Investigation of clustering effects on erbium-doped fiber laser performance

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To design a compact erbium-doped fiber laser, a high-concentration erbium-doped fiber (EDF) is needed. However, increasing the erbium ion (Er^{3+}) concentration can reduce the EDF performance via the $Er^{3+}-Er^{3+}$ interaction. In this Letter, we investigate the $Er^{3+}-Er^{3+}$ interaction effect by designing a tunable erbium-doped fiberring laser (EDFRL). This is the first time (to the best of our knowledge) that someone has considered different numbers of ions per cluster and simulated the EDFRL output power degradation due to ion-ion interaction. If the number of ions in the cluster is increased, the lasing output power will decrease accordingly. The most dominant effect is seen in the 1530 nm wavelength region, where the EDF shows a higher signal absorption compared to the other wavelength region. Moreover, a comparison has been done for lasing performance analysis with different dopant ion concentrations. The comparison results show that a higher dopant concentration is advantageous for longer-wavelength lasing.

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Erbium-doped fiber lasers (EDFLs) have attracted considerable attention from different research groups due to their potential applications in wavelength division multiplexing (WDM) systems, sensing, optical metrology, high-resolution spectroscopy, and as a biomedical light source^[1–3]. To design a compact EDFL, a highly doped erbium-doped fiber (EDF) is necessary, which reduces the total cavity length and the dispersion introduced by the fiber. Moreover, a smaller cavity length is advantageous for single-mode lasing operations and the design of L-band active devices^[4,5].

However, increasing the dopant concentration degrades the EDF performance due to the upconversion mechanism between ions residing in pairs or larger clusters. Generally, the degree of clustering in EDFs increases with the increase of the dopant concentrations. Dong et al. demonstrated the negative effect of clustering on the EDFL output power⁶. They considered the pair-induced quenching effects and noticed the higher power degradation at shorter wavelength bands, especially around the 1530 nm wavelength region, than longer wavelength bands. Dong et al. also reported that the lasing output power flatness of tunable EDF-ring lasers (EDFRLs) degrades due to concentration quenching in the highly doped fiber^[5,7]. In their theoretical model, they assumed that erbium ions can exist as two distinct species: single ions and paired ions. However, this assumption is not viable when the erbium ion concentration is very high. For high-concentration EDFs, the larger cluster size needs to be taken into account. In the large cluster model, each ion can transfer its energy to the other ions in the cluster. For example, if n ions of a cluster are excited to the metastable state, n-1 ions will decay back to the ground state due to the energy transfer^[8]. In this way, the excited-state population is reduced, which will

subsequently reduce the quantum conversion efficiency of the EDF.

There is another process, known as excited state absorption (ESA), which can limit the performance of EDFs. There are two important ESA processes, pump ESA and signal ESA, that reduce the quantum conversion efficiency of erbium-doped fiber amplifiers (EDFAs) and EDFLs. The pump ESA is responsible for visible green light emission. On the other hand, the signal ESA limits the EDF performance at longer wavelengths (around 1590 nm) region^[9,10]. Yamashita *et al.* observed the rapid power drops of EDFLs around the longer wavelength band due to ESA effects^[11]. On the contrary, lasing output power degradation due to ion-ion interactions is significant in the shorter wavelength region. Therefore, we ignore the negative effect of the ESA to clearly reveal the ion-ion interaction impact on the lasing performance.

Usually, manufacturers do not provide the clustering information of EDFs. Therefore, it is difficult to investigate the ion-ion interaction effects on the EDFRL performance by using commercially available EDFs. Kir'yanov et al. demonstrated a technique to measure the homogeneous upconversion (HUC) and inhomogeneous upconversion (IUC) parameters of two commercial EDFs which were fabricated through the modified chemical vapor deposition and direct nanoparticle deposition processes^[12]. They found that the IUC process is related to the relative number of the cluster percentage and the number of ions per cluster. The parameters related to the IUC processes monotonously go up with the increasing doping ion concentrations. Their demonstration would help in determining the clustering information in commercial EDFs before designing practical EDF devices. As the clustering increases, the EDF device performance will degrade accordingly. Therefore, it is quite important to investigate the performances of EDF devices with different cluster sizes. In one of our previous works, we reported the EDFA performance based on the HUC and IUC processes. In the IUC process, we considered different numbers of ions per cluster and simulated the EDFA performance^[13]. The simulation was done using the OptiSystem simulation tool. In the OptiSystem simulation tool, cluster parameters can be varied by changing the relative number of the cluster percentage and the number of ions per cluster.

