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Investigations of multimode interference structures made by ion exchange in glass

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Experimental results obtained by the visualization method of modal interference in gradient-index multimode interference structures made by Ag^+-Na^+ and K^+-Na^+ ion exchange process in glass are presented. The investigation concerns the self-imaging phenomena for symmetrical and paired interference for TE, TM and unpolarized light excitation. A comparison between experimental results obtained and beam propagation method (BPM) simulations is also presented.

Keywords: multimode interference structures, ion-exchange.

1. Introduction

In recent years multimode interference (MMI) structures have been the subject of intensive studies [1], [2]. The majority of works on MMI concerned interference structures made on the basis of step-index waveguides. In paper [3], the possibility of self-imaging effects appearing in gradient-index waveguides made by ion-exchange in glass is shown. The first application of MMI gradient-index structures made by Ag^+-Na^+ was proposed in [4]. Gradient structures made by ion exchange in glass can be attractive for MMI technology. The ion exchange technique making use of multi-step diffusion processes makes it possible to change the modal properties of the waveguides which decide on intermode interference effects.

In work [5], an experimental method which allows visualization of modal interference in MMI structures is presented. Some testing results for gradient index MMI structures made by K^+-Na^+ ion exchange, excited by unpolarized light are also shown.

Using this method, we show the results of experimental investigation of MMI structures made by K^+-Na^+ and Ag^+-Na^+ ion exchange. We determine the dependence of self-imaging properties on the geometry (width and length), technological process parameters and polarization of the input light. The experimental results obtained are compared with those of BPM simulations.

2. Self-imaging phenomena

MMI structure consists of a group of single-mode waveguides (*a*) of the window width *w*, defining the input field $E(x, y, 0)$, a multimode section (*b*) of the width *W*, where the mode field interference effects are observed and single-mode output waveguides (*c*) of the input geometry, see Fig. 1.

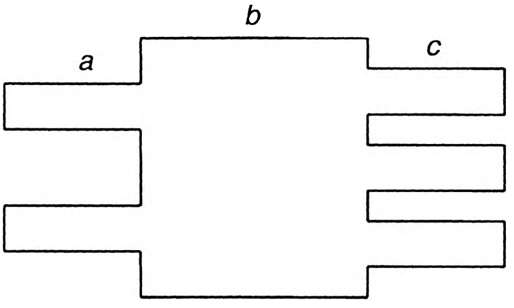


Fig. 1. Scheme of MMI structure: group of single-mode waveguides (*a*), multimode section (*b*), single-mode output waveguides (*c*).

According to the theory for step-index waveguides [2], for propagation lengths *z* satisfying conditions:

$$z = \frac{n}{N}(3L_z) \quad \text{for } n = 0, 1, \ldots; \quad L_z = \frac{\pi}{\beta_0 - \beta_1} \tag{1}$$

where β_0 and β_1 denote propagation constants of two basic modes, *N*-fold images of the input field are formed

$$E(x, y, z) = \frac{1}{C} \sum_{q=0}^{N-1} E(x - x_q, y, 0)\exp(j\phi_q), \tag{2}$$

situated round the points

$$x_q = (2q - N)\frac{W}{N} \quad \text{for} \quad q = 1, \ldots, N-1, \tag{3}$$

with the phase shift

$$\phi_q = n(N-q)\frac{q\pi}{N} \tag{4}$$

which is an inherent feature of *N*-fold interference images. The dependences presented characterize the so-called general interference. It can also be shown [1] that for the input field position x_{in} satisfying conditions

$$x_{\mathrm{in}} = i\frac{W}{N} \quad \text{for} \quad i = 0, 1, ..., \tag{5}$$

some of the input field images overlap giving, in general, a non-uniform field distribution at the output. Only for selected input field positions:

$$x_{\mathrm{in}} = \frac{W}{2}, \quad x_{\mathrm{in}} = \frac{W}{3}, \quad x_{\mathrm{in}} = \frac{2W}{3}, \tag{6}$$

self-imaging effects with uniform distribution of the energy of the field are observed. It is the case of the so-called restricted interference – symmetric and paired, when mode fields are selectively excited.

3. Experimental method

The MMI sections under investigation are produced in the ion exchange process of:

– Ag^+-Na^+ during 40 min and at a temperature of 385 °C in BK-7 glass,

– K^+-Na^+ during 1 h and at a temperature of 400 °C in BK-7 glass.

