

# Optimizing the pumping configuration for the power scaling of in-band pumped erbium doped fiber amplifiers

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**Abstract:** A highly efficient (~80%), high power (18.45 W) in-band, core pumped erbium/ytterbium co-doped fiber laser is demonstrated. To the best of our knowledge, this is the highest reported efficiency from an in-band pumped 1.5  $\mu\text{m}$  fiber laser operating in the tens of watts regime. Using a fitted simulation model, we show that the significantly sub-quantum limit conversion efficiency of in-band pumped erbium doped fiber amplifiers observed experimentally can be explained by concentration quenching. We then numerically study and experimentally validate the optimum pumping configuration for power scaling of in-band, cladding pumped erbium doped fiber amplifiers. Our simulation results indicate that a ~77% power conversion efficiency with high output power should be possible through cladding pumping of current commercially available pure Erbium doped active fibers providing the loss experienced by the cladding guided 1535 nm pump due to the coating absorption can be reduced to an acceptable level by better coating material choice. The power conversion efficiency has the potential to exceed 90% if concentration quenching of erbium ions can be reduced via improvements in fiber design and fabrication.

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**OCIS codes:** (140.3510) Lasers, fiber; (140.4480) Optical amplifiers; (060.2410) Fibers, erbium.

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## References and links

1. Y. Jeong, S. Yoo, C. A. Codemard, J. Nilsson, J. K. Sahu, D. N. Payne, R. Horley, P. W. Turner, L. Hickey, A. Harker, M. Lovelady, and A. Piper, "Erbium: ytterbium codoped large-core fiber laser with 297-W continuous-wave output power," *IEEE J. Sel. Top. Quantum Electron.* **13**(3), 573–579 (2007).
2. M. Dubinskii, J. Zhang, and V. Ter-Mikirychev, "Record-efficient, resonantly-pumped, Er-doped single mode fibre amplifier," *Electron. Lett.* **45**(8), 400–401 (2009).
3. P. C. Becker, N. A. Olsson, and J. R. Simpson, *Erbium-Doped Fiber Amplifiers: Fundamentals and Technology* (Academic Press, 1999).
4. P. Blixt, J. Nilsson, T. Carlnas, and B. Jaskorzynska, "Concentration-dependent upconversion in Er<sup>3+</sup>-doped fiber amplifiers: experiments and modeling," *IEEE Photon. Technol. Lett.* **3**(11), 996–998 (1991).
5. E. Delevaque, T. Georges, M. Monerie, P. Lamouler, and J. F. Bayon, "Modeling of pair-induced quenching in erbium-doped silicate fibers," *IEEE Photon. Technol. Lett.* **5**(1), 73–75 (1993).
6. P. Myslinski, D. Nguyen, and J. Chrostowski, "Effects of concentration on the performance of erbium-doped fiber amplifiers," *J. Lightwave Technol.* **15**(1), 112–120 (1997).
7. J. Nilsson, B. Jaskorzynska, and P. Blixt, "Performance reduction and design modification of erbium-doped fiber amplifiers resulting from pair-induced quenching," *IEEE Photon. Technol. Lett.* **5**(12), 1427–1429 (1993).
8. D. Boivin, T. Fohn, E. Burov, A. Pastouret, C. Gonnet, O. Cavani, C. Collet, and S. Lempereur, "Quenching investigation on new erbium doped fibers using MCVD nanoparticle doping process," in *Proc. SPIE* **7580**, 75802B-1–75802B-9(2010).
9. S. Sergeev, S. Popov, and A. T. Friberg, "Influence of the short-range coordination order of erbium ions on excitation migration and upconversion in multicomponent glasses," *Opt. Lett.* **30**(11), 1258–1260 (2005).
10. S. Sergeev, S. Popov, D. Khoptyar, A. T. Friberg, and D. Flavin, "Statistical model of migration-assisted upconversion in a high-concentration erbium-doped fiber amplifier," *J. Opt. Soc. Am. B* **23**(8), 1540–1543 (2006).

