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Continuous tuning of radiation frequency in fibre and waveguide lasers by a controllable Bragg grating

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***Abstract*.** **A method for fast radiation wavelength tuning is proposed for a single-frequency fibre laser. A diffraction grating written on a waveguide electrooptical modulator serves as the mirror of the external cavity and as the selector. The voltage supplied to the grating electrodes shifts the reflection band of the grating and hence tunes the emitted radiation range. The radiation frequency tuning within the grating reflection band is carried out by using an intracavity waveguide electrooptical cell. The spectral characteristics of laser radiation are calculated. It is shown that the tuning range of such a laser achieves 0.2 nm for a control voltage up to 5 V, the switching time being shorter than 0.7 ns.**

Keywords: *fibre Bragg grating, waveguide electrooptical modulator, waveguide and fibre lasers.*

1. Introduction

Compact tunable lasers have found wide applications in fibreoptic communication and sensing systems and other devices. The most suitable for such applications are fibre lasers doped with rare-earth (e.g., erbium) ions, in which a fibre diffraction (Bragg) grating (FBG) [1 – 5] is used as a selector. It is known that at a certain wavelength, coupling between the modes propagating in the forward and backward directions occurs in a FBG, and its reflectivity has a maximum in a narrow spectral interval (of the order of fractions of a nanometer). The wavelength corresponding to the maximum reflectivity depends on the FBG parameters. Therefore, the region of maximum reflectivity of the grating can be shifted by varying the grating parameters, thus tuning the frequency of laser radiation.

The spectral interval between the lasing modes is described by the expression

$$\delta\nu = \frac{c}{2nL}, \tag{1}$$

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where L is the laser cavity length, n is the refractive index, and c is the velocity of light. To perform continuous tuning (or, at least, tuning with a small step) from one mode to another, lasers with long cavities are required [4]. However, the radiation line width for such lasers is determined by the transmission band of the fibreoptic grating and contains many spectral components. Such a laser is not a single-frequency device, which limits its application (especially in spectroscopic measurements).

Fibre lasers with a short linear cavity are more suitable from this point of view [1 – 3]. The optical feedback in such lasers is usually realised by using either reflecting mirrors, or fibre diffraction gratings. In the latter case, the laser linewidth is limited and the wavelength is tuned with the help of a FBG written directly in the fibre. In the case of a small cavity length (of the order of 0.5 – 2 cm), the FBG reflection band contains from one to three longitudinal modes on which lasing takes place. Note that the small cavity length increases lasing stability.

However, pump radiation has no time for being absorbed significantly in a short segment of the fibre and, hence, the output power of such a laser is low [1, 6]. An increase in the Er ion concentration makes it possible to increase the absorption of pump radiation, but the ion – ion interaction for a concentration exceeding $(3-4)\times10^{24}$ ion m^{-3} leads to degeneracy of the metastable Er level and lowers the lasing efficiency [7]. This difficulty can be overcome by using optical fibres doped simultaneously by Er and Yb ions with optimal concentrations [1, 2, 8].

Another disadvantage of short-cavity lasers is that it is impossible to tune them continuously because of a large intermode interval. By varying the FBG parameters, we can only switch lasing from one cavity mode to another with a step defined by expression (1). In addition, the switching time in such systems achieves several milliseconds because the laser is tuned by changing the FBG parameters mechanically [3] or with the help of the piezoelectric effect [4].

Lasers are usually continuously tuned by varying the parameters of the external cavity, for example, its length. In Ref. [9], a tunable laser with an electrooptical cell in the external cavity was considered. A bulk diffraction grating was used as a mirror in the external cavity. When voltage was applied to the electrooptic crystal, the optical length of the cavity changed, leading to the laser tuning. To change the optical length of the cavity (the tuning range) significantly, a control voltage of the order of 400 V is required. A similar approach was also used in a fibre laser with a ring cavity [10] in which an electrooptical phase modulator was used for fast frequency tuning.

In this paper, we propose an intracavity electrooptical cell in the form of a waveguide modulator to be used for fast continuous and controllable wavelength tuning of radiation emitted by fibre and waveguide lasers. Such a cell makes it possible to tune the laser radiation wavelength within the FBG reflection bandwidth. The range of controllable wavelength tuning can be increased by using a diffraction grating with a tunable reflection band, which is also written on the waveguide electrooptical modulator.