Diffusion is performed through the mask openings, in which, depending on the direction of excitation, either symmetric or paired interference can be observed [5]. The geometry and the exemplary micro-image of the single mask designed are presented in Fig. 2. The widths W_M of the masks of MMI sections are 30, 39, 51, 60, 69 and 81 μm.

Investigations of MMI structures are carried out in the arrangement described in paper [4], as shown in Fig. 3. The MMI section in which the interference of the mode

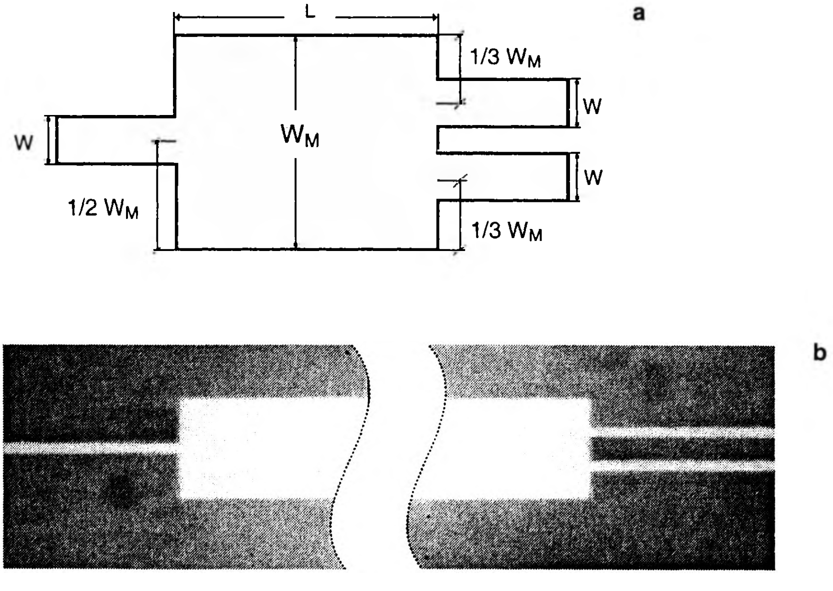


Fig. 2. Geometry of the mask designed (a) and micro-image of the end of the mask (b).

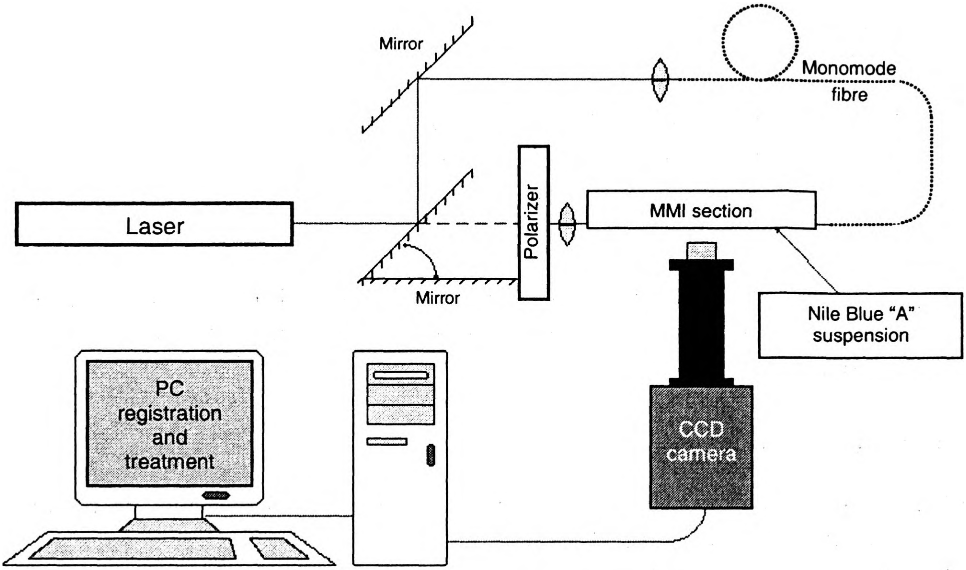


Fig. 3. Experimental arrangement, from [5].

fields is observed, excited by the laser light of wavelength $\lambda = 0.63$ µm is covered with fluorescent substance by spin-coating. This substance is the Nile Blue "A" perchlorate suspension in PMMA [5].

The fluorescent substance produces lightening proportional to the energy of the excited modes. Recording of the successive sequences of mode field interference patterns by CCD camera on PC makes it possible to find the propagation lengths L_N for N-fold images and to determine their dependences on the window width, and the polarization of guided light.

