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Restricted homogeneous system of tunnel-coupled waveguides and Bragg diffraction of light in it

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***Abstract*. A system of tunnel-coupled straight waveguides is studied. The dependence of the number of modes in this system on the number N of waveguides, the distance between waveguides, and the number of modes in an individual waveguide is considered. It is shown that modes of the order $m = N$ and $N + 1$ in the system of coupled waveguides are Bragg modes, i.e., the angle between their propagation direction and the system axis is close to the Bragg angle. The effective refractive indices n^* of these modes are different, i.e., the dependence $n^*(m)$ changes abruptly. It is found that radiation modes play an important role in the formation of Bragg modes if an individual waveguide of the system is single-mode and the distance between the waveguides is sufficiently large. It is shown that the angular excitation regions of guided and radiation modes of the system near Bragg angles are overlapped.**

Keywords: *tunnel-coupled modes, Bragg diffraction, guided modes, radiation modes.*

1. Introduction

A system of tunnel-coupled waveguides is called homogeneous if it is formed by equidistant waveguides in which light propagation constants are independent of the longitudinal and transverse coordinates. The simplest system of this type is a standard dielectric multilayer interference mirror. Another example is an array of channel waveguides produced in a planar waveguide film lying on a substrate with a low refractive index. The channel-waveguide systems attract recent interest in waveguide laser optics in connection with the possibility of increasing their output power [1]. The propagation of light in homogeneous channel-waveguide systems was earlier studied in papers [2, 3]. It was pointed out, in particular, that the Bragg diffraction of light in them is of special interest [4]. In this connection we attempted in this paper to study in more detail the Bragg diffraction of light in a passive, i.e., without amplification, system of coupled waveguides in order to elucidate the possibility of formation of a laser resonator with the improved mode selection due to this process.

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2. Experimental realisation of a restricted homogeneous system of coupled waveguides

A homogeneous system of channel waveguides was prepared by applying 50 pairs of SiO_2 and SiON layers with the refractive-index difference $\Delta n = 5 \times 10^{-3}$ on a silica substrate. The waveguide-layer thickness was 2 μm and the distance between the layers was 1 μm. The SiO_2 layer of thickness 50 μm was deposited on the last waveguide surface. The waveguide system was prepared by the SPCVD (surface plasma chemical vapour deposition) method developed for the preparation of fibre preforms.

Note here that the transverse size of our waveguide system is $H = 150$ μm. In this connection it is reasonable to consider Bragg diffraction in such a system. Recall that a restricted system of tunnel-coupled waveguides forms a common waveguide with $H \simeq 150$ μm and many modes. To find out whether the so-called Bragg modes are present among these modes, we considered the problem about the number of modes in a system of tunnel-coupled waveguides. We assume that an individual waveguide is symmetric, has the thickness h and the refractive index n_f and the refractive index of a surrounding medium is n_s. The normalised frequency of such a waveguide is $V = kh(n_f^2 - n_s^2)^{1/2}$, where $k = 2\pi/\lambda$. Let us now assume that there exists a similar waveguide with $H = Nh$, where N is the number of waveguides of thickness h. The normalised frequency of such a waveguide is

$$V_\Sigma = kNh\left(n_f^2 - n_s^2\right)^{1/2}, \quad (1)$$

and the number of modes in it is

$$M = N\frac{V}{\pi}. \quad (2)$$

This means that for $V < \pi$, the number of modes of the total waveguide is smaller than N, whereas for $V > \pi$ it is larger than N. Let us now draw apart individual waveguides so that they remain tunnel-coupled and equidistant. The gap between the waveguides has the thickness s and the refractive index n_s. Consider the dependence of the number of modes in the waveguide system on the gap thickness s and frequency V. Figure 1 shows the dependences $M(s)$ for the waveguide system with $N = 50$, $n_f = 1.465$, and $n_s = 1.46$ ($\lambda = 0.63$ μm) for the different thickness h of an individual waveguide, calculated by the method similar to the one described in [5]. Note that we developed earlier the program for numerical calculations of the number of modes and the effective refractive indices n^* both for the guided and radiation modes in multilayer waveguides. The program is based on the analysis of the dependence of the phase of a wave propagating across the waveguide structure on the effective refractive index. After the determination of n^*, one can calculate the distribution of the mode field and losses of radiative modes.

