Concentration-induced nonuniform power in tunable erbium-doped fiber lasers

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We report, for the first time to our knowledge, the presence of concentration-induced nonuniform power in tunable erbium-doped fiber lasers. A theoretical model is proposed with pair-induced quenching taken into account. We obtain good agreement between numerical and experimental results of a high-concentration erbium-doped fiber ring laser with a large tuning range of over 100 nm. These findings are useful for the design of lasers with doped fibers. © 2004 Optical Society of America

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Erbium-doped fiber lasers (EDFLs) have been studied extensively for their potential applications in wavelength-division-multiplexed transmission systems and for performance testing of components.[1–3] Recently, EDFLs with widely tunable ranges covering both the conventional wavelength band (*C* band) and the long-wavelength band (*L* band) have been demonstrated to have a low threshold, a high signal-to-noise ratio, and a modest effective linewidth (0.1–1.0 GHz).[4,5] A tuning range of 100 nm within a 1-dB power flatness has been demonstrated in a ring cavity EDFL with low erbium concentration.[5] However, it is shown here that in a ring cavity EDFL with high-concentration erbium-doped fiber (EDF) the power flatness deteriorates significantly over a large tuning range of 100 nm. This phenomenon, to our knowledge, has not been previously reported. In this Letter we show by theoretical modeling that the nonuniform power in tunable EDFLs is caused mostly by concentration quenching in the highly doped EDF.

Concentration quenching has been identified as the main cause of performance degradation in EDFs.[6,7] It has been suggested that, in highly doped fibers, erbium ions tend to cluster in pairs and that a rapid cross-relaxation process, called pair-induced quenching (PIQ), takes place between doubly excited pairs. In this process one of the two ions transfers its energy to the other ion and is then nonradiatively transferred to the ground state ($^4I_{15/2}$) while the other ion is upconverted to the $^4I_{9/2}$ level, where it mostly relaxes rapidly to the metastable level ($^4I_{13/2}$).[6] Only approximately 1/10,000 of the upconverted ions decay radiatively to the ground state, which is sufficiently small and can therefore be neglected in the theoretical model.[6] This process has caused a decrease in the population inversion and hence quantum efficiency, resulting in a reduction of gain in EDF amplifiers and an increase in the threshold of EDFLs.[8–11]

To study the effect of concentration quenching on the performance of tunable EDFLs, we model a tunable erbium-doped fiber ring laser with PIQ taken into account. The supposed laser, as shown in Fig. 1, has both forward and backward pumps that may be of the same or different frequency to meet lasers with different pump configurations. Other components include a tunable narrow bandpass filter, an output coupler, wavelength-division-multiplexed couplers, an optical isolator, a polarization controller, and a length of EDF.

It is assumed that all the erbium ions exist as two distinct species: single ions and paired ions. The concentration of the paired erbium ions is denoted as $n^p = 2kn_t$, where n_t is the total concentration of erbium ions, k is the relative number of pairs, and $2k$ is the percentage of ions in pairs. Thus the concentration of the single erbium ions can be written as $n^s = (1 - 2k)n_t$. If we consider the erbium fiber

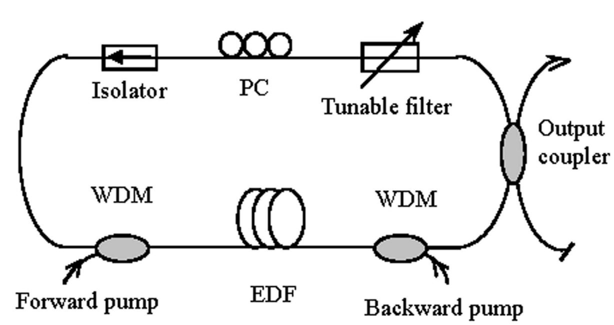

Fig. 1. Schematic diagram of a proposed EDFL: PC, polarization controller; WDM, wavelength division multiplexer.

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as a homogeneously broadened two-level laser system, steady-state rate equations for the single ions and paired ions can be written, respectively, as[11,12]

$$\frac{dn_1^s(z)}{dt} = -\frac{dn_2^s(z)}{dt} = -W_a(z)n_1^s(z) + \left[W_e(z) + \frac{1}{\tau}\right]n_2^s(z) = 0\,, \tag{1a}$$

$$\frac{dn_1^p(z)}{dt} = -\frac{dn_2^p(z)}{dt} = -W_a(z)n_1^p(z) + \left[W_e(z) + W_a(z) + \frac{1}{\tau}\right]n_2^p(z) = 0\,, \tag{1b}$$

where n_1^s and n_2^s are the population densities of the ground and metastable levels for the single ions, respectively; n_1^p and n_2^p are the population densities of the ground and metastable levels for the paired ions, respectively; and τ is the lifetime of the metastable level. $W_a(z)$ and $W_e(z)$ are the stimulated absorption and stimulated emission rates, respectively, which are given by

$$W_{a,e}(z) = \sum_v \frac{\sigma_{a,e}(z)}{A_{\text{eff}}hv}[P^+(z,v) + P^-(z,v)]\eta(v)\,. \tag{2}$$

