

NUMERICAL ANALYSIS OF A DFB-FL SENSOR BY USING COUPLED-MODE EQUATIONS

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ABSTRACT: This paper is pointing to an investigation of various aspects of distributed feedback fiber laser sensors and their interaction with environment and of possible applications by numerically solving coupled-mode equations system describing the laser field propagation. The developed numerical analysis has the aim of a better understanding of DFB-FL itself and of its interaction with environment in order to be operated as a sensor. The main idea of the paper consists into investigating how various environment parameters modify the coefficients of coupled-mode equations describing laser field propagation through the DFB-FL structure. Basically, this is the key of understanding operation of DFB-FL sensors.
KEY WORDS: DFB-FL; sensor; coupled-mode equations; coupling coefficient; gain coefficient.

1. INTRODUCTION

Distributed feedback fiber lasers (DFB-FL) are optoelectronic devices with an increasing number of applications in various fields, being the subject of much research over the past ten years. They proved high reliability, fiber compatibility, high output power, narrow bandwidth good beam quality, low phase noise, and low relative intensity noise (RIN) [1-4]. DFB-FL can be designed with a grating structure to provide high output power (up to 60 mW), single frequency, single polarization and high optical signal-to-noise ratio. DFB-FLs have been widely used in sensing [5], communication systems [6-9], and high precision spectroscopy [10] all of which require single-mode, single-frequency lasers. A number of different active dopants, such as erbium, ytterbium, neodymium, and thulium, can be used in order to cover different windows of the optical spectrum and offer extended coverage.

Single polarization and narrow line bandwidth of DFB-FL lasers are very desirable for a large number of applications among which sensor systems are an important one [5]. Alternatively, DFB lasers can be made to operate in stable dual polarization regime, defined with respect to the induced spatial modulation of the core index of refraction (Bragg grating), so that simultaneous measurements can be carried out [6-8]. In addition to the sensing and telecommunication applications, DFB fiber lasers suitable for high-power applications have been demonstrated [9]. In order to obtain increased output power DFB-FL, doping levels have been increased to allow more pump light to be absorbed with the doping densities of commercial Erbium ($Er3^+$) and Ytterbium ($Yb3^+$) ions co-doped fibers. With the commercial availability of over 500 mW-pump single emissive structure diode lasers, the absorption transition inside doped optical fiber relative easy becomes saturated. The phenomenon of un-pumped lengths of optical fiber appearance is immediately implied. In this article, effect on output power and mode discrimination, pointing to the implications as sensor use. In the following sections several items of DFB-FL subject are investigated. A "conventional" model based on coupled-wave equations is sketched and applied to several cases of possible DFB-FL structures.

An accurate model of these types of lasers is very desirable since the simulations can reduce the design and development time and cost significantly. A model can also help to improve the physical insight on the device or system under investigation by allowing one to carry out calculations and hypothetical experiments, which in many cases can be extremely difficult in laboratory conditions. The full description of a fiber laser considering the phenomena developed in the active medium would include many linear and nonlinear equations. The second difficulty is the measurement of the actual values of the parameters and coefficients that appear in these equations [14 – 20].The solution of the ideal model with all the possible transitions is impractical. Therefore, in practice, the solution of complex active medium equations, whether it is an analytical or numerical solution, inevitably requires simplifications and approximations. Ignoring some of less significant transitions in the active medium, a set of equations reported to be successfully modeling the amplifier regime [14] and purely theoretical works investigating the implications of these simplifications have been reported [15,16]. An important part of such an improved accuracy numerical simulation model will be dedicated to the investigation of pumping and output beams propagation along the optic fibre defining the active medium volume. One reason for which fibre laser are preferred against other laser types consists in their high ratio output power versus pumping. A small volume of fibre laser active medium can be obtained by using coils of doped optic fibre. Bending loss of laser power induced into the optic fibre become of importance in order to achieve a proper simulation and design of fibre lasers. In this paper preliminary results obtained in investigating the laser field propagation through non-deformed and deformed optic fibre are presented. Symmetrical deformation of optic fibre should be considered in order to simulate its bending at microscopic scale (micro-bending).

In this article, a first stage results obtained by numerical simulation of effects of gain apodization in DFB-FL are presented. At a first glance, the impact on threshold behavior of DFB-FL structure is explored along with its effect on output power and mode discrimination, pointing to the implications as sensor use. In the following sections several items of DFB-FL subject are investigated. A "conventional" model based on coupled-wave equations is sketched and applied to several cases of possible DFB-FL structures. The physics of gain apodization in DFB lasers is necessarily studied and a comparison with conventional configurations is performed.