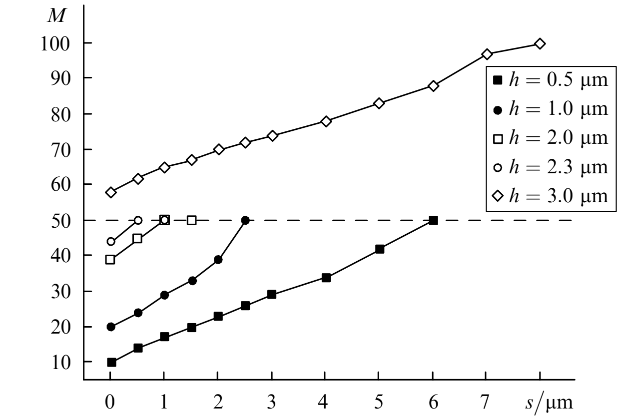

Figure 1. Dependences of the number M of guided modes in a system of coupled waveguides on the thickness s of gaps between them.

It is known that for $V < \pi$, a waveguide is single-mode, while for $V > \pi$, it is two-mode. The introduction of a gap between individual waveguides changes the number of modes in the waveguide system. In the limit $s \to \infty$, the number of modes M for $V < \pi$ tends to the number N of waveguides forming this system, and for $2\pi > V > \pi$, to $2N$. In the waveguide system with $M > N$, the effective refractive indices of the modes with orders $m > N$ abruptly decrease (Fig. 2) because the maxima of the field distributions for these modes lie in the regions between the waveguides where $n_s < n_f$. In such waveguide systems, modes with the orders $m = N$ and $N + 1$ are the Bragg modes because the angle between the waveguide axis and the direction of light beams forming these modes (the glancing angle) is most close to the Bragg angle $\theta_{Br} = \arcsin[\lambda/(2\Lambda n_{av})]$, where n_{av} is the averaged refractive index of the layered medium, and Λ is the period of the waveguide structure. Because the jump Δn^* in the system of tunnel-coupled waveguides appears when an individual waveguide of the system is two-mode, it follows from calculations that $n_N^* \approx n_1^*$ and $n_{N+1}^* \approx n_2^*$, where n_1^* and n_2^* are the effective refractive indices of the first (fundamental) and second modes of an individual waveguide.

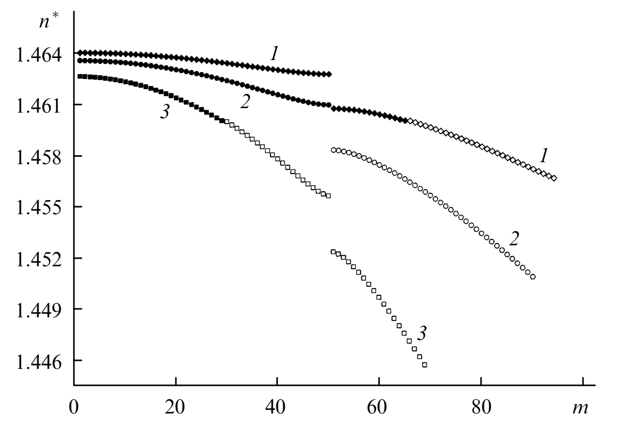

Figure 2. Dependences of the effective refractive index n^* on the mode order m for the modes in systems of coupled waveguides with $M > N$, $h = 3.0$ μm, $s = 1.0$ μm (*1*); $M = N$, $h = 2.0$ μm, $s = 1.0$ μm (*2*); and $M < N$, $h = 1.0$ μm, $s = 1.0$ μm (*3*). Dark and light points correspond to the guided and radiation modes of the waveguide system, respectively.

In the system of tunnel-coupled waveguides with the number of modes smaller than the number of individual single-mode waveguides ($M < N$), the Bragg modes are located among the radiation modes of the system. Figure 2 shows the dependence of the effective refractive index of the modes of the system with $N = 50$, $h = 2.0$ μm, and $s = 1.0$ μm (see Fig. 1) on the mode order. As follows from calculations, the dependence $n^*(m)$ on the radiation modes of the coupled-waveguide system does change abruptly in passing from the $m = 50 = N$ mode to the $m = 51 = N + 1$ mode. Thee modes are the Bragg modes of this waveguide system.

The waveguide system that we realised is an intermediate system because in it $M = N$. Recall that the thickness s for this system is 1 μm and the number of modes, according to Fig. 1, is 50, i.e., $M = N$. For the last guided mode, $n^* = 1.4609$, and this mode is one of the Bragg modes. Another mode is the radiation mode of the waveguide system. Figure 2 shows the dependences $n^*(m)$ for the waveguide system with $N = M$ and for systems with $M > N$ and $M < N$. These dependences were obtained for guided and radiation modes.

