Bend Structures in Optical Diffusion Waveguides

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***Abstract*—In this paper, we analyse waveguide bends in optical waveguides manufactured by an ion exchange process in thin glass sheets. The waveguides have large dimensions and are highly multimodal. We adapted concepts for single mode waveguides and improved the design for our application in bidirectional optical couplers. Efficiency calculations were carried out using a ray tracing technique.**

I. INTRODUCTION

Integrated optical waveguides for use in printed circuit boards gain growing attention, given the rapid increase of data rate in computer systems [1]. For fully autarkic optical communication systems on board level the development and integration of several active and passive optical components is necessary. On the passive part investigations on production and optical properties of single waveguides, as well as optical couplers have been carried out. Nonetheless, the design of bends and curves in diffusion waveguides has not gathered too much attention. In [2] bends for single mode waveguides have been analysed and produced. The focus lay on optimum bend radii and transition losses.

We investigated, how far the mentioned ideas could be adapted for use in multimodal waveguides with large dimensions. The concept could be applied for optimisation of splitters and couplers, as well as general directional changes of single waveguides. Additionally we extended our analysis software to calculate absorption losses, which would lead to better predictability of the waveguides properties.

II. OPTICAL WAVEGUIDES IN THIN GLASS SHEETS

The manufacturing of optical waveguides in thin glass sheets has been extensively studied in the past years [3], [4]. The process is based on ion exchange. Silver ions in an Ag^+ melt diffuse into a glass sheet in exchange to Na^+ ions. The resulting Ag^+ concentration in the glass sheet is linearly dependent to the refractive index of the glass leading to a waveguide structure. Thus, by adding a mask to the glass sheet the position of a waveguide can be determined. The size of the mask openings determines the resulting size of the waveguide, with the latter being far larger. In our investigations structures with large dimensions ($> 30\mu m$) are used, leading to highly multimodal waveguides.

III. MATHEMATICAL METHODS

A. Finite Element Method

The manufacturing of optical waveguides by ion exchange method can be described by Fick's Law. We solved this equation for our three-dimensional problems using the Finite Element Method (FEM).

B. Geometrical Optics

The analysis of the optical properties of the waveguide structures, which were, due to there dimension, highly multimodal, has been carried out using geometrical optics, based on the solution of the Eikonal equation. For our simulations we used an excitation of the waveguides, using rays, whose density was shaped as Gaussian distribution with a uniform power distribution. The entrance angle was chosen to be in the area of the local numerical aperture to guarantee the excitation of the full angular spectrum of guided rays. The theory of optical waveguides has been extensively described in [5].

IV. BEND STRUCTURES

A. Abrupt Bends

Abrupt bends offer good efficiency for small angle changes. Figure 1 shows the mask structure of an abrupt bend with bend angle ϑ and a mask width w. We modified the angle ϑ from 0 to $15°$ as well as the mask width w from 30 to $60\mu m$ and calculated the efficiency η with our ray tracing approach. The results are depicted in figure 2. It is quite obvious, that for angles larger than $10°$, the losses are quite high, making this angular spectrum unusable for general application. However, the efficiency slightly grows with growing mask width, leading to possibilities of design improvements for applications in splitters or couplers. This is especially valid for large angles, as with $15°$ the efficiency grows by almost 10%. Nevertheless, the conclusion can be drawn that abrupt bends in their simplest form, are not suitable for large changes of a waveguides' position.

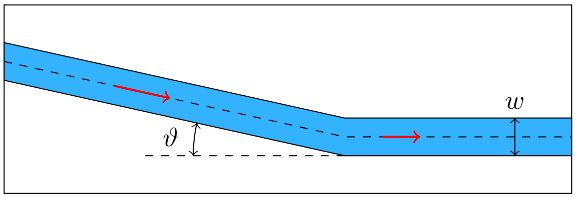

Fig. 1. Mask structure of abrupt bend

B. Radial Bends

Additionally we analysed radial bends. As described above, the general concept of [2] was taken and it was tried to adapt it to multimodal waveguides with curved structures. Due to the highly multimodal properties of the created waveguides with large dimensions, we expect the radii of the bends to be far larger than with the single mode bends in [2]. We

