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Theoretical investigation of active fiber Bragg grating

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Abstract

Active uniform fiber Bragg grating (FBG) written in the Er-doped or Er:Yt-co-doped fiber is theoretically investigated. We found that when pumped, two symmetric maximums arise in the reflectivity spectrum of such an FBG near the edges of its bandwidth. By increasing the pumping rate these peaks grow, and at a critical pumping value they diverge, which indicates lasing onset at wavelengths that correspond to the peaks. By further increasing pumping, lasing ceases at the first wavelengths and begins at another pair of wavelengths. Thus, lasing wavelengths change through a set of discrete values depending on the pumping rate. At the same time, conventional negative phase slope of reflective function becomes positive in the regions around the lasing wavelength. Proposed active FBG can serve as a narrowband filter or multi-wavelength switchable laser in DWDM technique. Positive phase slope in such active FBG can be used in novel approaches to increase the performance of interferometric sensors.

Keywords: Fiber lasers; Bragg gratings; DWDM technique; Phase slope

1. Introduction

Doping of an optical fiber core with rare-earth ions gives both a low propagation loss and interesting laser properties. Many configurations of fiber lasers using FBG were proposed and investigated [1]. The ability to incorporate gratings within the doped fiber with low loss, wavelength selectivity, and insensitivity to outside perturbations has revolutionized fiber laser technology. Distributed feedback (DFB) lasers using UV-written FBG on doped fibers feature highly stable frequency and high power operation, thus they are promising for applications in optical fiber communications as well as fiber sensor systems [2,3]. Different modifications of these lasers have been investigated, based on the conventional lasing scheme of an active medium between two FBG, serving as the mirrors. In this paper, we investigate a new variant of fiber laser, which is based on uniform FBG written in the rare-earth-doped fiber, and show that under certain values of pump rate the FBG becomes a laser, emitting at wavelengths from a set of discrete wavelengths. The calculations are carried out by coupled mode equations (CME) method [4], which is the conventional tool for FBG investigations.

2. Principal expressions

According to CME method, the electric field E of the light in FBG is expressed as the sum of two

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counter-propagating waves (modes) with slowly varying amplitudes as follows:

$$E = u(z)\exp(\mathrm{i}kz) + v(z)\exp(-\mathrm{i}kz). \tag{1}$$

Here $k = \omega n_{\mathrm{eff}}/c$, $n_{\mathrm{eff}} = n + \mathrm{i}\alpha$, c is the speed of light in vacuum, α is a coefficient describing either absorption if $\alpha > 0$, or gain when $\alpha < 0$ under the influence of external pump. Refractive index n changes within the FBG (in region $0 < z < L$) as

$$n = n_0\left(1 + \frac{\Delta n}{2}\cos(2\pi z/\Lambda_{\mathrm{B}})\right). \tag{2}$$

Here Δn is the depth of refractive index modulation, Λ_{B} is Bragg wavelength.

Functions $u(z)$ and $v(z)$ describe amplitudes of counter-propagating modes, satisfying the following CME:

$$\begin{aligned} \frac{\mathrm{d}u}{\mathrm{d}z} &= \mathrm{i}\mu q v\exp(-2\mathrm{i}Kz), \\ \frac{\mathrm{d}v}{\mathrm{d}z} &= -\mathrm{i}\mu q u\exp(2\mathrm{i}Kz), \end{aligned} \tag{3}$$

where $q = \omega(n_0 + \mathrm{i}\alpha)/c$, $K = q - \pi/\Lambda_{\mathrm{B}}$, $\mu = \Delta n/4$.

In the case of a nonuniform FBG, where μ or Λ_{B} are not constant quantities but depend on z, these equations have no exact analytical solution. However, several useful asymptotic approaches (WKB approximation [5] and the more advanced R approximation [6]) and numerical methods for their evaluation have been developed. In our case of a uniform FBG the depth of refractive index modulation Δn and its period Λ_{B} are assumed to be constant quantities, i.e., we consider the FBG without chirp and apodization. In this case, the solution of CME (3) is obtained exactly analytically, that result to the following expression for reflective function r of FBG:

$$\begin{aligned} r \equiv R\mathrm{e}^{\mathrm{i}\varphi} &= \frac{v(0)}{u(0)} \\ &= -\frac{\mu q(1 - \exp(2\mathrm{i}QL))}{Q + K + (Q - K)\exp(2\mathrm{i}QL)}, \end{aligned} \tag{4}$$

where $Q = (K^2 - \mu^2 q^2)^{1/2}$, $R = |r|$, $\varphi = \arg(r)$.