11. J. Zhang, V. Fromzel, and M. Dubinskii, "Resonantly cladding-pumped Yb-free Er-doped LMA fiber laser with record high power and efficiency," *Opt. Express* **19**(6), 5574–5578 (2011).
  12. J. C. Jasapara, M. J. Andrejco, A. DeSantolo, A. D. Yablon, Z. Vrallyay, J. W. Nicholson, J. M. Fini, D. J. DiGiovanni, C. Headley, E. Monberg, and F. V. DiMarcello, "Diffraction-Limited fundamental mode operation of core-pumped very-large-mode-area Er fiber amplifiers," *IEEE J. Sel. Top. Quantum Electron.* **15**(1), 3–11 (2009).
  13. E. L. Lim, S. U. Alam, and D. J. Richardson, "Highly efficient, high power, inband-pumped erbium/ytterbium-codoped fiber laser," in *CLEO*, p. CTu11 (2011).
  14. S. U. Alam, A. T. Harker, R. J. Horley, F. Ghiringhelli, M. P. Varnham, P. W. Turner, M. N. Zervas, and S. R. Norman, "All-fibre, high power, cladding-pumped 1565nm MOPA pumped by high brightness 1535 nm pump sources," in *CLEO*, p. CWJ4 (2008).
  15. M. Laroche, S. Girard, J. K. Sahu, W. A. Clarkson, and J. Nilsson, "Accurate efficiency evaluation of energy-transfer processes in phosphosilicate Er<sup>3+</sup>-Yb<sup>3+</sup>-codoped fibers," *J. Opt. Soc. Am. B* **23**(2), 195–202 (2006).
  16. K. Aiso, Y. Tashiro, T. Suzuki, and T. Yagi, "Development of er/yb co-doped fiber for high-power optical amplifiers," *Furukawa Review* **20** (2001).
  17. S. Tammela, M. Hotoleanu, P. Kiiveri, H. Valkonen, S. Sarkilahti, and K. Janka, "Very short Er-doped silica glass fiber for L-band amplifiers", in *Proc. Optical Fiber Comm.(OFC)*, paper WK3 (2003).
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## 1. Introduction

High power 1.55  $\mu\text{m}$  erbium (Er) based fiber lasers are attractive for numerous applications, such as materials processing and military applications, where light scattered off-target is a great concern in terms of eye safety. The realization of high power 1.55  $\mu\text{m}$  Er-based high power lasers however presents a number of key challenges, not least, achieving sufficient pump absorption per unit length, obtaining sufficiently high power conversion efficiency and the availability of suitably high brightness pumps at the desired wavelengths. Compromises need to be struck to realize practical devices and the optimum design choices made will depend strongly on the specific application. Here, we focus on scaling to high average output powers.

A fundamental requirement is clearly that sufficient pump power must first be absorbed by the active fiber over a reasonably short length scale to generate high signal output power. However, the absorption coefficient of the Er<sup>3+</sup> ion at the peak absorption wavelength of  $\sim 980$  nm is rather low. To circumvent this, erbium doped fiber (EDF) has long been co-doped with ytterbium (Yb) ions to increase the pump absorption. The absorbed pump energy is then resonantly transferred from the Yb<sup>3+</sup> to the Er<sup>3+</sup> ions with high efficiency. Using this approach, average output powers as high as 297 W at 40% conversion efficiency have been demonstrated [1]. However, under high power operation, this pumping scheme is prone to spurious lasing of the Yb<sup>3+</sup> ions at wavelengths around 1.06  $\mu\text{m}$  which results in a roll off in conversion efficiency at higher power levels. Furthermore, the relatively large quantum defect results in a high thermal load per unit length which further limits the prospect for substantial power scaling.

To improve the conversion efficiency significantly an in-band pump approach can be employed, (also known either as resonant or tandem-pumping), theoretically enabling quantum defects of less than 5%. To date the best conversion efficiency reported (output power/absorbed pump power) is 85% obtained in a pure Erbium-doped fiber operated in a core pumped configuration at low average powers of up to just 0.35 W [2].

The gain fiber used in this instance was engineered to have low Er<sup>3+</sup> ion clustering and the core composition carefully optimized to provide a high pump to signal conversion efficiency. However, the core absorption of the fiber ( $\sim 9$  dB/m at 1530 nm) is far too low to allow the same fiber core composition to be realistically used for simple power scaling via direct diode based cladding pumping since the pump absorption would be reduced to impractical levels by the low core to inner cladding area ratio.

To increase the absorption would necessitate either using a far larger core diameter (which would grossly compromise the output beam quality), or a higher Er-concentration. However, as the Er<sup>3+</sup> ion concentration is increased the concentration quenching effect rapidly starts to become significant [3–10], resulting in lower optical-to-optical conversion efficiencies.

So far the record value of conversion efficiency in the multi-Watt regime for a cladding pumped Er fiber laser is ~69% [11]. It is important to note that this laser was pumped directly using a high power InGaAs/InP laser diode module which is highly desirable from a practical perspective.

Power scaling of erbium fibers is obviously possible using higher brightness pump sources and core-pumping [12,13] and indeed herein we describe experiments on an in-band, core pumped EYDF delivering 18.5 W output power at 1562.5 nm with ~80% power conversion efficiency ( $PCE = (\text{output signal power} - \text{input signal power}) / \text{absorbed pump power}$ ), which we believe to be a record PCE for a fiber laser operating in the multi-tens of Watt regime [13]. However, this approach is ultimately limited by the scalability of high power single mode pump sources and is much less desirable than diode based solutions. Moreover, as we illustrate in this paper, this approach is far more susceptible to compromised efficiencies due to concentration quenching.

