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Effect of pump power on the tuning range of a filterless erbium-doped fiber ring laser

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ABSTRACT In this paper, we establish the influence of pump power on the tuning characteristics of a filterless erbium-doped fiber laser, operating in the *L* band. Tunable action is achieved with the control of intra cavity loss. The explicit dependence of tunability on the average inversion levels is brought out. The shift in the lower limit of tuning range and the non-linear dependence of lasing wavelength on the intra cavity loss are analytically deduced using the gain spectra and experimentally interpreted using amplified spontaneous emission spectra. Continuous tunability is achieved with the careful control of pump power.

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1 Introduction

Erbium-doped fibers are strong candidates for the construction of tunable lasers in the *C* and *L* bands, thus leading to several applications in communication, spectroscopy and sensors [1]. Filter-less erbium-doped fiber lasers (EDFL) have attracted significant attention in the recent past. During this time, it was typical to observe lasing at wavelengths corresponding to the two main peaks of the erbium gain profile, centering at 1530 nm and 1560 nm. Tunable action with such a laser was demonstrated by changing the wavelength independent reflectivity of the output coupling mirror [2, 3]. An exhaustive theoretical model was developed to study the effect of cavity loss, erbium concentration and the fiber length on the lasing wavelength and the slope efficiency [3, 4]. It is also possible to obtain wavelength tunability by changing the cold cavity loss and the concept of 'forbidden regions' in the tuning range is reported [3]. A cw tunable laser operating in the *L* band, with bidirectional pumping of the erbium-doped fiber, was demonstrated for the first time in the wavelength range of 1587 nm to 1606 nm [5]. A single mode fiber taper was bent using a micrometer drive, which controls the cavity loss in this design. Lin et al. [6, 7] recently demonstrated a coupling ratio controlled wavelength tunable EDFL using both 980 nm and 1480 nm pumping and achieved continuous tuning from 1567 nm to 1612 nm. The influence of the magnitude of pump power on the tunability of a filterless laser has not been covered in any of the earlier works on this subject. In this paper, we demonstrate the explicit influence of pump power on the tunability of a cavity loss controlled tunable EDFL. It does not involve the use of pump diodes at multiple wavelengths. The results are analyzed using the fiber characteristics. The analysis provides a formulation to increase the extent of tuning.

2 Principle of operation

The fiber laser considered has a short length of heavily doped erbium-doped fiber (procured from M/s Fibercore) in a typical ring cavity configuration, with an isolator in the cavity to ensure unidirectional traveling wave operation [1, 8]. The schematic configuration of the ring cavity EDFL used in the experiments is shown in Fig. 1. The pump wavelength is chosen to be 980 nm, since this wavelength is reported to have the maximum influence in the fluorescence spectrum of a heavily doped fiber [9]. Wavelength division multiplexers (WDM) at either ends of the EDF are used to couple the pump power from a semiconductor laser diode into and out of the cavity. A fraction (R) of the output power from the fiber is fed back to the input through a directional coupler to complete the ring cavity structure. A variable optical attenuator (VOA) inserted in the cavity at position A of Fig. 1 introduces an additional loss α. The spectral characteristics

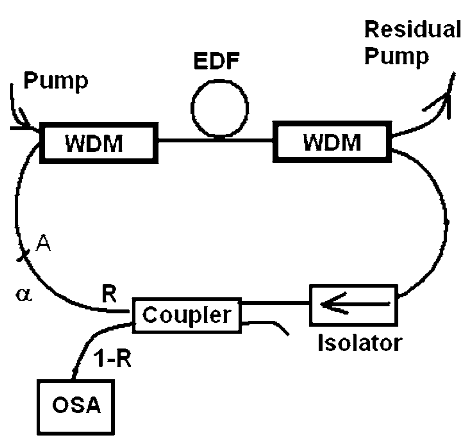

FIGURE 1 Schematic of the erbium-doped fiber ring laser. 'A' indicates the position for the inclusion of optical attenuator which introduces a loss (α)

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of the output are observed using an optical spectrum analyzer (OSA) of resolution 0.1 nm.