2. Structure and spectral characteristics of a laser

Fig. 1 shows the scheme of a continuously tunable fibre laser. The principal elements of the laser are a piece of an optical fibre doped with Er and Yb ions and an electrooptical waveguide doped with lithium niobate. One of the cavity mirrors is a broadband FBG written on the doped optical fibre. The variations of the effective refractive index of the order of 5×10^{-3} that can be induced in the photosensitive fibre doped with Er and Yb ions makes it possible to obtain a FBG with a reflectivity exceeding 99 % for a fibre length of 1 cm [2].

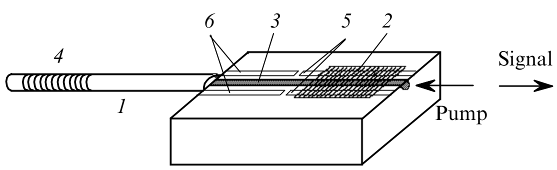


Figure 1. Scheme of a tunable single-frequency fibre laser: (*1*) Er-doped optical fibre, (*2*) controllable waveguide Bragg grating, (*3*) intracavity electrooptical cell, (*4*) cavity mirror (FBG), (*5*, *6*) electrodes of FBG and electrooptical cell.

A Bragg grating written at one end of the electrooptical waveguide serves as the cavity mirror. The other part of the waveguide is inside the cavity and is used as an electrooptical cell. Two systems of electrodes are deposited on the electrooptical waveguide. The continuous tuning within the FBG reflection band is performed by applying a voltage to the electrodes of the intracavity electrooptic cell. The tuning range can be increased by applying the voltage to the electrodes of the diffraction grating, which shifts its reflection band.

It is expedient to use an apodized waveguide diffraction grating as a narrow-band cavity mirror. The amplitude of variation in the waveguide refractive index changes along the axis of an apodized FBG, resulting in the suppression of the side peaks of the reflection function [11]. The spectral dependence of the reflectivity of an apodized grating written on the waveguide electrooptical modulator based on a lithium niobate crystal was calculated using the line method [12, 13] for various values of the applied electric field. The period of a grating with a bell-shaped apodization function was 0.335 μm and its length was approximately 1 cm. The width of the principal reflection maximum of such an FBG was 0.1 nm. Therefore, as follows from expression (1), the cavity length required for single-frequency operation of the laser should be approximately 0.9 cm.

Fig. 2 shows the spectral characteristics of radiation emitted by a tunable fibre laser with a controllable FBG and an electrooptical cell. One can see that an applied voltage leads to a continuous shift of the emission line of the fibre laser towards shorter wavelengths. At a voltage of 5 V across the electrodes of the intracavity cell and of the FBG the emission wavelength shifts by more than 0.2 nm.

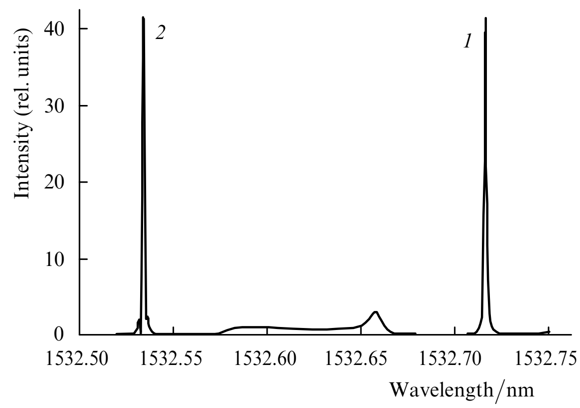


Figure 2. Emission spectrum of a fibre laser in the absence of a voltage across the electrodes of FBG and intracavity cell (curve *1*) and for a 5-V voltage (curve *2*).

3. Lasing dynamics

One of the most important characteristics of a tunable laser is the time of switching to another wavelength. Because we use a waveguide electrooptical modulator with a low control voltage (the time of variation of the refractive index in the lithium niobate crystal under the action of the electric field is of the order of 10^{-12} s), the time of laser switching to another wavelength is limited only by the time of lasing stabilisation. Thus, the tuning rate can be estimated by analysing the lasing dynamics.