In this paper, we investigate the strategy for the power scaling of high power in-band pumped Er-based fiber amplifiers. First, we assess the performance of two different fibers and develop simulation models that are fitted to experimental results for both fibers. The simulation shows that the performance of the high power fiber amplifier is strongly affected by concentration quenching. With the experimentally validated model, we compare the performance of the amplifiers with different pumping arrangements, i.e. core-pumping scheme (CRS) versus cladding-pumping scheme (CLS) and forward-pumping (FP) versus backward-pumping (BP) scheme. Our results show that the both CLS and BP can be exploited to mitigate the detrimental effect of concentration quenching. Hence, we predict that ~77% PCE with high output power is feasible using backward cladding pumping in conjunction with operation at long signal wavelengths around 1605 nm. Finally, we validate this prediction with cladding pumped experiments identifying in the process that excess pump loss in this instance due to the high absorption by the cladding materials is an impediment to this in current commercial fibers

## 2. Core-pumped MOPA

### 2.1 Experiment setup

Figure 1 shows the experimental setup of a FP-CRS master oscillator power amplifier (MOPA) system. The seed is an external cavity tunable laser (Agilent 8164A) delivering 1 mW of average output power in the C-band. A commercial high power amplifier (IPG-EAD-5-K-C) is used to boost the seed power. The pump source is a fiber Bragg grating (FBG) stabilized 1535 nm single mode fiber laser providing a maximum output power of 21.4 W [14]. The signal and pump beams are combined and launched into the core of the gain fiber via a wavelength division multiplexer (WDM). We have investigated two different active fibers, namely Fiber 1 and Fiber 2.

Fiber 1 is an in-house made EYDF with an estimated mode field diameter (MFD) of 12  $\mu\text{m}$  (fundamental mode) and a core numerical aperture (NA) of 0.22. The measured core absorption is ~58 dB/m at 1535 nm. With the core absorption, we estimate the optimal fiber length for CRS experiment in the absence of concentration quenching as ~3.5 m. Hence, a 3.75 m fiber is used. Fiber 2 is a commercial pure Erbium doped double clad fiber (Liekki Er 60-40/140DC) with a 40  $\mu\text{m}$  core diameter with a corresponding NA of 0.10, a cladding diameter of 140  $\mu\text{m}$  with a corresponding NA of 0.46. The core absorption is 60 dB/m at 1530 nm. Based on the core absorption, we estimated the optimal length as ~3 m prior to the purchase of the fiber. In the absence of concentration quenching, the output power is not strongly dependent on optimal fiber length (see the discussion relating to Fig. 3 in Section 2.4). Hence, we opted to purchase 5 m of the fiber for use in our experiments. The fiber length was reduced by ~0.1 m as a result of preliminary splicing trials. Hence, the actual length of Fiber 2 used in our experiments was ~4.9 m.

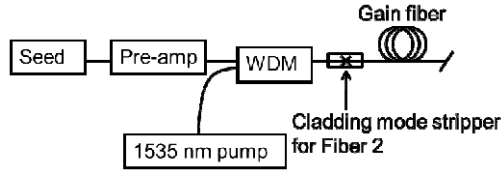


Fig. 1. Experimental setup of the FP-CRS configuration. Cladding mode stripper was used only for Fiber 2.

## 2.2 Experiment results

The performance of Fiber 1 was first investigated at a signal wavelength of 1565 nm for input signal-power levels of 62.5 mW, 250 mW and 1000 mW as shown in Fig. 2(a) with circles. The results show that a high input signal level is needed to achieve a high PCE (PCE = (output signal power-input signal power)/absorbed pump power). The optimal wavelength of operation of the final stage amplifier was determined to be ~1562.5 nm. For an input signal power of 1.5 W at 1562.5 nm, the MOPA output increased linearly with increasing 1535 nm input pump power. A maximum output power of 18.45 W was measured for 21.38 W of input pump power corresponded to a PCE of ~80%. The absence of roll-off of the signal output power at the maximum available pump power signifies that the maximum signal output power is pump-power limited. The output spectrum at maximum power (inset in Fig. 2(a)) shows a good Optical to Signal Noise Ratio (OSNR) and negligible residual pump power. Overall, the performance of Fiber 1 agrees with our initial estimates.