The arrangement presented allows excitation of structures under investigation by:
– polarized (TE or TM) field from laser trough the polarizer,
– unpolarized field from single-mode fibre.

Experimental results were compared with those of BPM simulation in which the distribution profile of the refractive index of MMI section obtained in the diffusion process is calculated numerically from the nonlinear diffusion equation [6]. In simulations we do not take into consideration the changes of the refractive index caused by stresses which can be observed in structures made by ion exchange technology [7]. Due to the stresses the material birefringence in diffused structures occurs.

4. Experimental results

4.1. MMI structures made by Ag^+-Na^+ ion exchange

First we demonstrate the results for MMI structures prepared by silver-sodium ion exchange, because the material birefringence in this process is not significant [7].

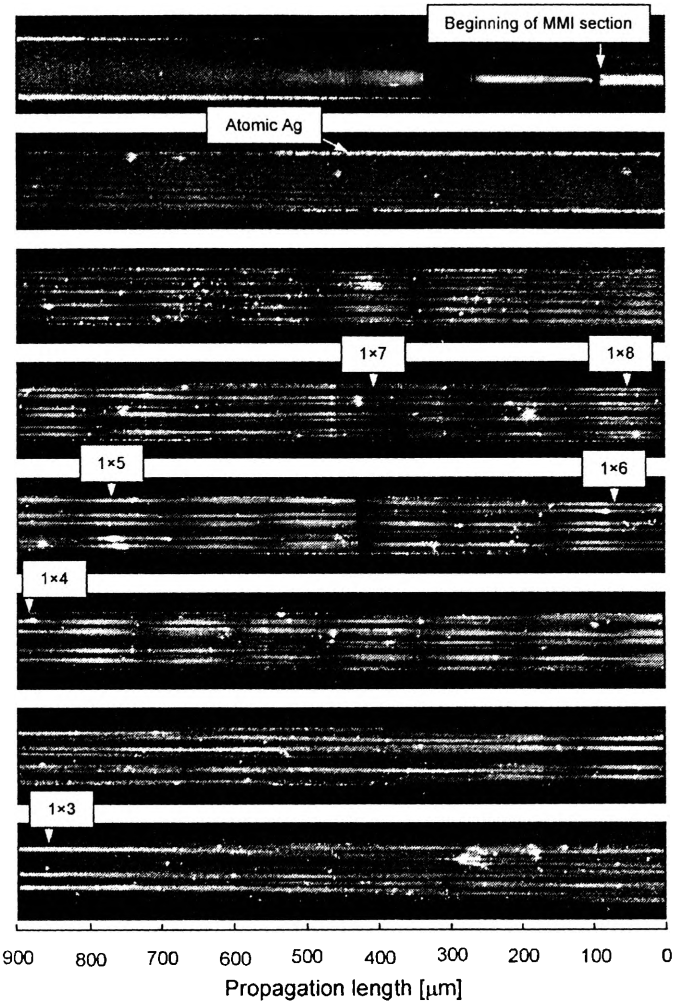


Fig. 4. Successive sequences of recorded mode field interference images for MMI section of the width 81 μm, made by Ag^+-Na^+ ion exchange, excited at one third of the section width.

The MMI structures were excited by unpolarized field from a single-mode fibre. Figure 4 presents successive sequences of the recorded modal paired interference images for gradient index MMI section made by Ag^+-Na^+ ion exchange for the window width 81 μm.

The input field coming out of the single-mode waveguide extends as a result of diffraction, reaching waveguide boundaries. Then, during successive reflections, the field matches the mode structure and next the evolution of interference patterns along the propagation length is observed. For the section presented distinctly visible are 1×8, 1×7, 1×6, 1×5, 1×4 and 1×3 self-images marked in the interference pattern. Also visible are the shining borders of the waveguide. This is probably caused by the reduction of silver ion to the atomic silver in ion exchange process when the metallic mask is applied [8].

