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**DYNAMIC RESPONSE ANALYSIS OF DFB FIBRE LASERS**

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Abstract: We present a model for relative intensity noise (RIN) in DFB fibre lasers which predicts measured characteristics accurately. Calculation results implies that the RIN decreases rapidly with stronger Bragg grating and higher pump power.

**Introduction**

In order to improve the stability of DFB fibre lasers [1] it is important to understand the dynamic behaviour in the presence of pump power fluctuations. The laser design can then be optimised to suppress relaxation oscillations around the peak of the RIN spectrum. Relaxation oscillations in Fabry-Perot fibre lasers have been analysed using two coupled rate equations [2]. This approach is not appropriate for DFB fibre lasers due to the presence of strong spatial hole-burning similar to semiconductor DFB lasers [3]. The dynamic behaviour of semiconductor DFB lasers has been studied using complex models such as the CLADISS [4] model, which combines coupled-mode theory with the rate equations. We propose here a simplified model based on three spatially independent rate equations to describe the dynamic response of erbium doped DFB fibre lasers on pump power fluctuations, using coupled-mode theory to calculate the steady-state hole-burning of the erbium ion inversion.

**Model and equations**

The conventional rate equations for DFB fibre lasers are as:

\[
\frac{dn}{dt} = \frac{c}{n_{df}} \left( \Gamma_n \sigma_a n_n + \Gamma_e \sigma_e n_e \right) x(t) = F(z,t)
\]

\[
\frac{dn^2}{dt} = -\frac{\Gamma_e}{n_{df}} \left( \mu \frac{\partial n^2}{\partial x} + \sigma_a n_e + \sigma_e n_e \right) x(t)
\]

\[
n_n = n_{in} + \rho \frac{P_{out}}{hV \sigma_a n_e} = \frac{n_{in} + \rho P_{out}}{n_{df} \sigma_a n_e}
\]

where subscript 's' is referred to signal, 'p' to pump, 'a' to absorption, 'e' to emission, 'g' to gain, and the lower and upper laser level population is denoted 'Nl' and 'N2' respectively. 's' is the Er3+-ion cross-section, 'I' the fibre confinement factor, 'c' the Er3+-ion inversion, 'n' the photon density, 'v' the light frequency in vacuum and 'p' is the Er3+-ion concentration. Further \( n_{df} \) denotes the effective refractive index, \( A_{df} \), the effective area of the fibre core, \( \tau_1 \) the upper laser level lifetime, \( P_{out} \) the output laser power, \( \nu \) the pump power, \( c \) the speed of light in vacuum and \( h \) the Planck's constant. \( n_{in} \) and \( n_{e} \) are the signal photon densities in the positive and negative directions, respectively.

The spatial distribution of the inversion, pump photon density and signal photon density is described using the envelope functions \( f_s, f_p \) and \( f_e \), respectively, while 'a' and 'e' describes the temporal variation of the inversion and power, respectively:

\[
x(z,t) = x_s f_s(z) + x_p f_p(z) + x_e f_e(z)
\]

\[
n_n(z,t) = n_{in}(1 + \varepsilon(t)) f_s(z), n_e(z,t) = n_{in}(1 + \varepsilon(t)) f_e(z)
\]

\[
x_s(z) = \frac{\partial x}{\partial z} \rho \varepsilon(t), x_p(z) = \frac{\partial x}{\partial z} (1 - \rho \varepsilon(t))
\]

The envelope functions \( f_s, f_p \) and \( f_e \), the average photon densities \( n_{in} \) and \( n_{out} \) and the average inversion \( x_s \) is calculated from the steady-state coupled-mode theory [5].

The spatially independent rate equations are obtained by integrating the rate equations over the entire cavity length \( L \), using the continuity conditions:

\[
f_s(0) = f_s(L), f_p(0) = f_p(L), f_e(0) = f_e(L) = 0
\]

Using the integral notation \( \langle \cdot \rangle \), we can normalise the envelope functions \( f_s, f_p \) and \( f_e \) as follows:

\[
\langle f \rangle = \frac{1}{L} \int_0^L f(z) dz, \langle f_s \rangle = \langle f_e \rangle = 1
\]

The new simplified and spatially independent rate equations for DFB fibre lasers are deduced as follows:

\[
d\alpha_s = \frac{F_s x_s}{\langle x_s \rangle^2} - \frac{F_e x_e}{\langle x_s \rangle^2} dt
\]

\[
d\alpha_e = \frac{F_s x_s}{\langle x_s \rangle^2} - \frac{F_e x_e}{\langle x_s \rangle^2} dt
\]

\[
\alpha_s = \langle \sigma_x + \sigma_{-x} \rangle \frac{\rho \delta n_x}{n_{in}} + \langle \sigma_{+,p} \rangle x_s + \langle \sigma_{-,p} \rangle x_p + \langle \sigma_{+,g} \rangle x_e + \langle \sigma_{-,g} \rangle x_e
\]

Relative intensity noise of DFB fibre laser (RINlaser) is defined as \( RIN_{laser} = \langle \Delta P_{out}^2 / P_{out}^2 \rangle \) (Hz^2), where \( \langle \Delta P_{out}^2 \rangle \) is the mean-square output laser power fluctuation (in a 1Hz bandwidth) at a specified frequency and \( P_{out} \) the average output power. The relative noise (RIN) is defined as: \( RIN = RIN_{laser} / RIN_{pump} \). The measured system noise (RIN\textsubscript{sys}) includes RIN\textsubscript{laser} plus thermal noise and shot noise in the receiver.

For simplicity, a white noise spectrum is assumed for the output laser power fluctuations, using coupled-mode theory to calculate the relative intensity noise of DFB fibre lasers on pump power fluctuations.

**Results and discussion**

Parameters used in calculations, unless otherwise specified, are: \( \rho = 1.7 \cdot 10^5 \) m^3, \( \nu = 10^5 \) s, \( \sigma_x = 1.85 \cdot 10^{-7} \text{ m}^2\).
The comparison between calculated and measured results for noise characteristics related to the coupling coefficient and the pump power are shown in Fig.3. When the pump power increases, the peak noise decreases, while the relaxation oscillation frequency increases.

Fig. 3: Calculated and measured variations of peak relative noise $RN$ and relaxation frequency $f_r$ with pump powers $P_{pump}$

Calculations also indicate that with moderate pump power fluctuation ($\delta < 1\%$), the laser relative noise peak ($RN$) is independent on the fluctuation magnitude $\delta$. To keep pump fluctuation as low as possible is always the most effective way of reducing laser noise, e.g., by introducing a negative feedback to the pump [6].

In conclusion, the simplified, spatially-independent rate equations considering the hole-burning effect are presented here to describe the dynamic response of DFB fibre lasers, especially the relative intensity noise characteristics due to pump power fluctuation. It implies efficient noise reduction using stronger Bragg grating, higher pump power and lower pump fluctuation.

References