The performance of Fiber 2 was tested in a similar manner. Since this was a double-clad fiber, a cladding mode stripper was used at the splice point between the WDM and Fiber 2 (as shown in Fig. 1) to ensure that any optical power leaking into the cladding was cleanly and safely removed from the system so as to minimize any measurement uncertainties at the amplifier output. The measured splice loss between the two quite dissimilar fibers was ~2 dB. As a result only 60% of the available pump and signal power was coupled into the fiber core. The performance of the fiber was tested at a signal wavelength of 1565 nm for input signal-power levels of 24 mW, 70 mW, 140 mW, 282 mW and 563 mW as shown in Fig. 2(b) (circles). The maximum signal output power was measured to be ~1.93 W at 0.563 W of input signal power and 7.05 W input pump power, which corresponded to a maximum PCE of ~19.4%. It should be mentioned that no residual pump was measurable in the experiment. This experiment result differs significantly with our initial estimation, and motivates us to investigate the impact of concentration quenching to the performance of the high power erbium doped fiber amplifier (EDFA).

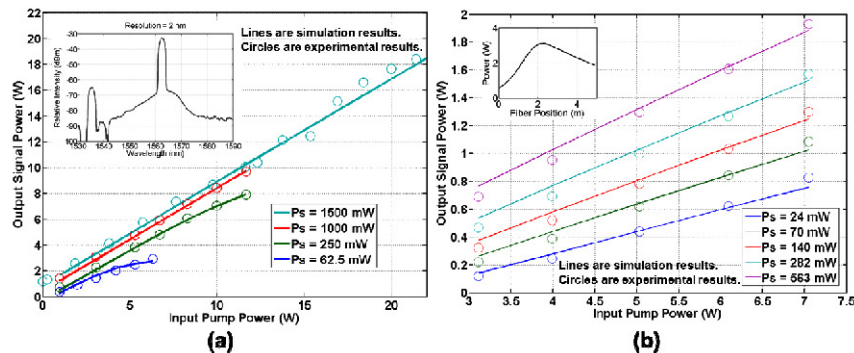


Fig. 2. Experimental (circles) and simulation (lines) results for (a) Fiber 1 and (b) Fiber 2. The inset in (a) is the output spectrum of Fiber 1 at the maximum output signal power. The inset in (b) is the simulated signal power distribution along Fiber 2 for the case of 563 mW input signal power and 7.05 W input pump power.

### 2.3 Simulation model

Several models to describe the concentration quenching in erbium doped fiber are to be found in the literature [3–10]. Among them, the physical mechanism of concentration quenching in erbium doped fiber can best be described by the statistical model of migration assisted upconversion [9,10]. However, since the main objective of this paper is to investigate the design strategy for power scaling of in-band pumped EDFAs, in this work the concentration quenching is modeled using a phenomenological model instead, i.e. the homogeneous upconversion (HUC) and pair-induced quenching (PIQ) model [6]. Despite the simplicity of the phenomenological model, it has successfully been used previously to characterize and describe the performance of high concentration EDFAs [3–8].

In this model, the optical power in the amplifier was modeled using the propagation equation in the standard EDFA model [3], while the effect of the concentration quenching is considered in the rate equation for the erbium ions in the active fiber [3–8]. The ions are assumed to have undergone two possible types of ion-ion interactions, namely the HUC and PIQ [3–8]. In the model, all ions are classified as belonging to one of two distinct species of ion: independent ions and paired-ions. In the case of paired-ions, two ions form an ion-cluster due to their close proximity. If  $2k$  is defined as the fraction of paired-ion and  $N_t$  is the total ion concentration, then the total ion concentration existing in a paired-ion state,  $N_t^k$ , is given by  $N_t^k = 2kN_t$ . Likewise, the total number of independent ions,  $N_t^i$ , is given by  $N_t^i = N_t - N_t^k = N_t(1 - 2k)$ .

The independent ions can undergo HUC, where the nonradiative energy transfer between the two  ${}^4I_{13/2}$ -excited ions results in one ion decaying to the ground state whilst another ion is excited to the  ${}^4I_{9/2}$ -state. The  ${}^4I_{9/2}$ -excited ions then rapidly relax to either the  ${}^4I_{11/2}$  or  ${}^4I_{15/2}$ -state. Under the steady state condition, the rate equation for independent ions is [3,4]:

$$N_2^i = \frac{R_{12}^i N_t^i}{A_i + R_{12}^i + R_{21}^i + (1 + \frac{1}{m})CN_2^i}. \quad (1)$$

In the above equation, the superscript  $i$  signifies rates for independent ions.  $1/m$  is the branching ratio between relaxation process to  ${}^4I_{11/2}$  and  ${}^4I_{15/2}$ ,  $N_2^i$  is the population density of the upper lasing level ( ${}^4I_{13/2}$ ),  $C$  is the upconversion coefficient.  $R_{12}^i$ ,  $R_{21}^i$  and  $A^i$  are the absorption, stimulated emission and spontaneous emission rates respectively.

