PACS numbers: 42.82.Bq; 42.82.Et
DOI: 10.1070/QE2004v034n04ABEH002682

An inhomogeneous system of coupled waveguides and propagation of light in it

B.A. Usievich, V.A. Sychugov, J.Kh. Nurligareev,
K.M. Golant, A.A. Goncharov, K.K. Svidzinsky

***Abstract*.** **Propagation of light in a circular system of coupled waveguides is studied. The system of cylindrical waveguides is constructed with the help of SPCVD technology used for synthesising optical fibre preforms. It is shown that a 0.63-μm light beam focused at the entrance of a cylindrical system propagates in it with radiation power losses. The radiation is spatially modulated, which makes possible to estimate the period of beam width oscillations inside the waveguide system.**

Keywords: *coupled waveguide system, optical fibres.*

1. Introduction

In recent years, considerable interest has been evoked to the problem of light propagation, amplification, and generation in a system of tunnel-coupled waveguides. This is primarily due to the practical requirement for improving the quality and radiation power of fibre and semiconductor lasers [1, 2]. However, even the use of devices based on a system of channel waveguides requires a deep understanding of the peculiarities of light propagation in them [3, 4]. Channel waveguides can be divided into two types: homogeneous and inhomogeneous. The former have been realised and studied in detail, while the latter have not been subjected to detailed investigations so far and were used only in Refs [5, 6]. This paper is devoted to a new realisation of an inhomogeneous system of coupled waveguides and an analysis of light propagation in them.

2. An inhomogeneous system of coupled channel waveguides

A system of channel waveguides is called inhomogeneous if the light propagation constant in a waveguide varies according to a certain law from one channel waveguide to another. In the simplest case considered here, this variation is linear, which means that the increment $\Delta\beta = \gamma$ in the propagation constant upon transition from one waveguide to another is constant.

It was found in Refs [5, 6] that light coupled into a channel of an inhomogeneous system does not 'spill' over all other waveguides (unlike the case of a homogeneous channel waveguide system) during its propagation but is localised in a few waveguides (the number of waveguides $W \simeq 8\chi/\gamma$, where χ is the coefficient of coupling between waveguides). Moreover, light in a system of channel waveguides is collected again in the initially excited waveguide after travelling distances z_0, $2z_0$, $3z_0$, ..., etc., where $z_0 = 2\pi/\gamma$.

Such a pattern of light propagation is explained by the fact that an inhomogeneous system of channel waveguides ($\Delta\beta = \gamma = \mathrm{const}$) is characterised by an equidistant set of eigenmodes whose interference leads to the observed intensity distribution.

Two ways of realising an inhomogeneous system of channel waveguides were proposed in Refs [5, 6] and focusing of light in it was demonstrated experimentally. Let us consider the simplest method in which (single-mode) waveguides with identical parameters are arranged equidistantly on concentric circles of quite large radius (Fig. 1). Assuming that propagation constants in these waveguides are identical and the input and output ends of all waveguides lie in two planes passing through their respective radii of curvature, the signal at the system output will experience a phase delay during transition from one channel waveguide to another in the case of their in-phase excitation. It can be assumed that this phase delay is caused by a change in the light propagation constant in each waveguide relative to the adjacent one. Such an approach to the problem of light propagation in a curvilinear system of channel waveguides

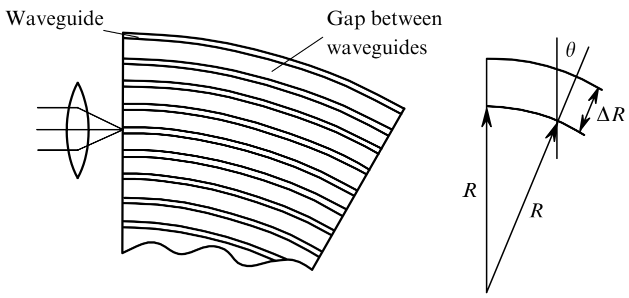

Figure 1. Arrangement of channel waveguides in the system of coupled waveguides.