4.2. MMI structures made by K^+-Na^+ ion exchange

The birefringence is more important in structures prepared by potassium-sodium ion exchange [7] and to excite them we used the polarized (TE and TM) and unpolarized fields. In Figs. 5, 6, there are presented, for example, successive sequences of recorded mode field interference images for gradient index MMI section made by K^+-Na^+ ion

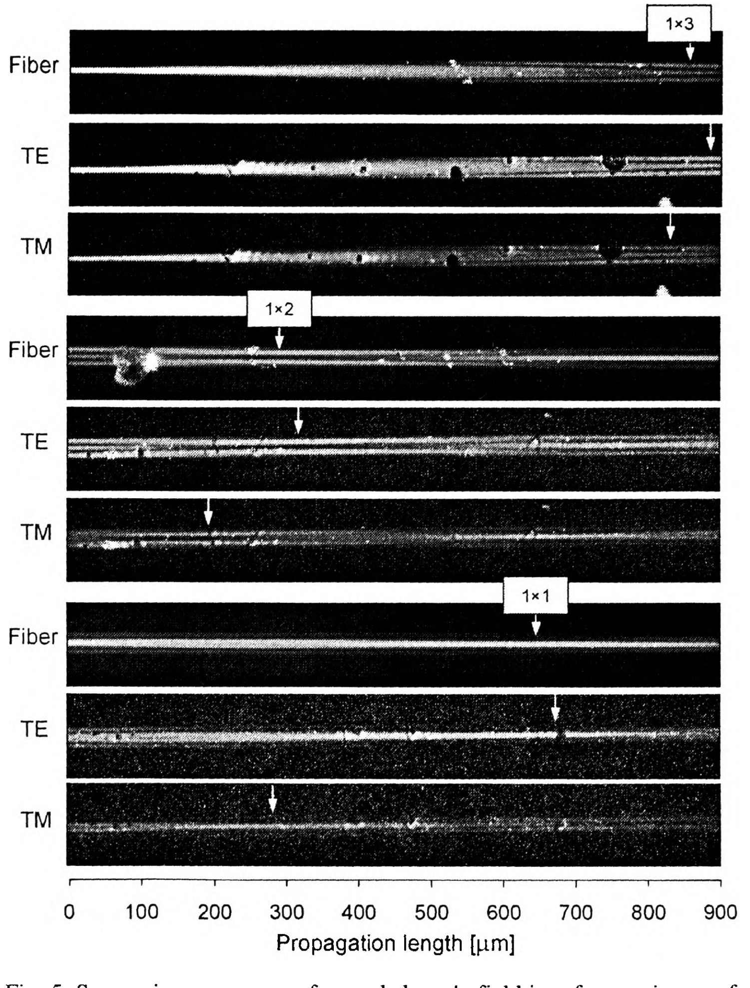


Fig. 5. Successive sequences of recorded mode field interference images for MMI section of the width 30 μm, made by K^+-Na^+ ion exchange, symmetrically excited.

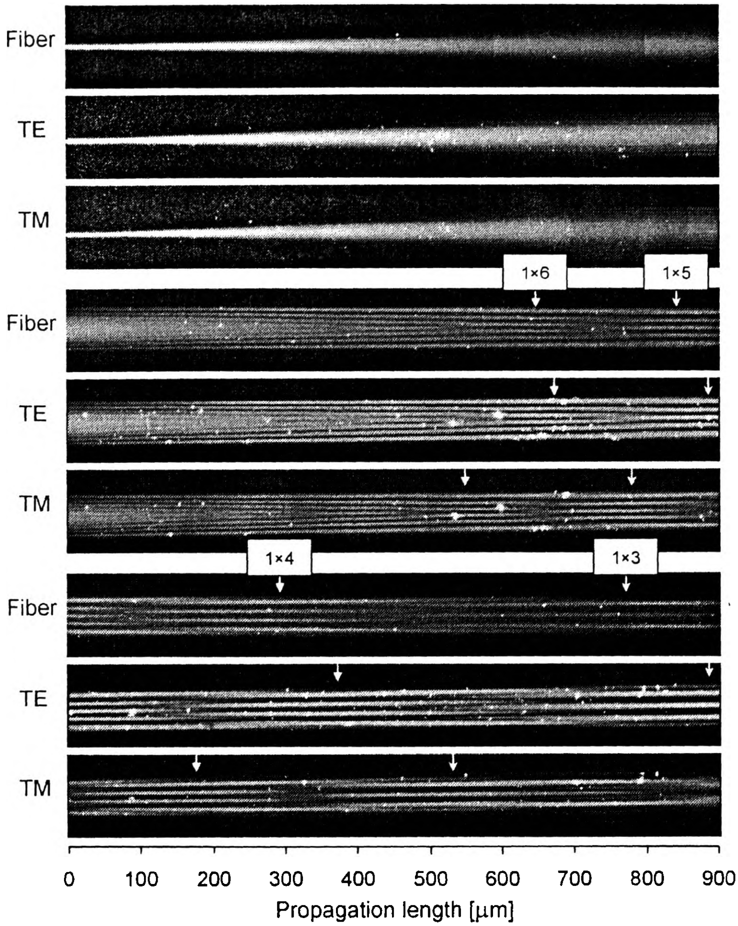


Fig. 6. Successive sequences of recorded mode field interference images for MMI section of the width 60 μm, made by K^+-Na^+ ion exchange, symmetrically excited.

exchange for the window width 30 μm and 60 μm. Sections are symmetrically excited and the effects of symmetric interference are observed.

