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Theoretical and experimental investigation of the intensity response of DFB-FL to external acoustic excitation

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ABSTRACT

The intensity response of Distributed-Feedback fiber laser (DFB-FL) to external acoustic excitation has been investigated theoretically and experimentally. The transfer function for external acoustic excitation modulation has been obtained, and the intensity response characteristics of DFB-FL to external acoustic excitation are described by simulation. Through experiments we observe a signal of 16.5 kHz with 25 dB in the DFB-FL RIN spectrum as the external acoustic pressure is 10.25 Pa. The signal power obtained in time domain is 0.033 μW and acoustic pressure sensitivity which is calculated as −169.8 dB re μW/μPa at 16.5 kHz, which confirms that DFB-FL has the potential to be used as an intensity-type acoustic sensor.

1. Introduction

Distributed-Feedback fiber laser (DFB-FL) acoustic sensors have attracted much attention for more than 10 years and have found a number of potentially useful applications for its high-performance and miniaturization [1–3]. The DFB-FL relative intensity noise (RIN) plays an important role in determining the minimum detectable signal and has been investigated by many researchers [4–6]. Granch et al. have modeled the RIN of Er^{3+} doped DFB-FL according to the rate equations; the transfer functions for pump perturbation and loss modulation have been derived. Lina Ma et al. have modeled the RIN characteristics of DFB-FL with external laser injection, and the RIN enhancement for each sensing unit in the array could be evaluated exactly. Furthermore, the influence of external environment on DFB-FL characteristics calls for attention, which needs to be eliminated because the extra intensity introduced during exciting procedure can reduce accuracy and sensitivity of the sensors. When there is external acoustic excitation applied on the phase-shift grating, the fiber is physically lengthened or shortened due to the elasticity of the fiber, and the refractive index of the fiber is modified because of the photo-elasticity [7]. These two physical effects give rise to changes in both the Bragg reflection wavelength $\lambda_B = 2n_{eff}\Lambda$ and the DFB-FL output power fluctuation. As a result, the effect of external acoustic excitation modulation which may contribute significantly to the DFB-FL intensity should be analyzed and discussed. On the other hand, we could obtain the fixed external acoustic excitation signal intensity through the filtering system. It means that the DFB-FL has the potential to be used as an intensity-type acoustic sensor [8–9]. In the former work of our laboratory, we have done a lot of basic experimental research and parts of the experimental results have been published [10,12]. In this paper, we present the theoretical model of the intensity response of DFB-FL to external acoustic excitation firstly, and an experimental configuration is designed to demonstrate the intensity response. The acoustic pressure sensitivity at 16.5 kHz and the frequency response at frequencies ranging from 5 kHz to 16.5 kHz are obtained by experiments.

2. Theoretical model

The rate equations of an Er^{3+} doped DFB-FL can be given by Eq. (1) in terms of excited ion density n_2 and cavity photon density q [5]:

$$\frac{dn_2}{dt} = (W_P + W_a)(1-n_2) - n_2\left(W_e + \frac{1}{\tau_2}\right)$$
$$\frac{dq}{dt} = W_e n_2 N_0 - W_a(1-n_2)N_0 - \frac{q}{\tau_c} \tag{1}$$

where the pump absorption W_p, signal absorption W_a and signal emission W_e are denoted as

$$W_P = \Gamma_p \sigma_P P / A_c h\nu_P, \quad W_a = \sigma_a cq/n = qr_{qa}, \quad W_e = \sigma_e cq/n = qr_{qe} \tag{2}$$

Here $r_{qa} = \sigma_a c/n$, $r_{qe} = \sigma_e c/n$, and we define $\Delta r_q = r_{qa} + r_{qe}$. τ_c is the lifetime of laser photons within the cavity which can be expressed as $\tau_c = nl_e/c\gamma$, $\gamma = -\ln(1-4\exp(-\kappa l))$ is the cavity loss, and the other

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Table 1
Parameters and values.

