Resonant pumped erbium-doped waveguide lasers using distributed Bragg reflector cavities

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This Letter reports on an optical pumping scheme, termed resonant pumping, for an erbium-doped distributed feedback (DFB) waveguide laser. The scheme uses two mirrors on either side of the DFB laser, forming a pump cavity that recirculates the unabsorbed pump light. Symmetric distributed Bragg reflectors are used as the mirrors and are designed by matching the external and internal quality factors of the cavity. Experimental demonstration shows lasing at an optical communication wavelength of around 1560 nm and an improvement of 1.8 times in the lasing efficiency, when the DFB laser is pumped on-resonance. © 2016 Optical Society of America

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Erbium-doped waveguide lasers [1] present several advantages for laser integration on a silicon photonics platform [2]. Such lasers permit monolithic integration [3], are compatible with low-cost complementary metal-oxide-semiconductor (CMOS) processes [4], and have been shown to achieve high-performance ultranarrow linewidths [5]. One underlying issue, however, is that, unlike fiber lasers [6], erbium-doped waveguide lasers are typically limited in pump absorption lengths, particularly because of their small footprint size. To allow sufficiently short pump absorption lengths, erbium-doped waveguide lasers are doped with higher levels of erbium concentrations [7], which can, however, lead to increase in energy transfer upconversions [8] and concentration-quenching effects [9]. Alternatively, pump recirculating schemes can be used to effectively increase the number of pump passes over a short length. For instance, a highly reflective mirror can be placed at the end of an erbium-doped waveguide laser and reflect the unabsorbed pump back into the laser [10]. This permits two pump passes but prevents dual-sided pumping, from the side of the highly reflective mirror. To allow multiple pump passes, an additional reflective mirror can be placed at the laser input, forming a pump cavity. Such a scheme has been discussed in [11], for erbium-doped fiber lasers.

In this Letter, we report on a multiple-pump-pass scheme, termed resonant pumping, for an erbium-doped distributed feedback (DFB) waveguide laser. By placing reflective mirrors on either side of the DFB laser, a pump cavity is formed where multiple pump passes can be sustained at resonant frequencies. We use symmetric distributed Bragg reflectors (DBRs) as reflective mirrors and an input pump diode with an optical wavelength matching a cavity resonance, at 976 nm. We demonstrate lasing at an optical communication wavelength of around 1560 nm and show that when pumped on-resonance, a 1.8 times improved lasing efficiency can be achieved.

In the integrated DFB laser and DBR pump cavity design, silicon nitride ($\text{SiN}_x$) layers are used to define the waveguide and grating features [4]. A layer of erbium-doped aluminum oxide ($\text{Al}_2\text{O}_3$:$\text{Er}^{3+}$) is deposited on top as a final process step, for producing gain. Figure 1(a) shows the top view ($x$–$z$ plane) of the $\text{SiN}_x$ layers that define the DFB laser and DBR pump cavity. A multisegmented $\text{SiN}_x$ design is used to reduce the wavelength sensitivity of the overlaps between the laser and pump optical modes [3]. It is also used to maintain a high overlap within the gain region while maintaining a thick $\text{SiN}_x$ for passive device integration [12]. The width of a single $\text{SiN}_x$ segment is 0.6 μm, while the gap between them is 0.4 μm. The DFB laser (quarter-wave phase-shifted) consists of perturbations with a period of 0.487 μm, formed by placing stubs 0.5 μm away from the first and last $\text{SiN}_x$ layers. The stub width is 0.4 μm. The DBR pump cavity is realized by placing DBR gratings on either side of the DFB laser. The grating perturbations have a period of 0.298 μm and are formed by etching out 0.1 μm from both sides of the center $\text{SiN}_x$ layer. The center $\text{SiN}_x$ has a width $W_z$ of 0.458 μm. The lengths of the DFB grating and DFB laser are 350 μm and 2 cm, respectively. Some length exists between the ends of the DFB laser and the DBR gratings, and, hence, the total length of the DFB pump cavity is 2.11 cm. The integrated DFB laser and DBR pump cavity were fabricated in a standard CMOS foundry, with a fabrication process similar to that in [4].
cross-sectional view ($x$–$y$ plane) is shown in Fig. 1(b). The thickness of the SiNx layers and the SiO$_2$ gap are both 0.2 μm. The thickness of the Al$_2$O$_3$:Er$^{3+}$ film is 1.26 μm, as measured using the prism coupling method [13]. A layer of index-matching fluid (SiO$_2$, $n = 1.45$) is placed on top of the laser during measurement, as will be discussed, subsequently. The intensity distributions of the fundamental TE mode for both the pump (976 nm) and laser (1550 nm) modes are shown in Fig. 1(c). Good laser–pump mode overlaps can be achieved owing to their similar intensity distributions.