We can see similar effects of creating *N*-fold images of input field as in the case of silver diffusion. The quantity of *N*-fold input field images depends on the input field spreading and MMI section width. For the narrower section distinctly visible are 1×3, 1×2 and 1×1 self-images marked in the interference pattern. In the wider section, observation of 1×6, 1×5, 1×4 *N*-fold images is also possible. The lengths of *N*-fold images depend on the polarization of guided light.

Interference images shown in Fig. 7 for MMI sections of the width 60 μm excited at one third of the section width are the examples of paired interference. The images

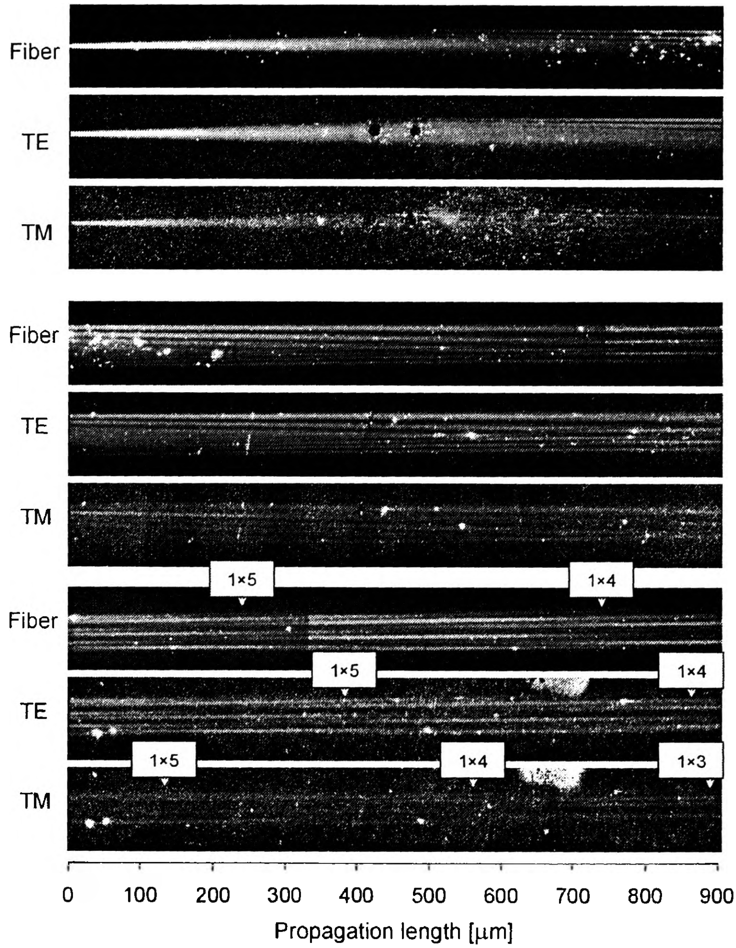


Fig. 7. Successive sequences of recorded mode field interference images for MMI section of the width 60 μm, made by K^+-Na^+ ion exchange, excited at one third of the section width.

are not as clear as in the case of symmetrical interference. This can be explained by the effects of polarization, particularly important for asymmetrical excitation.

5. Analysis of experimental results

The analysis of the experimental interference patterns is carried out in relation to the theory for step-index waveguides. Base on it, we determine the dependences which describe self-imaging effects in MMI gradient structures.

In Figure 8, the propagation lengths are shown for which the N-fold images appear for MMI structure made in Ag^+-Na^+ ion exchange for the window width 81 μm. On the vertical axis the theoretical values of propagation lengths for N-fold images are