3. Calculation results and discussions

Reflective function of FBG has been investigated by numerical evaluation of (4). For several values of gain coefficient α reflectivity R spectrum was calculated (Fig. 1). As it is seen, when α becomes negative (it means that a pump is applied) two symmetrical maximums near the edges of FBG reflection band arise. These maximums grow when pumping increases. In this case, the active grating becomes a narrowband filter, or amplifier. This phenomenon was described earlier in [7] and proposed for the implementation in the OCDMA coder and decoder [8]. The locations of the maximums are coincident with the grating transparency points with small shift toward the central wavelength. The dependence of maximum reflectivity on the gain coefficient is shown in Fig. 2. When α reaches some threshold, the reflectivity diverges, which indicates the onset of lasing in two symmetrical wavelengths. Further increase of the pump rate ceases lasing, causing it to resume at another pair of wavelengths. Three-dimensional image in Fig. 3 clearly shows this behavior of reflectivity spectrum proving that an active FBG has a discrete spectrum of lasing wavelengths. Hence, by choosing an appropriate value of pump rate, one can obtain a desirable lasing wavelength within a set of discrete values. This is the main distinguishing feature of the proposed laser in comparison with earlier investigated DFB lasers. Such kind of behavior of lasing wavelengths upon pumping rate can be explained qualitatively as follows. The lasing is possible when the gain is above the minimum value necessary in power consideration, and when the phase advance of the waves along FBG is equal to integer number of π.

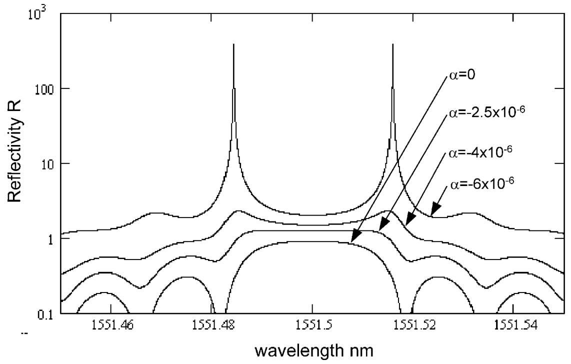

Fig. 1. Evolution of reflectivity spectrum. $L = 2$ cm, $\mu = 0.00005$.

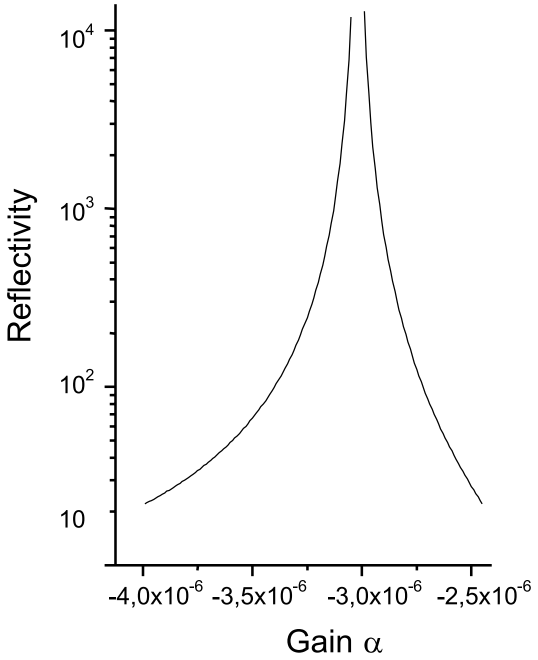

Fig. 2. Maximum reflectivity versus gain α. $L = 3$ cm, $\mu = 0.000025$.

These two conditions can be satisfied together in discrete values of wavelength. Suppose that by increasing of the gain the first lasing wavelength is reached. Further increase of gain changes the phase advance, because phase velocity of coupled modes depends on both real and imaginary parts of refractive index. As a result, phase condition is violated and therefore the lasing ceases. Next lasing arises at the gain value when the phase advance in some other point converges again to integer π.