B.A. Usievich, V.A. Sychugov, J.Kh. Nurligareev, A.A. Goncharov, K.K. Svidzinsky Laser Materials and Technologies Research Center, A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia;
e-mail: borisu@kapella.gpi.ru;
K.M. Golant Fiber Optics Research Center, A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia

Received 22 September 2003, revision received 8 January 2004
Kvantovaya Elektronika **34** (4) 371 – 374 (2004)
Translated by Ram Wadhwa

leads to a relation establishing the equivalence of an inhomogeneous system of rectilinear waveguides to a system of identical curvilinear waveguides. This relation has the form [7]

$$\Delta\beta = k\Delta n^* = kn^* \frac{\Delta R}{R}, \quad (1)$$

where R is the radius of curvature of a waveguide with the effective refractive index n^*; ΔR and Δn^* are respectively the change in the radius of curvature and the effective refractive index of the adjacent waveguide; $k = 2\pi/\lambda$; and λ is the wavelength of light. Relation (1) gives the focusing length of light in a curvilinear system of waveguides:

$$z_0 = \frac{2\pi}{\gamma} = \frac{R\lambda}{n^*\Delta R}. \quad (2)$$

This expression for z_0 is identical to the one obtained in Ref. [8] where the problem of light propagation in a curvilinear system of channel waveguides was solved rigorously. The parameters of the curvilinear system of waveguides used in Ref. [8] lead to estimates for the waveguide coupling constant χ and the quantity γ: $\gamma = 60.9$ cm^{-1} for $R = 6$ mm, and $\gamma = 30.45$ cm^{-1} for $R = 12$ mm; in both cases, $\chi = 27.96$ cm^{-1}. Using the beam propagation method (BPM) [7] and the known value of γ, we can calculate, for example, the spectral dependence of the signal passing through a curvilinear system of waveguides with a radius of curvature $R = 6$ mm and length $L = 10z_0$ [8]. Figure 2 shows the dependence of the normalised light intensity in an excited channel waveguide at the output of a system of length $L = 10z_0$ for a rectilinear system of waveguides. A comparison of the theoretical dependence with that obtained in Ref. [8] reveals a certain discrepancy between them, which is apparently due to different boundary conditions at the edges of the waveguide array.

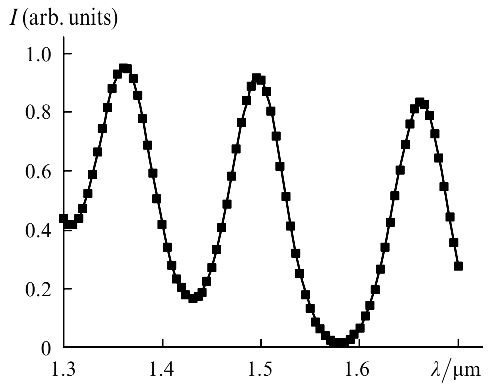

Figure 2. Spectral dependence of the signal transmitted through a circular system of waveguides with a radius of curvature $R = 6$ mm [8]. The signal is recorded at the output of excited channel waveguide.

It follows from (2) that the condition of maximum transmission of light of wavelength λ_0 by a system of channel waveguides is expressed by the relation

$$L = Nz_0 = N2\pi/\gamma, \quad (3)$$

where $\gamma = 2\pi n^* d/(\lambda_0 R)$; d is the channel repetition period in the system; and N is a positive integer. For $N \gg 1$, additional peaks are formed at the left and right of the central peak, the closest of these being at a distance $|\Delta\lambda| \simeq \lambda_0/N$ from the central peak.

3. Curvilinear system of channel waveguides

The behaviour of light in a multilayer system of planar waveguides in a plane perpendicular to this system will undoubtedly be similar to the behaviour of light in a system of coupled channel waveguides on a plane substrate. In view of this, it is sufficient to deposit a multilayer system of cylindrical waveguides on a cylindrical substrate for producing a curvilinear system of channel waveguides.

We constructed the cylindrical system of channel waveguides using the SPCVD technology developed for synthesising preforms of optical fibres [9]. A structure comprising 50 pairs of layers with alternating refractive indices was formed on the inner surface of the bearing quartz tube with an outer diameter of 20 mm and a wall thickness of 2 mm (Fig. 3). Each pair consisted of a 1-μm thick layer of undoped SiO_2 and a 2-μm thick layer of nitrogen-doped SiO_2. The difference Δn in the refractive indices of the layers was estimated by us at about 5×10^{-3} (from the data on the technological conditions of deposition). A supplementary 50 μm thick inner layer of SiO_2 was deposited to prevent damage of the structure from chipping during polishing. Transverse cuts of semiannular tubes with polished edges for introduction of radiation were used in our experiments. Light propagated in the waveguide structure at right angles to the generatrix of the cylindrical tube.

