD Received 2 Nov 2011; accepted 6 Dec 2011; published 12 Dec 2011

## 2. Experimental results

The experimental setup of the MM-EDFA, configured to assess the amplification performance of modes of different polarization and different transverse mode group, is shown in Fig. 1(a).



(a) (b)

Fig. 1. (a) Experimental layout to characterize MM-EDFA. LD: Laser Diode, PMF: Polarization Maintaining Fiber, MS: Mode Stripper ($LP_{11}$), TMF: Two Moded Fiber, LPG: Long Period Grating, HWP: Half Wave Plate, PBS: Polarization Beam Splitter, PC: Polarization Controller, DM: Dichroic Mirror, TM-EDF: Two Moded Erbium Doped Fiber; (b) Typical transmission curve of the mechanical LPG.

The seed comprised a fixed wavelength DFB diode laser at 1558.9nm (input 1) and an external cavity laser (ECL) tunable across the C-band (input 2). The single-mode, single polarized output of the DFB and the ECL were spliced to passive multimode optical fibers. For simplicity we used a fiber with a core diameter of 19.7µm and a numerical aperture (NA) of 0.12 which effectively guides only two transverse mode groups, namely the $LP_{01}$ and $LP_{11}$ mode groups (comprising 6 distinct modes including all degeneracies and polarizations). A mechanical long period grating (LPG) was applied to the two moded fiber (TMF) spliced to the end of the DFB pigtail to convert input light in the $LP_{01}$ to the $LP_{11a}$ mode [17,18]. A typical transmission curve of the mechanical LPG is shown in Fig. 1(b) showing that strong mode conversion to the $LP_{11}$ mode was achieved with an extinction ratio of 30dB when a single polarization $LP_{01}$ mode at 1559nm was coupled into the TMF. For ease of demultiplexing the modes at the amplifier output, we first considered only the y-polarized $LP_{01}$ mode (i.e. $LP^y_{01}$) and the $LP_{11a}$ mode along the x-polarization, i.e. $LP^x_{11a}$. The $LP^y_{01}$ mode from the ECL and $LP^x_{11a}$ from the DFB are polarization multiplexed using a polarization beam splitter (PBS) and coupled into a second length of passive TMF. The launch end of the TMF was flat cleaved to enable clean excitation of the fiber modes (this has the slight downside that it leads to an increased build-up of amplified spontaneous emission (ASE) at the amplifier output at low input signal powers). The output of the input length of passive TMF was analyzed to assess the degradation in polarization extinction ratio (PER) between the two orthogonal modes as well as any mode cross-coupling during the free space launch. A PER in excess of 20dB was measured for both the modes, which is sufficient for amplification and polarization demultiplexing of the two orthogonal signal modes at the output of the amplifier. The passive fiber was then spliced directly to a 5m length of either of two mode-matched $Er^{3+}$-doped active fibers each exhibiting different fiber refractive index profiles (FRIPs), namely Fiber #1 and Fiber #2, as shown in Fig. 2(a) and Fig. 2(b) respectively. Note that the distribution of erbium in the fiber perform was measured by secondary mass ion spectroscopy (SIMS) which show that the $Er^{3+}$-doping profile closely

#157482 - $15.00 USD Received 2 Nov 2011; accepted 6 Dec 2011; published 12 Dec 2011

follows the refractive index profiles of the active fibers. A 980nm fiber pigtailed diode laser was used to pump the active fibers and was free-space coupled into the MM-EDFA using a dichroic mirror. The free ends of the active fibers were angle-cleaved to suppress Fresnel reflection. A second PBS was used at the output of the amplifier to separate the two orthogonal polarization modes.