In the paired-ion case, when both ions of the ion-cluster are excited, the non-radiative energy transfer between them is so fast that only one ion of the ion-cluster can remain in the excited state [3,5–7]. The difference between PIQ and HUC is that, in the case of HUC, if an ion is excited, it does not prohibit neighboring ions moving to the excited state. However, in the case of PIQ, when one ion of an ion-cluster goes to the excited state, the other ion in the ion-cluster must be in its ground state [3]. As a result, the ion-cluster can be in either of two states: State I: two ions in the ground state, or State II: one ion in the excited state and one ion in the ground state. Under steady state conditions, the rate equation describing the ion population density of paired ions is [7]:

$$N_2^k = \frac{R_{12}^i N_t^k}{A_i + 2R_{12}^i + R_{21}^i}. \quad (2)$$

In the above equation, the superscript  $k$  signifies the rate for ion-cluster.  $N_2^k$  is the ion population density of paired ions in the upper lasing level ( ${}^4I_{13/2}$ ).

Overall, the population density of the excited ions in the steady state considering the effects of both HUC and PIQ is [6]:

$$N_2 = N_2^i + N_2^k = \frac{R_{12}^i N_i (1 - 2k)}{A_i + R_{12}^i + R_{21}^i + (1 + \frac{1}{m}) C N_2^i} + \frac{R_{12}^i 2k N_i}{A_i + 2R_{12}^i + R_{21}^i}. \quad (3)$$

#### 2.4 Fitting results

Although Fiber 1 is an Er/Yb co-doped fiber, the Yb<sup>3+</sup> ions do not play any active role in the amplification process since Yb<sup>3+</sup> ion does not exhibit emission and absorption in 1.5-1.6 μm spectral range. Therefore, the Yb<sup>3+</sup> ions can be neglected in the simulation. In the fitting process, the following parameters are either known or estimated: length of the EYDF = 3.75 m, core absorption = 58 dB/m at 1535 nm, core diameter = 14 μm, the Er-doping diameter = 8.9 μm and concentration of Er<sup>3+</sup> ion = 2.45 × 10<sup>25</sup> /m<sup>3</sup>. The following parameters are obtained from literature: m = 1 × 10<sup>4</sup> [4], <sup>4</sup>I<sub>13/2</sub> fluorescence lifetime of Er<sup>3+</sup> ion = 10 ms [3] and the emission and absorption cross sections from [15]. The values of C and k are obtained as fitting parameters. The behavior of the amplifier can be best-fitted with C = 2.0 × 10<sup>-22</sup> m<sup>3</sup>/s and k = 0.2% (shown by the lines in Fig. 2(a)). Similarly for Fiber 2, the following parameters are known or estimated: fiber length = 4.9 m, core absorption = 60 dB/m at 1530 nm, Er-doping diameter = 40 μm, core diameter = 40 μm, concentration of Er<sup>3+</sup> ion = 3.23 × 10<sup>25</sup> /m<sup>3</sup>. The <sup>4</sup>I<sub>13/2</sub> fluorescence lifetime of Er<sup>3+</sup> ion = 10 ms and the absorption/emission cross section from [3]. With k as the fitting parameter and C = 0, a good fit is achieved with k = 4.1% (shown by the lines in Fig. 2(b)). The inset in Fig. 2(b) shows the simulated signal distribution along the fiber for 563 mW input signal and 7.05 W input pump power. Based on the simulation results, we predict that a maximum signal power of ~3.1 W could be achieved if ~2.3 m of active fiber were to be used, corresponding to an estimated PCE of ~37%. Hence, even using an optimum fiber length, the PCE is still far from the quantum limit due to the presence of PIQ. We did not cut back our sole sample of Fiber 2 to validate this prediction since it was needed for other experiments, for example the experiment described in Section 3.2.

The lower k-value of Fiber 1 compared to Fiber 2 may be due to the lower Er<sup>3+</sup> ion concentration of Fiber 1, the high solubility of Er<sup>3+</sup> ion in the EYDF phosphosilicate-glass host and/or the presence of Yb<sup>3+</sup> ions in the EYDF [16]. Meanwhile, for a pure Er-doped fiber, the k-value of Fiber 2 represents quite a low value compared to those reported in [6]. This low k-value can be attributed to the direct nanoparticle deposition (DND) technologies used in the fiber fabrication process [17]. To further illustrate the detrimental effect of PIQ, the signal distribution along the fiber for a 0.5 W input signal power at 1565 nm and 20 W of input pump power is simulated for 5 different k-values in the forward core pumping configuration as shown in Fig. 3 (all the simulations are based on the parameters of Fiber 2, unless specified otherwise). The result shows that an increase in k-value from 0.0% to 1.1% decreases the PCE from ~93% to ~67%, while it drops down to ~30% when the k-value increases to 4.1%. After the optimal fiber length (~3.5 - 4.0 m), the signal power with a higher k-value decreases more rapidly. This increase of signal reabsorption is caused by the PIQ. Hence, a stronger PIQ causes the output signal power to be far more sensitive to the optimal choice of fiber length.