The impact of gain apodization on phase-shifted DFB fiber lasers is investigated; lasing thresholds and the output power ratio from both ends of the fiber lasers are analyzed; and, finally, techniques for using gain apodization as an optimization tool are discussed.

2. THEORY

Distributed feedback laser action is made by the presence of periodic perturbations in the gain medium that provide feedback by backward Bragg scattering, as is presented schematically in Fig. 1 [11-13]. Instead of the conventional cavity mirrors, the feedback for lasing oscillation was provided via backward Bragg scattering in periodic structures. As a result, the DFB structures are compact and provide a spectral selection of high degree. The periodic perturbations can be realized from the spatial modulation of the refractive index or gain, or a combination of both. In a waveguide structure, such as a single mode optic fiber a periodic change of the refractive index was also proven effective in producing DFB laser action [13]. The periodic perturbations can be permanent or transient, with the transient effect often produced by crossing two beams from the output of the same laser to generate a concentration grating [11,12]. The linear coupled-wave model based on the scalar wave equation developed by Kogelnik and Shank is described in this paper [11-13].

Also, it has to be considered the fact that the starting point of a model describing DFB-FL structures consists of the problem of a mode propagating on a straight fiber or waveguide fabricated from non-absorbing, non-scattering materials will in principle propagate indefinitely without any loss of power. However, if a bend is introduced, the translational invariance is broken and power is lost from the mode as it propagates into, along and out of the bend. This applies to the fundamental mode in the case of single-mode fibers and waveguides and to all bound modes in the case of bent multimode fibers or waveguides.

Fig. 1 shows a simplified illustration which demonstrates the oscillation mechanism of a DFB structure. There are two waves in the diagram represented by arrows, one of which travels to the left and the other to the right. As each wave travels in the periodic structure, it receives light at each point along its path by Bragg scattering from the oppositely traveling wave. This creates a feedback mechanism which is distributed throughout the length of the periodic structure. So we name it as "distributed feedback". Since the periodic structure has gain, with sufficient feedback, there will be a condition for laser oscillation. Also, spectral selection occurs due to the wavelength sensitivity of the Bragg effect.

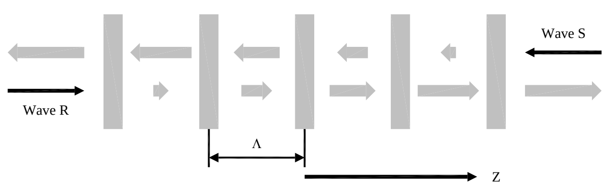

Figure 1. Schematic representation of the oscillation mechanism of a DFB structure. Wave R - left-to-right propagating wave, Wave S - right-to-left propagating wave, Λ - Bragg grating wavelength, Z – propagation coordinate [13].

Coupled-wave theory of DFB lasers is a linear theory. A linear analysis is made to describe the modes of a DFB structure, and to predict the resonant frequencies, the corresponding threshold gain and the spectral selectivity. Nonlinear effect such as gain saturation is not considered. The model is based on the scalar wave equation for the electric field:

$$\frac{\partial^2}{\partial z^2}E + k^2 E = 0 \tag{1}$$

where E is the complex amplitude of a field of angular frequency ω, which is assumed to be independent of the x and y coordinates. The constants of the laser medium are also independent of x and y, but vary periodically as a function of the **z** coordinate, which points in the direction of propagation (figure 1). The index of refraction and gain coefficient are considered as constant in planes transverse to the direction of propagation, being independent of the x and y coordinates and having only on the z coordinate [5,8-9, 12-16]:

$$\begin{aligned} n(z) &= n + n_1\cos(2\beta_0 z) \\ \alpha(z) &= \alpha + \alpha_1\cos(2\beta_0 z) \end{aligned} \tag{2}$$

In equation (2) n and α are the constant values of the refractive index and respectively of the gain coefficient, n_1 and α_1 are the amplitudes of the z modulation and β_0 is the propagation constant defined as:

$$\beta_0 = \frac{n\omega_0}{c} \tag{3}$$

In principle, a periodic perturbation of the medium generates an infinite set of diffraction orders. But in the vicinity of the Bragg frequency only two orders are in phase synchronism and of significant amplitude. All other orders are neglected in the coupled-wave model [11-13]. As indicated in figure 1, the two significant waves in the DFB structure are two counter-propagating waves R and S. These waves grow because of the presence of gain and they feed energy into each other due to Bragg scattering. We describe these waves by complex amplitudes $R(z)$ and $S(z)$, and write the electric field as the sum:

