Characterization of Erbium Ytterbium Co-Doped Waveguide Amplifier (EYDWA) Utilizing Co/Counter Propagating Pumping Configurations

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ABSTRACT

In this paper, EYDWA (erbium ytterbium doped waveguide amplifier) is characterized for a wavelength division multiplexed (WDM) system operating in C+L bands with channels being spaced at 0.4 nm interval. In order to analyze the gain characteristic of EYDWA, two pumping configurations: co-propagating and counter propagating have been used. The system is analyzed on the basis of gain and noise figure at different pumping powers in wavelength range of 1540 nm to 1579.6 nm and with pumping wavelength of 970 nm. The waveguide parameters (such as doping concentration, waveguide length) and pump power are optimized in order to obtain overall enhanced gain spectra in this paper and some useful results are obtained by employing two pumping configurations i.e. counter and co-propagating pumping.

Keywords-- WDM, EYDWA, Gain, Noise Figure

I. INTRODUCTION

The recently improved performance of the available optical gain of optical waveguide amplifiers has attracted more and more interest in this research area. These integrated devices offer the prospect of combining passive and active components on the same substrate while producing compact and robust devices at lower cost than commercially available fiber-based counterpart. However, the way to implement all-optical network relies on the control of gain variation of amplifiers which is sensitive to total input power variation. Several works have been devoted to stabilize optical amplifier gain by electronic and optical means [1-8]. However, a solution for extreme operation conditions such as to achieve large gain flatness among integrated dense wavelength division multiplexed (DWDM) channels with waveguide amplifiers at reduced channel spacing (0.2 nm) is still to be solved.

Jiang et al., (2004) solved the rate and evolution equations which are based on the combined model of EDWA with enhance erbium ion concentration. The dependence of the gain on EDWA parameters (such as pumping power, erbium ion concentration, and waveguide length) has also been checked. For better performance the optimization has been done and it was reported that with the optimized parameters (such as pump wavelength: 980 nm laser, pumping power: 150 mW, and waveguide length: 15 cm, and erbium doping concentration: $6 \times 10^{26}$ m$^{-3}$ the gain may reach 35 dB [9].

Etnser et al., (2005) realized an optical gain clamped-erbium doped waveguide amplifier (OGC-EDWA) and further they compared the performance of OGC-EDWA with EDFA. The EDWA presented the better performance over EDFA in order of reducing maximum overshoot during transients. As the EDFA needed higher extra pump power for long haul optical communication, the OGC-EDWA require lower extra power and therefore, the cost will be strongly reduced. As compared to other conventional doped fiber amplifier, EDWAs has an easy mass production potentiality at low cost and smaller footprint. Further enhance its suitability for metro applications [10].

Wang et al., (2009) proposed a technique in which performance is measured in terms of gain for phosphate glass Er3+ – Yb3+-co-doped waveguide amplifiers and observed effects of pumped styles on power conversion efficiency. He works at the pump wavelength 980 nm, signal wavelength 1550 nm and at very low ion concentration i.e. Er3+ (1.0 x 10$^{25}$m$^{-3}$), Yb3+ (2.0 x 10$^{27}$ m$^{-3}$) [11].

Yeh et al., (2009) proposed two erbium fiber amplifier modules to retrieve gain-flattened and gain-claimed functions simultaneously. Firstly, they characterized the proposed gain-flattened erbium fiber amplifier module using two-stage EDWA and EDFA in serial and further confirmed it into system level. They proposed two models for gain flatness and gain clamping. In first scheme only gain flatness has been investigated and
achieved the maximum gain variation of 2.5 dB. It was observed that, over the effective range of wavelength starting from 1528 nm to 1562 nm, the entire gains are above 35 dB. In the second scheme, by optical feedback method in the proposed fiber amplifier, they achieved GF and GC efficiencies simultaneously. Thus, the maximum gain variations of ± 0.8 and ± 1.8 dB can be obtained in the operating range from 1530 to 1564 nm, when input powers are fixed to -16 and -40dBm, respectively [12].

Singh and Kaler, (2014) proposed split-band mixture waveguide amplifier (HWA) is proposed utilizing parallel design of Er-doped waveguide amplifier (EDWA) and Er-Yb co-doped waveguide amplifier (EYDWA) for C+L-band dense wavelength division multiplexed system at 0.2 nm interval. This HWA assumes a part to help the DWDM signals and giving a larger gain while keeping the little power/gain variations over effective gain bandwidth product. With the proposed amplifier, the gain and power variation is diminished from 7.2 to 3.1 dB without utilizing any exorbitant gain clamping techniques. Further, the effect of different parameters of EDWA/EYDWA has been examined and execution has been assessed in the term of optical power [13].