The pump cavity DFB grating design was based on matching the grating external quality factor ($Q$) to the internal $Q$ of the pump cavity, for critical coupling [14]. The internal $Q$ was calculated from the total pump loss that consists of both the background loss in the pump cavity, for critical coupling [14]. The internal $Q$ was calculated using the following relation [16]:

$$Q = \frac{\omega}{\log\left(\frac{c}{2\pi f}\right)},$$

where $v$, is the phase velocity, $L$ is the length of the cavity (2.11 cm), and $R$ is the grating reflectivity, which was determined by the coupled-mode theory [17]. We assume symmetric gratings on either end of the cavity. Figure 2 plots the DBR reflectivity for different center widths $W_c$, on the left $y$ axis. The corresponding external $Q$s are plotted on the right $y$ axis (in log scale). From the plot in Fig. 2, we can deduce that the external $Q$ matches the internal $Q$ of 5.66 (plotted as a dashed–dotted line), when the center width $W_c$ is about 0.47 μm. Following the grating design, transfer matrix calculations were performed to determine the amount of field enhancement produced by the cavity, at resonance. The amount of enhancement was calculated as the ratio between the field intensity in the cavity and the intensity in a single-pass case. This can be expressed at various points along the cavity as

$$\zeta(z) = \frac{|E_f(z) + E_r(z)|^2}{|E_f(z)|^2},$$

where $E_f(z)$ and $E_r(z)$ are the forward and backward propagating electric fields along the cavity, respectively, and $E_f(z)$ is just the forward electric field in the single-pass case. A standing wave is formed in the cavity, with periodic maximum and minimum electric-field fluctuations. Figure 3(a) shows a contour plot of the maximum field enhancements for various cavity lengths and erbium doping concentrations. The maximum value was taken at the center of the cavity, where much of the DFB laser intensity exists. Note that these calculations assumed $Q$-matched grating reflectivities. Figure 3(b) further shows a contour plot of the average field enhancements, averaged throughout the pump cavity. It can be easily deduced that the enhancement increases as the cavity length shortens or the erbium concentration reduces. For a cavity length of 2.11 cm and an erbium doping concentration of $1.5 \times 10^{20}$ ions/cm$^3$, the maximum and average field intensity enhancements are 2.7 and 1.5, respectively. We hence expect laser performance improvements, within this range, when pumped on-resonance.

To experimentally confirm the lasing performance of the same DFB laser, under both on- and off-resonance pumping, we consider shifting the pump grating response by applying a layer of index-matching fluid on the laser. The input pump
diode center wavelength is kept fixed at around 976.2 nm. Several other methods were considered such as heating/cooling the laser to shift the grating response and tuning the pump diode, instead, while keeping the grating response fixed. In the former approach, the amount of heating/cooling was not sufficient to tune the broad grating response of 1.3 nm. Furthermore, condensation was observed while cooling, which caused difficulty in pump coupling. In the latter approach, the tunability of a narrow-linewidth laser diode is relatively limited (around 0.1 nm) and tuning the pump wavelength can change the absorption cross sections. Applying an index-matching fluid on the laser can be an effective way to sufficiently tune the grating response (around 1 nm), although care should be taken to not change the laser cavity characteristics drastically. Table 1 shows the confinement factor ($\Gamma$) and grating strengths ($\kappa$), with and without the index-matching fluid on the laser cavity, at both the pump and signal wavelengths. The difference in confinement factor, between the cases of with and without the index-matching fluid, is small and not very significant, at both pump and signal wavelengths. The grating strength at the pump wavelength is almost the same, and, hence, any grating loss would be similar. The grating strength at the signal wavelength does reduce with the index-matching fluid. This would make it slightly harder to lase. The reason for a relatively similar laser cavity, between the cases of with and without the index-matching fluid, is because of a thick $\text{Al}_2\text{O}_3:\text{Er}^{3+}$ film.

