Analysis of Concentration Dependencies for an Optical Directional Coupler Design

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***Abstract*—An integrated directional coupler is designed for a bidirectional communication on a single waveguide by separating both data streams within individual branches. Thereby, an adjustment of the numerical aperture of the transmitting branch is a promising optimization approach. As the couplers are manufactured by a field-assisted diffusion process the numerical aperture is directly related to the exchange ion concentration. The efficiency of the designed coupler and it's optimization approaches is calculated with a geometrical optics algorithm.**

I. Introduction

Optical intra-board links have been figured out as promising technology for future board level communication [1]. Integrated optical waveguides and devices are manufactured with a field-assisted diffusion process within thin glass sheets, which can be embedded as optical layers in conventional printed circuit boards [2]. Since space is limited at board level applications, a bidirectional communication on a single waveguide is required. Therefor, a directional coupler manufactured with a field assisted ion-exchange process is designed which realizes a separation of both transmission directions [3], [4].

II. Directional Coupler Design and Optimization

The directional coupler, which is designed for simultaneous bidirectional communication on a single waveguide, has the basic idea of extracting both signal directions by separating them into two individual branches. Therefor, a mask structure for a field-assisted ion exchange with different optimization approaches is investigated. As illustrated in Figure 1 the directional coupler consists of an S-bend which guides the received signals to the optical receiver and a straight waveguide branching that works as a transmitting branch.

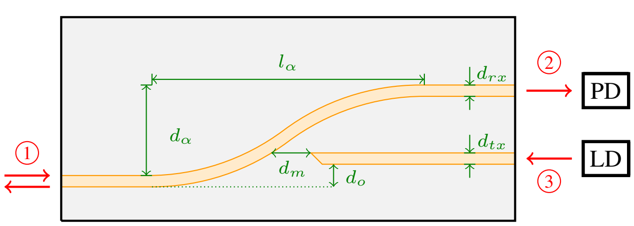

Fig. 1. Mask design of an S-bend with a branching and the optimization approaches of mask bridge d_m, coupling angle α and mask opening width of the transmitting branch d_{tx}.

The efficiency η of the designed couplers is determined by the forced losses in both transmission directions

$$\eta = \eta_{rx} \cdot \eta_{tx}. \tag{1}$$

Therefor different approaches to minimize damping are investigated. A mask bridge d_m between both branches, an offset d_o of the transmitting branch and the coupling angle $\alpha = \arctan(d_\alpha/l_\alpha)$ have already been characterized as promising optimization techniques in the previous works [3] and [5]. The exchange ion concentration c, that is related to the mask opening width d_{tx} as shown in Figure 2, is an additional promising technique to increase the efficiency of the designed coupler. Since the exchange ion concentration c is directly related to the refractive index [6]

$$n_s(\vec{r}) = n_{sub} + \Delta n_{ex} \cdot c(\vec{r}), \tag{2}$$

the numerical aperture of the transmitting branch can be modeled by a variation of d_{tx}.

III. Mathematical Methods

For the investigation of concentration dependencies on the efficiency of the designed directional coupler's the field-assisted ion exchange is modeled by solving the continuity equation for the ionic flux [7]

$$\frac{\partial c}{\partial t} = \frac{D}{1-\alpha c}\left(\triangle c + \frac{\alpha(\nabla c)^2}{1-\alpha c} - \frac{q\vec{E}}{kT}\vec{\nabla} c\right) \tag{3}$$

with the finite-element-method. The geometrical dimensions of the manufactured waveguides are thereby mainly depending on the chosen process parameters of diffusion time t, electrical field strenght E and process temperature T. The designed

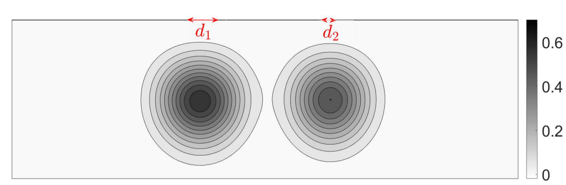

Fig. 2. Cross section of two waveguides manufactured with a field-assisted ion exchange from different mask opening widths d_1 and d_2.

