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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 imply 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:

\[
\begin{align*}
\frac{dn}{dt} &= \frac{c}{\tau_s} \left( \Gamma_s n_s + \Gamma_x n_x \right) - \frac{n}{\tau_p} - \frac{n}{\tau_s} - \frac{n}{\tau_p} \\
\frac{dn}{dt} &= \frac{c}{\tau_s} \left( \Gamma_s n_s + \Gamma_x n_x \right) - \frac{n}{\tau_p} - \frac{n}{\tau_s} - \frac{n}{\tau_p} \\
\end{align*}
\]

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_s' and 'N_p', respectively. '\(\Gamma_s\)' is the Er\(^{3+}\)-ion cross-section, '\(\Gamma_x\)' the fibre confinement factor, '\(\Gamma\)' the fibre attenuation factor, '\(n_s\)' the Er\(^{3+}\)-ion inversion, '\(a\)' the photon density, '\(c\)' the speed of light in vacuum and '\(h\)' the Planck's constant. \(n_s\) and \(n_p\) 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 by 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.

\[
x(z,t) = x_s f_s(z) + a_s(t) x_s(z) + a_p(t) x_p(z)
\]

\[
n_s(z,t) = n_o (1 + e_s(t)) f_s(z), n_e(z,t) = n_o (1 + e_e(t)) f_e(z)
\]

\[
x_s(z) = \frac{\partial x_s}{\partial n_s}, x_e(z) = \frac{\partial x_e}{\partial n_e}
\]

The envelope functions \(f_s, f_p\) and \(f_e\), the average photon densities \(n_s\) and \(n_p\), and the average inversion \(n\), 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 \(<\cdot>\), we can normalise the envelope functions \(f_s, f_p\) and \(f_e\) as follows:

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

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

\[
\frac{dn}{dt} = \langle F \cdot x_s \rangle - \langle F \cdot x_p \rangle - \langle F \cdot x_e \rangle
\]

\[
\frac{dn}{dt} = \langle F \cdot x_s \rangle - \langle F \cdot x_p \rangle - \langle F \cdot x_e \rangle
\]

Relative intensity noise of DFB fibre laser (RIN_{laser}) is defined as

\[
RIN_{laser} = \langle \Delta P_{out} / P_{out} \rangle / \langle P_{out} \rangle (Hz^{-1}),
\]

where \(\Delta P_{out}\) 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:

\[
RIN = RIN_{laser} / RIN_{pump}
\]

Results and discussion

Parameters used in calculations, unless otherwise specified, are:

\[
p = 1.7 \times 10^{15} m^{-3}, \quad \tau_{p} = 10^{-4} s, \quad \alpha_{sp} = 1.85 \times 10^{7} m^{-1}, \quad
\]

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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 σ2 introduced in [3] can be calculated as the spatial variation of ∂x:

\[ σ_2 = (f_r') - 1. \]

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⁺⁺⁺⁺-ion concentration. Further, the non-uniformity factor σ2 increases and relative noise peak decreases with stronger grating, but they keep almost constant with different Er⁺⁺⁺⁺-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 σ2 with a) coupling coefficient κ (µ=1.18·10⁻⁵ m⁻¹) and b) Er⁺⁺⁺⁺-ion concentration nEr⁺⁺⁺⁺ (~130nm⁻³).

Fig. 2: Calculated and measured system relative noise (RNmeas) spectrums with 40mW pumping.

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.

References