We calculated the far-field intensity distributions of guided and radiation modes as functions of the excitation angle θ in air. These dependences (Fig. 3) give in fact the angular dependences $\eta(\theta)$ of the end-excitation efficiency of

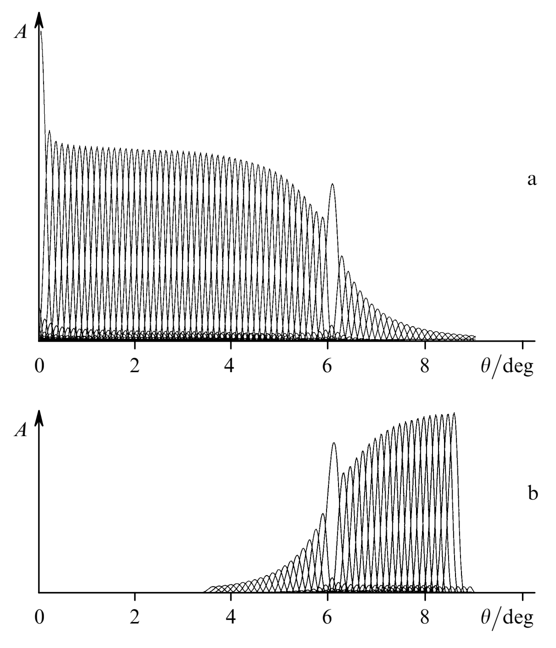

Figure 3. Angular dependences of the distribution of the field amplitude A of guided (a) and radiation (b) modes characterising the far-field excitation efficiency η of these modes for the waveguide system with $M = N$.

modes. They show first of all that angles at which Bragg modes propagate are virtually identical and are determined by the relation

$$\theta_{\mathrm{Br}} \approx \arcsin\frac{\lambda}{2\Lambda}. \tag{3}$$

Figure 4 shows the angular dependence of η for guided modes. The similar dependence $\eta(\theta)$ is also obtained for radiation modes; however, η increases with increasing angle rather than decreases, as in the case of guided modes. Therefore, these dependences distinctly show that both guided and radiation modes are generated upon end excitation. The radiation modes rapidly decay in a waveguide due to emission of light into a substrate. Figure 5 shows the dependence of the part of the power of these modes at the output of a 30-mm long waveguide on the radiation-mode number. One can see that the number of radiation modes generated in our waveguide system does not exceed 5–6 and their intensity amounts to no more than -10 dB of the intensity of the first radiation mode.

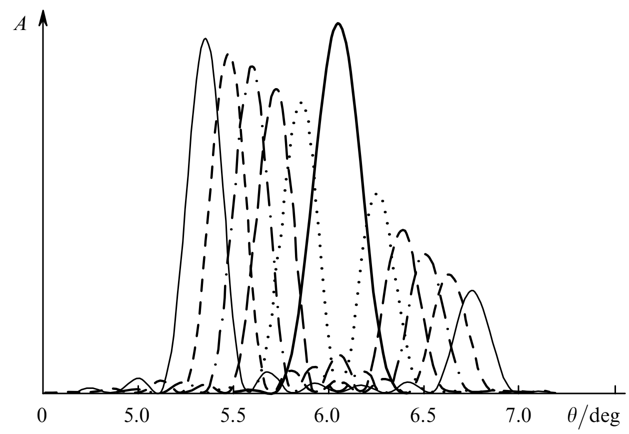

Figure 4. Angular dependences of the distribution of the field amplitude A of guided modes, characterising the far-field excitation efficiency η of these modes, at angles close to the Bragg angle for the waveguide system with $M = N$. The thick solid curve corresponds to the Bragg mode, while the curves of the same type (one before the Bragg mode and another after it) characterise two directions for other guided modes.

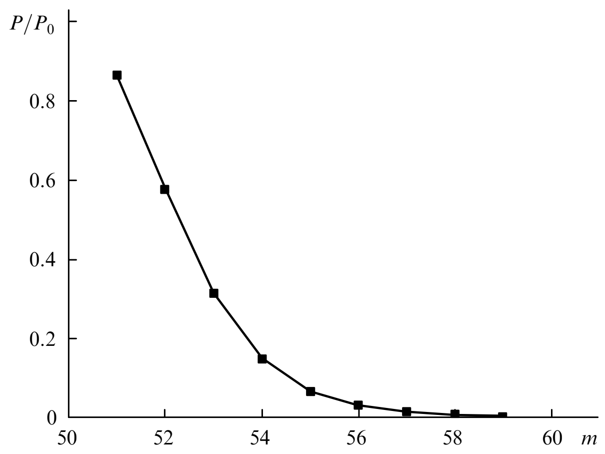

Figure 5. Dependence of the light power fraction P/P_0 at the output of the waveguide system with $M = N$ on the number of a radiation mode in this system.