With the increase in length (L) of the fiber and the reflectivity (R) of the coupler, the lasing wavelength (λ_{las}) is known to shift to longer wavelengths. However, lasing occurs at shorter wavelengths when the cavity loss (α_{tot})is increased [1, 8, 10, 11]. Since λ_{las} is the one for which the cavity gain matches the total loss, a tunable laser can be designed by changing R or α. Choosing a longer L would increase the tunability, assuming that sufficient pump power is available for inversion. Maximum R into the cavity will push λ_{las} to the largest possible value to start with and hence result in an enhanced tunability. When α increases, though the power fed back to the doped fiber in a single round trip decreases, the output power at λ_{las} is not expected to be significantly different throughout the tunable range due to multiple passes within the cavity and subsequent saturation at that wavelength. Obtaining tunability by tailoring R or by changing α are conceptually the same. However, a cavity-loss-controlled tunable laser is a preferred filterless design due to the uniform output power at different wavelengths. Depending on L and R, the tunability is restricted to certain wavelength ranges, and is decided primarily by the spectroscopic nature of the fiber used [3, 12, 13].

The existing analytical models do not predict a direct dependence of the tuning characteristics on the pump power. But this dependence can be deduced in a simplistic way as follows: Any change in pump power reflects as a change in the average inversion level (d) in the fiber. Hence, the influence of pump power on tunability can be predicted qualitatively through the gain coefficient (g) calculated for different values of inversion levels for this fiber. Gain coefficient can be calculated as [14]

$$g = \Gamma_s \varrho L \left[\sigma_e(\lambda_s) \left(\frac{1+d}{2} \right) - \sigma_a(\lambda_s) \left(\frac{1-d}{2} \right) \right], \quad (1)$$

where Γ_s accounts for the transverse overlap of the signal beam with the dopant ions, while σ_e and σ_a are the emission and absorption cross sections at the signal wavelength, λ_s . In this model, the system is approximated as a two level system and the factor d is indicative of the average inversion level of the entire fiber. The spectral dependence of the emission and absorption cross sections of the fiber used for the experiment, as provided by the manufacturer, are shown in Fig. 2. Assuming the fundamental mode to be a Gaussian, we calculate Γ_s using the relation

$$\Gamma_s = 1 - \exp \left[- \left(\frac{a_0}{\omega_s} \right)^2 \right], \quad (2)$$

with a_0 being the radius up to which the core is doped with erbium. For the fiber considered, the erbium doping density has a step like distribution which is uniform throughout the core radius (a) and hence, $a_0 = a = 1.6\ \mu$m. ω_s is the mode field radius at the signal wavelength, which can be calculated using the relation [14]

$$\omega_s = \frac{a}{\sqrt{2}} \left(0.65 + \frac{1.619}{V^{1.5}} + \frac{2.879}{V^6} \right) \quad (3)$$

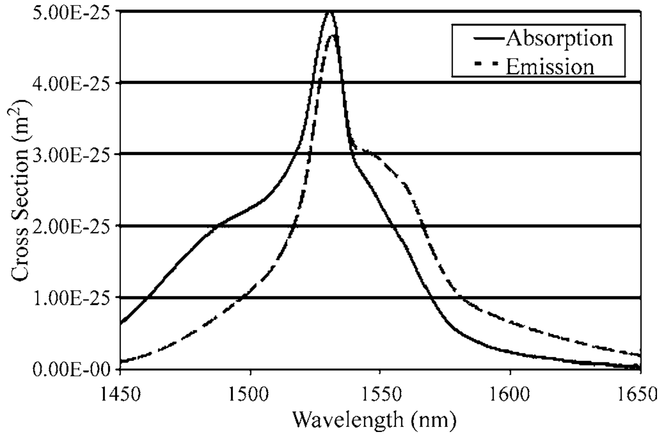

FIGURE 2 Emission and absorption cross-sections of the fiber studied

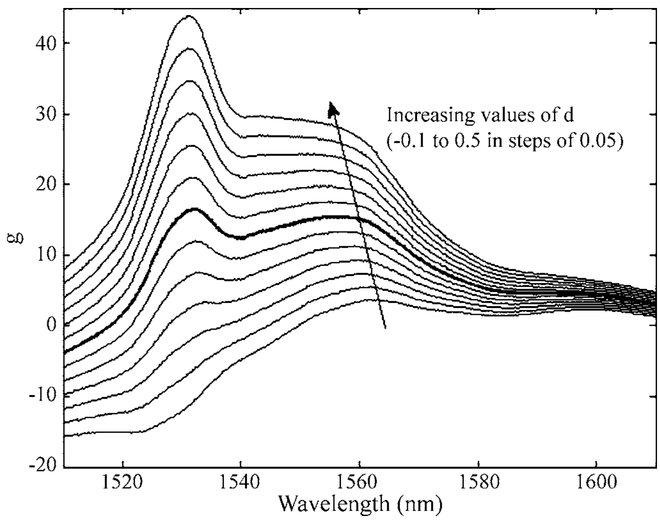

FIGURE 3 Gain coefficient at different wavelengths calculated for different values of average inversion levels in the fiber