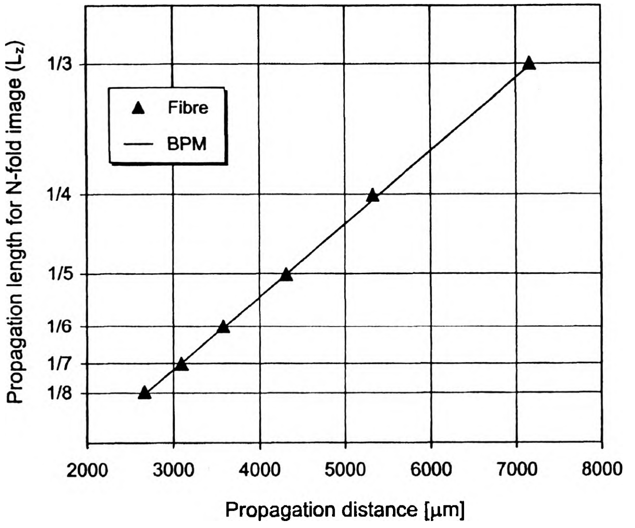


Fig. 8. Comparison between experimental and theoretical dependences of propagation lengths for N-fold images on the propagation distance; MMI section of the width 81 μm, made by Ag^+-Na^+ ion exchange, excited at one third of the section width.

marked. According to the theory for step-index waveguides these images should appear at distances L_N which obey the relation

$$L_N = \frac{L_z}{N} \tag{7}$$

for L_z described in Eq. (1). A comparison between experimental results and BPM simulations is presented. A very good conformity between the theory and the experiment can be noticed.

The main problem in the MMI structures made in Ag^+-Na^+ ion exchange is atomic silver precipitation at borders of the waveguides. This disadvantage influences the strong increase of propagation losses.

The MMI structures produced in K^+-Na^+ ion exchange show low propagation losses. Figure 9 presents dependences of the lengths of N-fold images on the window width for symmetric (Fig. 9**a**) and paired (Fig. 9**b**) interference. Experimental dependences are compatible with the theory for step-index waveguides which demonstrate quadratic dependence L_z on the window width W [1].

Based on Eq. (7), it is possible to predict the propagation lengths on which N-fold images should appear. Figure 10 shows a comparison of experimental results with those of BPM simulations for MMI section of window width 60 μm for symmetric (Fig. 10**a**) and paired (Fig. 10**b**) interference. In both cases the propagation lengths for N-fold images decrease in comparison to theoretical predictions, together with an

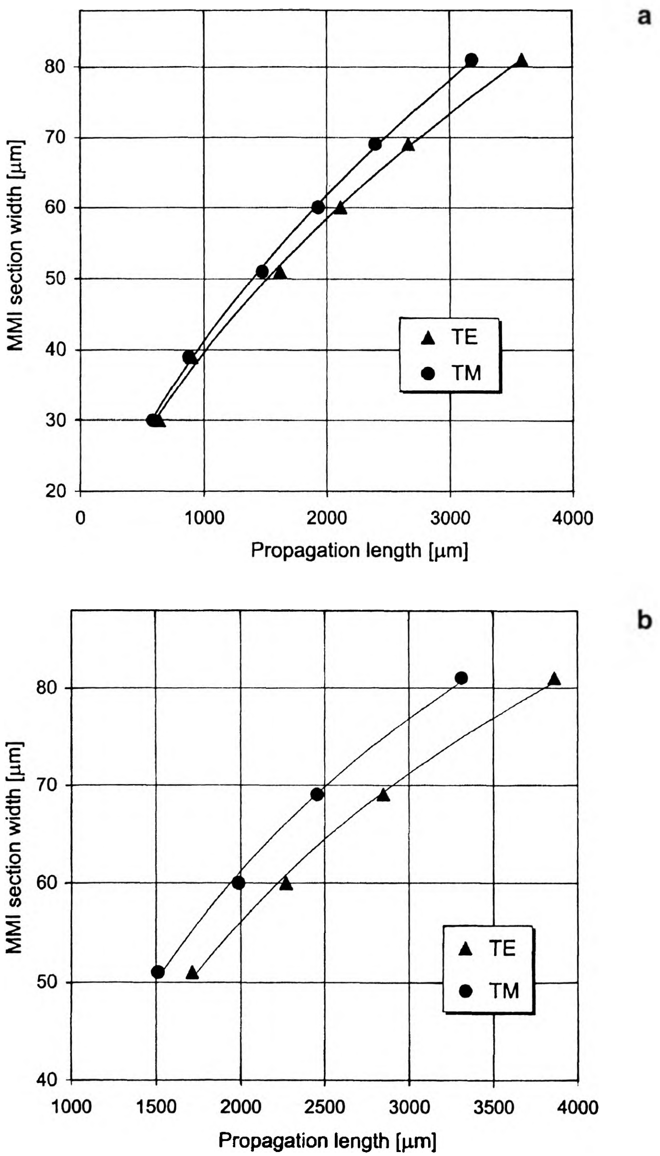


Fig. 9. Dependence of length of N-fold images on the window width for MMI section made by K^+-Na^+ ion exchange; **a** – for symmetric interference, **b** – for paired interference.