3. Experimental observation and identification of radiation modes in the coupled-waveguide system

We fabricated a homogeneous system of coupled waveguides consisting of 50 pairs of SiO_2 and SiON layers deposited on a silica substrate. The excitation of modes in this waveguide was studied on the setup whose scheme is presented in Fig. 6. The length of samples with waveguides was 30 mm.

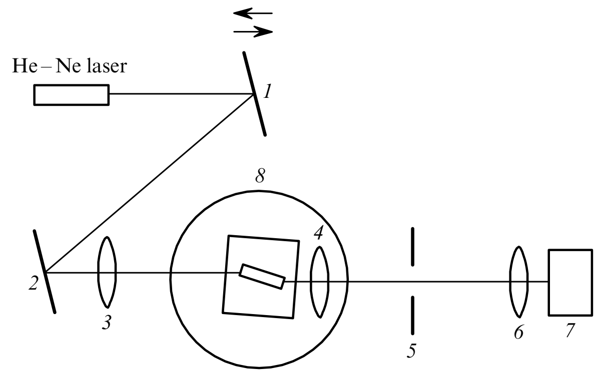

Figure 6. Optical scheme of the experimental setup for excitation of modes in a system of coupled waveguides: (*1*) movable mirror; (*2*) fixed mirror; (*3*) long-focus lens; (*4*) microobjective; (*5*) aperture; (*6*) focusing lens; (*7*) photodetector; (*8*) G5M goniometer.

The modes were first generated by exciting the waveguide through the end. Radiation from a He–Ne laser was focused by an optical system consisting of movable (*1*) and fixed (*2*) mirrors and a long-focus lens ($F = 60$ cm). Depending on the position of movable mirror (*1*), the laser beam spot at the input end of the waveguide had a diameter between 50 and 200 μm. Measurements were performed for two values of the laser beam radius equal to 50 and 100 μm. The angle of incidence of the exciting laser beam was varied by rotating a G5M goniometer table on which a sample in a cell with immersion liquid was mounted as well as $50^{\times}$ microobjective (*4*) producing a magnified image of the output end of the sample on a screen with aperture (*5*). The required sites of the image were separated by varying the size and position of the aperture. The radiation power transmitted through the waveguide was measured by focusing radiation by lens (*6*) ($F = 40$ cm) to photodetector (*7*).

Curve (*1*) in Fig. 7 shows the light intensity transmitted through the waveguide excited through the end as a function of the excitation angle θ. In the case under study the laser spot radius at the input end was ~ 50 μm. For small excitation angles ($\theta \leqslant 3^\circ$), the measured radiation intensity is virtually independent of θ because losses in the waveguide of length 30 mm are rather low. For angles $4.5^\circ \leqslant \theta \leqslant 5.5^\circ$, both guided and radiation modes can be excited simultaneously in the system, the losses related to the latter being substantially greater than for the former. This can explain the observed decrease in the transmitted light intensity for $4.5^\circ \leqslant \theta \leqslant 5.5^\circ$. Some increase in the radiation intensity measured at angles $\theta \approx 6^\circ$ can be related to the Bragg mode excitation.

When radiation was coupled to the waveguide system through its end at the angles of incidence $\varphi \leqslant 4^\circ$, a bright image of the end of waveguide layers was observed, as well

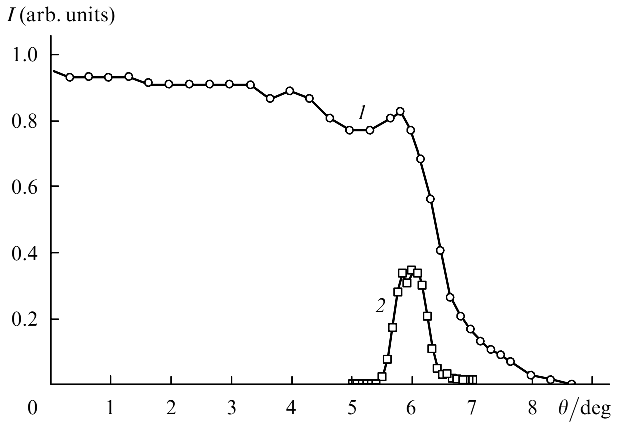

Figure 7. Angular dependences of the light intensity I at the output of a system of 50 single-mode waveguides considered in the paper ($M = N = 50$) upon end (*1*) and side (*2*) excitation.

as a set of spots caused by the diffraction of the light beam from the input and output ends of the waveguide system. It was found that the displacement of the exciting beam with respect to the waveguide system axis resulted in the decrease in the intensity of diffraction spots, which allowed us to control the incident-beam positioning on the input end by the maximum of the intensity of these spots.

