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Upconversion assisted self-pulsing in a high-concentration erbium doped fibre laser

Research Article

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Abstract: We report results on experimental and theoretical characterisation of self-pulsing in high concentration erbium doped fibre laser which is free from erbium clusters. Unlike previous models of self-pulsing accounting for pair-induced quenching (PIQ) on the clustered erbium ions, new model has been developed with accounting for statistical nature of the excitation migration and upconversion and resonance-like pump-to-signal intensity noise transfer. The obtained results are in a good agreement with the experimental data.

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Keywords: fibre lasers • upconversion • erbium • optical instabilities

1. Introduction

Self-pulsing in high concentration erbium doped fibre lasers (HC EDFLs) has been intensely studied during the last 15 years in the context of applications in communications, reflectometry, distributed fibre optic sensing, medicine *etc.* [1–9]. For a long time the presence of the clustered erbium ions and their behaviour as a saturable absorber has been considered as the only possible mechanism responsible for the self-pulsing [1–6, 9]. However, detailed microscopic study of erbium-doped glasses by means of X-ray absorption fine structure spectroscopy (XAFS) has found a short range coordination order of erbium ions rather than pair-clustering [10]. As follows from XAFS experiments, the pair-correlation function has maxima at R_1 = 3.5 Å and R_2 = 3.9 Å, whereas it takes approximately a constant value for $R > 4.5$ Å [10]. It was found also that suppression of the short-range order leads to improved characteristics of high concentration erbium doped fibre amplifiers and lasers and can be realized by increasing the solubility of erbium in host matrix (co-doping by Al [11] or using phosphate glass [12]) or by modification of deposition process (Direct Nanoparticle Deposition [13]). Application of such fibres as an active media for HC EDFLs resulted in auto-oscillations with two characteristic frequencies of about 10 kHz and 100 kHz and

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two threshold pump powers. The first pump power was slightly above and the second one was 10 times exceeding the first threshold [7, 8]. Thus, unlike pair-clusters, alternative approaches to self-pulsing in HC EDFLs have to be developed. Although the model explaining mechanism of the auto-oscillations in HC EDFLs with accounting for upconversion processes is still absent, it was already experimentally shown in Ref. [8] that pump-to-signal noise transfer can play a significant role in appearance of low frequency self-pulsing. In addition, power-dependent thermo-induced lensing has been suggested as a mechanism for high-frequency (100 kHz) self-pulsing [7].

In this paper we develop an advanced model of HC EDFL accounting for the statistical nature of migration and upconversion processes [14–22]. We apply this model to calculate the pump-to-signal intensity noise transfer function and demonstrate that resonance behaviour of this function can lead to appearance of the low-frequency auto-oscillations in the limited range of erbium concentrations. We show that the obtained results are in a good agreement with our experimental data.

2. Experimental and theoretical characterisation of low-frequency self-pulsing in high concentration erbium doped fibre laser

Experimental set-up is shown in Fig. 1. Laser cavity comprises high concentration ($c_{Er} = 3.7 \times 10^{25}$ ions/m^3) erbium doped fibre (Liekki Er40-4/125) of 10 m length along with Faraday mirror (*R=90%*) and fibre Bragg grating (λ_{peak}=1556 nm, $\Delta\lambda_{3dB}$=0.2 nm, R=86%) as reflectors. In view of strong intracavity losses (splice losses, strong pump light absorption along the full length of erbium doped fibre), we have used 978 nm laser diode (LD) with varying pump power of 20 – 200 mW along with an additional LD with pump power of 200 mW and central wavelength at 1480 nm. When pump power for 978 nm LD is slightly exceed first threshold, *i.e.* $I_{p,980} = 1.03 I_{pth,980}$, we have observed low frequency (~3 kHz) and high frequency (~150 kHz) auto-oscillations without any pump modulation (Fig. 2).

For theoretical characterization of the low-frequency auto-oscillations we develop a new model of HC EDFL with taking into account statistical nature of migration-assisted upconversion [14–22] and pump-to-signal intensity noise transfer [5]. By combining rate equations that describes dynamics of the excitation localization on the erbium ions located at the first and the second excited level [14–22] with equation for the lasing power, we result

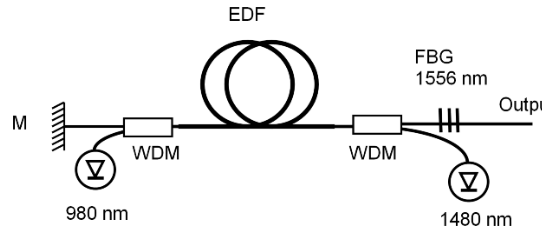

Figure 1. High concentration erbium doped fibre laser.