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coupler, presented in this work, is modeled as a highly multi-modal waveguide with large geometrical dimensions compared to the optical wavelength. For this reason, a geometrical optics algorithm solving the ray equation

$$\frac{d}{ds}\left(n\frac{dr}{ds}\right) = \nabla n(r) \tag{4}$$

is used as an efficient method for the loss calculation [8]. The ray extinction is thereby modeled as a gaussian pulse [9].

IV. Investigation Series and Calculated Results

For the purpose of optimizing the efficiency of the structure several approaches have been mentioned before. The mask bridge d_m which is modeled from $0\mu m$ to $500\mu m$ should realize a decoupling of both branches. For the bend angle $\alpha = 5°$ is applied. Thereby, α mainly influences the losses in receiving direction [10]. For the investigation of concentration dependencies of the designed coupler the mask opening width d_{tx} of the transmitting branch is varied in a range of $1\mu m$ to $3\mu m$. This leads to a smaller numerical apertures of the transmitting that should increase the efficiency in receiving direction. The transmitting branch offsets are varied from $0\mu m$ to $20\mu m$. In Figure 3, the calculated efficiencies are visualized in both directions, wherein the receiving direction is continuously represented and the transmitting direction is dashed. Figure 3 shows that smaller mask openings d_s of the transmitting branch lead to higher efficiencies, especially in sending direction (TX) for small offsets d_o. For larger offsets d_o, the effect of mask opening width d_{tx} decreases because the efficiencies converge faster against their final value for increasing mask bridges d_s. From a multiplication of the curves in both directions the overall efficiency η can be derived which is shown in Figure 4. By reducing the mask opening width d_{tx} of the transmitting branch, an increase of the overall efficiency can be achieved for larger offsets d_o. A maximum overall efficiency of 67.4% can be achieved with a mask opening width of $d_{tx} = 1\mu m$ compared to 61.3% which has been the maximum efficiency in further investigations [3].

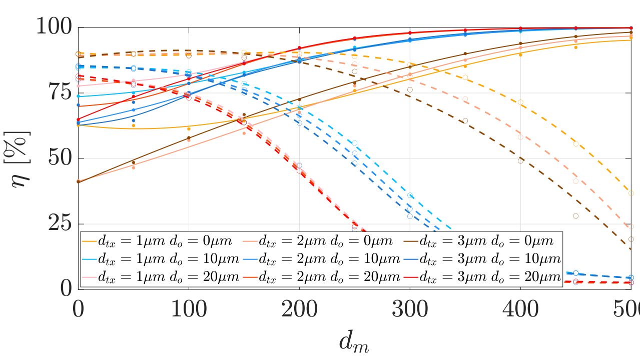

Fig. 3. Calculated efficiencies in receiving direction (RX,continuous) and transmitting direction (RX, dashed) that is depending on various optimization parameters.

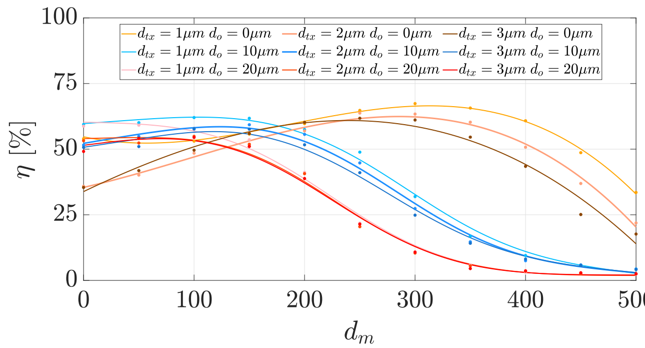

Fig. 4. Calculated overall efficiency η that is derived by a multiplication of the efficiencies η_{rx} and η_{tx} in both directions.

V. Conclusion

In this work a promising optimization approach for an integrated directional coupler which is manufactured by a field-assisted ion-exchange is presented. By reducing the mask opening width d_{tx} of the transmitting branch, the overall efficiency can be increased by 6.1% compared to previous results [3]. The numerical aperture of the transmitting branch is thereby adjusted by the mask opening width d_{tx}. This requires for further investigations a quantitative analysis of the refractive index profiles for different mask opening widths and a verification of the calculated results by measurements to evolve an optimized directional coupler structure.

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