symbol	Description	Value	Symbol	Description	Value
σ_p	Pump absorption cross section	2.15×10^{-25} m^2	τ_2	Lifetime of excited ions	0.0102 s
σ_a	Laser photon absorption cross section	2.8445×10^{-25} m^2	σ_e	Laser photon emission cross section	2.3793×10^{-25} m^2
l	Grating length	4.2 cm	N_0	Er^{3+} ions density	1.5×10^{25} m^{-3}
p	Pump power	80 mW	n	Refractive index	1.456
A_c	Pump mode effective area	16.62 μm^2	κ	Grating coupling coefficient	120 m^{-1}
l_e	Effective cavity length	$1/\kappa$	Γ_p	Pump overlap factor	1
P_{11}	Elasto-optical coefficient	0.121	P_{12}	Elasto-optical coefficient	0.27
E	Young's modulus	7×10^{10} N/m^2	μ	Poisson ratio	0.17

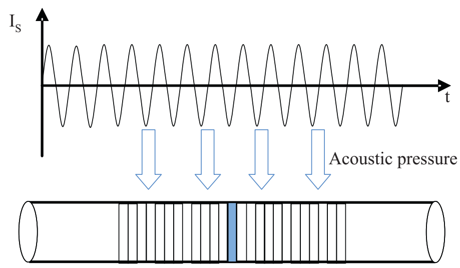

Fig. 1. Schematic diagram of DFB-FL with π phase shift under the effect of acoustic pressure.

parameters are shown in Table 1, the values of fiber parameters are quoted from Ref. [6]. The solution of Eq. (1) in steady state is obtained:

$$n_{20}=\frac{r_{qa}N_0+1/\tau_c}{\Delta r_q N_0},\quad q_0=\frac{\tau_c}{\Delta r_q}\left[W_{P0}N_0\Delta r_q-(r_{qa}N_0+1/\tau_c)(W_P+1/\tau_2)\right] \tag{3}$$

To investigate the intensity response of DFB-FL to external acoustic excitation, we suppose that an external acoustic sinusoidal pressure $P(t)$ operates on the DFB-FL. To make it simpler, the pressure is assumed to be uniform and the pressure frequency is far larger than the fiber grating period. Fig. 1 shows the schematic diagram of DFB-FL with π phase shift under acoustic pressure. Here we ignore the pressure induced phase change, and consider the fiber length and refractive index changes only. The perturbations added to the fiber length and refractive index are homogeneous along the cavity, expressed as $l(t)=l_0+\Delta l(t)$ and $n(t)=n_0+\Delta n(t)$. Here $\Delta l(t)$ and $\Delta n(t)$ are revealed as Eq. (4), and the parameters in the equations are given in Table 1.

$$\Delta l(t)=-\frac{(1-2\mu)P(t)l}{E},\quad \Delta n(t)=\frac{n^3P(t)(1-2\mu)(2P_{12}+P_{11})}{2E} \tag{4}$$

To determine the dynamic behavior of excited ion density n_2 and cavity photon density q, small perturbation terms are added to each relevant parameters such as $W_p(t)=W_{p0}+\delta W_p(t)$, $n_2(t)=n_{20}+\delta n_2(t)$, $q(t)=q_0+\delta q(t)$ and $\gamma(t)=\gamma_0+\delta\gamma(t)$ [5]. Substituting these into Eq. (1), removing the steady-state terms and retaining only first-order terms, we can get

$$\begin{aligned}\frac{d\delta n_2(t)}{dt}&=-\left(W_{p0}+\Delta r_{q0}q_0+\frac{1}{\tau_2}\right)\delta n_2(t)-(n_{20}\Delta r_{q0}-r_{qa0})\delta q(t)\\&\quad+(1-n_{20})\delta W_p(t)+((1-n_{20})q_0\sigma_a c-n_{20}q_0\sigma_e c)\delta n(t)\\\frac{d\delta q(t)}{dt}&=N_0\Delta r_{q0}q_0\delta n_2(t)+\left(n_{20}N_0\Delta r_{q0}-N_0r_{qa0}-\frac{\gamma_0 c}{n_0l_e}\right)\delta q(t)\\&\quad-\frac{cq_0}{n_0l_e}\delta\gamma(t)+(q_0N_0n_0(n_{20}\Delta r_{q0}-r_{qa0})-q_0\gamma_0c)\delta n(t)\end{aligned} \tag{5}$$

Here $\delta n(t)=-\Delta n(t)/(n_0(n_0+\Delta n(t)))$ is the refractive index perturbation. In the derivation process, the fiber length perturbation is ignored. Cavity loss modulation seems to be generated due to the fiber length perturbation by direct observation of the formula: $\gamma=-\ln(1-4\exp(-\kappa l))$. But in fact, the Bragg period is changed proportionally with the fiber length change. The grating coupling coefficient κ is inversely proportional to the Bragg period, so this means the coupling coefficient change is inversely proportional to the fiber length change. So in conclusion, the cavity loss γ would not change with the fiber length perturbation. And here in our theoretical derivation, we consider the refractive index perturbation only.