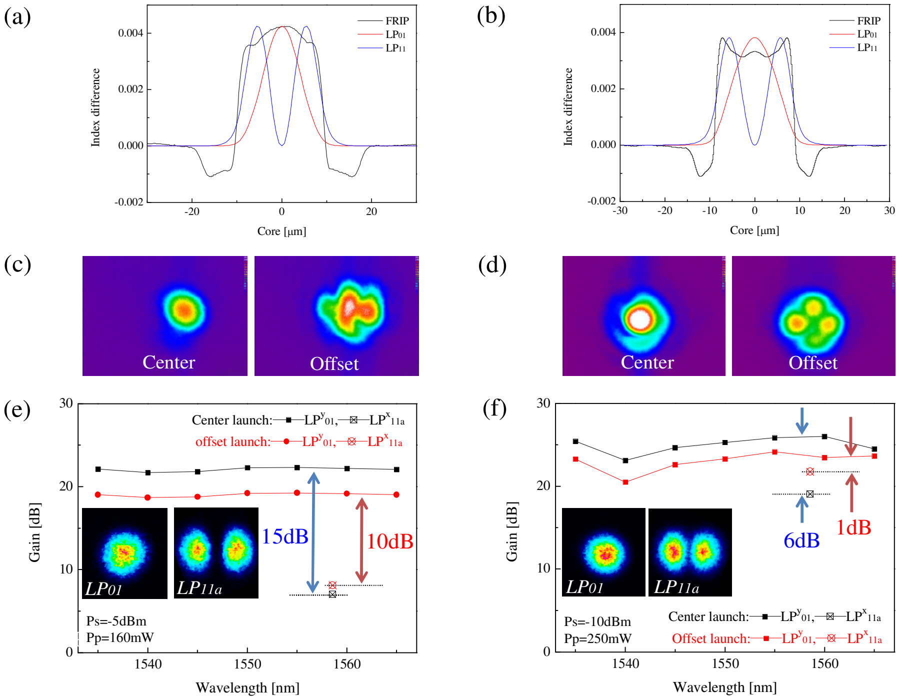


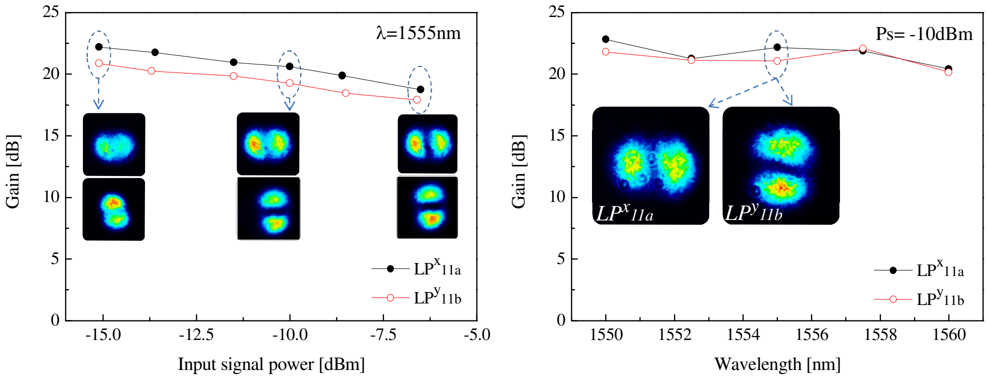
Fig. 2. (a, b) FRIP and calculated mode profiles supported by the two fabricated active fibers, (c, d) pump mode profiles coupled into the respective doped fibers for center and offset launch, (e, f) gain vs wavelength for $LP^y_{01}$ and $LP^x_{11}$ modes for center and offset launch.