Lasing transient dynamics was calculated with the help of a theoretical model for an Er/Yb doped fibre laser with a linear cavity, which is based on the rate equations [1, 14]. The variation in the pump power $P_{\rm p}(z, \nu_{\rm p})$ and the power $P_{{\rm s}j}^{\pm}(z, \nu_{{\rm s}j})$ of stimulated radiation over the length of the laser cavity is described by the system of differential equations:

$$\frac{{\rm d}P_{\rm p}(z,\nu_{\rm p})}{{\rm d}z} = -\Gamma_{\rm p}\left[\sigma_{13}^{\rm Er}\bar{n}_1 + \sigma_{56}^{\rm Yb}\bar{n}_5 - \sigma_{65}^{\rm Yb}\bar{n}_6\right] \times P_{\rm p}(z,\nu_{\rm p}) - l_{\rm p}P_{\rm p}(z,\nu_{\rm p}),$$

$$\frac{{\rm d}P_{{\rm s}j}^{\pm}(z,\nu_j)}{{\rm d}z} = \pm\Gamma_{{\rm s}j}\left[\sigma_{21}^{\rm Er}(\nu_j)\bar{n}_2 - \sigma_{12}^{\rm Er}(\nu_j)\bar{n}_1\right]P_{{\rm s}j}^{\pm}(z,\nu_j) \pm 2h\nu_j\Delta\nu_j\Gamma_{{\rm s}j}\sigma_{21}^{\rm Er}(\nu_j)\bar{n}_2 \mp l_{{\rm s}j}P_{{\rm s}j}^{\pm}(z,\nu_j) \qquad (2)$$

with the initial and boundary conditions

$$R_2(\nu_j)P_{sj}^{+}(L,\nu_j) = P_{sj}^{-}(L,\nu_j),$$
$$R_1(\nu_j)P_{sj}^{-}(0,\nu_j) = P_{sj}^{+}(0,\nu_j), \qquad (3)$$

$$P_{\rm p}(0,\nu_{\rm p}) = P_{\rm p0}\,, \qquad (4)$$

where $j = 1, \ldots, M$; M is the number of longitudinal modes that can be generated by the laser; $\nu_{\rm p}$, ν_j and $l_{\rm p}$, l_{sj} are the radiation frequencies and optical losses of the pump and laser wave; $R_1(\nu_j)$ and $R_2(\nu_j)$ are the reflectivities of the cavity mirrors (Bragg gratings); L is the cavity length, $\sigma_{ik}^{\rm Er}$ and $\sigma_{ik}^{\rm Yb}$ are the absorption and emission cross sections for erbium and ytterbium for transitions from level i to level k (see [1, 14]); $\Gamma_{\rm p}$ and Γ_{sj} are the overlap integrals between the cross section of radiation fields and the active region of the fibre; n_1, n_2, n_3, and n_4 are the populations of the levels $^4I_{15/2}$, $^4I_{13/2}$, $^4I_{11/2}$ and $^4I_{9/2}$ of Er^{3+} ions; n_5 and n_6 are the populations of the levels $^2F_{7/2}$ and $^2F_{5/2}$ of Yb^{3+} ions. The term $2h\nu_j\Delta\nu_j\Gamma_{sj}\sigma_{21}^{\rm Er}(\nu_j)\bar{n}_2$ in the second equation in system (2) describes the input equivalent noise power and is included in the equation for the initiation of lasing.

The system of equations (2) was solved numerically by the Runge–Kutta method. The average populations $\bar{n}_i$ of the levels were determined for each step in z by using the rate equations from Ref. [1]. The maximum reflectivity of a broadband FBG written in a doped fibre was assumed to be 100 %.

The core radius of the doped fibre is 2.2 μm,, its aperture NA = 0.2, the loss factor of the optical pump wave is $l_{\rm p} = 0.15$ dB m^{-1}, and the loss factor for the laser wave is $l_{sj} = 0.1$ dB m^{-1}. The remaining parameters of the fibre used in calculations are the same as in Ref. [1]. The cavity length is 1 cm. The active region of the laser cavity may include both a doped optical fibre and an electrooptical cell. In this case, the optical lithium niobate waveguide must be doped with resonance impurity ions [15].

We have analysed the lasing efficiency $\eta = P_{\rm s}/P_{\rm p0}$ as a function of the reflectivity R of the output cavity mirror, where $P_{\rm s}$ is the output laser radiation power in the steady-state lasing mode for a given pump power. This dependence is presented in Fig. 3. The Er^{3+} and Yb^{3+} ion concentrations are $N_{\rm Er} = 4 \times 10^{25}$ ion m^{-3} and $N_{\rm Yb} = 5 \times 10^{26}$ ion m^{-3}, and the input pump power is $P_{\rm p0} = 40$ mW.