In this Letter, we have investigated the lasing output power variation due to the ion–ion interaction process. For this investigation, both the HUC and IUC factors are taken into consideration. For the IUC case, we have considered larger cluster sizes by increasing the number of ions per cluster and observed the lasing output power degradation. As the number of ions per cluster is increased, the overall lasing output power decreases. It is interesting to note that the most dominant power degradation is seen around the 1530 nm wavelength band.

EDFAs with higher dopant ion concentrations show degraded gain performances due to the ion-ion interaction process. There are two types of ion-ion interaction processes: HUC and IUC. In the HUC process, it is assumed that erbium ions are homogenously distributed in the EDF core and energies are transferred from the one ion to its neighbor via the HUC factor^[14]. However, ions are not homogenously distributed in the EDF core for the IUC process. Moreover, the distance between neighboring ions is very small as compared to the HUC process. In this process, some ions tend to cluster in pairs following a cross-relaxation process. The paired ions in the EDF can be in three different states: a zero-photon state (no ion in the excited state), a onephoton state (one ion in the excited state), and a twophoton state (both ions are in the excited state). When both ions of a pair are excited to the metastable state $^4I_{13/2},$ energy is rapidly transferred from the donor to the acceptor ions. This phenomenon causes the donor ion to non-radiatively decay back to the ground state ${}^{4}I_{15/2}$ and the acceptor ion to go to the higher energy state ${}^{4}I_{9/2}$. Finally, the upconverted ion rapidly decays back to the metastable state ${}^{4}I_{13/2}$, as shown in Fig. <u>1</u>. Therefore, the lifetime of the two-photon state, where both ions are in the excited state, is too short [4,15,16].

If the pump power is below the paired ions' saturation power, which is in the order of watts, one of the paired ions is always quenched for that pump power. This phenomenon is known as pair-induced quenching. Therefore, it is not possible to invert the population paired with a moderate pump power^[17]. This reduces the pump-power conversion efficiency.

A typical forward pump tunable fiber ring laser configuration is shown in Fig. 2. This laser configuration is modeled using OptiSystem version 13 to observe the Er^{3+} - Er^{3+} interaction effects on the lasing performance. The corresponding simulation model is shown in Fig. 3. Here, a laser diode (LD) is used to pump the EDF via an ideal WDM multiplexer with a pump power of 100 mW



Fig. 1. Energy level diagram of Er^{3+} and upconversion process^[4].



Fig. 2. Forward pump tunable EDFRL configuration.



Fig. 3. Simulation model of forward pump tunable EDFRL.

emitting at 980 nm. An ideal optical isolator is also used to make a unidirectional lasing operation. The lasing wavelength is determined by the intra-cavity transmission type filter with a 0.1 nm bandwidth. The insertion loss and return loss of the filter are chosen to be 0 and 65 dB, respectively. The lasing wavelength is varied by changing the central wavelength of the intra-cavity filter, and the lasing output is recorded in an optical spectrum analyzer (OSA) via a 90:10 output coupler. In our simulation, we have used 20 passes of amplification to get the lasing output. To determine the ion-ion interaction effects on the lasing performance, different parameters have been set in the simulation tool, and the performance data are recorded via the OSA. The detailed simulation parameters are provided in Table $\underline{1}$.

Table 1. Simulation Parameters for EDFRL

 Performance Evaluation

| Parameters | Value |
|-----------------------------|--|
| Pump power | 100 mW |
| Pump wavelength | 980 nm |
| Erbium ion concentration | 300 and $600~\mathrm{ppm}$ |
| Erbium metastable lifetime | 10 ms |
| Fiber core radius | 1.8 µm |
| Erbium doping radius | 1.6 µm |
| Numerical aperture | 0.32 |
| EDF length | 13 m |
| HUC Coefficient | $15 \times 10^{(-24)} \text{ m}^{-3}/\text{s}$ |
| Ions per cluster | 2, 6 and 10 |
| Relative number of clusters | 10% |

To investigate the lasing output power reduction in the 1530 nm wavelength region, we have used a simulation model to analyze the absorption characteristics of EDFs with different ion concentrations. The simulation model is shown in Fig. 4. In this model, the power of the continuous-wavelength laser is set to -20 dBm, and the input wavelengths are varied from 1450 to 1650 nm to measure the absorption coefficient with different erbium ion concentrations. To determine the absorption coefficient value, two different EDF lengths (2 and 0.5 m) have been chosen, and the corresponding output powers are measured for each EDF length. Finally, these measured output powers are used to determine the EDF absorption coefficient. In the OptiSystem simulation tool, the absorption coefficient for the EDF can be measured using a simple relation shown below^[18]:

$$\alpha(\lambda) = \frac{P_{\text{out}}(\lambda, L = 0.5m) - P_{\text{out}}(\lambda, L = 5m)}{2 - 0.5}, \quad (1)$$

where $P_{\text{out}}(\lambda, L = 0.5m)$, and $P_{\text{out}}(\lambda, L = 5m)$ represent the output powers measured for the 0.5 and 5 m EDFs, respectively.