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$$\begin{aligned}\frac{dn_{1k}}{dt} =&\delta_1 n_{2k} + (1 - n_{1k}\beta_s - n_{2k})\, I_L - n_{1k} - 2n_{1k} \sum_{i=1,\, i\neq k}^{n_1 N} P_{ki} \\ &- n_{1k} \sum_{j=1, j\neq k}^{N} W_{kj} + \sum_{j=1,\, j\neq k}^{N} W_{kj}\, n_{1j}, \\ \frac{dn_{2k}}{dt} =& (1 - n_{1k} - n_{2k})\, I_p - \delta_1 n_{2k} + n_{1k} \sum_{i=1,\, i\neq k}^{n_1 N} P_{ki}, \\ \frac{dI_L}{dt} =&\delta_2 I_L \left[\alpha_L L\, (\beta_L n_1 + n_2 - 1) - k_L L\right].\end{aligned} \tag{1}$$

Here time t is normalized to lifetime τ_1 of first excited level; $\delta_1 = \tau_1/\tau_2$, $\delta_2 = \tau_1/\tau_r$, where τ_2, τ_r are the lifetime of the second excited level and photon intracavity round-trip time; n_{1k}, n_{2k} are the probabilities of the localization of the excitation on ion number k located at the first and the second excited level correspondently, N is the total number of ions, and n_1, n_2 are the populations of the first and the second excited levels ($n_i = \lim_{N\to\infty} \sum_{k=1}^{N} n_{ik}/N$). Further, $\beta_L = (\sigma_{aL} + \sigma_{eL})/\sigma_{aL}$; pump I_p (λ_p=980 nm) and lasing power I_L are normalized on the corresponding saturation powers: $I_{is} = hcAc_{Er}/(\lambda_i \alpha_i \tau)$, $(i = L, p)$;A is an effective area of the erbium distribution, $\alpha_i = \Gamma \sigma_{ai} c_{Er}$ is the small signal absorption of HC EDFL at wavelength λ_i (λ_L=1556 nm, λ_p=980 nm); σ_{ai} and σ_{ei} are the absorption and emission cross-sections at the lasing ($i = L$) and the pump ($i = p$) wavelength, $\Gamma_i = 1 - \exp(-2b^2/w_i^2)$ is overlap factor, b is the erbium ion dopant radius, w_i is mode field radius at wavelength λ_i; L is fibre length, c_{Er} is the concentration of Er^{3+} ions. The rates of upconversion P_{ki} and migration W_{kj} (from ion k to ions i and j) for the dipole-dipole mechanism of excitation energy transfer are given as [14–22]

$$P_{ki} = \left(\frac{R_{up}}{R_{ki}}\right)^6, \quad W_{kj} = \left(\frac{R_m}{R_{kj}}\right)^6, \tag{2}$$

where R_{up} and R_m are the critical distances for upconversion and migration respectively [8].