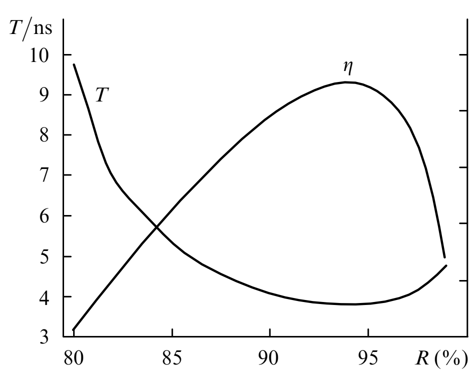


Figure 3. Dependences of lasing efficiency η and the time T of establishment of steady-state lasing on the reflectivity R of the cavity output mirror.

Fig. 3 also shows the dependence of the lasing stabilisation time T as a function of the reflectivity R. One can see that the minimum lasing stabilisation time is attained for the output mirror reflectivity of about 95 % and corresponds to the maximum lasing efficiency.

Fig. 4. shows the output radiation power as a function of pump radiation power. One can see that the lasing efficiency strongly depends on the concentration of doping elements and may achieve almost 50 % at high concentrations. The calculated lasing efficiency is much larger than the values obtained in experiments [2, 3] because in our calculations we neglect the pump coupling losses in the fibre and the losses due to misalignment of laser elements. It will be shown below that when these losses are included, the lasing efficiency decreases and is in agreement with the experimentally obtained values.

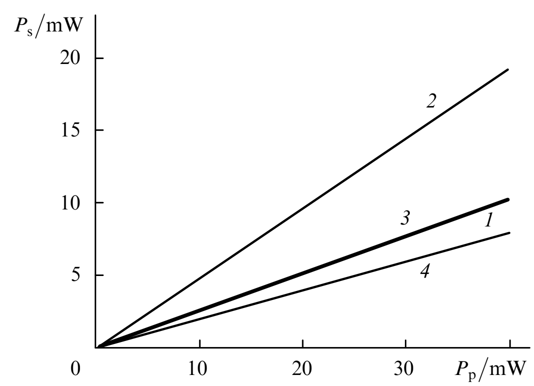
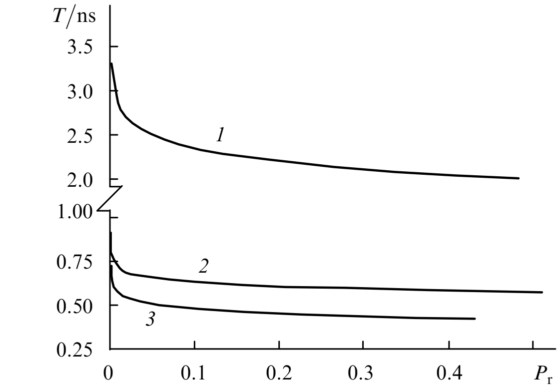


Figure 4. Dependences of the output radiation power on the pump power for the Er and Yb ion concentrations 4×10^{25} and 5×10^{26} ion m^{-3}, respectively (*1*), 2×10^{26} and 2.5×10^{27} ion m^{-3} (*2*, *3*), and 3×10^{25} and 3.75×10^{26} ion m^{-3} (*4*). Lines (*1*), (*2*), and (*4*) are calculated by neglecting the alignment losses, while curve (*3*) takes these losses into account. Straight lines (*1*) and (*3*) coincide completely.

Obviously, the lasing stabilisation time at a certain wavelength strongly depends on the intensity of the initial signal at this wavelength and on the lasing efficiency (see Fig. 3). Fig. 5a shows the time of laser switching to another wavelength as a function of the relative power of the residual signal $P_{\rm r} = P_{\rm s0}/P_{\rm s}$, where $P_{\rm s0}$ is the absolute power of the residual signal. One can see that the switching time for a residual signal equal to half the steady-state signal may amount to 0.55 ns. This level of the residual signal (see Fig. 2) corresponds to the laser radiation wavelength shift $\Delta\lambda = 0.01$ nm. It follows from Fig. 2 that the minimum residual signal $P_{\rm r}$ over the entire range of switching of the tunable laser under study is equal approximately to 0.025. Thus, the maximum switching time for a waveguide laser with a controllable FBG and an electrooptical cell will not exceed 0.7 ns for the optimal choice of the parameters of its elements (curve *2* in Fig. 5a).