These results signify the importance of minimizing PIQ in high power CRS-EDFAs. We have demonstrated better than 80% PCE from an EDF with low PIQ and further enhancement in PCE may be possible by eliminating the PIQ completely.

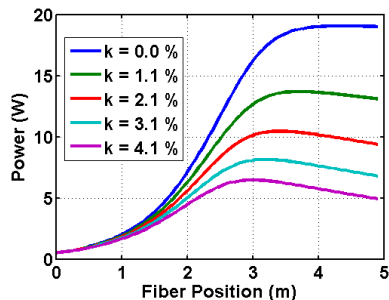


Fig. 3. Simulated signal power distribution along the gain fiber for 5 different  $k$ -values with 0.5 W 1565 nm input signal power and 20 W input pump power in FP-CRS configuration.

### 3. Power scaling of in-band pumped EDF

#### 3.1 Simulation

Although we have achieved 18 W of output power with a record PCE, power scaling in this scheme will ultimately be limited by the availability of high power single mode pump sources at 1535 nm as well as passive optical components e.g. WDM couplers capable of handling such high average power. Moreover, the optical-to-optical efficiency from diode to laser output is only  $\sim 32\%$ . To improve the efficiency figure and to avoid the potential power scaling bottleneck presented by the need for an intermediary fiber pump laser, direct cladding pumping using InGaAs/InP-laser diodes will be the preferred solution [11].

To assess the performance and to identify the optimum pump configuration for power scaling of in-band pumped EDF MOPAs, and to investigate the impact of PIQ in this instance, we have modeled such systems for different pumping arrangements using the parameters of Fiber 2 but choosing the  $k$ -value to be either  $k = 0.2\%$  (as for Fiber 1) or  $4.1\%$  (as for Fiber 2). For ease of discussion, we label the various pumping schemes with the following notation “signal wavelength-pumping direction-pump coupling mechanism”. For example, the notation “1565 nm-FP-CRS” represents the pumping condition where the 1565 nm signal is amplified using a forward-propagating (FP) core-pumped amplifier (CRS). The input signal and pump powers are assumed to be 1 W and 100 W respectively. The signal wavelengths of 1565 nm and 1605 nm are studied, as each of them represents the optimal wavelength for CRS and CLS respectively. In the case of CLS, the overlap factor at the pump wavelength is reduced by a factor given by the ratio between the core to the inner cladding area.

In the case of CRS, a fiber length of 4.4 m was chosen since this represents the length at which the maximum output power is achieved for a 1565 nm-BP-CRS system with  $k = 4.1\%$ . With this length, the pump absorption at 1535 nm was estimated to be  $> 18$  dB in the case of a 1565 nm signal. In the case of CLS, an active fiber length of 15.0 m was chosen since this represents the length where the maximum output power can be achieved for a 1605 nm-BP-CLS with  $k = 4.1\%$ . With this length, the pump absorptions are  $> 14$  dB in the case of 1565 nm signal and  $> 21$  dB in the case of 1605 nm signal. The difference in the pump absorption is due to the difference in the signal saturation power,  $P_{\text{sat}}$ , which is inversely proportional to  $(\sigma_e + \sigma_a)$ , where  $\sigma_e$  and  $\sigma_a$  are the emission and the absorption cross sections at the signal wavelength respectively. The lower  $P_{\text{sat}}$  at 1565 nm leads to reabsorption of the signal and increases the inversion level of the gain medium. Therefore, the pump absorption in the presence of the 1565 nm signal is lower than is the case of a 1605 nm signal. Overall, most of the pump power has been absorbed in all cases. Furthermore, a slight variation of fiber length ( $\pm 0.1$  m) does not change the simulation results significantly.