increase of the propagation distance. It can also be noticed that the effect is bigger for TM polarization. These deviations, which are not observed for Ag^+-Na^+ ion exchange, can be probably explained by stresses. Participation of stresses in refractive index formation in K^+-Na^+ is significant and in BK-7 glass amounts to 30% for TM and 40% for TE of the total refractive index value [7]. This could be the reason for the

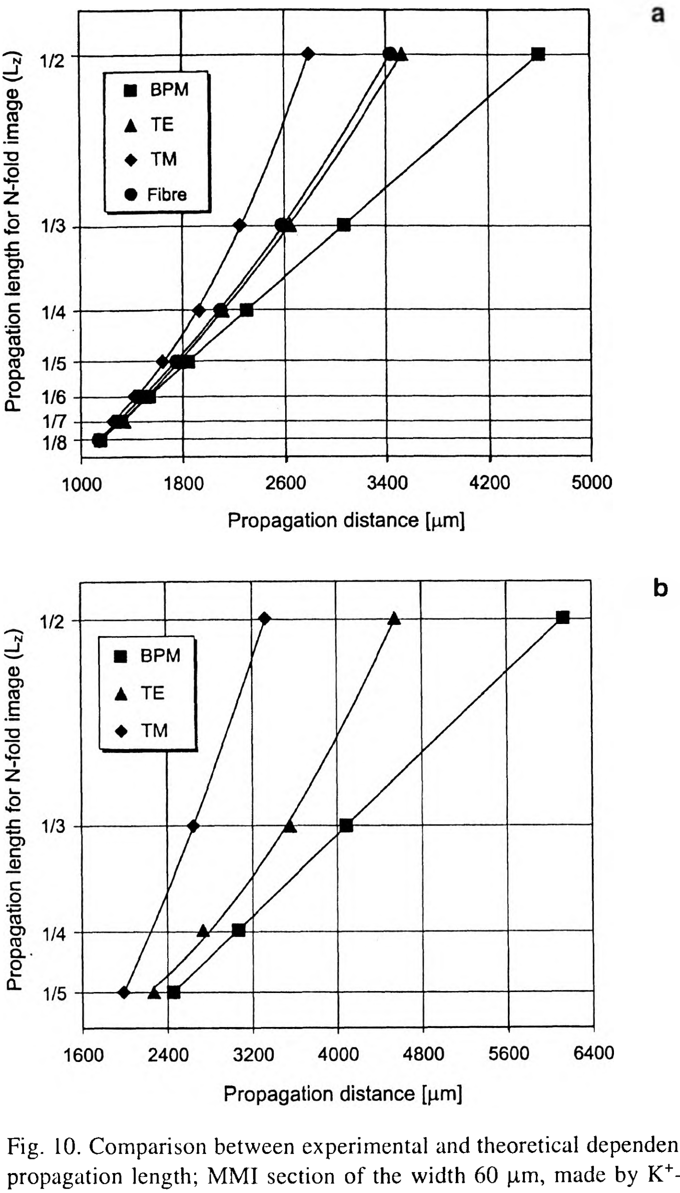
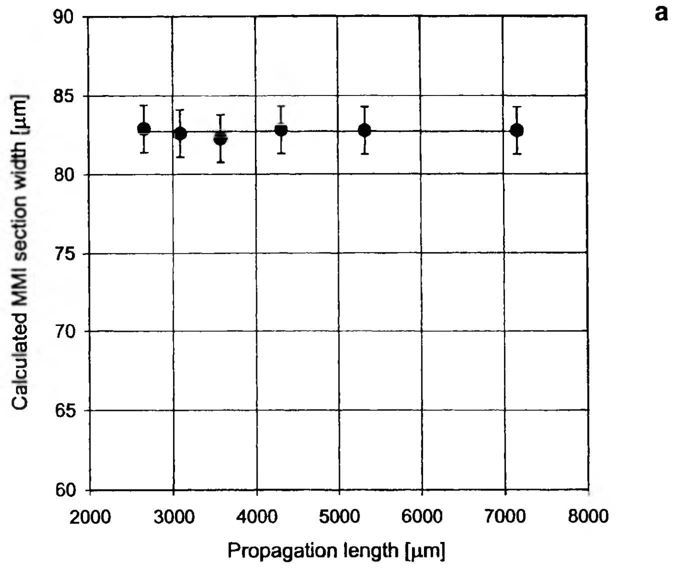


Fig. 10. Comparison between experimental and theoretical dependences of lengths of N-fold images on propagation length; MMI section of the width 60 μm, made by K^+-Na^+ ion exchange; **a** – symmetric interference, **b** – paired interference.

dependence of propagation constants on the mode number which determine self -imaging effects being different than quadratic one.