under Gaussian approximation for the fundamental mode. In the above equation, V stands for the conventional V-parameter of the fiber for each wavelength. A numerical aperture of 0.23 is used for the calculation of the V-parameter.

Figure 3 shows a family of curves indicating g, calculated for $L = 12$ m, using (1) for the entire spectral range, at different values of d. The dopant concentration ϱ used for the calculation is 3.535×10^{25} ions/m^3. When the cavity loss increases, the gain required to compensate the loss increases. Since the effective gain is higher for shorter wavelengths up to 1530 nm, λ_{las} will shift to the shorter wavelength side with the increase in α. The gain curves are fairly flat in the L band beyond 1575 nm, making this region highly sensitive to attenuation. The non-linear nature of the gain curves predict a similar non-linear dependence of λ_{las} on α. The gain curve in the wavelength range 1558 nm to 1533 nm (read from right to left in the figure) has a decreasing trend for smaller d, and is flat at larger values of d. Hence it is practically impossible to achieve tunability in that wavelength range by merely adjusting α in the cavity. The onset of this flat region leads to a lower limit in the tunable range. This limit is found to decrease with larger inversion levels, as indicated by the arrow in Fig. 3. Hence it is expected that larger pump powers would lead to a larger tunability. It has to be noted that the gain curves shown are specific to the length of the fiber used for calculations.

3 Results and discussion

The ring cavity EDFL is constructed with all the components fusion spliced, to minimize the other losses in the cavity. The maximum pump power (P) used for the experiment is 190 mW. Wavelength tunability is studied at different values of P for $L = 12$ m and $R = 0.99$ and the results are shown in Fig. 4. λ_{las} with minimal α is 1604 nm for all the values of P used in the experiment and this is completely characteristic of ϱ, L, R and α. An increase in pump power does not change the center wavelength of lasing experimentally, since the gain curves are seen to lie very close around this λ_{las} in Fig. 3. Consequently, the variation of λ_{las} with α is also found to be similar for all values of P, for smaller values of α. As α increases, the range of wavelengths up to which the system can be tuned, is found to increase with the increase in P. The system is tunable only up to 1567.5 nm for $P = 30$ mW, while it is tunable up to 1559.5 nm for $P = 190$ mW. The decrease in the lower limit of tunable range and the corresponding increase in tunability follow the trend predicted in Sect. 2. The value of α required in the cavity to enhance the tuning range is also found to increase with P. The non-linear dependence of λ_{las} as predicted in the gain curves is also evident in the experimental results shown in Fig. 4. An excess loss of 3.8 dB shifts the lasing wavelength from 1604 nm to 1585 nm, whereas, to tune the laser from 1577 nm to 1558 nm, the excess loss introduced is about 27 dB. This is due to the linear nature of the gain curve in this latter wavelength range. The maximum tunability extends from 1559.5 nm to 1604 nm, except for a range of wavelengths (1577–1587 nm), which is not tunable at all values of P considered for this length of the fiber. It is indicated in Fig. 3 that, for lower values of d, there is a wavelength range within the L band, where the gain curve shows an inflection. This would mean that the wavelengths in this valley cannot be made to lase with the continuous change of loss in the cavity. At larger values of d, the extent of inflection is found to decrease and g is found to vary monotonously in the L band. Thus to achieve optimum tunability, the average inversion has to be maximized. This can be done by increasing the pump power for a given L. However, even for the maximum power used in the experiment, the average inversion in the fiber is not large enough to result in a monotonously decreasing trend with wavelength in the gain curve, avoiding flat regions and inflections, as required for continuous tunability.

The amplified spontaneous emission (ASE) spectrum, observed in the absence of an input signal is an experimental signature of population inversion and the gain curves at different pump power levels. In order to corroborate the above analysis, the ASE spectrum is measured at the output port of the coupler at different values of pump powers for the same length of fiber and is shown in Fig. 5a. The shift in the ASE peak to lower wavelengths with an increase in power also indicates a shift in the lower limit of tuning discussed earlier. The inflection around 1580 nm, leading to a forbidden range in tunability is also evident in the ASE spectra at all values of P.

