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Spatial Fourier analysis of modes at the output of a homogeneous restricted system of coupled waveguides

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***Abstract*. The propagation of light in restricted homogeneous systems of tunnel-coupled waveguides is studied. The Fourier analysis of modes at the output of the waveguide system depending on the end-excitation angle of waveguides revealed the region of excitation angles corresponding to excitation of Bragg modes. The expressions for the Bloch vector for a great number of separate waveguides are presented which describe the reflection of light in a periodic layered medium. It is shown that the Bragg diffraction of light waves in film lasers can considerably change their radiation parameters.**

Keywords: *coupled-waveguide system, Bloch waves, Bragg reflection.*

1. Introduction

The propagation of light in restricted homogeneous systems of tunnel-coupled waveguides was studied in papers [1, 2]. It was found that Bragg modes in coupled-waveguide systems are of great scientific and practical interest because their propagation regime can substantially affect the spatial divergence of radiation in such waveguide system and the radiation power in the case of active waveguides [3]. In this connection we performed a detailed Fourier analysis of modes at the output of a system of coupled waveguides and considered the prospects for using Bragg modes in single-frequency lasers.

2. Fabrication of the structure and experimental results

The system of tunnel-coupled waveguides was fabricated by the SPCVD method on a quartz substrate by the deposition of 50 pairs of alternating SiO_2 and SiON layers with the refractive-index difference $\Delta n = 5 \times 10^{-3}$ [1]. To provide a high-quality polishing of the ends of the system, a $\sim$ 100-μm thick SiO_2 layer was deposited over the structure. The waveguide layer thickness was $h = 1.1$ μm and the separation between the layers was $s = 1.3$ μm, so that the structure period was $\Lambda = 2.4$ μm.

According to our calculations, 34 guided modes appear in this system, while the rest of the modes are radiation modes. The Bragg modes of the waveguide system are located among radiation modes [2].

By using the setup shown in Fig. 1, we performed the spatial Fourier analysis of modes at the system output depending on the end-excitation angle of the waveguide system. This scheme differs from the scheme that we used in papers [1, 2] by the presence of a long-focus lens for the observation of Fourier spectra of output radiation on a remote screen. We calculated the field distribution at the output of the waveguide system for one of the modes (with the mode order $m = 5$) by the RPM method (reflection pole method) [4] (Fig. 2). The Fourier analysis of radiation on the system end revealed a series of points corresponding to spatial harmonics in the radiation pattern. Typical spectra are presented in Fig. 3. These spectra were processed to obtain the main results of our study in the form of the dependence shown in Fig. 4.

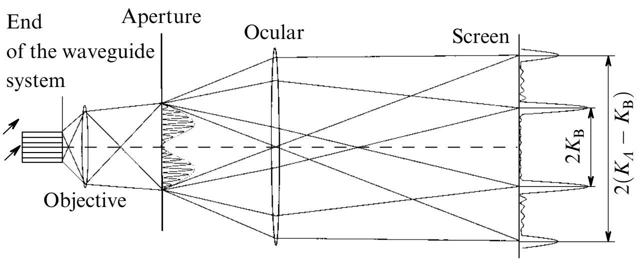

Figure 1. Scheme of the experimental setup for the spatial Fourier analysis of output radiation.

On the abscissa in Fig. 4a the component $k \sin\varphi$ of the incident-wave vector perpendicular to the waveguide axis is plotted, and on the ordinate – the modulus K_B of the Bloch wave* [5] and the moduli $\pm m 2\pi/\Lambda_B \pm K_B$ ($m = 1, 2$) of vectors at the waveguide output. Here, Λ is the waveguide system period; $2\pi/\Lambda$ is the lattice vector; and φ is the angle between the system axis and the incident beam. A characteristic feature of Fig. 4a is the intersection region of curves K_B

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* Bloch waves are the eigenvalues of the wave equation in a periodic medium of the type $\exp(iK_B x)u(x)$, where $u(x)$ is a periodic function with period determined by the medium.

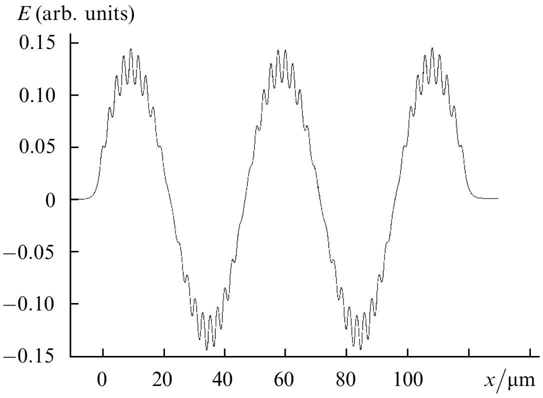

Figure 2. Distribution of the fifth mode field of the system of coupled waveguides at the output end of the waveguide system.