4. Lasing parameters taking into account alignment losses

The coupling of an optical fibre and an FBG written in a waveguide electrooptical modulator may give rise to additional losses which considerably affect the laser effi-



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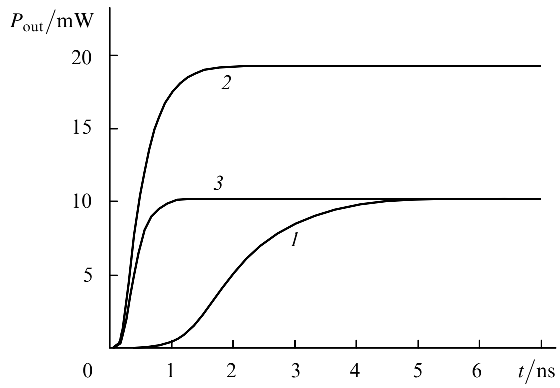

b

Figure 5. Dependences of the laser switching time on the relative power of the residual signal (a) and of the output signal power on time (b) for the ion concentrations $N_{Er} = 4 \times 10^{25}$ ion m^{-3} and $N_{Yb} = 5\times 10^{26}$ ion m^{-3}, $P_{p0} = 40$ mW (curve *1*) and $N_{Er} = 2 \times 10^{26}$ ion m^{-3} and $N_{Yr} = 2.5 \times 10^{27}$ ion m^{-3}, $P_{p0} = 90$ mW (curves *2* and *3*). Curves (*1*) and (*2*) are calculated by neglecting the alignment losses, while curve (*3*) takes these losses into account.

ciency and dynamics and, hence, the tuning rate. To estimate the effect of these losses, we calculated the lasing dynamics using the mathematical model (2)–(4) in which the first boundary condition in (3) is replaced by

$$R_{st}(v_j)R_2(v_j)P_{sj}^{+}(L, v_j) = P_{sj}^{-}(L, v_j), \qquad (5)$$

where $R_{st}(v_j)$ is the loss factor taking into account the misalignment between the optical waveguide and the optical fibre. The results of calculations are presented by curves (*3*) in Figs 4 and 5.

As expected, the lasing efficiency is reduced significantly due to additional losses. For example, curve (*3*) in Fig. 4, which describes the output laser power for concentrations $N_{Er} = 2 \times 10^{26}$ ion m^{-3} and $N_{Yb} = 2.5 \times 10^{27}$ ion m^{-3} taking losses into account completely coincides with curve (*1*) for a laser with lower concentrations of doping elements, for which such losses were neglected. However, the time of laser switching to another lasing wave taking additional losses into account turned out to be considerably shorter (see Fig. 5a). This can be explained with the help of Fig. 5b illustrating the dynamics of stabilisation of lasing for a residual signal power $P_{s0} = 0.1$ mW. One can see from Fig. 5b that additional losses lead to a decrease in the rate of lasing power build-up. However, the steady-state lasing power also decreases in this case and, hence, it can be attained much more quickly. Thus, the lasing stabilisation time and, accordingly, the maximum time of laser switching to another emission wavelength (for $P_r = 0.025$) decreases from 0.7 to 0.5 due to additional losses caused by misalignment.

5. Conclusions

Thus, the electrooptical effect can be used for continuous tuning a fibre laser. The switching time is about 0.7 ns for a cavity length of the order of 1 cm. The small cavity length and the employment of a Bragg waveguide grating as a selector makes it possible to attain a single-frequency lasing.

Because such a scheme provides continuous wavelength tuning with a high speed, it can be used for creating an electric feedback required for stabilising the radiation frequency of fibre lasers.

Additional losses emerging in the alignment of the optical fibre with the FBG written in the waveguide electrooptical modulator reduce the laser switching time, but the efficiency of lasing also decreases simultaneously. Alignment losses can be avoided by using a monolith laser, e.g., a laser based on a lithium-niobate optical waveguide in which both mirrors in the cavity are waveguide gratings [15]. The active element of such a laser is the part of the optical waveguide doped with Er ions. On the other hand, lithium niobate crystals can also be used for manufacturing optical fibres [16]. In Ref. [17], polymer optical fibres were considered that also exhibit the electrooptical effect. By writing diffraction grating in such fibres, one can control their parameters and, hence, create a an all-fibre tunable laser. Such a structure is preferable for coupling lasers with fibreoptic communication and processing systems.

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