For the angles of incidence $\varphi \approx 4.5° - 6°$, new groups of spots appeared in the image plane, which were located symmetrically on both sides of the waveguide region image. The observed picture demonstrated simultaneous excitation of guided and radiation modes.

Then, we excited radiation modes from the substrate by illuminating the side surface of the waveguide by radiation from a He–Ne laser. To couple radiation through the side surface, the input end of the waveguide system was displaced in a plane perpendicular to the optical axis. In this case, the intensity in diffraction spots decreased almost to zero. Upon side radiation coupling, a weakly illuminated region, corresponding to waveguide layers, was observed on the screen, and two groups of distinctly localised spots were located on both sides of this region. The radiation intensity was maximal in spots that were most remote from the system axis. These spots are related to radiation modes excited in the waveguide system.

Upon weak variations in the angle of incidence of the exciting beam, the location of spots in symmetric groups almost did not change. However, their intensity changed and new groups of spots appeared, whose intensity increased when the angle of incidence was further changed. (Radiation as if 'leaked' for one group of spots to another.) The features of the picture observed in this case can be explained by excitation of a set of radiation modes, whose mode composition changed upon variation of the angle of incidence.

Curve (*2*) in Fig. 7 shows the light intensity transmitted through the waveguide upon side excitation (from the substrate side) as a function of the excitation angle θ. In this case, the laser spot radius was ~ 100 μm. For $\theta \leqslant 6°$, the light intensity is low, which means that guided modes are not excited in this case. We assign the intensity maximum observed at $\theta \sim 6°$ to excitation of radiation modes, for which losses are not very large in this case (see Fig. 5).

4. Discussion of the results

We found in our experiments that losses of light propagating through a system of coupled waveguides in the form of Bragg modes are rather low even when the Bragg mode is the radiation mode of the system. It is clear intuitively that this should be the case. The calculations of losses performed by using the program mentioned above (see section 2) confirm an intuitive notion of low radiation losses in Bragg modes (see Fig. 5).

By considering the propagation of light through the waveguide system, it is necessary to take radiation-mode losses into account because guided and radiation modes are excited simultaneously, as shown in Fig. 3. The consideration of these losses during the light transfer in the waveguide system (by multiplying the data presented in Figs 3b and 5) gives the angular dependence of light transmission. Figure 8 shows the calculated angular dependence of the light intensity (characterising its transmission) at the output of the waveguide system. This dependence is in quite good agreement with the corresponding experimental dependence [curve (*1*) in Fig. 7]. Upon side excitation of radiation modes, we found only one split peak of light transmission appearing at angles close to the Bragg angle [curve (*2*) in Fig. 7]. In our opinion, this peak appears because the side excitation of the Bragg radiation mode is inefficient, while the efficiency of adjacent radiation modes is still sufficiently high.

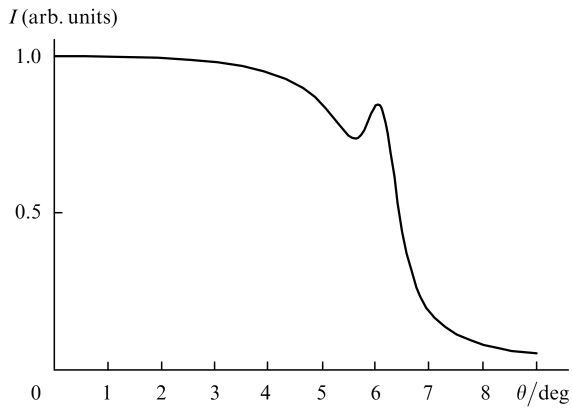

Figure 8. Calculated angular dependence of the light intensity I at the output of the system of coupled waveguides ($M = N = 50$).

From the point of view of mode selection, of most interest is a system with the number M of usual modes smaller than the number N of waveguides because Bragg modes in this case prove to be localised among radiative modes with high losses. A further selection can be performed by an appropriate choice of the active region in the system of coupled waveguides. For example, by locating the active region in waveguides, we will select the first Bragg mode of the system (i.e., the Nth mode), and by locating the active region in the gaps between the waveguides, we select the second Bragg mode (i.e., the $N+1$th mode).

This circumstance can be used in applications of laser systems of coupled channel waveguides. Such systems are now being successfully developed [6].

Therefore, our study of the propagation of light through a system of coupled waveguides has demonstrated the important properties of Bragg diffraction of light in a homogeneous system of coupled waveguides. These properties can be used for the mode selection and improving the quality of radiation generated in such active systems.

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