According to Eqs. (2) and (3), the width of MMI section can be determined from the transversal distance between images in each particular N-fold interference pattern. In Fig. 11, dependences of calculated MMI section widths on the propagation length are presented. Figure 11**a** shows this dependence for MMI structures produced in



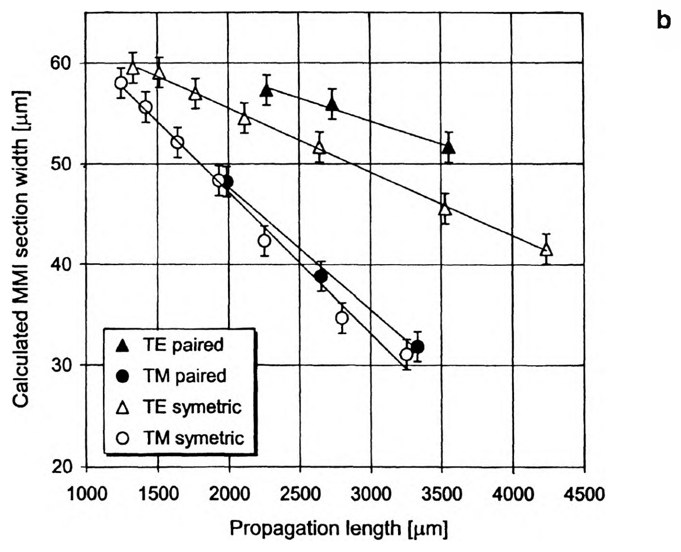


Fig. 11. Dependence of calculated MMI section width on the propagation length; **a** – MMI section of the width 81 μm, made by Ag^+-Na^+ ion exchange, **b** – MMI section of the width 60 μm, made by K^+-Na^+ ion exchange.

Ag^+-Na^+ ion exchange for the window width of 81 μm. The values obtained show very good agreement with the theory for step-index waveguides. Figure 11**b** presents the same dependence for MMI structures produced in K^+-Na^+ ion exchange for the window width 60 μm. As we can see, the calculated MMI section widths decrease with the increase of the propagation distance for both polarizations. The decrease of the transversal distance observed between images is stronger for TM modes. It is a similar situation as in the case of the reduction of propagation lengths L_N (Fig. 10).

6. Conclusions

In the paper, experimental investigation of MMI structures produced by Ag^+-Na^+ and K^+-Na^+ ion-exchange is carried out. The investigation concerns self-imaging phenomena for symmetrical and paired interference depending on the input field polarization.

We have shown that for interference patterns obtained in MMI structures made by Ag^+-Na^+ ion exchange, a very good compatibility of experimental results with theoretical predictions is observed. Lengths of N-fold images and transversal distances between N-fold images are in accordance with the step-index waveguides theory. It can be stated for MMI structures produced in K^+-Na^+ ion exchange that:

– Propagation length for N-fold image for symmetric and paired interference depends on MMI section width similarly as in the theory for step-index waveguides.

– Reciprocal relations between propagation lengths for N-fold images for symmetric and paired interference are similar to relations from the theory for step -index waveguides.

– Propagation length for N-fold image depends on polarization of guided light; for TE modes the distances L_N obtained are longer and for TM modes are shorter. Results for the excitation by unpolarized light from fibre average the effects for TE and TM modes.

– Propagation lengths for N-fold images and transversal distances between images decrease in comparison to theoretical predictions for step-index waveguides. The decrease observed is proportional to propagation distance and depends on polarization.

Using the self-imaging phenomena gradient index splitters and couplers $N\times M$ and $1\times N$ can be produced having very good optical properties in which the splitting of the input field is effected within a small area.

It should be emphasized, however, on the basis of our experimental results, that when designing splitters and couplers made by K^+-Na^+ ion exchange technology we cannot use analytical expressions from the theory for step-index waveguides. The geometry of each splitter and coupler designed has to be determined separately.

The observed deviation of experimental results from theoretical predictions in potassium diffused structures requires further investigation. It is also necessary to elaborate the technology of Ag^+-Na^+ ion-exchange which allows producing MMI structures with low losses without atomic silver precipitation.

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