In order to experimentally achieve a significant change in the inversion levels and a continuous tunability with the available pump power, a shorter length (4.6 m) of the same type of fiber is chosen and the ASE spectrum is studied. Figure 5b shows a comparison between the ASE spectra from two different lengths of the fiber at $P = 190$ mW. The spectral features of ASE from the 4.6 m fiber are indicative of larger values of d when compared to that of the 12 m fiber. It is inferred that the shorter length is not sufficient for the complete absorption around 1530 nm, resulting in dominant peaks around that wavelength. At larger values of pump power, the fiber connectors to the OSA, which act as mirrors of very small R, result in spurious lasing peaks around 1530 nm. These peaks are absent at smaller values of P. The shift in the lower limit of tuning range, similar to the 12 m fiber was also observed.

The tunability of the laser is studied for $L = 4.6$ m to assess the above inferences and the results are shown in Fig. 6. The system is found to be continuously tunable in the wave-

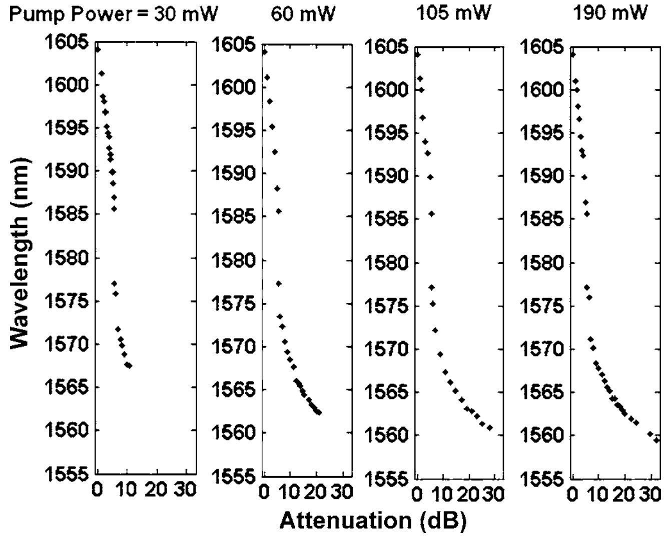

FIGURE 4 Lasing wavelength at different values of α for different pump powers with $L = 12$ m, $R = 0.99$

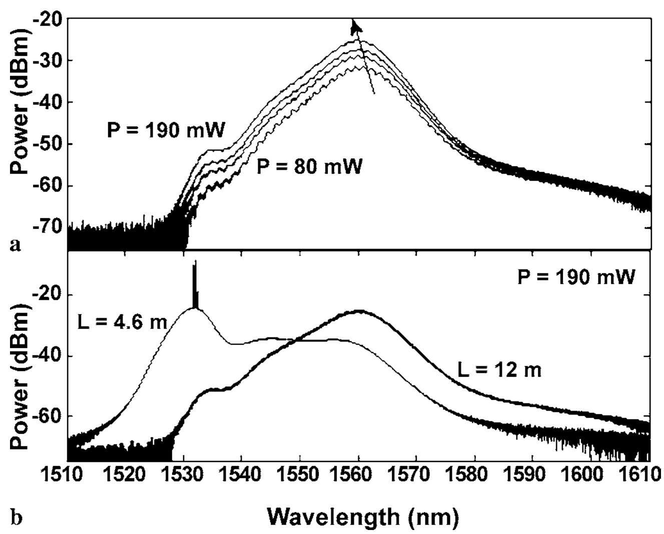

FIGURE 5 (**a**) ASE spectrum at the output coupler, with a single pass through the EDF for $L = 12$ m; (**b**) ASE spectrum for $L = 12$ m and $L = 4.6$ m at $P = 190$ mW. The wavelength scale is identical for both the plots