Table 1. Laser Cavity Characteristics With and Without Index-Matching Fluid on Top

<table>
<thead>
<tr>
<th></th>
<th>976$^\Gamma$</th>
<th>1550$^\Gamma$</th>
<th>976$^\kappa$</th>
<th>1550$^\kappa$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without index matching</td>
<td>0.73</td>
<td>0.846</td>
<td>143.8/m</td>
<td>568.7/m</td>
</tr>
<tr>
<td>With index matching</td>
<td>0.76</td>
<td>0.850</td>
<td>144.5/m</td>
<td>502.6/m</td>
</tr>
</tbody>
</table>

Figure 4(a) shows the measured reflection (broad DBR grating response), with and without the index-matching fluid. With the index-matching fluid, the response shifts toward the input pump center wavelength. The grating bandwidth is 1.3 nm. Figure 4(b) shows a zoomed-in view of the measured reflection around the pump center wavelength, where very fine Fabry–Perot cavity resonances can be seen. The free-spectral range (FSR) of these resonances is 0.013 nm, which corresponds to the theoretical FSR of a 2.11 cm long cavity.

Figure 5 is the experimental setup used to measure the laser power from the integrated DFB laser and DBR pump cavity. An Innovative Photonics Solutions narrow-linewidth 976 nm pump diode (<1 MHz) is coupled onto the chip through a directly spliced isolator, a 980 nm polarization controller, and a 980/1550 nm wavelength-division multiplexer (WDM). Laser output is collected from the 1550 nm outputs of both the right and left WDMs, and measured using an optical spectrum analyzer. By insertion loss measurements, we estimate coupling losses per facet of 4.2 and 5.7 dB for 976 and 1550 nm, respectively, without the index-matching fluid on the chip. The coupling losses are 3.3 and 4.5 dB for 976 and 1550 nm, respectively, with the index-matching fluid. Figure 6(a) shows the lasing spectrum when the laser is pumped on-resonance. Lasing is observed at 1563 nm. Figure 6(b) shows the on-chip laser power versus the on-chip pump power for cases when the laser is pumped on- and off-resonance. From the plot, the slope efficiencies can be estimated to be 2.2% and 1.2% with on- and off-resonance pumping, respectively. An improvement of 1.8 times is thus achieved when the laser is pumped on-resonance. This improvement falls within the predicted enhancement ranges of 1.5 and 2.7, as discussed above. The 2.2% efficiency achieved, when pumped on-resonance, is comparable to, if not better than,
The current demonstration of a resonant pumped DFB laser sets up potentially interesting works in the future. Shorter laser cavities (<1 cm), which previously suffered from low pump absorption [18], can in the future be investigated with resonant pumping, to recirculate the pump light and improve the laser performance. The benefits of reducing the laser length include a smaller footprint size, a relatively even distribution of the pump light, and easier single-longitudinal-mode lasing [18]. Figures 3(a) and 3(b) show a possible enhancement of at least 2.5 times when the cavity length is reduced to 1 cm. If the erbium concentration is further reduced to $1.0 \times 10^{20}$ ions/cm$^3$, the enhancement increases to 3.5 times. Several variations of resonantly pumped shorter laser cavities can be developed by working with varying laser lengths and erbium concentrations to achieve improved lasing performances. Similar pump cavity designs can be developed for DFB lasers pumped at 1480 nm and for DBR lasers pumped at both 980 and 1480 nm.

In summary, this Letter has demonstrated resonant pumping for an erbium-doped DFB laser. A pump cavity was formed by placing DBR gratings on either side of the DFB laser. The design of the DBR gratings was based on matching the internal and external $Q$s. Experimental measurements showed an improvement of 1.8 times in the lasing efficiency when the DFB laser was pumped on-resonance. The proposed resonant pumping scheme can be potentially useful for shorter laser cavities, which previously suffered from low pump absorption. Further efforts in designing shorter laser cavities with resonant pumping can be demonstrated in the future.

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**REFERENCES**