As we observed that above techniques are restricted to very low ion concentration and also very less work had been done on gain spectra optimization in C+L band employing erbium ytterbium waveguide amplifier. So, in this article, we have characterized an erbium ytterbium doped waveguide amplifier by varying its structural parameters (such as erbium ion concentration and ytterbium ion concentration) and pump power by utilizing counter propagating and co-

Propagating configuration. This article proceeds in fulfillment of following objectives: 1. characterize counter propagating pumped erbium ytterbium doped waveguide amplifier and then vary the various parameters (such as pump power and pump frequency) with an aim to obtain better gain and low noise figure, 2. characterize co-propagating pumped erbium ytterbium doped waveguide amplifier and then vary the various parameters (such as pump power and pump frequency) in order to obtain better gain and low noise figure.

The rest of the article is organized as follows: in section 2, characterize the counter propagating pump with the erbium ytterbium doped waveguide amplifier to achieve low noise figure and better gain and gain flatness. In section 3, characterize the co-propagating pump with the erbium ytterbium doped waveguide amplifier to attain better performance. In section 4, illustrates results and discussion for erbium ytterbium doped waveguide amplifier with counter and co-propagating pump. In section 5, concentrates on the conclusion made from this work.

II. SIMULATION SETUP: COUNTER-PROPAGATING PUMPED CONFIGURATION

The simulation setup deployed for the characterization of counter propagating pumped erbium ytterbium doped waveguide amplifier is displayed in Fig. 1 as follows:

As displayed in Fig.1, proposed technique, C+L band wavelengths centered at 1540 nm to 1579 nm with channel spacing 0.4nm are fed to wavelength division multiplexer (WDM), with each source transmitter emitting power of -20 dBm, and NRZ modulation type data at 10 Gbps rate. Then wavelength division multiplexer transmits these wavelengths to erbium and ytterbium doped waveguide amplifier. one pump laser is deployed in setup, feeding the EYDWA in a counter propagating manner, whose operational wavelength is varied from 975 nm to 980 nm in order to obtain the better gain flatness and low noise figure. Further power of the pump laser is also varied

![Fig.1: Simulation setup deployed for the characterization of counter propagating pumped erbium ytterbium doped waveguide amplifier (EYDWA) for channel spacing (0.4nm).](image-url)
from 10 dBm to 30 dBm to achieve better results. After amplification, various wavelength signals are then de-multiplexed using optical DEMUX and are then fed to respective receiver sections (RX) comprising of combination of following elements: PN diode, low-pass filter etc.

### III. SIMULATION SETUP: CO-PROPAGATING PUMPED CONFIGURATION

The simulation setup deployed for the characterization of counter-propagating pumped erbium ytterbium doped waveguide amplifier is displayed in Fig. 2 as follows:

As appeared in Fig. 2, WDM multiplexer is used to transmit 100 channels (1540 nm to 1579 nm with channel spacing 0.4 nm) and each laser emits a light signal with -20 dBm of power, which is modulated with NRZ data at 10 Gbps rate. Another pump laser is used, centered at 970 nm is fed into EYDWA by co-propagating manner. Both C+L wavelengths and pump laser combined together in EYDWA. Further EYDWA gives output to de-multiplexer, where all these outputs de-multiplexes and fed to receiver section for detection.

### IV. RESULTS AND DISCUSSIONS

As the erbium ytterbium doped waveguide amplifier (EYDWA) is placed in the system with reduced channel spacing, the gain flattening and noise figure is obtained for each channel. To illustrate the performance of erbium ytterbium doped waveguide amplifier to achieve better gain, various parameters are varied (such as pump frequency, pump power, erbium doping concentration and ytterbium doping concentration).