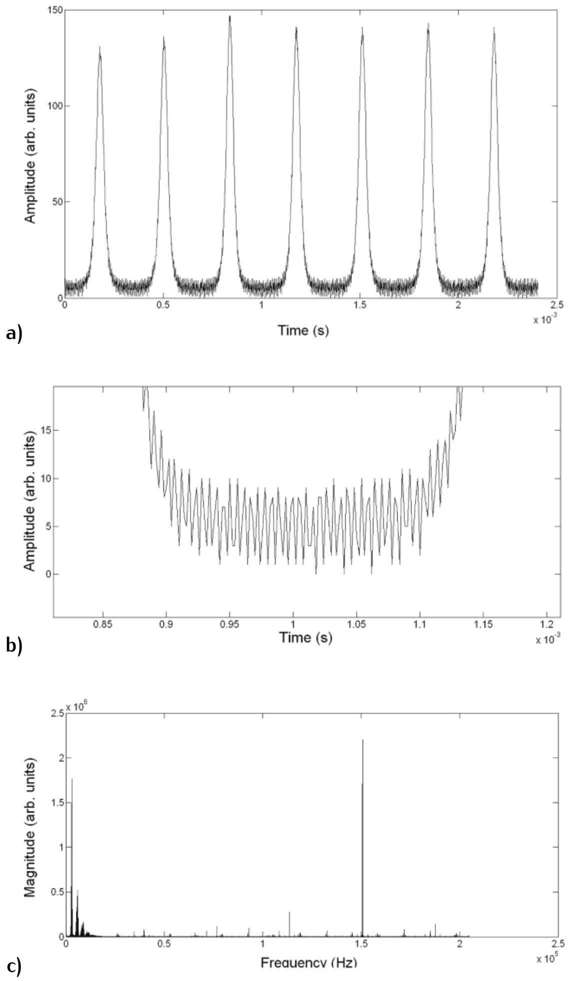

Figure 2. Low- and high-frequency auto-oscillations in high concentration erbium doped fibre laser (a, b), high-frequency auto-oscillations (b), Fourier transform of the dynamics is shown in Fig. 2c.

It is easy to show that the excited state absorption (ESA) in Eqs. (1) can be neglected if inequality $I_p\left(\sigma_{esa}+\sigma_{ap}\right)/\sigma_{ap} \ll \delta_1$ holds. This is justified because of we consider low pump powers of 1.03 and just 10.03 times of the first threshold pump power [15].
As follows from Eqs. (1), the model, unlike erbium cluster model, takes into account only variance in the distances between excited erbium ions and variance in the interaction probabilities, correspondingly. Averaging over the variance in the separations with taking into account cw operation $\frac{dn_{ik}}{dt}=0$, $\frac{dI_L}{dt}=0$ and mean-filed approximation [14–22] $\sum\limits_{j=1,j\neq k}^{N} W_{kj}n_{1j} \approx n_1 \sum\limits_{j=1,j\neq k}^{N} W_{kj}$, we derive the following system of macroscopic equations from which the excited levels populations n_1, n_2, cw rate of upconversion W_{up} and the lasing power I_L can be found as function of the normalised pump power I_p and normalised concentration of erbium ions $\gamma = c_{Er}/c_{up}$ ($c_{up}=\left(\frac{4\pi}{3}R_{up}^3\right)^{-1}$ is the critical concentration for upconversion).

$$\begin{aligned}
n_1 &= \frac{B(1+B)^{-1}\left(\sqrt{A}\,n_1+\sqrt{r/2}\right)F\left(\frac{\sqrt{\pi}\gamma\left(\sqrt{A}\,n_1+\sqrt{r/2}\right)}{2\sqrt{1+B}}\right)}{\sqrt{A}\,n_1+\sqrt{r/2}\,F\left(\frac{\sqrt{\pi}\gamma\left(\sqrt{A}\,n_1+\sqrt{r/2}\right)}{2\sqrt{1+B}}\right)},\\
n_2 &= \frac{2(1-n_1)I_p+(1-\beta_L n_1)I_L-n_1}{\delta_1+2I_p+I_L},\\
W_{up} &= \frac{(1-n_1-n_2)I_p+(1-\beta_L n_1-n_2)I_L-n_1}{n_1},\\
\beta_L n_1 - n_2 - 1 &= \frac{k_L}{\alpha_L L}.
\end{aligned} \tag{3}$$

Here $A=2-\frac{\delta_1-I_L}{\delta_1+I_p}$, $B=\beta_L I_L+\frac{\delta_1-I_L}{\delta_1+I_p}I_p$, $F(x)=1-\sqrt{\pi}x\exp\left(x^2\right)\mathrm{erfc}(x)$, $r=\left(\frac{R_m}{R_{up}}\right)^6$.
Close to the cw operation the dynamic behaviour of HC EDFL can be caused by small pump power fluctuations, *i.e.* we can write $I_p(t)=I_p+\Delta I_p(t)$, $n_{ik}(t)=n_{ik}+x_{ik}(t)$ *(i=1,2)*, $I_L(t)=I_L+x_3(t)$. By substituting these expressions into Eqs. (1) with accounting averaging procedure, we result in the following equations

$$\begin{aligned}
\frac{dx_1}{dt} &= -a_1\left(\gamma,I_p\right)x_1+a_2\left(\gamma,I_p\right)x_2-a_3x_3,\\
\frac{dx_2}{dt} &= b_1\left(\gamma,I_p\right)x_1-b_2\left(I_p\right)x_2+b_3\left(\gamma,I_p\right)\Delta I_p,\\
\frac{dx_3}{dt} &= c_1\left(\gamma,I_p\right)\beta_L x_1+c_1\left(\gamma,I_p\right)x_2.
\end{aligned} \tag{4}$$

