# Numerical Prediction of Propagation Characteristics for Integrated Optical Couplers

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***Abstract*—The field-assisted ion-exchange process for manufacturing integrated optical couplers is multivariate. For this reason, a precise prediction of the optical propagation characteristics of manufactured devices is needed. Two numerical calculation methods are compared with measured results for an integrated coupler to assess its applicability for a precise prediction.**

## I. Introduction

Integrated optical components within thin glass sheets can be manufactured for an integration into electrical-optical printed circuit boards (EOPCBs) by field-assisted ion-exchange processes [1], [2]. The technical implementation of field-assisted diffusion is highly complex, as it is a multi parametric process [3]. The diffusion barrier, which mainly determines the structure of the manufactured component, can be structured arbitrarily. Thus, numerical analyses are necessary to predict the propagation properties of manufactured components. Therefor, an integrated optical coupler is analyzed by means of a ray optics and a beam-propagation algorithm (BPM). The calculated results are compared with measurements.

## II. Directional Coupler Design and Optimization

The integrated optical coupler which is numerically analyzed in this investigation is designed as a directional coupler. The phenomenological basis of signal extraction in both directions is a physical separation within two individual branches [4]. As illustrated in Figure 1, the receiving branch is implemented as an S-Bend whereas the transmitted signals from the laser diode are guided into the bidirectional branch via a straight waveguide.

In order to determine an optimal configuration, the mask structure of the field-assisted ion exchange with different design parameters is investigated. This optimization includes the variation of the mask bridge $d_m$, the offset of the transmitting branch $d_o$ and the bend angle $\alpha = \arctan(d_\alpha/l_\alpha)$ [5]. The efficiency $\eta$ of the coupler is determined in both transmission directions:

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

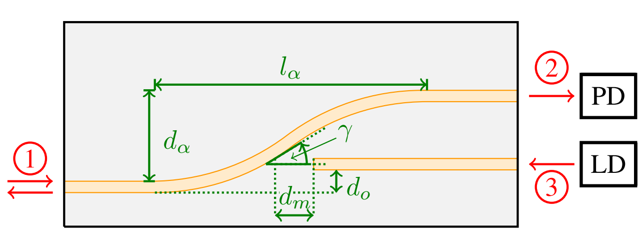


Fig. 1. Mask design of an S-bend with a branch. The optimization approach involves the variation of mask gap $d_m$, offset $d_o$ and coupling angle $\alpha$.

## III. Mathematical Methods

The field-assisted ion-exchange is modeled by the continuity equation for the ion flux [3]

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

which can be solved by the finite element method. As the local optical properties of the glass are affected by the exchange ions, the local refractive index $n_s(\vec{r})$ is directly related to the exchange ion concentration $c$ which is diffused into the substrate [3], [6]:

$$n_s\left(\vec{r}\right) = n_{\text{glass}} + \mathit{\Delta} n_{Ag} \cdot c_{Ag}\left(\vec{r}\right). \tag{3}$$

Since the directional coupler is designed as a waveguide with a $50\mu m$ core diameter, it is highly multimodal and features large geometrical dimensions compared to the guided wavelength. For this reason, a geometrical optics algorithm is used in order to solve the ray equation

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

which is an efficient method to calculate the couplers' propagation characteristic [7]. The BPM-algorithm used for the investigations in the work is based on finite differences and utilizes Padé(1,1) approximant operators. This wide-angle approach ensures that the dependencies of the coupler in the direction of propagation are modeled correctly [8].

The exciting power distribution for both numerical calculation methods is modeled as a gaussian beam. For a qualitive comparison of the calculated and measured result, the efficiency in the receiving direction $\eta_{rx}$ is determined by the power measured in port $P_2$ and then normalized by the total power in both port 2 and port 3. The efficiency in the transmitting direction is described by the normalized power in port 1:

$$\eta_{rx} = \frac{P_2}{P_2 + P_3}, \quad \eta_{tx} = \frac{P_1}{P_0}. \tag{5}$$

## IV. Investigation and Results

In this investigation, a coupler configuration with an offset of the transmitting branch of $d_o = 20\mu m$ is analyzed. The mask bridge $d_m$ is varied from $d_m = 0\mu m$ to $d_m = 500\mu m$ in steps of $50\mu m$ and the coupling angles $\alpha = 3°$, $\alpha = 4°$ and $\alpha = 5°$ are chosen. Previous investigations indicate that a variable mask bridge and coupling angle increase the efficiency in the receiving direction but introduce higher losses in transmitting direction [4], [5]. Figure 2 illustrates the efficiencies in the receiving direction.