#### 4.1. Results for Counter Propagating Configurations

It can be noticed from Fig. 3-6 that at fixed pump frequency i.e. 970 nm and fixed waveguide length (0.02778 m), when we increase the concentration from \(\text{Er}=4\times10^{26}\) to \(7\times10^{27}\) of erbium and \(\text{Yb}=7\times10^{27}\) to \(10\times10^{27}\) of ytterbium, then the gain is increasing. Further, it has been observed that when pump power is incremented from 10 to 30 dBm, the performance in terms of overall gain enhances. Additionally, Peak gain obtained for various cases of Er and Yb concentrations in counter pumped configuration are presented in Table 1.
Figure 4: Gain spectrum of EYDW A for Er = 5 x 10^{-26} m^{-3}, Yb = 8 x 10^{-27} m^{-3} in the case of counter propagating configuration

Figure 5: Gain spectrum of EYDW A for Er = 6 x 10^{-26} m^{-3}, Yb = 9 x 10^{-27} m^{-3} in the case of counter propagating configuration

Figure 6: Gain spectrum of EYDW A for Er = 7 x 10^{-26} m^{-3}, Yb = 10 x 10^{-27} m^{-3} in the case of counter propagating configuration

Table 1: Peak Gain of proposed EYDWA in counter propagating configuration at various erbium and ytterbium concentrations

<table>
<thead>
<tr>
<th>Erbium Ion Concentration in EYDWA [m^{-3}]</th>
<th>Ytterbium Ion Concentration In EYDWA [m^{-3}]</th>
<th>Gain in Counter Propagating [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 x 10^{-26}</td>
<td>7 x 10^{-27}</td>
<td>8.994</td>
</tr>
<tr>
<td>5 x 10^{-26}</td>
<td>8 x 10^{-27}</td>
<td>11.347</td>
</tr>
<tr>
<td>6 x 10^{-26}</td>
<td>9 x 10^{-27}</td>
<td>12.642</td>
</tr>
<tr>
<td>7 x 10^{-26}</td>
<td>10 x 10^{-27}</td>
<td>13.236</td>
</tr>
</tbody>
</table>
Further, it can also be noticed from Fig. 7-10, that noise figure (NF) also depends on concentration of erbium and ytterbium and pump power. As the concentration of erbium and ytterbium is increased, NF decrements and also by increasing the pump power, NF decreases further. It can be observed from Fig. 7-10 that lowest NF for all Er and Yb concentrations is obtained when pump power = 30 dB is used.

Figure 7: NF spectrum of EYDW Afor Er=4x10^{26} m^{-3}, Yb=7x10^{27} m^{-3} in the case of counter propagating configuration

Figure 8: NF spectrum of EYDW Afor Er=5x10^{26} m^{-3}, Yb=8x10^{27} m^{-3} in the case of counter propagating configuration

Figure 9: NF spectrum of EYDW Afor Er=6x10^{26} m^{-3}, Yb=9x10^{27} m^{-3} in the case of counter propagating configuration
4.2 Results for Co-Propagating Method

In Fig. 11-14 the variations in gain spectrum of EYDWA for various concentrations of Er and Yb ions in co-propagating pumping configuration considering fixed waveguide length (0.02778 m) and fixed pump frequency i.e. 970nm have been presented. It can be noticed from Fig. 11-14 that when we increase the concentration from Er=4x10^{26} to 7x10^{26} of erbium and Yb =7x10^{27} to 10x10^{27} of ytterbium, then the gain is increasing. We further noticed that when the pump power is incremented from 10 towards 30dBm, the performance in terms of overall gain enhances. Additionally, Peak gain obtained for various cases of Er and Yb concentrations in counter pumped configuration are presented in Table 2.

Figure 10: NF spectrum of EYDW A for Er=7x10^{26} m^{-3}, Yb=10x10^{27} m^{-3} in the case of counter propagating configuration

Figure 11: Gain spectrum of EYDWA for Er=4x10^{26} m^{-3}, Yb=7x10^{27} m^{-3} in the case of co-propagating configuration

Figure 12: Gain spectrum of EYDWA for Er=5x10^{26} m^{-3}, Yb=8x10^{27} m^{-3} in the case of co-propagating configuration
Figure 13: Gain spectrum of EYDWA for Er=$6 \times 10^{26}$ m$^{-3}$, Yb=$9 \times 10^{27}$ m$^{-3}$ in the case of co-propagating configuration

Figure 14: Gain spectrum of EYDWA for Er=$7 \times 10^{26}$ m$^{-3}$, Yb=$10 \times 10^{27}$ m$^{-3}$ in the case of co-propagating configuration

Table 2: Peak Gain of proposed EYDWA in co-propagating configuration at various erbium and ytterbium concentrations

