Spectral Properties of a Heterogeneous System of Coupled Channel Waveguides and Its Practical Realization

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Abstract—The spectral dependence of the optical transmittance of a heterogeneous system consisting of single-mode channel waveguides is studied. The waveguides are equidistant along concentric circles. It is demonstrated that the spectral dependence exhibits oscillatory behavior. The spectral distance between the nearest transmittance peaks and their widths depend on the length of the structure and the coupling coefficient of the waveguides, respectively. The spectral dependence of the optical transmittance of a waveguide system with a sign-alternating radius of curvature of the waveguides is also analyzed. It is demonstrated that, in this case, the transmittance curve exhibits a single central peak. A heterogeneous system of coupled waveguides is experimentally realized with the aid of the surface plasma chemical vapor deposition technology used to synthesize blanks for fiber waveguide pulling. The possibility of waveguide propagation of light near the inner edge of a system of coupled concentric waveguides is experimentally demonstrated.

INTRODUCTION

There has been considerable recent interest in photonic crystals [1]. One-dimensional photonic crystals have attracted great interest owing to the practical possibilities for realizing them [2]. A system of channel waveguides with tunnel coupling is a good example of the realization of a one-dimensional photonic crystal whose properties have been well-studied and applied in practice. Nevertheless, a few practically important aspects remain unstudied. One of them is the variation in the spectrum of a light beam passed through a system of heterogeneous channel waveguides and the realization of such a system. In this work, we analyze the possibility of using a system of channel waveguides as an optical filter and attempt to realize such a filter.

LIGHT BEAM IN A HETEROGENEOUS SYSTEM OF CHANNEL WAVEGUIDES

A system of channel waveguides is heterogeneous if the propagation constants of individual waveguides vary in accordance with a certain law. In the simplest case, this law is linear, which means that the increment of the propagation constant $\Delta \beta = \gamma$ remains unchanged when we pass from one waveguide to another. It is demonstrated in [3, 4] that light introduced in a single channel is not spread over the waveguides in the course of propagation (like in a homogeneous system of channel waveguides); it remains localized in a few waveguides ($W \approx \frac{8\chi}{\gamma}$, where $\chi$ is the coupling coefficient of the waveguides). Moreover, in such a system of channel waveguides, light is concentrated in the initially excited waveguide at distances of $z_0 = \frac{2\pi}{\gamma}$, $2z_0$, $3z_0$, ..., from the waveguide entrance.

The reason for such a scenario of light propagation is the fact that a system of channel waveguides ($\Delta \beta = \gamma$ = const) is characterized by an equidistant set of eigenmodes, whose interference results in the pattern observed. Figure 1 demonstrates the distribution of the wave field along the system of channels for the case of initial excitation of one channel. Note that the recovery of the periodic beam along the system is related to the

Fig. 1. Spatial distribution of the light wave field ($\lambda = 632.8$ nm) in a heterogeneous system of waveguides with tunnel coupling for the initial excitation of a single channel waveguide ($\chi = 6$ cm$^{-1}$ and $\gamma = 2$ cm$^{-1}$).
phase shifts in the channel waveguides. To trace the phase evolution in the beam, it is expedient to consider a few (more than one) waveguides. For example, we consider seven waveguides with $\chi = 6 \text{ cm}^{-1}$ and $\gamma = 2 \text{ cm}^{-1}$. In this case, the wavelike propagation of the light beam (Fig. 2) is an analog of the Bloch oscillations. The in-phase input beam remains in-phase at the distance $z_0$. However, at the distance $z_0/2$, the beam is antiphase, and we observe two output beams of equal intensity, which means that the phase shift in the neighboring waveguides equals $\pi$. Apparently, at the intermediate points $0 < x < z_0/2$ and $z_0/2 < x < z_0$, the phase shift in the neighboring channels ranges from $0$ to $\pi$ and from $\pi$ to $2\pi$. Consider the field distribution for an ultimately narrow beam at point $z_0/2$. In this case, the total set (from $0$ to $\pi$) of the phase shifts in the excited waveguides is seen across the beam. Figure 3 shows the field distribution inside and outside the system of waveguides, clearly demonstrating the aforementioned range of the phase shift, and the distribution of the phase shift with respect to the direction of the increase in the propagation constant along the system of channel waveguides. This result is important for the further analysis.