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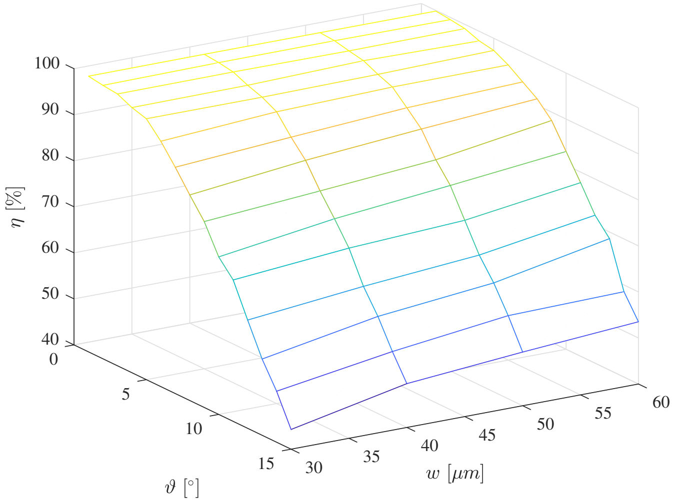

Fig. 2. Efficiency η of abrupt bends with bend angle ϑ and mask width w

simulated the efficiency of a quarter circle. Figure 3 shows the results. As can be clearly seen, efficiency of radii below below $1000\mu m$ is almost zero and below $2000\mu m$ efficiency is still quite low. With radii growing towards $3000\mu m$ efficiency kept growing to almost 80%. Radii beyond $3000\mu m$ could not be successfully simulated due to the high memory demand. Nevertheless, it is predictable, that efficiency will enhance towards 100% with growing radii.

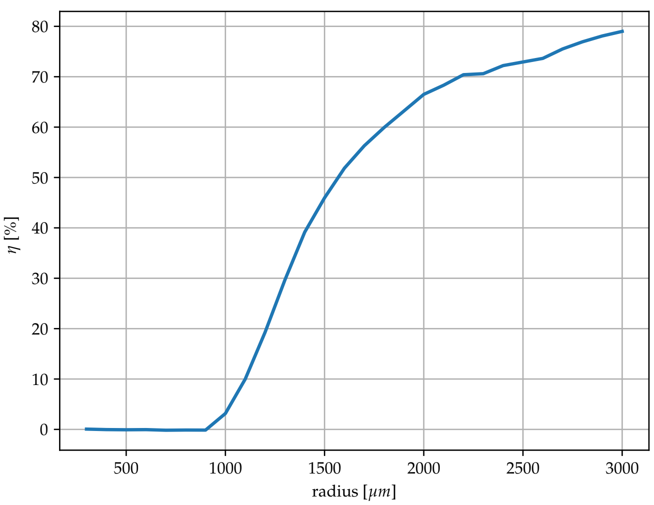

Fig. 3. Efficiency η of quarter circles versus circle radius with mask width $w = 30\mu m$

C. Comparison

To compare both types of bends, we investigated the space needed for a horizontal change of the waveguides' position by $40\mu m$. This was obviously dependent on the bend angle and the waveguide radius, respectively. By this means, it was determined, that radial bends offer great advantages concerning dimensions of the waveguide and efficiency regarding positional changes compared to abrupt bends.

V. MATERIAL ABSORPTION

The problem arising when using geometrical optics for efficiency calculations of optical waveguide structures is the missing possibility to direct handling of wave optic effects like absorption. However, in [5] an approach is presented, that models these effects by a mathematical description. In general both the core and the cladding of the waveguide absorb energy, but with diffusion waveguides the main portion of the absorption takes place in the core with silver ions. Hence only the core absorption has to be evaluated, which is quite simple. Firstly, the complex part of the refractive index has to be considered, which is responsible for power loss. By defining a factor α which describes the fraction of power absorbed per unit length

$$\alpha(\mathbf{r}) = \frac{4\pi n_i(\mathbf{r})}{\lambda}, \tag{1}$$

with $n_i(\mathbf{r})$ the imaginary part of the refractive index. The power $P(s)$ of a ray at a travelled distance s can then be calculated by

$$P(s) = P(0) \cdot \exp\left\{-\int_0^s \alpha(\mathbf{r})\mathrm{d}s\right\}. \tag{2}$$

By this means absorption losses can be calculated. However, as the imaginary part of the refractive index is needed for the calculation, a model has to be applied, providing these information dependent on the process parameters and thus the silver ion concentration.

VI. CONCLUSION

Bend waveguide structures can be used in optical coupler structures, as found in [6], but also for general routing of waveguides on the board level. Depending on the specific application the use of abrupt or radial bends offers advantages. Especially for large changes of direction radial bends offer better efficiency results, whereas abrupt bends are more suited for small changes.

The possibility of including calculations of power loss due to absorption offers more accurate results, which help to predict the waveguide structure properties prior to manufacturing.

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