Figs. 1 and 3 show that the increase of pump rate results in inversion of the reflectivity spectrum, i.e., the minimums become maximums and vice versa. The approximate values of lasing wavelengths are found from (4), where transparency points are determined by the condition Re $(QL) = \pi m$, $m = 1, 2\ldots$

$$\Lambda_m \approx 2n_0\Lambda_{\mathrm{B}}\left(\frac{1-\mu}{1 \pm \sqrt{\mu^2 + (m\Lambda_{\mathrm{B}}/L)^2}}\right). \qquad (5)$$

Actually, the lasing wavelengths are slightly shifted from transparency points in direction of the central wavelength. The value of α that provides lasing depends on the FBG length and modulation depth. The stronger the FBG, the lower the gain required for lasing (Fig. 4). For convenience, the values of α can be expressed using the intensity amplification A of 1 m of that fiber from which the FBG was made, by using the formula:

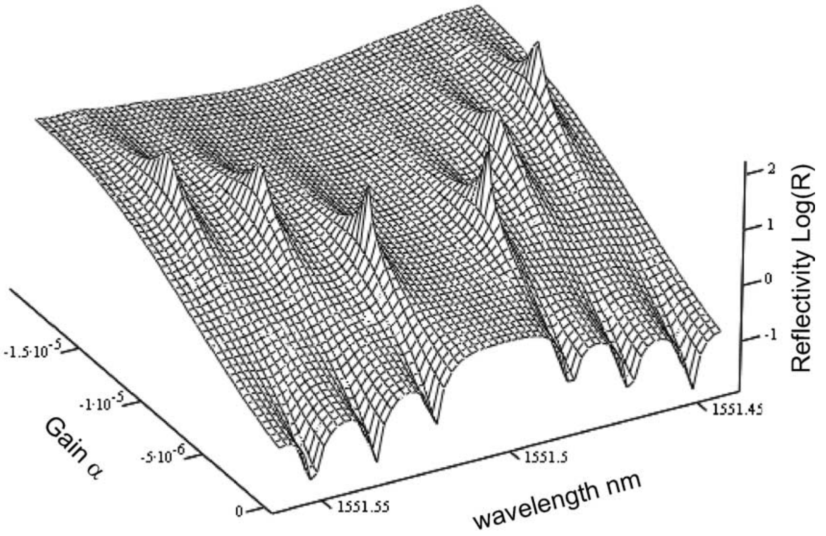

Fig. 3. Reflectivity evolution versus gain and wavelength. $L = 5$ cm, $\mu = 0.000005$.

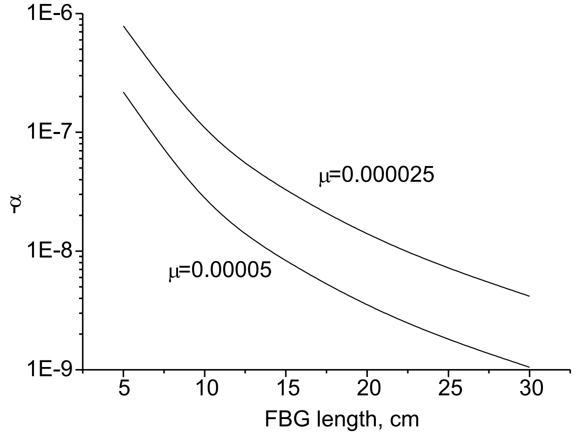

Fig. 4. The values of gain providing lasing versus FBG length.

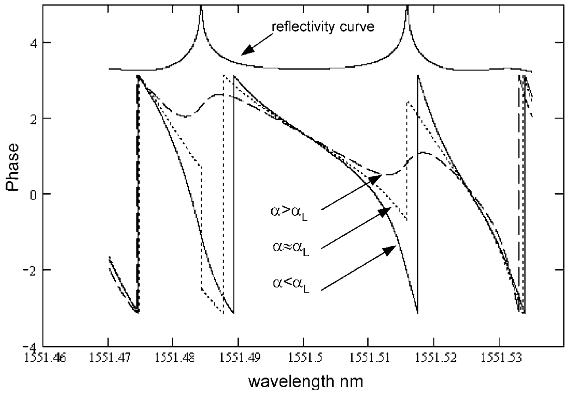

Fig. 5. Behavior of phase spectrum around lasing point.

$$A\ (\mathrm{dB/m}) = 20\,\lg\left(\exp(-2\pi\alpha/\Lambda)\right) \approx -3.5\times10^{7}\alpha. \tag{6}$$

Then, for example in an FBG with length 5 cm and refractive index modulation depth $\Delta n = 0.0002$, the first two symmetrical lasing wavelength arise when $\alpha = -2\times10^{-7}$, which correspond to the amplification value ≈ 7 dB/m.