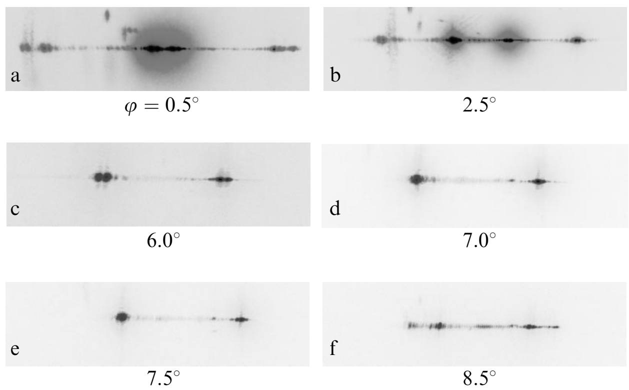

Figure 3. Fourier spectra of output radiation for different excitation angles of the waveguide system.

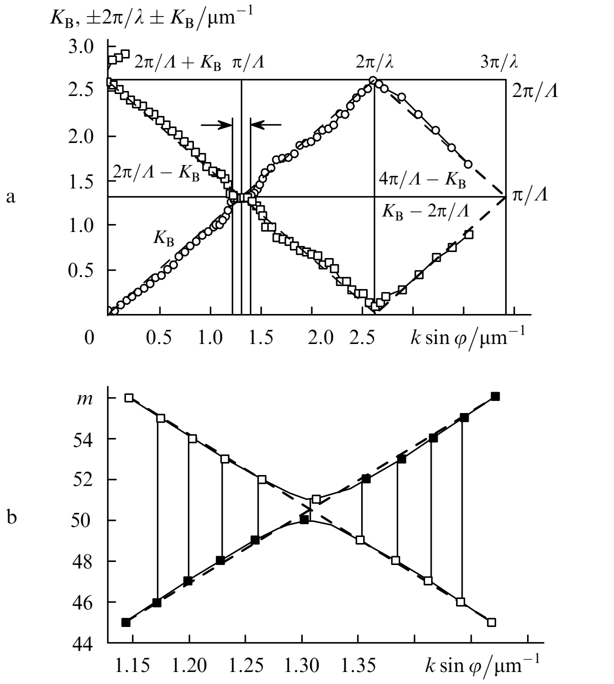

Figure 4. (a) Experimental dependences of the Fourier spectra of output radiation (dashed lines are calculations) and (b) calculated dependences of the mode order (■ – K_B, □ – $2\pi/\Lambda - K_B$) on the excitation angle of the waveguide system for $\lambda = 0.63$ μm and $\Lambda = 2.4$ μm.

and $2\pi/\Lambda - K_B$ determined by the equality $\pi/\Lambda = \mathrm{Re}K_B$. In this region the counterpropagating Bloch waves are coupled with the coupling coefficient $\varkappa = \mathrm{Im}K_B$. The curves intersect at the instant of Bragg reflection of light in the waveguide system. The plot in Fig. 4a illustrates the Bragg resonance in a restricted system of tunnel-coupled waveguides. Note that Bragg modes in this waveguide system are radiation modes.

3. Theoretical analysis of the mode distribution in a restricted system of tunnel-coupled waveguides

We calculated the distribution of the mode fields for the waveguide system and their Fourier transforms by the method described in [4] and then compared these distributions with experimental data. The points in Fig. 4a present the experimental dependences of the modulus of the Bloch vector K_B and the modulus of the vector $2\pi/\Lambda - K_B$ on $k \sin\varphi$, while Fig. 4b presents the calculated and experimental dependences of the orders of modes close to Bragg modes on the same quantity. Complete agreement between experimental and calculated data suggests that we correctly interpret the process of simultaneous excitation of two modes with the same amplitudes upon the Bragg resonance. The coupling coefficient of Bloch waves can be defined as

$$|\varkappa| = \frac{\pi \Delta n^* \bar{n}}{\lambda \sin\varphi}, \tag{1}$$

where $\bar{n}$ is the averaged refractive index of the system; $\Delta n^* = n_N^* - n_{N+1}^*$ is the difference of the effective refractive indices of Bragg modes; and N is the number of waveguides forming the system.

We studied so far the propagation of light in a restricted system of tunnel-coupled waveguides in which light propagated along the waveguides. The periodicity in the arrangement of waveguides made it possible to demonstrate a great role of Bloch waves in the light propagation process. It was found in [5] that the approach based on the Bloch waves can be also applied for the Bragg reflection of light in an infinite medium, when light propagates arbitrarily with respect to the layers of a periodic system. If the wave vector of light is directed at an angle of θ with respect to the layers, the Bloch vector can be written in the form

$$K_B = k\bar{n}\cos\theta \pm \mathrm{i}\left[\varkappa^*\varkappa - \left(\frac{\Delta\beta}{2}\right)^2\right]^{1/2}, \tag{2}$$

where

$$\varkappa = \frac{\mathrm{i}(1 - \cos m\pi)}{2m\lambda\cos\theta}\,\frac{\sqrt{2}(n_2^2 - n_1^2)}{(n_2^2 + n_1^2)^{1/2}} \quad \text{for the TE waves}$$

and

$$\varkappa = \frac{\mathrm{i}(1 - \cos m\pi)}{2m\lambda\cos\theta}\,\frac{\sqrt{2}(n_2^2 - n_1^2)}{(n_2^2 + n_1^2)^{1/2}}\cos 2\theta \quad \text{for the TM waves;}$$

and $\Delta\beta = 2k\bar{n}\cos\theta - 2m\pi/\Lambda$ is the detuning from the resonance, $k = 2\pi/\lambda$.