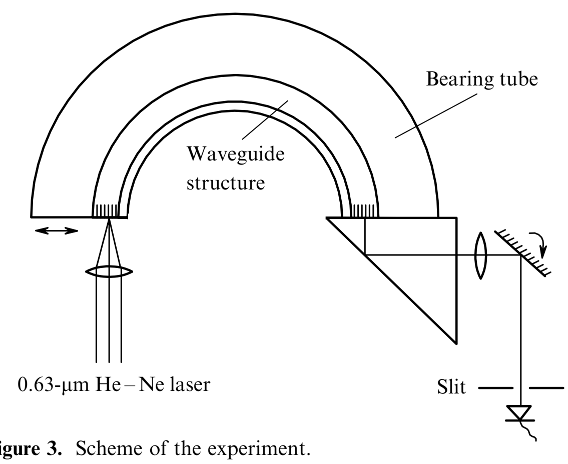

Figure 3. Scheme of the experiment.

The main aim of the experiment was to confirm the possibility of light propagation in a curvilinear (circular) system of tunnel-coupled waveguides. According to the computations carried out earlier [7], the excitation of one waveguide at the (inner or outer) edge of a system of coupled waveguides leads to localisation of light in the vicinity of this edge. Its localisation near the inner edge was found to be quite unexpected since there is no volume analogue to such a propagation of light.

The distribution of light intensity at the output of a system of coupled waveguides was recorded in the experiments as a function of the position of the exciting light beam having Gaussian form and a waist of the order of 3 μm ($\lambda = 0.63$ μm). Since $\Delta n \simeq 5 \times 10^{-3}$, the polarisation of radiation did not play a significant role. The distribution of light intensity at the output was measured by scanning the magnified ($M = 50$) image of the end face of the system of coupled waveguides. For this purpose, a slit of width 50 μm was moved over the image plane.

The results of measurement of the light intensity distribution at the output of the system provided a convincing confirmation of our initial assumptions on the process of light propagation in a circular system of coupled waveguides. However, a detailed analysis of the obtained light intensity distribution at the output of the structure revealed that during the excitation of central waveguides, its width exceeds the value $W = 8\chi/\gamma$ predicted from the above-mentioned relation.

Moreover, the intensity distribution structure does not display any regularity (Fig. 4). All this prompted us to carry out a more detailed analysis of light propagation in an inhomogeneous system of coupled channel waveguides.

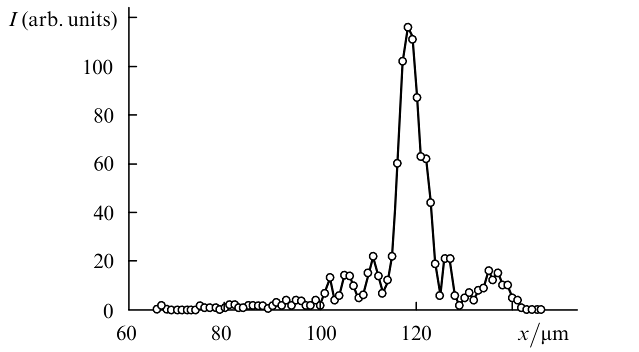

Figure 4. Experimental distribution of the light intensity I at the output end of the waveguide system during excitation of the central waveguide. The coordinate x is measured from the inner edge of the buffer layer.

4. Analysis of light propagation in an inhomogeneous system of coupled channel waveguides

While analysing Bragg diffraction in a homogeneous system of coupled channel waveguides, the authors of Ref. [10] found that light propagating in the gaps between waveguides plays a significant role in this process. In order to determine its role in the case being considered by us here, we used the BPM technique [7]. Initially, a Gaussian distribution of field amplitude of width $w = 4.24$ μm ($w = 3$ μm on intensity distribution scale) was specified at the input of the waveguide structure under consideration and localised so that the centre of the input beam coincided with the centre of the gap between the waveguides. Figure 5 shows the results of calculations of field amplitude variation along the waveguide structure.