Fig. 4. Simulation model for determining EDF absorption coefficient $^{[18]}$.

During the absorption coefficient measurement, other physical parameters of the EDF (erbium metastable lifetime, fiber core radius, erbium doping radius, and numerical aperture) are kept the same, as given in Table $\underline{1}$.

The lasing wavelength versus the output power variation is shown in Fig. 5. The simulation results show that the EDFRL provides the best performance if the ion interaction processes are not considered. However, the introduction of ion-ion interaction processes decreases the lasing output power. The effect of the HUC process on the lasing output power is not that dominant because of the larger ion separation. In the comparatively large scale, the lasing output power degradation due to the HUC process is almost indistinguishable when compared to the case without upconversion. The small degradations of the lasing output power due to the HUC process are shown in the insets of Figs. 5 and 6. In the IUC case, as the number of ions per cluster is increased, the lasing output power decreases accordingly due to the ion-ion interaction mechanism, as previously explained. The most dominant power reduction of lasing output power is seen in the 1530 nm region.

It is observed that the lasing output power around the 1530 nm wavelength region decreases more abruptly than the other wavelength regions. This happens due to the high absorption around the 1530 nm region. From the absorption characteristics of the EDF, as shown in Fig. 7, it is clear that in the 1530 nm wavelength region, the signal is more highly absorbed than in other wavelength regions, and consequently, the EDFRL provides the lowest output power around the 1530 nm wavelength region. It is worth mentioning that the worst lasing output power is observed when both the HUC and IUC ion interaction processes are considered.

For comparison purposes, the lasing performance has been evaluated again with different dopant ion concentrations. The lasing wavelength versus the output power variation for a 600 ppm ion concentration is shown in Fig. <u>6</u>. As the erbium ion concentration increases from 300 to 600 ppm, the absorption at the 1530 nm wavelength region



Fig. 5. EDFRL performance with a doping concentration of 300 ppm.



Fig. 6. EDFRL performance with 600 ppm doping concentration.

increases accordingly, as shown in Fig. <u>7</u>. Moreover, a comparatively higher number of dopant ions decreases the dopant ions' separation. Therefore, the ion–ion interaction effects will increase, and a comparatively lower output power is obtained for a higher dopant ion concentration.

For a detailed comparison, the best and worst performances of EDFRLs with concentrations of 300 and 600 ppm are superimposed in the same figure. The superimposed lasing performance is shown in Fig. 8. For the higher-dopant-concentration EDF, the lasing output power at the 1530 nm wavelength region is lower as compared to the lower dopant concentration of the EDF. As the erbium ion concentration increases, detrimental ionion interaction effects increase, which in turn reduce the lasing output power. Moreover, the higher-concentration EDF absorbs more of the 1530 nm region signals, as shown in Fig. 7. Therefore, the lasing output power decreases more sharply around the 1530 nm wavelengths region as compared to the other wavelength regions. However,



Fig. 7. EDF absorption characteristics.



Fig. 8. Comparative EDFL performance analysis with different ion concentrations.

the signal absorption of the 1530 nm wavelength region will subsequently help in exciting the ground-state electrons to a higher energy state. This phenomenon is helpful for longer-wavelength lasing, as shown in Fig. $\underline{8}$.

To investigate the lasing output power reduction around the 1530 nm wavelength region, we have analyzed the absorption characteristics of EDFs. The absorption characteristics of EDFs with different ion concentrations are shown in Fig. 7. From the simulation results, it is clear that the signal absorption increases for the entire wavelength starting from 1450 to 1650 nm with the increasing dopant concentration. Moreover, there is a dominant absorption near the 1530 nm wavelength region for the EDF. Therefore, it is highly likely that the lasing output power of the 1530 nm region will be significantly affected due to the high signal absorption by the EDF.

We show that ion-ion interactions reduce the overall lasing output power of EDFRLs. In this Letter, both HUC and IUC are considered for investigating the ion-ion interaction effects on the tunable EDFRL lasing performance. Moreover, a larger cluster size is considered for the IUC case. From the investigation results, we can conclude that IUC is the dominant factor for overall lasing output power reduction. However, the most dominant power reduction is observed in the shorter wavelength region, especially around 1530 nm, due to the high signal absorption. As the number of ions per cluster is increased, the excited state population will decrease due to the ion-ion interaction, which in turn reduces quantum conversion efficiency of EDFs. Therefore, it is very important to reduce the cluster formation in EDFs to obtain a flatter lasing output.

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