The amplified output powers of the $LP^y_{01}$ and $LP^x_{11a}$ modes, shown in Figs. 2(e) and 2(f), critically depend on the pump modes. For the centered launch condition which promotes the excitation of the symmetric pump modes (Fig. 2(c) and Fig. 2(d)), the measured gain of the $LP^y_{01}$ mode for Fiber #1 (Fig. 2(a)) was found to be substantially higher (>15dB) than the $LP^x_{11a}$ mode due to better spatial overlap with the pump modes as well as the $Er^{3+}$-dopant distribution. For the offset launch the asymmetric pump modes dominate over the symmetric ones and the differential gain between the two modes was measured to be around 10dB. However this comes at the expense of lower average output power due to the reduced pump coupling efficiency. Fiber #2 was designed to have a higher $Er^{3+}$- density at the edges of the refractive index profile in order to achieve reduced pump field sensitivity for the modal gains. For the centered launch condition the gain difference between the $LP^y_{01}$ and $LP^x_{11a}$ mode was measured to be ~6dB for an input signal power of −10dBm. This could be brought down to less than 1 dB with the optimum offset launch shown in Fig. 2(f). Those results show that the differential gain between the two signal modes can be managed by controlling either the relative strength of the pump modes as indicated in Ref [15], or the $Er^{3+}$-doping distribution, or both. Large scale gain differentials between the modes can be addressed by manipulating the FRIP whilst fine tuning can be achieved by controlling the strength of the individual pump modes. Figures 2(e) and 2(f) also highlights that a relatively flat gain profile with a maximum gain variation of 3dB across the full C-band was achieved for the $LP_{01}$ mode. The CCD

Received 2 Nov 2011; accepted 6 Dec 2011; published 12 Dec 2011

images of the output beam confirm that the modal integrity of the signals is well preserved through the amplification process.. A maximum signal output power of ~80mW was measured for both fiber types for a center launched pump power of 200mW, corresponding to an optical-to-optical conversion efficiency of ~32%. The output power dropped to 60mW for off-axis pump launching due to the reduction in coupled pump power. Since Fiber #2 provides a lower differential gain between the two modes, we focused our attention on just this fiber in the more detailed investigation of the MM-EDFA that follows.

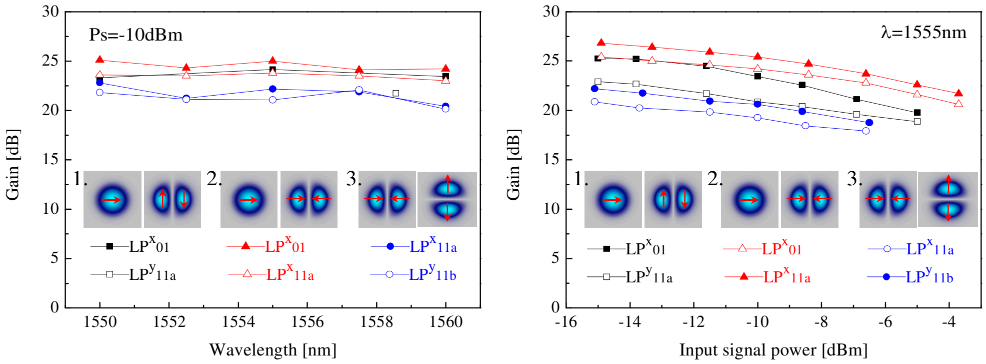
In our next set of experiments we investigated the simultaneous amplification of the orthogonal polarization modes of the $LP_{11}$ mode group namely $LP^{x}_{11a}$ and $LP^{y}_{11b}$ modes. A second mechanical LPG was introduced in the input 2 arm and the fixed wavelength DFB diode laser of input 1 replaced with another ECL to allow wavelength tuning for both modes. The asymmetrical deformation induced by the mechanical LPG grating can be used to selectively excite one of the spatial modes ($LP_{11a}$, $LP_{11b}$) of the second-order mode. The x-polarized fundamental mode ($LP^{x}_{01}$) can couple to the second-order $LP^{x}_{11a}$ mode when the asymmetrical deformation occurs in the vertical direction ($LPG^{x}$) and $LP^{y}_{01}$ can couple to $LP^{y}_{11b}$ with the deformation applied in the horizontal direction ($LPG^{y}$). The $LP^{x}_{11a}$ mode from input 1 and $LP^{y}_{11b}$ from input 2 were polarization multiplexed and coupled into a second length of passive TMF. The passive fiber was then spliced directly to a 3m length of Fiber #2. As shown in the CCD images in Fig. 3(a), two spatial modes of the second-order mode ($LP^{x}_{11a}$ and $LP^{y}_{11b}$) can be cleanly demultiplexed at the output of the TM-EDF. The gains for both $LP^{x}_{11a}$ and $LP^{y}_{11b}$ were measured to be ~20dB for an input signal power of −10dBm and a launched pump power of ~200mW. Offset pump launch condition was applied to maximize the gain for the $LP_{11}$ modes. Both modes experienced gain reduction with an increase in input signal powers. The CCD images of the two modes are well defined at high signal input powers however the quality of the images degraded with decreasing input signal power due to the increasing dominance of unpolarized ASE light the various transverse modes and which appears in both arms after the PBS. As shown in Fig. 1(b), the response of the LPG is wavelength sensitive and this limited the tuning range over which reliable modal gain measurements could be made to around ~10nm. Figure 3(b) shows the gain plots for both the modes as a function of operating wavelength for fixed signal input power of −10 dBm. Both modes experienced greater than 20dB gain across the tuning band with similar gain profiles.