Note first of all that the width of the beam introduced into the gap between waveguides, as well as the beam introduced into a channel waveguide, experiences periodic spatial oscillations along the structure with a period determined by the coefficient γ ($z_0 = 2\pi/\gamma$). The maximum width of this beam at the system output is equal to the width of the 'waveguide' beam. However, the radiation loss of light along the structure of the beam between waveguides is initially (for $L \sim (5-6)z_0$) much higher than for the beam introduced into the channel waveguide, but the fraction of light reaching the end face for a waveguide structure length $L = 22.5$ mm used by us in the experiments is close to the

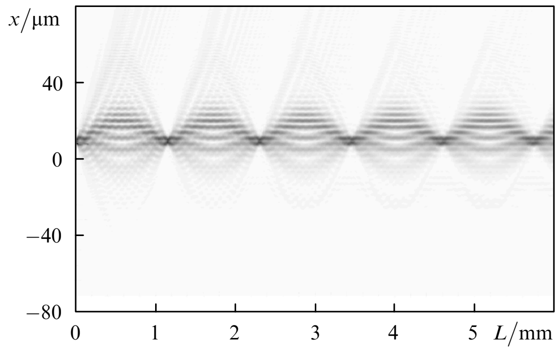

Figure 5. Theoretical dependence of the amplitude of a light beam coupled into the gap between waveguides on the length of its path in the system.

fraction of light at the output in the case of waveguide excitation.

Calculations show that the field distributions at the system output are practically identical for various positions of the light beam relative to the centre of a waveguide localised at the centre of the system.

In the experiment, the tuning of the input beam to a particular waveguide was estimated from the reading of the corresponding micrometer screw whose error of measurement was not higher than 0.5 μm. It is shown by the results of our experiments and confirmed by calculations that the precision of tuning of the input light beam at any point on the middle waveguide at the input of the structure under consideration practically does not change the intensity of light at its output indeed.

It must be noted that during the preparation of investigated samples of the circular waveguide system, its length L is slightly lower (~ 2 mm) than half the circumference of the inner surface of the bearing tube. Consequently, the waveguides approach the end face of the system at an angle $\theta \approx 6^\circ$. Hence we calculated the distribution of the output field of a light beam as a function of the angle θ between the beam axis and the normal to input endface of the structure. It was found that the width of the input field profile distribution depends considerably on θ. Figure 6 shows the output distribution of the field amplitude for two different angles of coupling of light into the waveguide ($\theta = 0$ and 6°). More detailed calculations (for $\theta = 1, 2, 3, 4, 5, 6^\circ$) show that the distribution width increases with angle θ.

Note also that radiation losses also increase with θ. For example, the loss at $\theta = 6^\circ$ is twice as high as for $\theta = 0$. The dependence of transmission of light of the waveguide system under consideration on the excitation beam width is also quite interesting. Figure 7 shows the results of calculations in the case of a light beam introduced in the middle of a system for $\theta = 0$. The highest transmission of light by the system is observed at $w = 15$ μm and, in our opinion, is due to finite size of the system, i.e., to a finite number of waveguides $W = 50$.

Thus, our calculations show that the experimentally observed increase in the width of light intensity distribution at the output of the structure can be explained completely by taking into consideration the fraction of light energy propagating in the space between the waveguides and the angle θ at which light is introduced into the waveguide system.

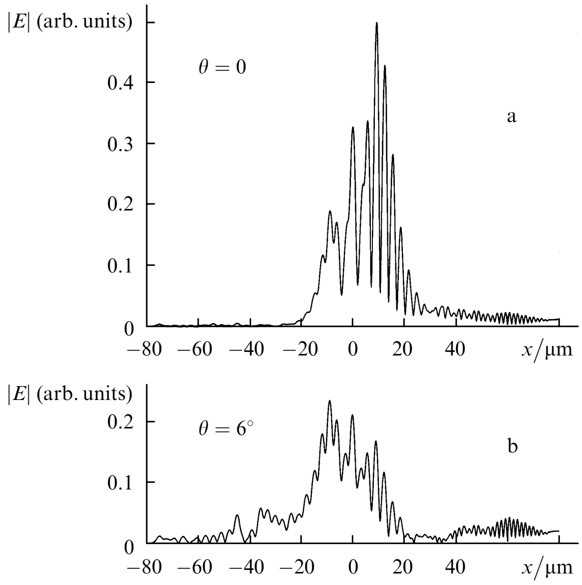

Figure 6. Distribution of the field amplitude $|E|$ at the output of a system for two angles θ of coupling of the light beam into the waveguide system.