$$E(z) = R(z)\cdot\exp(-j\beta_0 z) + S(z)\cdot\exp(j\beta_0 z) \tag{4}$$

In view of equation (4) these amplitudes are varying slowly with the z coordinate so that their second derivatives can be neglected. The complex waves $R(z)$ and $S(z)$ have real and imaginary parts which have to satisfy the time stationary simultaneous coupled differential equations:

$$\begin{aligned} \frac{d}{dz}R_{re}(z) &= \alpha R_{re}(z) - \delta R_{im}(z) - \kappa_{re}S_{im}(z) - \kappa_{im}S_{re}(z) \\ \frac{d}{dz}R_{im}(z) &= \alpha R_{im}(z) + \delta R_{re}(z) + \kappa_{re}S_{re}(z) - \kappa_{im}S_{im}(z) \\ \frac{d}{dz}S_{re}(z) &= \alpha S_{re}(z) - \delta S_{im}(z) + \kappa_{re}R_{im}(z) - \kappa_{im}R_{re}(z) \\ \frac{d}{dz}S_{im}(z) &= \alpha S_{im}(z) + \delta S_{im}(z) - \kappa_{re}R_{re}(z) - \kappa_{im}R_{im}(z) \end{aligned} \tag{5}$$

Index re denotes the real parts and index im denotes the imaginary parts of complex wave $R(z)$ and $S(z)$. κ represents the coupling coefficient of the complex waves and the Bragg grating, re and im denoting its real and imaginary parts. α and δ denote the real and imaginary parts of the gain coefficient [18-23].

The use of a DFB-FL structure as a sensor for various environment parameters basically relies on gain and/or coupling coefficients variations. It appears as a logical observation that solving the simultaneous coupled differential equations (5) for different combinations of gain and coupling coefficients can show how good the structure as a sensor is. The apparatus of coupled differential equations (5) can be applied to several cases of possible DFB-FL structures with different doping type [14-18].

3. NUMERICAL SIMULATION RESULTS

The system of simultaneous coupled differential equations is numerically solved using Runge-Kutta-Felhberg-45 algorithm considering boundary conditions. A regular DFB-FL structure is considered. The case of Erbium (Er^{3+}) doped optic fiber is investigated. The gain coefficient is defined on the basis of fiber laser analysis. The gain coefficient does not depend on the pumping wavelength (980 nm or 1480nm). The integration z coordinate was varied between 0 and 50 mm, a common value of commercial fiber Bragg grating length. The system of differential equations (5) is solved considering different real and imaginary parts of α and κ coefficients.

The boundary conditions were considered as:

$$
\begin{aligned}
R_{re}(0) &= 0 \\
R_{im}(0) &= 0 \\
S_{re}(0) &= \frac{\sqrt{L}}{2} \\
S_{im}(0) &= \frac{\sqrt{L}}{2}
\end{aligned}
\qquad (6)
$$

First we studied the sensitivity of the sensor to gain coefficient α variations. The coupling coefficient κ and gain coefficient δ were kept constant, at values $\kappa_{im} = \kappa_{re} = 150$ and $\delta = 2$. The complex wave amplitude $R(z)$ and $S(z)$ for two very different values of gain coefficient α ($\alpha = 5$ and $\alpha = 0.5$) along the Bragg grating length is shown in figure 2. A measure of the sensitivity of the sensor to gain coefficient variations is the maximum of the $S(z)$, reached for $z = 0$.

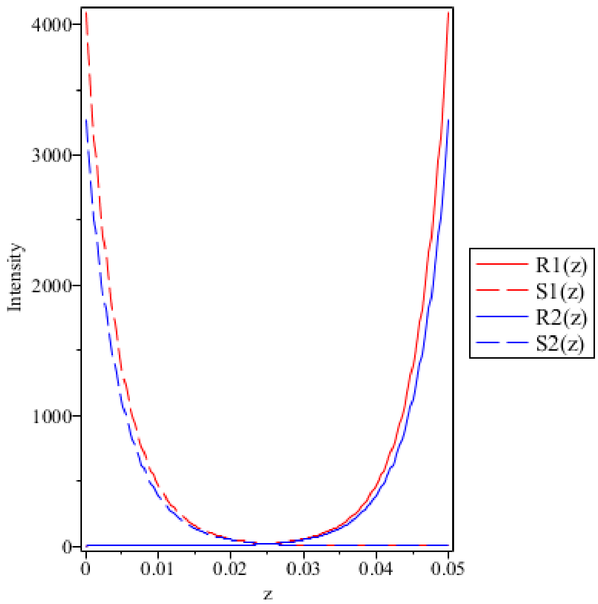

Figure 2. The complex wave amplitude $R(z)$ and $S(z)$ for two values of gain coefficient α. R1(z) and S1(z) correspond to $\alpha = 5$, and R2(z) and S2(z) correspond to $\alpha = 0.5$.