In Eq. (2), $\sigma_{a,e}$ is the appropriate absorption or emission cross section; h is Planck's constant; A_{eff} is the effective fiber core area; $\eta(v)$ is the overlap integral between the LP_{01} mode intensity distribution and the erbium doping density function; and $P^{\pm}(z,v)$ are the forward- and backward-propagated powers that include the pump, laser, and amplified spontaneous emission (ASE) powers at frequency v and at the longitudinal fiber coordinate z ($0 \leq z \leq L$). We consider all the frequency components from 1450 to 1640 nm by dividing them into 950 slots of 0.2-nm frequency interval and adding a slot for the pump if the frequency of the pump is not in the range (e.g., 980 nm).

From Eqs. (1) and (2) the population inversion is calculated separately for the single and paired ions at each point along the EDF length. The total population inversion is given as $n_2(z) = n_2^p(z) + n_2^s(z)$ and $n_1(z) = n_t - n_2(z)$. Thus the power propagation equation is given by

$$\frac{dP^{\pm}(z,v)}{dz} = \pm 2hv\Delta v\eta(v)\sigma_e(v)n_2(z) \pm [\sigma_e(v)n_2(z) - \sigma_a(v)n_1(z)]\eta(v)P^{\pm}(z,v)\,, \tag{3}$$

with boundary conditions of $P^+(0,v_p^+) = P_{p0}^+$ and $P^-(L,v_p^-) = P_{p0}^-$ for forward and backward pump powers, respectively; $P(0,v_s) = VP(L,v_s)$ for laser power; and $P^+(0,v_{\text{ASE}}) = P^-(L,v_{\text{ASE}}) = 0$ for ASE slot powers. Here v_p, v_s, and v_{ASE} denote the frequency for the pump, laser, and ASE, respectively. V is the total loss of the ring cavity at the laser frequency selected by the tunable filter, which includes the insertion loss of the output coupler.

In the following experiment and analysis we consider an erbium-doped Ge–Al-codoped fiber with an absorption coefficient of 15 dB/m at 1530 nm and 7 dB/m at 1480 nm, a doping concentration of 9.2×10^{24} ions/m^3, a core diameter of 3.2 μm, and a numerical aperture of 0.27. The data for the absorption and emission cross sections are given by the fiber supplier, which at a wavelength of 1530 nm are 6.69×10^{-25} and 6.68×10^{-25} m^2, respectively. τ is assumed to be 8 ms (a typical value). The EDF was backward pumped at 1480 nm with an incident power of 90 mW. The tunable filter has a bandwidth of 0.2 nm and a tuning range of 120 nm (1500–1620 nm), and its details can be found in Ref. 13. The total loss of the ring cavity was measured to be 6.6 dB, and the output coupler ratio is 50:50.

Figure 2 shows the simulated laser output power against the emission wavelength for various percentages of paired ions of $2k = 0$, 3%, 6%, and 9%. The length of the EDF is 8.0 m. The power profile within a range of 90 nm (1520–1610 nm) is very flat for the case of $2k = 0$, but, when the value of k increases, the average power and the tuning range are reduced. The power flatness deteriorates noticeably, mostly because of a rapid reduction of power in the shorter wavelength region, especially at ~1530 nm. Figure 3 shows the simulated and measured laser output powers against the emission wavelength for EDF lengths of 5.0, 8.0, and 12.5 m, where the simulated results are obtained with $2k = 5.2\%$. It can be seen that the tuning range is very sensitive to the length of the EDF. The largest tuning range of 104 nm (1512–1616 nm) was obtained from 8.0 m of EDF. Good agreement between the measured and simulated results is obtained for all three cases. The

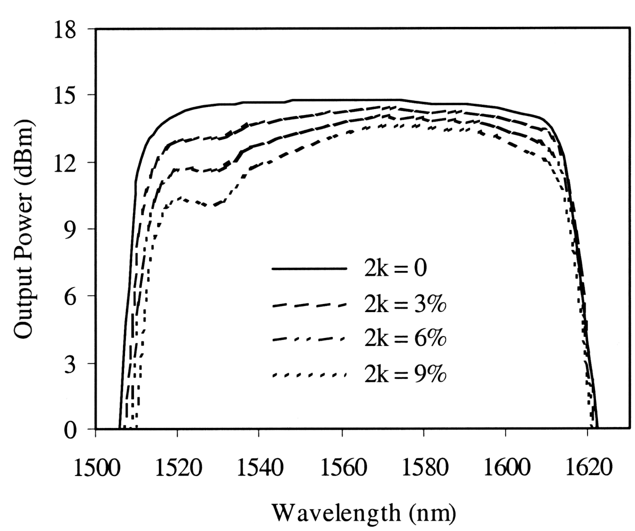

Fig. 2. Simulated laser power against emission wavelength at different percentages of paired ions. The length of the EDF is 8.0 m.

