Structural Detuning of Pump Absorption Rate in Doped Fiber for the Enhancement of Power Conversion Efficiency

Hansuek Lee, Choong Hee Lee, Wonsub Choi, and Namkyoo Park
Optical Communication Systems Laboratory, School of Electrical Engineering and Computer Science, Seoul National University
Phone: +82-2-872-3577, Fax: +82-2-885-5284, E-mail: nkpark@plaza.snu.ac.kr

Abstract: We propose a novel doped fiber structure along with its design criteria, for the enhancement of power conversion efficiency in L-band Erbium Doped Fiber Amplifier. With proper adjustments on doping profiles for the reduction of pump absorption rate, it becomes possible to optimize pump evolution map inside the doped fiber to get better power efficiency, while suppressing the development of pump-depleting, detrimental ASE. Exemplary analysis shows significant enhancement in the saturation output power of more than 2.0dB, when compared to conventional doping profiles.

©2003 Optical Society of America.
OCIS codes: (060.2410) Fibers, erbium; (060.2320) Fiber optics amplifiers and oscillators

I. Introduction

With the proved potential of doubling the current transmission gain bandwidth, long-wavelength band erbium-doped fiber amplifier (L-band EDFA) now became a tempting option for aggressive system integrators. Still, have been studied in the past, the L-band EDFA suffers from a well-recognized drawback in its power conversion efficiency (PCE), which is much lower in its value when compared to its hybrid, the C-band EDFA. Briefly stated, this problem stems from the relatively faster absorption rate of pump wave (more significantly for 980nm pump) in the L-band EDFA, and resulting strong development of C-band amplified spontaneous emission (ASE) – which waste the pump photons those otherwise could have been used for the amplification of L-band signal. To achieve a sound implementation of power-efficient L-band EDFA in the network, there have been various efforts to find a way to get around this problem, either by suppressing / reusing backward ASE [1], or injecting a seed, ASE suppressing signal in the C-band [2],[3]. Another approach, different in its nature from those mentioned above, has been sought with the introduction of wavelength-detuned pumping sources [4],[5]. By utilizing reduced pump absorption cross-section at detuned pump wavelengths, suppression of pump-consuming backward ASE power and achievement of higher PCE has been demonstrated without much adaptation in the amplifier structure which was necessary (additional source, extra WDM components, etc.) in prior arts [1-3]. Smart in its principle, still, securing a different set of special-order wavelength inventory for the highly expensive pump laser diode (LD), different from the C-band application would result in the increase for the amplification cost of L-band EDFA, and thus affect the successful deployment of L-band amplifier. In this report, we show that it is possible to transfer the effective but costly approach of wavelength detuned-pumping, to the structural domain of the doped fiber - thus at much reduced final cost - while achieving the same PCE enhancement effect, further also with better signal saturation power characteristics. Implementation example with optimized doping structure shows the enhancement of PCE in L-band EDFA, for more than 2dB at 980nm pump wavelength and 0.38dB with 1480nm pump LD, with negligible penalties in the noise figure.

![Fig. 1(a) Doping profile of Type C / L EDF](image1)

![Fig. 1(b) Normalized mode envelop profiles](image2)

Table 1. EDF parameters used in the study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Radius</td>
<td>1.16 µm</td>
</tr>
<tr>
<td>Scattering capture fraction</td>
<td>0.0025</td>
</tr>
<tr>
<td>Cutoff wavelength (λc)</td>
<td>876 nm</td>
</tr>
<tr>
<td>Doping Concentration (m⁻³)</td>
<td>6.1e²⁴ m⁻³</td>
</tr>
<tr>
<td>Background Loss 1550 nm</td>
<td>3.86 dB/km</td>
</tr>
<tr>
<td>Background Loss of 980nm</td>
<td>10 dB/km</td>
</tr>
<tr>
<td>Pairing Percentage</td>
<td>1 %</td>
</tr>
<tr>
<td>Peak Absorption CrossSection</td>
<td>8.15e⁻²⁴ cm⁻³</td>
</tr>
<tr>
<td>980nm Absorption CrossSection</td>
<td>3.17e⁻²⁵ cm⁻³</td>
</tr>
<tr>
<td>1480nm Absorption CrossSection</td>
<td>3.42e⁻²⁵ cm⁻³</td>
</tr>
</tbody>
</table>
II. Principle