Where

$$\begin{aligned}
&a_1\left(\gamma,I_p\right)=1+2W_{up}\left(\gamma,I_p\right)+\beta_L I_L\left(\gamma,I_p\right),\\
&a_2\left(\gamma,I_p\right)=\delta_1-I_L\left(\gamma,I_p\right), \qquad a_3=\frac{k_L}{\alpha_L},\\
&b_1\left(\gamma,I_p\right)=W_{up}\left(\gamma,I_p\right)-I_p, \quad b_2\left(I_p\right)=\delta_1-I_p,\\
&b_3\left(\gamma,I_p\right)=1-n_1\left(\gamma,I_p\right)-n_2\left(\gamma,I_p\right),\\
&c_1\left(\gamma,I_p\right)=\delta_2 L\alpha_L I_L\left(\gamma,I_p\right).
\end{aligned} \tag{5}$$

Here $x_{1(2)}=\langle x_{1(2)k}\rangle_{S_1,S_2}$ are fluctuations of the populations of the first and second excited levels averaged over the stochastic variables S_1 and S_2 which are presenting the excitation upconversion and migration processes [14, 22]. During the averaging procedure, the approximation

$$\langle S_1 x_{1k}\rangle/\langle x_{1k}\rangle \approx W_{up} \tag{6}$$

has been used. Taking the Laplace transform of the Eqs. (4): $\tilde{x}_i(p) = \int_0^\infty \exp(-pt)\, x_1(t)dt$ and defining $p = -i\omega$, we can obtain the following normalized transfer function for the pump-to-signal noise transfer which describes, in the frequency domain, the response of laser power to the perturbations in the pump power [5]:

$$H_p(\omega, I_p, \gamma) = \frac{x_3/I_L^{(CW)}}{\Delta I_p/I_P^{(CW)}}. \quad (7)$$

As follows from Ref. [5], relative intensity noise (*RIN*) for the HC EDFL is proportional to $\left|H_p(\omega, I_p, \gamma)\right|^2$. As a result, we find $|H_p(\omega)|^2$ from Eqs. (4) and (5) as following:

$$\begin{aligned} |H_p(\omega)|^2 = &\left(c_1(0.1, I_p)\frac{\gamma}{0.1}\right)^2 b_3(\gamma, I_p)^2 I_p^2\left[\left(a_1(\gamma, I_p) + \beta_L a_2(\gamma, I_p)\right)^2 + \omega^2\right]^2 \\ &\times I_L(\gamma, I_p)^{-2}\left\{\left[\omega^2\left(a_1(\gamma, I_p) + b_2(I_p)\right)^2 - c_1(0.1, I_p)\frac{\gamma}{0.1}a_3\left(b_1(\gamma, I_p) + \beta_L b_2(I_p)\right)\right]^2\right. \\ &\left. +\omega^2\left[-a_1(\gamma, I_p)\, b_2(I_p) + \omega^2 + b_1(\gamma, I_p)\, a_2(\gamma, I_p) - c_1(0.1, I_p)\frac{\gamma}{0.1}\beta_L a_3\right]^2\right\}^{-1}. \quad (8) \end{aligned}$$

Here coefficients a_i, b_i and c_1 have been calculated with help of Eqs. (5).

3. Results and discussion

Pump-to-signal transfer function $\left|H_p(\omega, I_p, \gamma)\right|^2$ as a function of frequency, pump power and normalised concentration has been calculated for the following parameters: $k_L/\alpha_L = 0.2$, $r = 60$, $\gamma = 0.1$, 0.33, 0.5; $\alpha_L\delta_2 = 10^6$, $\delta_1 = 10^3$. The results of calculations are shown in Fig. 3 for the pump power $I_p = 1.03 I_{p,th}$ (a) and $I_p = 10.03 I_{p,th}$ (b) ($I_{p,th}$ is the threshold pump power). The conditions of the constant number of ions, *i.e.* $N \sim \alpha_L = const$, has also been used.