If we denote the central part of the reflection region corresponding to the equality $k\bar{n}\cos\theta = m\pi/\Lambda$ (or $\Delta\beta = 0$) by ω_0, expression (2) will take the form

$$K_{\rm B} = \frac{m\pi}{\Lambda} \pm {\rm i}\left[\varkappa^*\varkappa - \left(\frac{\bar{n}}{c}\right)^2 (\omega - \omega_0)^2 \cos^2\theta\right]^{1/2}, \qquad (3)$$

where $\bar{n} = \frac{1}{2}(n_1^2 + n_2^2)^{1/2}$. Expression (3) completely describes the reflection of light in a periodic layered medium.

We considered here the system of coupled waveguides with the period $\Lambda = h + s$. In fact, such a waveguide system is a plane lattice with the refractive index periodically varying along some direction. It is obvious that the Bragg interaction of light with such a lattice and a corrugated waveguide is the same in many respects. Therefore, it is pertinent to mention here film lasers with intracavity Bragg gratings. As far back as 1979 [6], a waveguide laser with a Bragg grating in the active region was built. The period Λ_1 of this grating was 1.5 μm, and two parallel gratings reflecting light in the second diffraction order ($\Lambda_2 =$ 0.4016 μm) were used for feedback. A film doped with rhodamine 6G was single mode. The laser emitted the line at $\lambda_0 = 0.5969$ μm propagating along the axis of the intermediate grating and the line at $\lambda_\theta = 0.5916$ μm corresponding to the Bragg wave reflected from the intermediate grating [6]. A characteristic feature of these waves was that the divergence of radiation at 0.5916 μm was 5–6 times smaller than that at 0.5969 μm.

In our opinion, this is explained by the distributed reflection of light from the grating with $\Lambda = 1.5$ μm in the active region of the laser. To obtain lasing only at $\lambda_\theta =$ 0.5916 μm, it was proposed in [6] to turn the feedback gratings to form the angle $\Psi = 2\theta$ between them (Fig. 5a). In this case, lasing along the grating lines in the active region should disappear due to a drastic increase in the lasing threshold. Instead of this, the feedback mirrors in papers [7, 8] were parallel to each other, while the active region of the laser and grating lines were inclined at an angle of θ to the laser mirrors so as to eliminate lasing along the normal to mirrors (Fig. 5b). Note that in [7] ~ 1 W of single-frequency output power was achieved in semiconductor lasers with the nearly diffraction-limited divergence of radiation.

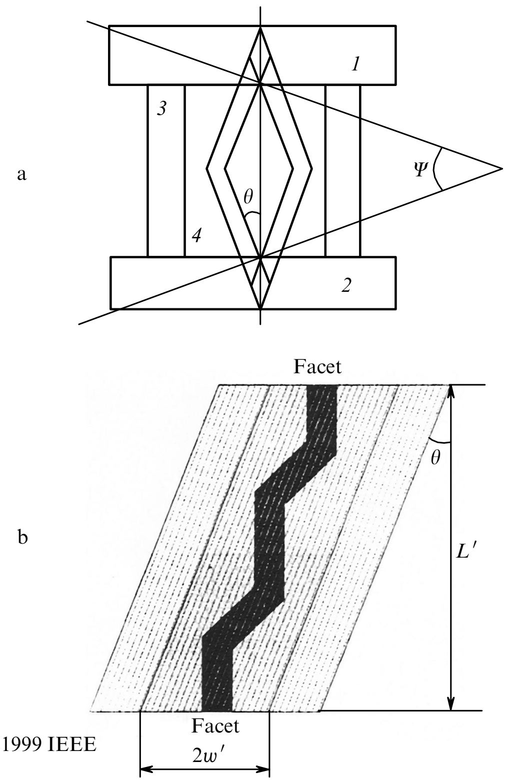

Figure 5. Schemes of the laser resonator from [6] (a) and [7, 8] (b): (*1*, *2*) second-order feedback gratings with $\Lambda_0 = 0.4$ μm; (*3*) grating in the active laser region with $\Lambda_1 = 1.5$ μm; (*4*) active laser region; θ is the Bragg diffraction angle; $\Psi = 2\theta$ is the turn angle of feedback mirrors providing single-frequency lasing.

4. Conclusions

The study of light propagation in the system of coupled waveguides has shown that this process (especially near the Bragg resonance) is substantially determined by the Bloch waves. It has been shown that Bragg modes in the system are produced upon the interaction of two counterpropagating Bloch waves with the coupling coefficient $|\varkappa| = \pi\Delta n^*\bar{n}\times(\lambda\sin\varphi)^{-1}$. It has been demonstrated by the example of grating resonances that Bragg reflection can provide high-power lasing with a low divergence of radiation.

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