**CURVILINEAR SYSTEM OF CHANNEL WAVEGUIDES WITH TUNNEL COUPLING**

Two methods for realizing a heterogeneous system of channel waveguides and the experimental demonstration of light focusing in such a system can be found in [3, 4]. Note that the simplest method for realizing such a waveguide system lies in placing identical (single-mode) waveguides at equal distances from each other at concentric circles with relatively large radii. We assume that the propagation constants of the waveguides are equal and that the entrances of all waveguides lie at one radius of curvature and the exits at another radius of curvature. Then, in the case of in-phase excitation, there exist phase shifts between the output signals of the waveguides. We can assume that the phase shifts are related to the difference between the propagation constants of the waveguides. In the framework of such an approach to the propagation of light in the curvilinear system of a channel waveguide, it is possible to infer a relationship that establishes the equivalence between the heterogeneous and curvilinear systems of waveguides [5]:

$$\Delta \beta = k \Delta n^* = k n^* \frac{\Delta R}{R},$$

(1)

where $R$ is the radius of curvature of a waveguide with the effective refractive index $n^*$, $\Delta R$ is the variation in the radius of curvature of the neighboring waveguide, $\Delta n^*$ is the variation in the effective refractive index of this waveguide, $k = \frac{2\pi}{\lambda}$, and $\lambda$ is the wavelength of

**Fig. 2.** Spatial distribution of the light wave field in a heterogeneous system of channel waveguides for the initial excitation of seven channel waveguides using a Gaussian beam.

**Fig. 3.** Spatial distribution of the light wave field in a planar waveguide coupled to a heterogeneous system of channel waveguides with length $z_0/2$ for the initial excitation of (a) a single channel and (b) seven channels.
light. Using expression (1), we derive the focusing length in the curvilinear system of waveguides:

\[ z_0 = l = \frac{2\pi}{\gamma} = \frac{R\lambda}{n^*\Delta R}. \]  

(2)

This expression coincides with the expression resulting from rigorous solution of the problem of the propagation of light in a curvilinear system of channel waveguides [6]. Using the parameters of the curvilinear system of waveguides from this work, one can estimate the coupling coefficient \( \chi \) and the value of \( \gamma \): \( \chi = 27.96 \text{ cm}^{-1} \) and \( \gamma = 60.9 \text{ (30.45) cm}^{-1} \) at \( R = 6 \text{ (12) mm} \).

Using the beam propagation method and the known value of \( \gamma \), we can calculate the spectral dependence of the signal transmitted by the curvilinear system of waveguides with the radius of curvature \( R = 6 \text{ mm} \) and length \( z = 10l \). Figure 4 shows this dependence calculated for the rectilinear equivalent system of waveguides. Comparison of the calculated curve and the dependence obtained in [6] yields minor differences apparently related to the difference in the boundary conditions at the edges of the waveguide array.

It follows from expression (2) that the condition for the maximum transmittance of the system of channel waveguides at wavelength \( \lambda_0 \) is written as

\[ z = NI = N \frac{2\pi}{\gamma}. \]  

(3)

where \( \gamma = \frac{2\pi n^* d}{\lambda_0 R} \), \( d \) is the repetition period of channels in the system, and \( N \) is a positive integer. If \( N \) is much greater than unity \( (N \gg 1) \), we observe additional transmission peaks lying to the left and right of the central peak, so the spacing between the nearest peaks and the central peak is \( |\Delta \lambda| \equiv \frac{\lambda_0}{N} \).

The practical importance of a filter based on curvilinear waveguides with a constant radius of curvature is fairly uncertain. Therefore, we analyze a curvilinear system of waveguides in which the radii of curvature in different fragments have different signs. Figure 5 demonstrates the scheme of waveguides that we use in calculations and the spectral dependence of its output signal. Note that the waveguide system under consideration exhibits a single peak in the spectral dependence of the transmittance, whose width and shape are close to those of the central peak in the curve shown in Fig. 4. The width of the peak depends on the length \( z \) of the system of coupled channel waveguides and the coupling coefficient \( \chi \) (in particular, the distance \( s \) between the waveguides). The decrease in this distance leads to an increase in \( \chi \) and a decrease in the difference between the propagation constants of the neighboring waveguides, which results in a narrowing of the transmittance peak provided the length of the system remains almost unchanged:

\[ z = N_1 \frac{2\pi}{\gamma_1} \equiv NI_1 \frac{2\pi}{\gamma_1}, \]  

(4)

where \( \gamma_1 = \frac{2\pi n^* d_1}{\lambda_0 R} \) and \( N_1 \) is a positive integer.