Taking the FFT transforms to both ends of Eq. (5), where $s=i2\pi f$ [6], we obtain

$$\begin{aligned}\frac{\Delta q(s)}{q_0}&=\frac{A_2A_4}{s^2+A_1s+A_3A_4-(A_3N_0+A_5)s-(A_3N_0+A_5)A_1}\frac{\delta W_p(s)}{W_{p0}}\\&\quad+\frac{A_5(s+A_1)}{s^2+A_1s+A_3A_4-(A_3N_0+A_5)s-(A_3N_0+A_5)A_1}\frac{\delta\gamma(s)}{\gamma_0}\\&\quad+\frac{A_4A_6+A_7(s+A_1)}{s^2+A_1s+A_3A_4-(A_3N_0+A_5)s-(A_3N_0+A_5)A_1}\frac{\delta n(s)}{n_0}\end{aligned} \tag{6}$$

where

$$\begin{aligned}&A_1=W_{p0}+\Delta r_{q0}q_0+1/\tau_2,\quad A_2=(1-n_{20})W_{p0}/q_0,\\&A_3=n_{20}\Delta r_{q0}-\Delta r_{qa0},\quad A_4=N_0\Delta r_{q0}q_0,\quad A_5=\frac{-\gamma_0c}{n_0l_e},\\&A_6=n_0\sigma_ac-n_{20}\Delta r_{q0}n_0^2,\quad A_7=N_0n_0^2(n_{20}\Delta r_{q0}-r_{qa0})-\gamma_0cn_0\end{aligned} \tag{7}$$

$H_p(f)$, $H_l(f)$ and $H_n(f)$ are defined as the transfer functions for pump power fluctuation, cavity loss modulation, and external acoustic excitation perturbation, respectively, and are expressed as

$$\begin{aligned}H_p(f)&=\frac{A_2A_4}{s^2+A_1s+A_3A_4-(A_3N_0+A_5)s-(A_3N_0+A_5)A_1}\\H_l(f)&=\frac{A_5(s+A_1)}{s^2+A_1s+A_3A_4-(A_3N_0+A_5)s-(A_3N_0+A_5)A_1}\\H_n(f)&=\frac{A_4A_6+A_7(A_1+s)}{s^2+A_1s+A_3A_4-(A_3N_0+A_5)s-(A_3N_0+A_5)A_1}\end{aligned} \tag{8}$$

The RIN of DFB-FL can be shown as [6]

$$RIN(f)=|H_p(f)|^2\frac{\delta W_p(f)^2}{W_{p0}^2}+|H_l(f)|^2\frac{\delta\gamma(f)^2}{\gamma_0^2} \tag{9}$$

The intensity response of DFB-FL to external acoustic excitation could be expressed as:

$$IR(f)=|H_p(f)|^2\frac{\delta W_p(f)^2}{W_{p0}^2}+|H_l(f)|^2\frac{\delta\gamma(f)^2}{\gamma_0^2}+|H_n(f)|^2\frac{\delta n(f)}{n_0} \tag{10}$$

The magnitude of transfer functions $H_p(f)$, $H_l(f)$ and $H_n(f)$ is plotted as shown in Fig. 2. The parameters used to generate Fig. 2 are given in Table 1. $H_p(f)$ and $H_l(f)$ contribute to the total RIN via Eq. (9), and $H_n(f)$ contributes to IR via Eq. (10). From the simulation, we observe that the effect of pump modulation is to drive the relaxation oscillation. The loss modulation is to significantly increase the RIN at frequencies around the relaxation oscillation and broaden the RIN peak. $H_n(f)$ exhibits the same profile as $H_l(f)$ but with higher magnitude, as indicated by Eq. (8), where $H_n(f)$ and $H_l(f)$ have similar expressions with very small differences lying in the numerator terms. And both of