As follows from Figs. 3a, b, when the pump power is slightly above ($I_p = 1.03 I_{p,th}$) and 10 times exceeding the first threshold value ($I_p = 10.03 I_{p,th}$), function $\left|H_p(\omega, I_p, \gamma)\right|^2$ demonstrates resonance-like behaviour at the low- (~10 kHz) and high-frequencies (~100 kHz). With the pump power increasing from $1.03 I_{p,th}$ to $10.03 I_{p,th}$, peak value of the transfer function decreases. In view of experimental results from Ref. [8] where it has been shown that modulation index of low-frequency auto-oscillations depends on the pump noise amplitude, our results gives an additional evidence that pump power fluctuations result in increased lasing intensity noise which works as an external resonance force to induce low-frequency self-pulsing ([8] and Figs. 2a-b). Unlike this, modulation index of high-frequency auto-oscillations is insensitive to the pump noise [8] and, therefore, resonance-like behaviour of the function $\left|H_p(\omega, I_p, \gamma)\right|^2$ can not result in high frequency auto-oscillations for the pump power exceeding the second threshold, *i.e.* for $I_p > 10 I_{p,th}$.

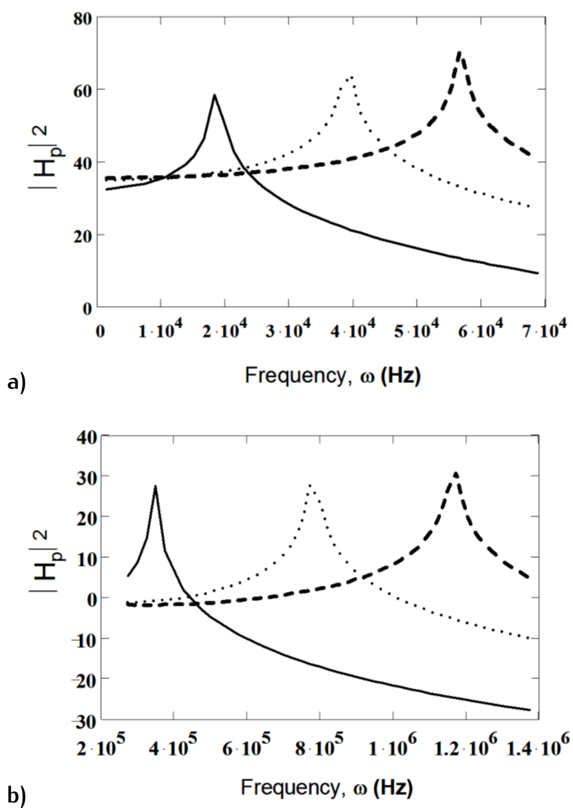

Figure 3. Pump-to-signal intensity noise transfer function as function of frequency and normalised concentration of erbium ions: γ=0.1 (solid line), γ=0.33 (dotted line), γ=0.5 (dashed line). Pump power $I_p = 1.03 I_{p,th}$. (a), Pump power $I_p = 10.03 I_{p,th}$.

As folows from Eqs. (8), $\left|H_p\left(\omega, I_p, \gamma\right)\right| \sim \alpha_L \delta_2 \sim c_{Er}$ in the maximum and, therefore, the function increase with increased concentration of erbium ions (Figs. 3a, b). Resonance frequency for low-frequency auto-oscillations coincides with frequency of relaxation oscillations ω_R which can be written as follows: $\omega_R = \sqrt{k_L\left(I_p/I_{pth}-1\right)/\left(\tau_1\left(\gamma\right)\tau_r\right)}$, where $\tau_1(\gamma)$ is the lifetime of the first excited level with accounting for upconversion [23]. Upconversion processes result in the decreased lifetime and, therefore, in increased resonance frequency (Fig. 3a).

In conclusion, we have presented a new advanced model of HC EDFL accounting for the statistical nature of migration and upconversion processes. By calculating the pump-to-signal intensity noise transfer function, we have demonstrated that resonance behaviour of this function can lead to appearance of the low-frequency auto-oscillations in the limited range of erbium concentrations. We show that the obtained results are in a good agreement with our experimental data and the data obtained in Ref. [8].

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