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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:

$$\frac{\partial x}{\partial t}=\frac{c}{n_{eff}}\left(\Gamma_s\sigma_{g,s}n_s+\Gamma_p\sigma_{g,p}n_p\right)-\frac{x}{\tau_{21}}\equiv F(z,t)$$

$$\frac{\partial n_s^\pm}{\partial t}=-\frac{c\Gamma_s\sigma_{g,s}n_s^\pm\rho}{n_{eff}}\mu\frac{c}{n_{eff}}\frac{\partial n_s^\pm}{\partial z}$$

$$n_s=n_s^{+}+n_s^{-}=\frac{p_{out}n_{eff}}{h\nu_s A_{eff}c},n_p=\frac{p_{pump}n_{eff}}{h\nu_p A_{eff}c},x=\frac{N_2}{N_1+N_2}=\frac{N_2}{\rho}$$

$$\sigma_{g,s}=\sigma_{a,s}-\left(\sigma_{a,s}+\sigma_{e,s}\right)x,\sigma_{g,p}=\sigma_{a,p}-\left(\sigma_{a,p}+\sigma_{e,p}\right)x$$

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 'N_1' and 'N_2', respectively. 'σ' is the Er^{3+}-ion cross-section, 'Γ' the fibre confinement factor, 'x' the Er^{3+}-ion inversion, 'n' the photon density, 'ν' the light frequency in vacuum and 'ρ' is the Er^{3+}-ion concentration. Further n_{eff} denotes the effective refractive index, A_{eff} the effective area of the fibre core, τ_{21} the laser upper level lifetime, p_{out} the output laser power, p_{pump} the pump power, c the speed of light in vacuum and h the Planck's constant. n_s^+ and n_s^- 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_x, f_p and f_s, respectively, while 'α' and 'ε' describes the temporal variation of the inversion and power, respectively:

$$x(z,t)=x_0f_x(z)+\alpha_s(t)x_s(z)+\alpha_p(t)x_p(z)$$

$$n_s^\pm(z,t)=n_{s0}(1+\varepsilon_s(t))f_s^\pm(z),n_p(z,t)=n_{p0}\left(1+\varepsilon_p(t)\right)f_p(z)$$

$$x_s(z)=n_{s0}\frac{\partial x(z)}{\partial n_{s0}},\ x_p(z)=n_{p0}\frac{\partial x(z)}{\partial n_{p0}}$$

The envelope functions f_x, f_p and $f_s\equiv f_s^+ + f_s^-$, the average photon densities n_{s0} and n_{p0}, and the average inversion x_0 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:

$$f_s^-(0)=f_s(0),f_s^+(L)=f_s(L),f_s^+(0)=f_s^-(L)=0$$

Using the integral notation $\langle f\rangle$, we can normalise the envelope functions f_x, f_p and f_s as follows:

$$\langle f\rangle=\frac{1}{L}\int_0^L f(z,t)dz,\langle f_x\rangle=\langle f_s\rangle=\langle f_p\rangle\equiv 1$$

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

$$\frac{d\alpha_s}{dt}=\frac{\langle F\cdot x_s\rangle\cdot\langle x_p^2\rangle-\langle F\cdot x_p\rangle\cdot\langle x_s\cdot x_p\rangle}{\langle x_s^2\rangle\cdot\langle x_p^2\rangle-\langle x_s\cdot x_p\rangle^2}$$

$$\frac{d\alpha_p}{dt}=\frac{\langle F\cdot x_p\rangle\cdot\langle x_s^2\rangle-\langle F\cdot x_s\rangle\cdot\langle x_s\cdot x_p\rangle}{\langle x_s^2\rangle\cdot\langle x_p^2\rangle-\langle x_s\cdot x_p\rangle^2}$$

$$\frac{d\varepsilon_s}{dt}=-\frac{c(1+\varepsilon_s)}{n_{eff}}\left\{A_s+\frac{f_s(0)+f_s(L)}{L}+\Gamma_s\rho\langle\sigma_{g,s}\cdot f_s\rangle\right\}$$

$$A_s=-\left(\sigma_{a,s}+\sigma_{e,s}\right)\Gamma_s\rho\left\{\alpha_s\langle x_s^2\rangle+\alpha_p\langle x_s\cdot x_p\rangle\right\}$$

Relative intensity noise of DFB fibre laser (RIN_{laser}) is defined as $RIN_{laser}=\left\langle\Delta p_{out}^2\right\rangle/p_{out0}^2$ (Hz^{-1}), where $\left\langle\Delta p_{out}^2\right\rangle$ is the mean-square output laser power fluctuation (in a 1Hz bandwidth) at a specified frequency and p_{out0} the average output power. The relative noise (RN) is defined as: $RN = RIN_{laser} / RIN_{pump}$. The measured system noise (RIN_{sys}) includes RIN_{laser} plus thermal noise and shot noise in the receiver.