Along with investigations of reflectivity the detailed analysis of reflective function phase spectrum has been carried out. Calculations show that the phase slope $\partial\varphi/\partial\Lambda$ is everywhere negative if the gain is small, then it becomes steeper when the gain increases, tending to the lasing value of gain α_L, and becomes positive around the first lasing wavelengths if gain exceeds the value needed for lasing (Fig. 5). Then new regions with positive phase slope are originating when pumping continue to increase as it is clearly seen in Fig. 6. Note that conventional gratings always manifest the negative phase slope independently of the sign of chirp. Positive phase slope (or negative phase slope with respect to frequency) is a rather unusual

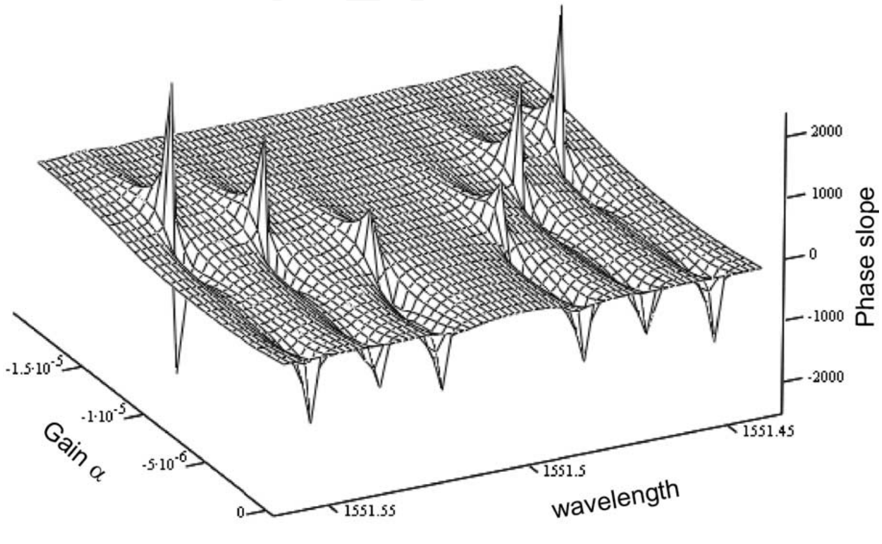

Fig. 6. Phase slope evolution versus gain and wavelength, $L = 5$ cm, $\mu = 0.000005$.

property, leading to some unique phenomenon, which has recently drawn much interest. For example, in a medium with positive phase slope a superluminal propagation of a pulse amplitude has been experimentally observed [9,10]. Positive phase slope is the crucial item as well in the novel method proposed to increase the performance of interferometric sensors used for detecting extremely small displacements and rotation rates [11,12].

4. Conclusions

Rare-earth-doped uniform FBG becomes a laser when pumped with a definite pump rate. The stronger is the FBG, the lower is the required pump rate. By choosing an appropriate value of pump rate, one can obtain a desirable lasing wavelength within the set of their discrete values. Such a laser can be used in a DWDM technique as a booster with controlled lasing wavelengths, and as a dual wavelength source for frequency shift keying (FSK). Phase slope of the reflection function at small pumping is negative. By increasing the pump, phase slope increases and then converts to positive value. Such positive phase slope can be used in novel experiments of superluminal propagation of pulse amplitude as well as in the novel method increasing the performance of interferometric sensors. Over the last years several methods have been studied to provide multi-wavelength sources for WDM applications. Much effort has been focused on dual and multiple wavelength operation with the self-seeding approach, based on wavelength selection in FBGs [13]. In this regard, the proposed dual wavelength fiber laser can play an important role as the number of channels increases. FSK modulation versus traditional amplitude shift keying (ASK) can achieve smaller channel spacing [14] and consequently higher channel number in DWDM systems. FSK prevents laser chirp, which have a destructive effect on dispersion in long haul networks [15,16], and proposed dual wavelength laser source can be a good choice for those purposes.

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