Secondly we studied the sensitivity of the sensor to the coupling coefficient variations. The gain coefficient was kept constant, at values $\alpha = 0.5$ (real part) and $\delta = 5$ (imaginary part). The complex wave amplitude $R(z)$ and $S(z)$ for different values of the coupling coefficient κ along the Bragg grating length is shown in figure 3. A measure of the sensitivity of the sensor to coupling coefficient variations is the maximum of the $S(z)$, reached for $z = 0$.

Table 1. The sensitivity of the sensor to gain coefficient variations ($S(0)$ vs. α).

α	δ	κ	$S(0)$
5.0	2.0	150.0	4101.111
0.5	2.0	150.0	3274.804

Table 1 summarizes the calculated values of $S(0)$ for the two values of gain coefficient α. As can be remarked, the variation is very slow, so it is not a suitable idea to make a sensor sensitive to DFB-FL gain variation.

Table 2. The sensitivity of the sensor to coupling coefficient variations ($S(0)$ vs. κ).

α	δ	κ	$S(0)$
0.5	5.0	50.0	2.784
0.5	5.0	100.0	95.438
0.5	5.0	120.0	392.562
0.5	5.0	130.0	796.16
0.5	5.0	140.0	1614.704
0.5	5.0	150.0	3274.804

Table 2 summarizes the calculated values of $S(0)$ for some values of coupling coefficient κ. This time the variation is steep, a sensor can be built on this property. This indicates that Bragg wavelength modifications are much more important than other DFB-FL structure parameter variations and hence for their use as sensors.

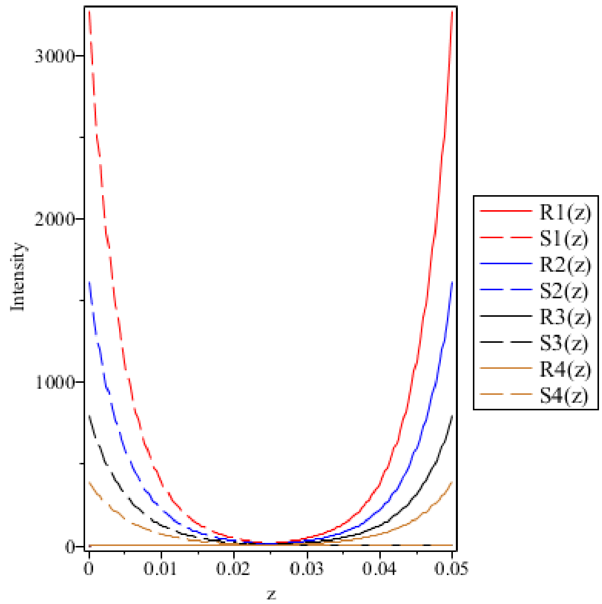

Figure 3. The complex wave amplitude $R(z)$ and $S(z)$ for four values of coupling coefficient κ. R1(z) and S1(z) correspond to $\kappa = 150$, R2(z) and S2(z) to $\kappa = 140$, R3(z) and S3(z) to $\kappa = 130$ and R4(z) and S4(z) to $\kappa = 120$.

4. CONCLUSIONS

The numerical simulation results presented in this paper are aiming to investigate the possible use of DFB-FL structures as sensors relying on certain internal parameter modification under the environment influence. The most important result of the performed numerical simulations is that use of coupling coefficient variations is more suitable than other DFB-FL parameters for design and construction of sensors relying on DFB-FL structures.

The main result of the presented theoretical analysis consists in the following conclusions, regarding the aeronautical application of interest: Depending on the magnitude of environment parameters to be observed, the pumping wavelength is chosen, in order to define a domain of linear response of the sensor covering the maximum value of the input environment parameter. In this sense the presented results are more than acceptable.

Depending on the magnitude of environment parameters to be observed, the pumping power level is set at an optimum such that noise due mainly to ASE is kept at an acceptable level.

An important factor of the performed analysis is the "time response" of the active FBG, meaning if there are disturbances of the sensor output signal regarding the time scale of environment parameters variations.

In this sense, the results presented illustrate that the active FBG acts like a high fidelity recorder, its characteristic times being much shorter than the observed pressure variations.

The presented preliminary theoretical analysis will be further developed pointing for various new aeronautic applications.

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