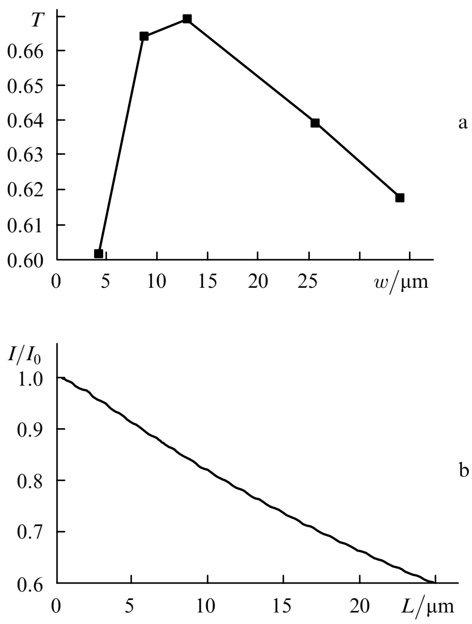

Figure 7. (a) Dependence of transmission T of light by a system of coupled waveguides on the width w of the beam and (b) dependence of the light intensity in the beam on the length L of the system for $w = 4.24$ μm.

Calculations of the amplitude profile of a light beam along the path of its propagation over the system show that if the equality $L = Nz_0$ is satisfied at the output of the structure, the width of the beam amplitude distribution over the channels is minimum. Such an equality can be fulfilled by varying the wavelength of the laser used in the experiment. In this case, the quantity z_0 can be estimated as follows:

$$z_0 \approx \frac{2L|\lambda_1 - \lambda_2|}{\lambda_1 + \lambda_2}. \tag{4}$$

According to our calculations, we require a laser whose tuning range is $\Delta\lambda \approx 30$ nm for $\lambda_m = 632.8$ nm (λ_m is the mean wavelength).

We estimated the pulsation period z_0 of a light beam in a system of coupled waveguides by recording the intensity distribution of light emitted outwards as a result of excitation of central channel waveguides in the system. Experiments revealed that this distribution has the periodic spatial modulation of radiation which, according to our calculations, is due to the pulsation of the size of the light beam propagating inside the waveguide system. Obviously, if D is the modulation period measured on a screen concentric with the waveguide system, the period in the system itself is defined as

$$z_0 = D\,\frac{r}{R_{sc}}, \tag{5}$$

where R_{sc} is the radius of curvature of the screen and r is the radius of the inner wall of the bearing tube. Immersing the screen on the outer surface of the bearing tube and measuring the oscillation period of the radiation emerging from the waveguide system, we found that $z_0 = 1.1 \pm 0.1$ mm. This value is in good agreement with the theoretical value (1.14 mm).

5. Conclusions

Circular tunnel-coupled waveguides fabricated by the SPCVD technique allowed us to observe a number of peculiarities of light propagation in them. An analysis of light propagation in the system using the BPM technique revealed the factors accounting for the obtained experimental results, and made it possible to propose two methods of determining the oscillation period for the width of a light beam propagating along the system of waveguides.

Acknowledgements. This work was supported by the Russian Foundation for Basic Research (Grant No. 03-02-16266)

References

1. Beach R.J., Feit M.D., Page R.H., Brasure L.D., Wilcox R., Payne S.A. *J. Opt. Soc. Am. B*, **19**, 1521 (2002).
2. Botez D., Napartovich A.P. *IEEE J. Quantum Electron.*, **30**, 975 (1994).
3. Smit M.K. *IEEE J. Selected Top. Quantum Electron.*, **2**, 236 (1996).
4. Abeeluck A.K., Litchinister N.M., Headley C., Eggleton B.J. *Opt. Express*, **10**, 1320 (2002).
5. Pertsch T., Dannberg P., Elflein W., Bräuer A. *Phys. Rev. Lett.*, **83**, 4752 (1999).
6. Morandotti R., Peschel U., Aitchison J.S., Eisenberg H.S., Silberberg Y. *Phys. Rev. Lett.*, **83**, 4756 (1999).
7. Goncharov A.A., Svidzinsky K.K., Sychugov V.A., Usievich B.A. *Kvantovaya Elektron.*, **33**, 342 (2003) [*Quantum Electron.*, **33**, 342 (2003)].
8. Lenz G., Talanina I., Martijn de Sterke C. *Phys. Rev. Lett.*, **83**, 963 (1999).
9. Pavy D., Moisan M., Saada S., Chollet P., et al. *Proc. XII Europ. Conf. on Opt. Commun.* (Barcelona, 1986) p. 19.
10. Goncharov A.A., Svidzinsky K.K., Sychugov V.A., Usievich B.A. *Laser Phys.*, **13**, 1017 (2003).