Figure 6 shows the spectral dependence of the optical transmittance of the above channel waveguide system with a smaller distance between the waveguides. The reason for the higher selectivity of this system of channel waveguides is the higher degree of transverse spreading of light along the channel waveguides upon passing from one focal point to another.
REALIZATION OF THE CURVILINEAR SYSTEM OF CHANNEL WAVEGUIDES

Undoubtedly, the behavior of light in a multilayer system of planar waveguides excited at the end surface is similar to the behavior of light in a system of coupled channel waveguides located on a plane substrate. In this connection, the realization of a curvilinear system of channel waveguides can be reduced to the creation of a multilayer system of cylindrical waveguides deposited onto a cylindrical substrate.

A system of cylindrical channel waveguides is realized using surface plasma chemical vapor deposition technology developed for the synthesis of fiber waveguide blanks [7]. At the inner surface of a reference quartz tube with an outer diameter of 20 mm and a wall thickness of 2 mm, we form a structure consisting of 50 pairs of layers with alternating refractive index. Each pair consists of a layer of undoped SiO₂ with a thickness of 1 μm and a 2-μm-thick layer of nitrogen-doped SiO₂. Based on the deposition technology data, we estimate the difference between the refractive indices of the layers as Δn ≈ 5 × 10⁻³. To protect the structure against chips in the course of polishing, we deposit an additional inner layer of SiO₂ with a thickness of 50 μm. In experiments, we employ the transverse cuts of the tube representing semirings with light input through the polished ends.

Inside the waveguide structure, light propagates along the normal to the generatrix of the cylinder. Figure 7 shows the configuration of the waveguide structure and the propagation of light inside it. The purpose of the experiment was to demonstrate the possibility of light propagation in a curvilinear (circular) system of waveguides with tunnel coupling. In accordance with the results of calculations from [5], the excitation of a single waveguide at the inner or outer edge of the system leads to the localization of light near the edge of the system of coupled waveguides. Especially unexpected is the localization of light in the vicinity of the inner edge, since there exists no volume analog to such propagation of light. In the experiment, we measure the distribution of light intensity at the exit of the system of coupled waveguides as a function of the position of an exciting Gaussian beam with a waist diameter of about 3 μm (λ = 0.63 μm). To measure the distribution of light intensity, we use a spectrometer with a grating and a photodetector. The light is incident on the entrance end of the system and propagates through the waveguide structure. The light intensity at the exit of the system is measured as a function of the position of the exciting beam. The results of the experiment are shown in Figure 8.

Fig. 6. Spectral dependence of the transmitted light intensity for a heterogeneous system of channel waveguides with the coupling coefficient χ ≈ 45 cm⁻¹ (this value is greater than that in Fig. 4).

Fig. 7. Experimental scheme for the study of light propagation in a system of concentric waveguides with tunnel coupling.

Fig. 8. Distributions of light at the exit of a ring waveguide system upon excitation of (1) the waveguide nearest to the buffer layer and waveguides located at distances of (2) 40, (3) 80, and (4) 120 μm from the buffer layer at the entrance of the system.
at the exit, we scan over the magnified \((M = 50)\) image of the side end of the waveguide system by moving a slit with a width of 50 \(\mu\)m along the image plane. Figure 8 shows the results of measuring the real beam width at the exit of the system. It is seen that the results obtained are in agreement with the original assumptions regarding the propagation of light in a circular system of coupled waveguides.

CONCLUSIONS

The results obtained show that one can realize a heterogeneous system of coupled waveguides using the surface plasma chemical vapor deposition technology developed for the synthesis of fiber waveguide blanks. Inside such a waveguide system, light can actually propagate in the vicinity of the inner boundary of the blank. In addition, study of the waveguide system with a sign-alternating radius of curvature yields the spectral limiting of light in this heterogeneous waveguide system.

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