The results for FP are presented in Fig. 4(a). When  $k = 0.2\%$  (similar to the case for Fiber 1), the maximum signal powers,  $P_{\text{max}}$ , for 1565 nm-FP-CRS (blue solid line), 1565 nm-FP-CLS (green solid line) and 1605 nm-FP-CLS (red solid line) pumping schemes are 89.7 W,

85.5 W and 91.5 W respectively. The maximum signal powers for various cases are also tabulated in Table 1. When the  $k$ -value increases to 4.1% (as for Fiber 2),  $P_{\max}$  for 1565 nm-FP-CRS (blue dash line), 1565 nm-FP-CLS (green dash line) and 1605 nm-FP-CLS (red dash line) are 26.1 W, 34.9 W and 63.1 W respectively. (Note that the location of the  $P_{\max}$  is different for the various configurations. For example, with  $k = 4.1\%$ , the  $P_{\max}$  occurs at 8 m for 1565 nm-FP-CLS and 12.2 m for 1605 nm-FP-CLS.) Therefore as the  $k$ -factor increases from 0.2% to 4.1%, the  $P_{\max}$  is reduced by 70.95%, 59.20% and 31.03% for 1565 nm-FP-CRS, 1565 nm-FP-CLS and 1605 nm-FP-CLS pumping schemes respectively. By comparing the reduction of 1565 nm-FP-CRS and 1565 nm-FP-CLS, we see that the effect of PIQ is less severe in the case of CLS. The advantage of CLS is even more obvious comparing the 1605 nm-FP-CLS case with the 1565 nm-FP-CRS case. In the CLS, the lower pump intensity reduces the detrimental effect of PIQ. Furthermore, since the ground state absorption at 1605 nm is lower, the 1605 nm signal is less likely to suffer from PIQ compared to the 1565 nm signal. These results clearly highlight that the CLS is far less susceptible to the detrimental effects of PIQ compared to the CRS. The simulation also indicates that with 1605 nm-FP-CLS and  $k = 4.1\%$ , the PCE can be of the order of 64%, which is comparable to the 69% reported in [11], where a similar fiber was used in a forward-pumped laser oscillator.

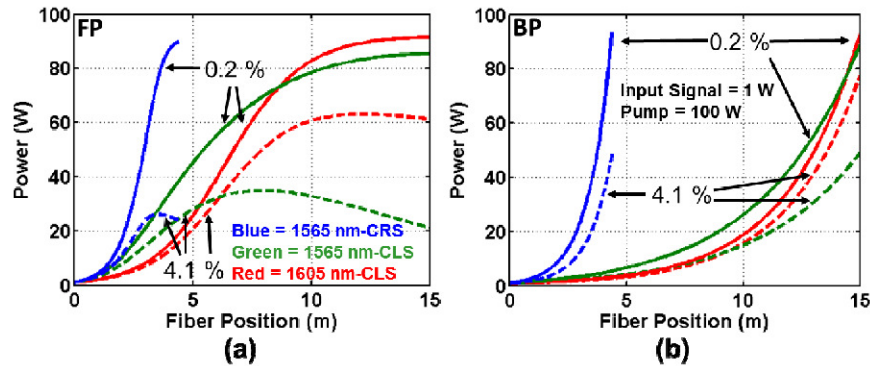


Fig. 4. Signal distribution at two different  $k$ -values (0.2% (solid lines) and 4.1% (dashed lines) under (a) forward-pumping scheme (FP) and (b) backward-pumping scheme (BP). Blue lines are 1565 nm-CRS and red lines are 1605 nm-CLS. The input signal power is 1 W and the input pump is 100 W.

Figure 4(b) shows the simulation results for the BP condition. In this case, the reductions in  $P_{\max}$  as the  $k$ -value increases from 0.2% to 4.1% are 51.07% (93.6 W to 45.8 W), 43.68% (88.7 W to 50.0 W) and 16.34% (92.6 W to 77.5 W) for the 1565 nm-BP-CRS (blue lines), 1565 nm-BP-CLS (green lines) and 1605 nm-BP-CLS (red lines) pumping schemes respectively. Similar to the FP scheme, the reduction in efficiency due to PIQ is more than that of the CLS. Furthermore, by comparing the  $P_{\max}$ -reduction for FP and BP for the same pump-coupling architecture and the same signal-wavelength (e.g. the reduction for 1565 nm-FP-CRS is 70.95% and for 1565 nm-BP-CRS is 51.07%), we conclude that the BP is less susceptible to the detrimental effects of PIQ compared to the FP. The physical reason for this is that in the case of BP, the backward propagating pump is strongest in the region where the signal is strongest. Thus, the inversion can be most efficiently depleted by the signal thereby reducing the peak local inversion within the fiber and thereby reducing the efficiency and net effect of the PIQ. Hence, the detrimental effect of the PIQ is mitigated. In terms of PCE, our simulation predicts that, with 1605 nm-BP-CLS and  $k = 4.1\%$ , ~77% PCE with high output power is feasible with the current commercially available fiber. A PCE of better than 90% should be possible if the  $k$ -value can be brought down to the level that we have achieved with our in-house fabricated fiber. The key results for the various schemes are summarized in Table 1.