For simplicity, a white noise spectrum is assumed for the pump source with constant amplitude δ over the entire frequency range, which is in reasonable agreement with measurement of the pump spectrum.

Results and discussion

Parameters used in calculations, unless otherwise specified, are: $\rho=1.7\cdot 10^{25}m^{-3}$, $\tau_{21}=10^{-2}s$, $\sigma_{a,s}=1.85\cdot 10^{-25}m^2$,

$\sigma_{a,p}$=2.08 · $10^{-25}m^2$, $\sigma_{e,s}$=3.38 · $10^{-25}m^2$, $\sigma_{e,p}$=0.72 · $10^{-25}m^2$, A_{eff}=1.256 · $10^{-11}m^2$, Γ_s=0.77, Γ_p=0.79, $\delta=10^{-4}$, L=0.05m, n_{eff}=1.45, p_{pump0}=40mW. The coupled-mode calculations use a Bragg grating with coupling coefficient κ and a *4mm* long distributed π phase-shift at the centre, pump wavelength *1480nm* and lasing wavelength *1560nm*. All variables are initialised to the unperturbed steady-state solutions in calculations. The non-uniformity parameter σ_2 introduced in [3] can be calculated as the spatial variation of f_s : $\sigma_2 \equiv \langle f_s^2 \rangle - 1$.

Fig.1 shows that the relaxation frequency will be lower with higher grating coupling coefficient, which is the same as predicted for semiconductor lasers [3], and also lower with lower Er^{3+}-ion concentration. Further, the non-uniformity factor σ_2 increases and relative noise peak decreases with stronger grating, but they keep almostly constant with different Er^{3+}-ion concentrations. This is different from the highly concentration dependent noise characteristics in Fabry-Perot fibre lasers [2].

Fig. 1: Calculated variations of peak relative noise (RN), relaxation frequency f_r and non-uniformity factor σ_2 with <a> coupling coefficient κ (ρ=1.18 · $10^{25}m^{-3}$) and <b> Er^{3+}-ion concentration ρ (κ=130m^{-1})

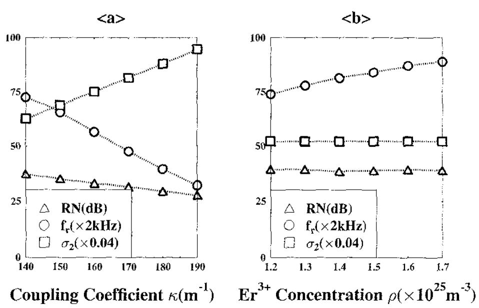


Fig. 2: Calculated and measured system relative noise (RN_{sys}) spectrums with 40mW pumping

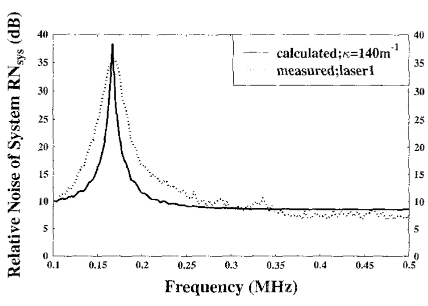
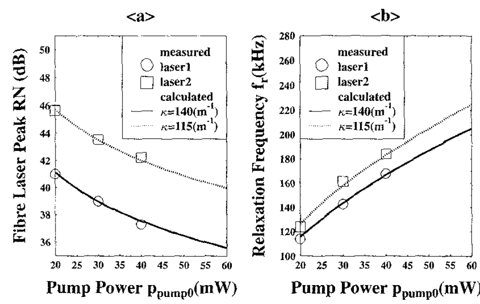


Fig.2 shows good agreement between the calculated and measured system relative noise RN_{sys} spectrums. The width of the measured noise peak is broader than the calculated, which may be due to the 10kHz resolution bandwidth of the measurement. In the calculation, it is supposed that the thermal noise is constant and dominates the system noise far from the noise peak.

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 <a> peak relative noise RN and <b> relaxation frequency f_r with pump powers p_{pump0}



Calculations also indicate that with moderate pump power fluctuation (δ <1%), the laser relative noise peak (RN) is independent on the fluctuation magnitude δ. 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.

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