length range between 1557.3 nm to 1591.3 nm. At higher pump powers, the output power levels at different wavelengths are fairly uniform, with a signal to noise ratio better than 35 dB. The tunable range is found to increase with the pump power. It is interesting to note that the system is now lasing at those wavelengths which were not tunable with a 12 m fiber and the gap corresponding to the non-tunable range gets filled up at higher pump powers. Specifically, when P is increased from 105 mW to 190 mW, more wavelengths could be invoked for lasing around the 1580 nm range (encircled in Fig. 6), while the other tuning characteristics remain the same. Multiple lasing is seen at wavelengths around 1590 nm at all pump power levels, and in the range 1573–1584 nm at high power levels due to a reduced slope of the ASE curve in those regions. This can be avoided by further increasing the pump power and hence the average inversion levels in the fiber. It is also seen that λ_{las} is highly sensitive to attenuation at smaller values of α at all pump powers, for the same reason as in the case of 12 m fiber. When α is more than 20 dB, the system lases simultaneously at 1558 nm and 1532 nm at larger values of pump powers. Multiple lasing at these widely separated wavelengths is also suggested in Fig. 5 for 12 m, corresponding to larger d as shown with a bold line. Such a possibility, however, does not exist experimentally for a 12 m fiber, for the power levels considered (obvious in Fig. 5a and Fig. 4). It is also found experimentally and from the analytical calculations that it is not possible to design a tunable ring cavity EDFL in the C band due to the nature of the gain curves in that region for the pump powers considered. However, for extremely high pump powers, or shorter fiber lengths where the fiber is completely inverted, it may be possible to obtain tunability in the C band.

It is important to emphasize that the resolution of the VOA required to obtain a given resolution in the tuning range of λ_{las} is different in different wavelength ranges as inferred from the non-linear nature of the plots in Figs. 4 and 6. A finer resolution in VOA is demanded in the longer wavelength side. A simple correspondence cannot be made between the resolution of the attenuator and the resolution of tuning in the entire range of operation. The line width of the output is also found to depend on α and P, due to inhomogeneous effects and these results are discussed elsewhere [15].

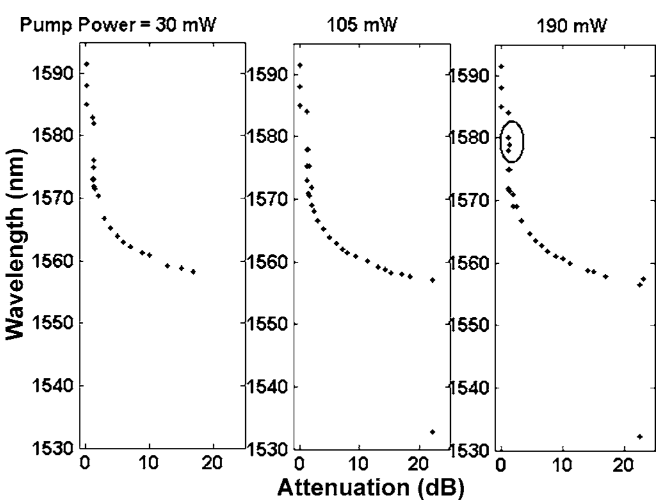

FIGURE 6 Lasing wavelength at different values of α for different pump powers with $L = 4.6$ m, $R = 0.99$

4 Conclusions

A filterless tunable erbium-doped fiber laser is studied in this work. Continuous tunability is achieved in the L band, with the change of cold cavity loss. It is found, in general, that there are certain wavelength ranges in which the system is tunable by controlling the cavity loss. It is established that continuous tunability is possible through a large wavelength range, without the use of bidirectional pumping or pumping at 1480 nm. This is made possible by carefully controlling the pump power and hence, the inversion levels in the fiber. The gain curves at different average inversion levels indicate qualitatively, the tuning characteristics of the laser. These curves can be associated with the amplified spontaneous emission spectrum in an experiment and the nature of these curves indicates the limits of tunability. It is also found that the lasing wavelength is not always a linear function of the attenuation, but largely depends on the region of operation and the pump power. In order to achieve a continuously tunable output, the average inversion in the fiber should be increased to a region where there is a monotonous decrease in the gain curve/ASE spectrum with the wavelength. This is possible with the use of shorter lengths of heavily doped fibers and with the control of pump powers. Under the experimental conditions discussed in this work, for a fiber of length 12 m, the largest available pump power does not result in continuous tuning, and this forbidden range is indicated as inflexions in the ASE spectra. This problem is circumvented with a shorter length of fiber, using which, continuous tunability was obtained from 1591.3 nm to 1557.3 nm at the maximum pump power available. Tunability can be further enhanced with a larger dopant concentration and higher pump powers.

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