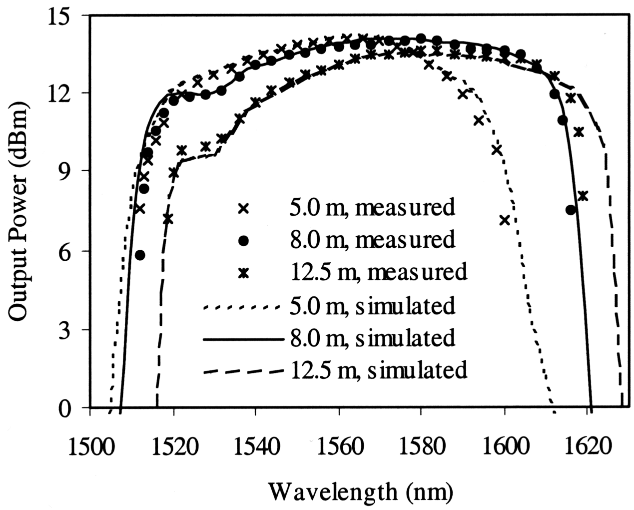

Fig. 3. Measured and simulated laser power against emission wavelength for different lengths of the EDF. The percentage of paired ions in the simulation is $2k = 5.2\%$.

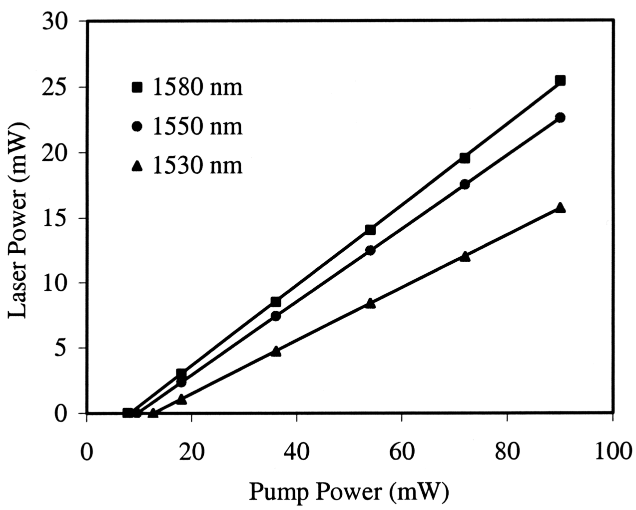

Fig. 4. Laser output power at 1530, 1550, and 1580 nm versus incident pump power.

small discrepancy may be due to different cavity loss (e.g., the difference in splicing loss) for different EDF lengths and the limited tuning range of the tunable filter at the long-wavelength end (for an EDF length of 12.5 m). However, we verified the accuracy of the theoretical model and showed that the nonuniform laser output power is caused by the effect of concentration (or pair-induced) quenching.

The threshold pump power for an EDFL was found to increase with the erbium concentration because of concentration quenching, but that study considered only one emission wavelength (e.g., ~1560 nm) because the laser was not tunable.[10] Here we study the laser's output characteristics at different emission wavelengths. Figure 4 shows the measured output power at 1530, 1550, and 1580 nm for various incident pump powers. The thresholds are 12.6, 9.6, and 7.8 mW, and the calculated slope efficiencies are 20.3%, 28.1%, and 30.8% for 1530, 1550, and 1580 nm, respectively. So the threshold and slope efficiency are also dependent on wavelength because of the PIQ-induced degradation, which, we believe, is related to the wavelength dependence of the absorption cross section. For example, as the laser emits at a wavelength with a higher absorption cross section, the stimulated absorption rate, W_a, is also higher [see Eq. (2)]. This will strengthen the effect of PIQ [see Eq. (1b)] and hence increase the loss in the population inversion and quantum efficiency, resulting in a larger threshold power and lower slope efficiency in the laser.

The percentage of paired ions generally increases with the doping concentration of erbium in EDFs. The best-fit percentage of paired ions in our case, 5.2%, considering the erbium concentration and the fact that the fiber was highly codoped with Al^{3+}, is comparable with the result reported in Ref. 10. The undesirable effects can be overcome by use of low-concentration EDF, but high-concentration EDF provides the advantage of small size, which is desirable for integrated devices and for linear cavity lasers to obtain single-mode output by reducing the length of cavity. Thus complete elimination of clustering in high-concentration EDFs is important for the optimal design of small size and widely tunable fiber lasers.

In summary, we have shown that concentration quenching can induce nonuniform power in a tunable laser with highly doped EDF and have proposed a comprehensive theoretical model with PIQ taken into account to explain the phenomenon. The results presented here are useful for the optimal design of EDFLs, as well as other rare-earth-doped fiber lasers.

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