To check the scalability of the simulation results, we repeated the simulation at much-higher pump powers (up to 10 kW) while keeping the input pump to signal ratio constant (i.e. at 100). The results show that the PCE and the signal gain are similar at higher pump powers and therefore indicate that our analysis for the different pump conditions is scalable to lasers with kW class output power.

**Table 1. Summary of key results for various schemes for 1 W input signal and 100 W input pump**

Scheme	$k = 0.2\%$		$k = 4.1\%$		$P_{\max}$ -reduction when $k$ -value increases from 0.2 to 4.1% (%)
	$P_{\max}$ (W)	PCE (%)	$P_{\max}$ (W)	PCE (%)	
1565 nm-FP-CRS	89.7	90	26.1	25	70.95
1565 nm-FP-CLS	85.5	88	34.9	44	59.20
1605 nm-FP-CLS	91.5	91	63.1	64	31.03
1565 nm-BP-CRS	93.6	94	45.8	45	51.07
1565 nm-BP-CLS	88.7	91	50.0	51	43.68
1605 nm-BP-CLS	92.6	92	77.5	77	16.34

### 3.2 Experimental validation: cladding pump case

To support the outcome of our numerical modeling, we performed a cladding pumped experiment with Fiber 2. The experimental setup was very similar to that for the core-pumped scheme shown in Fig. 1 other than that a tapered fiber bundle (TFB) was used to combine the pump and signal beams instead of a single mode WDM coupler. The 1535 nm single mode pump laser was spliced to the signal port of the TFB to explore the cladding pumping option. A commercial L-band high power amplifier (Keopsys CEFA-L-PB-HP) was used to boost the seed laser power into the final amplifier at both 1565 nm and 1605 nm.

The output powers with respect to the absorbed pump powers at the two signal wavelengths are shown in Fig. 5. In both cases 0.61 W of signal input power was coupled into the final amplifier. For ~11.5 W of absorbed pump, the output signal power was measured to be ~6.0 W for the 1605 nm case and ~4.6 W for the 1565 nm case. The corresponding PCEs are ~47% and ~38% for signal wavelengths of 1605 nm and 1565 nm respectively. These values are significantly lower than predicted by our theory

In trying to establish the reason for these relatively low measured PCEs we first characterized the pump absorption within the fiber. Using a passive version of Fiber 2 (Liekki Passive-40/140 DC) we measured the background loss of the cladding guided pump light to be ~0.15 dB/m at 1535 nm – a surprisingly large number. When this background loss is introduced into the simulation model, we obtained a very good fit (lines in Fig. 5) to the experimental results. This simple experiment clearly supports the prediction that the cladding pumping scheme in conjunction with a longer signal wavelength can mitigate the detrimental effects of concentration quenching and increase the PCE. In order to realize the predicted ~77% PCE and to achieve high power without damage concerns will require use of a different low-index polymer coating (the current coatings being suitable and optimized for diode pumping at shorter wavelengths).

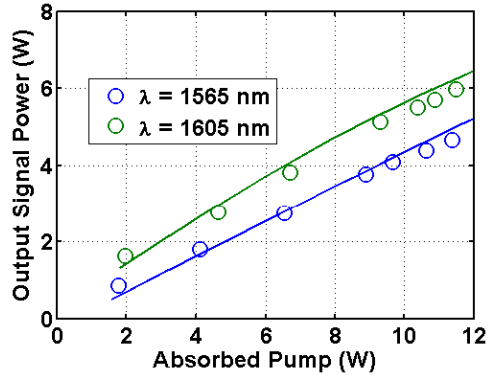


Fig. 5. The simulated (solid lines) and the experimental (circles) output signal power with respect to the absorbed pump power for the cladding pumped MOPA with input signals of 0.61 W at 1565 nm and 1605 nm.

#### 4. Conclusions

In conclusion, a highly efficient (~80%), high power (18.45 W) in-band core pumped, all-fiber EYDF MOPA is demonstrated. To the best of our knowledge, this represents the highest power conversion efficiency achieved from a “multi-watt” fiber amplifier at 1.5  $\mu\text{m}$ . We have identified through the fitting of the experimental results that concentration quenching can represent a major limiting factor in achieving highly efficient, high power, in-band pumped EDFAs. Through the use of numerical modelling, we have concluded that a backward, in-band cladding pumping with a signal wavelength at ~1605 nm should be employed not only to scale up the output power to the kW regime but also to mitigate the effect of concentration quenching. We have also validated our simulation results with a simple cladding pumped experiment. Based on our simulations and experiments, we predict that a ~77% power conversion efficiency with high output power is feasible providing the background loss suffered by the cladding guided 1535 nm pump can be reduced. This should open up the possibility for kW-class fiber lasers at 1.55  $\mu\text{m}$  once high-brightness multimode pumps at 153x nm become commercially available.