Acknowledging that the widely adopted EDF structure in C-band has the partial, confined doping area within the core (for example, type C fiber in Fig. 1(a)), we begin with discussions on the optimal doping structure of C-band EDF. As formerly addressed [6], by selectively doping those to-be excited erbium ions only at those regions where the pump power is sufficiently intense (a subset of core), those higher inversion level (>60%) required for the efficient C-band amplification can be achieved. Seems natural for the C-band, however, this approach needs to be modified for L-band EDFA, which requires much lower inversion level of 30–40%. Considering the current resolution for achieving lower average inversion for L-band amplifier - using longer lengths of doped fiber - the amplifier becomes to have fiber regions of low-inversion states where the detrimental ASE starts to develop, and regions of extremely high-inversion states where the C-band ASE amplification dominates. To avoid this problem, the formerly proposed pump-detuning method utilize wavelength-dependent, lower pump absorption coefficient to deliver pump power deeper into the fiber, and thus to eliminate these regions of extreme low / high-inversion level and to expand those useful L-band amplification regions.

Based on this observation, we tested one of the simplest possible EDF structures (Fig. 1(a), type L), which could provide equivalent effect on the inversion distribution inside the amplifier. With the annular doping structure, the pump wave becomes to experience relatively higher reduction in its absorption rate than signal waves, from the wavelength-dependent field distribution of the fiber (Fig. 1(b)). Fiber parameters from those conventional, commercial EDF (Table 1) have been used to calculate exact solutions of Bessel functions in order to get those precise radial distributions of pump/signal waves, and to be applied for the full numerical analysis of the EDFA. The accuracy of the simulator also has been tested in intensive manner over most of the operation conditions before the following main analysis, against other commercial, manufacturer-supplied programs, and experimental results [7].

![Fig.2](image-url) (a) EDFA output power as a function of normalized outer / inner doping radius (forward, 980nm single stage pump) (b) Pump propagation and inversion distribution as a function of normalized fiber length for Type C / L EDFs

III. Simulation results and discussion

For the sample analysis, we assumed a forward-pumped, single stage EDFA with the input signal / pump power at 0dBm (1585nm), and 100mW (both for 980nm or 1480nm) respectively. Output power and NF under various EDF structures then have been obtained at the optimal length of EDF where we achieved a maximum PCE. Fig. 2(a) shows the variation of gain with various outer / inner normalized doping radius \((R_{out} = r_{out} / r_c\) and \(R_{in} = r_{in} / r_c\), respectively. refer figure 1(a)). In this figure, \(R_{in} = 0\) line corresponds to the case of type C EDF (with increasing normalized-doping-radius), and other lines represent type L EDFs. As can be seen from the figure, it was possible to observe the enhancement of PCE as we increase the hole radius \((R_{in})\), until the radius of the hole reaches about to that of the core size. The other observation can be made is the proportional increase of the PCE to the doping area, at fixed hole radius. At the optimum design point \((R_{out}=2.2, R_{in} =1.0)\), the observed PCE enhancement was greater than 2.0dB (for 980nm pumping. 0.38dB for 1480nm pumping) when compared to that of commercial EDF (Type C, \(R_{out}=0.5, R_{in} =0)\), and the required EDF lengths for each case were 21m, and 41m respectively. The amount of NF degradation for the EDF at this optimum PCE design stayed well below 0.32dB and –0.07dB respectively, depending on the pump wavelengths (980nm, 1480nm).
Fig. 2 (b) also illustrate the pump power evolution and inversion distribution for type L (optimal design) and type C (commercial) EDFTs. As explained before, strong absorption of the pump power and higher inversion level for the type C EDF can be observed, especially at the pumping end where a significant development of backward ASE occur. In contrast, the overall reduction in the pump power depletion rate / inversion levels for annular-doped EDF was evident, which enables the higher efficiency of type L EDF in the L-band amplification. As additional measures of the power efficiency, we plotted in Fig. 3 (a) and (b) the amount of backward ASE power ratio (backward ASE power / output signal power) and wasted pump power ratio (unabsorbed pump power / output signal power) at various outer / inner normalized doping radius. As we increase the hole radius and doping area, again the suppression of backward ASE power and increase of wasted pump power was evident. To conclude, these graphs explain the existence of maximum-efficiency doping profile, determined from the trade-offs between the ASE suppression and wasted pump power depending on the signal / pump absorption rate in a specific design.

![Figure 3](image)

**IV. Conclusion**

To summarize, we proposed a novel structural detuning technique for the pump absorption rate, for the purpose of power conversion efficiency enhancement of L-band EDFA. Result shows that properly designed, annular-doped EDF could increase the PCE over 2dB when compared to conventional structure, without significant noise figure degradation. We also analyzed and explained the internal dynamics of proposed structure, in terms of the inversion map. Application to other types of rare-earth doped fiber with low average inversion level should be straightforward.

**References**