(a) (b)

Fig. 3. Gain for $LP^{x}_{11a}$ and $LP^{y}_{11b}$ modes as a function of (a) input signal power and (b) wavelength for offset pump launch condition.

We have also studied the modal amplification of the two transverse mode groups along the same polarization axis i.e. $LP^{x}_{01}$ and $LP^{x}_{11a}$ modes. In this case we replaced the polarization beam splitter (PBS) with a polarization insensitive beam splitter (BS) at the input end of the amplifier. A linear polarizer was added prior to the passive TMF to ensure single polarization excitation. To estimate signal gain, a 2nm bandpass filter was used to measure the amplified output power of the amplified individual modes (set with a wavelength separation of 5nm). In Fig. 4(a) we plot the gain as a function of signal wavelength and in Fig. 4(b) we plot the gain as a function of signal power for fixed pump power together with the other gain plots presented in Fig. 2 and Fig. 3. Note that unfortunately there is some variation in launched pump power for the different experiments (the launched pump power increased from ~200mW whilst studying mode groups 1 & 3 to ~275mW for mode group 2 due to variations in launch efficiency) which slightly complicates direct comparison of the various data sets, however it is clear that gains of order 20dB are possible in two channel experiments for all modal combinations investigated with differential modal gains of order 4-5dB.



(a) (b)

Fig. 4. Gain for pairwise combinations of the input modes as a function of (a) wavelength and (b) input signal power for the offset pump launch condition.

## 3. Conclusions

We present the first experimental implementation of a MM-EDFA for SDM transmission. We demonstrate that differential modal gain can be significantly improved by optimizing the pump launch. We also propose an improved EDF with a tailored central dip in both the refractive index and $Er^{3+}$-ion concentration, and show its advantages over a more standard fiber profile. Using this fiber with an offset pump launch exciting preferentially the $LP_{21}$ mode we achieved over 22dB gain for two modes at the same wavelength and in orthogonal polarizations. Furthermore, we also show that >20 dB gains can be achieved with modest gain differentials for different pairwise combinations of modes (specifically $LP^x_{11a}$ and $LP^y_{11b}$, $LP^x_{01}$ and $LP^x_{11a}$ and $LP^x_{01}$ and $LP^y_{11a}$ mode combinations) with relatively modest values of differential modal gain. Our experiments are still in train and it should be possible to reduce the gain differentials by optimizing the pumping arrangement and through further iterations on the fiber design. Experiments in which all 6-modes are simultaneously amplified will be undertaken once suitable mode multiplexers/demultiplexers become available to us.

## Acknowledgments

This work was supported by the European Communities 7th Framework Programme under grant agreement 228033 (MODE-GAP).

Received 2 Nov 2011; accepted 6 Dec 2011; published 12 Dec 2011