<table>
<thead>
<tr>
<th>Erbium Ion Concentration in EYDWA [m$^{-3}$]</th>
<th>Ytterbium Ion Concentration in EYDWA [m$^{-3}$]</th>
<th>Gain in Co-propagating [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4 \times 10^{26}$</td>
<td>$7 \times 10^{27}$</td>
<td>8.995</td>
</tr>
<tr>
<td>$5 \times 10^{26}$</td>
<td>$8 \times 10^{27}$</td>
<td>11.349</td>
</tr>
<tr>
<td>$6 \times 10^{26}$</td>
<td>$9 \times 10^{27}$</td>
<td>12.743</td>
</tr>
<tr>
<td>$7 \times 10^{26}$</td>
<td>$10 \times 10^{27}$</td>
<td>13.336</td>
</tr>
</tbody>
</table>

Moreover, it can be observed from Fig. 15-18 that NF also depends upon pump power and concentration of erbium and ytterbium. NF is decrementing, as the concentration of erbium and ytterbium is increased but with increase in pump power, NF decreases further.

Figure 15: NF spectrum of EYDWA for Er=$4 \times 10^{26}$ m$^{-3}$, Yb=$7 \times 10^{27}$ m$^{-3}$ in the case of co-propagating configuration
Further, it can be noticed from Table 1 & 2 that \( E_{r} = 7 \times 10^{26} \text{m}^{-3} \) and \( Y_{b} = 10 \times 10^{27} \text{m}^{-3} \) ion concentrations yields best results in terms of overall gain spectrum and NF by employing a 0.02778 m long EYDWA which is pumped with 30 dBm power at fixed pump frequency of 970nm. On further, studying Table 1 & 2 and Fig. 3-18, it can be observed that very marginal improvement is obtained in the case of co-propagating pumped case, as compared to counter-propagating pumped configuration.

Further, in order to illustrate, the level of development achieved using the proposed hybrid TDFA-RAMAN amplifier, a comparison with earlier reported amplification schemes is presented in Table 3 as follows:
Table 3: Comparison of proposed EYDWA amplifier with earlier reported amplification strategies

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Erbium Concentration</td>
<td>1.0 x 10^{-6} m³</td>
<td>1.0 x 10^{-6} m³</td>
<td>2 x 10^{-6} m³</td>
<td>2 x 10^{-6} m³</td>
</tr>
<tr>
<td></td>
<td>Ytterbium Concentration</td>
<td>Nil</td>
<td>2.0 x 10^{-7} m³</td>
<td>Nil</td>
<td>1 x 10^{-7} m³</td>
</tr>
<tr>
<td>Signal Wavelength</td>
<td>1550 nm</td>
<td>1550 nm</td>
<td>1540 nm</td>
<td>1540 nm</td>
<td></td>
</tr>
<tr>
<td>Pump Wavelength</td>
<td>980 nm</td>
<td>980 nm</td>
<td>980 nm</td>
<td>970 nm</td>
<td></td>
</tr>
<tr>
<td>Waveguide Length</td>
<td>15 cm</td>
<td>3 cm</td>
<td>0.07 m</td>
<td>0.09 m</td>
<td>0.02778 m</td>
</tr>
<tr>
<td>Pump Power</td>
<td>150 mW or 20 dBm</td>
<td>100 mW or 20 dBm</td>
<td>300 mW</td>
<td>30 dBm</td>
<td></td>
</tr>
<tr>
<td>Gain</td>
<td>35 dB</td>
<td>13.30 dB</td>
<td>14 dB</td>
<td>13.33 dB</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>Erbium</td>
<td>Er^{3+} and Yb^{3+}</td>
<td>Hybrid waveguide Amplifier</td>
<td>Er^{3+} and Yb^{3+}</td>
<td></td>
</tr>
</tbody>
</table>

V. CONCLUSION

In this work, the gain and NF characteristics of EYDWA waveguide amplifier have been enhanced in the scenario of co-propagating and counter propagating configurations by optimizing following parameters: Er and Yb doping concentration and pumping power. For erbium-doped glass planar waveguide amplifier pumped by 970 nm laser, the optimal parameters are: pumping power is near 1500 mW or 30 dBm, and waveguide length is 0.02778 m, and erbium doping concentration is 7 x 10^{-6} m³ and ytterbium doping concentration is 10x10^{-7} m³. The waveguide amplifier with these optimal parameters has the capability to exhibit Gain = 13 db in co-propagating as well counter propagating configurations.

REFERENCES

[11] Yu-Hai Wang, Chun-Sheng Ma, De-Lu Li and Da-Ming Zhang, "Effects of pumped styles on power conversion efficiency and gain characteristics of phosphate glass Er^{3+} – Yb^{3+}-co-doped waveguide