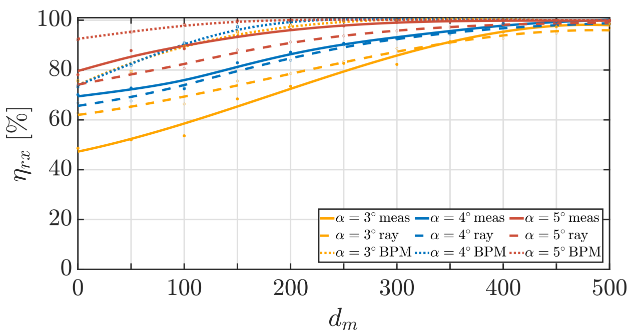


Fig. 2. Comparison of measured and calculated efficiencies $\eta_{rx}$ in the receiving direction (RX) for various combinations of the mask bridge $d_m$ and coupling angle $\alpha$.

As described before, the efficiency $\eta_{rx}$ in the receiving direction decreases as the mask bridge $d_m$ and coupling angle $\alpha$ increase. In contrast, in transmitting direction the efficiency $\eta_{tx}$ decreases which is illustrated in Figure 3.

Consequently, it can be determined for both directions that the tendencies, caused by an increase of the mask bridge and coupling angle, match the measurement results. The ray optical algorithm also shows a good match with respect to a qualitative prediction. In Figure 4 the overall efficiency $\eta$ is presented, which is derived from a multiplication of both curves in the transmitting and receiving direction.

Figure 4 shows that optimal parameter configurations with respect to the couplers' efficiency for $d_m$ and $\alpha$ can be

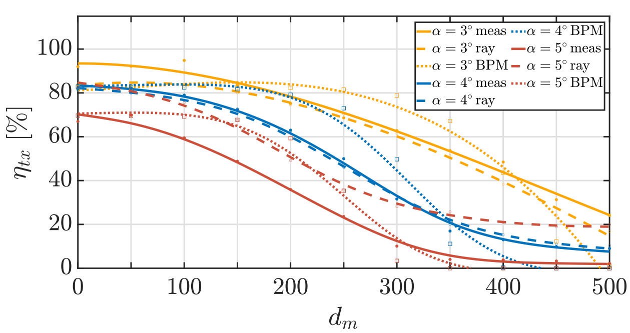


Fig. 3. Comparison of measured and calculated efficiencies $\eta_{rx}$ in the transmission direction (TX) for various combinations of the mask bridge $d_m$ and coupling angle $\alpha$.

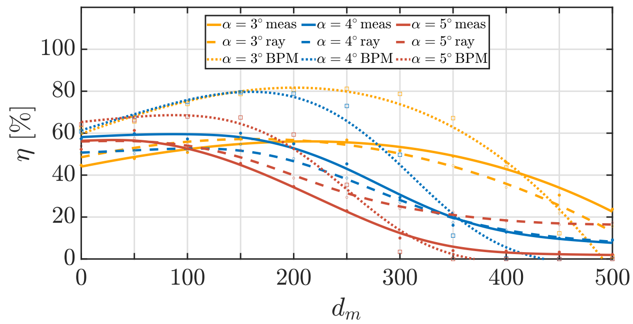


Fig. 4. Overall efficiency $\eta$ for various combinations of the mask bridge $d_m$ and coupling angle $\alpha$.

predicted by both numerical calculation methods as the configurations are in good agreement with the measurement results. The BPM curves of Figure 4 show a higher deviation from the measurements and a higher variation between the individual curves. This is because the BPM is more sensitive to local index changes caused by the mask bridge $d_m$ and variances caused by the BPM's absorption layer. Thus, the geometrical optics algorithm provides a more precise prediction.

## V. Conclusion

In this work, two numerical algorithms for a prediction of the propagation characteristics of an integrated optical coupler are compared with corresponding measurement results. Both approaches can be used to predict the impact of optimizations. Also, optimal parametric configurations for the bidirectional coupler can be predicted by BPM and geometrical optics calculations. For quantitative analyses, the ray optical approach matches the measured results better which qualifies the algorithm as an efficient approach for predicting optical propagation properties.

## References


[1] E. Griese, "A High-Performance Hybrid Electrical–Optical Interconnection Technology for High-Speed Electronic Systems", Advanced Packaging IEEE Transactions on, vol. 24, no. 3, pp. 375-383, Aug 2001.

[2] H. Schröder, L. Brusberg, N. Arndt-Staufenbiel, K. Richlowski, C. Ranzinger and K. Lang, "Advanced thin glass based photonic PCB integration," 2012 IEEE 62nd Electronic Components and Technology Conference, San Diego, CA, 2012, pp. 194-202.

[3] A. Tervonen, B. West, Brian and S. Honkanen, "Ion-exchanged glass waveguide technology: A review" 2011, Optical Engineering. 50. 10.1117/1.3559213.

[4] J. H. Stosch, T. Kühler and E. Griese, "Analysis of optical directional couplers in thin glass sheets for PCB integration," 2017 IEEE 21st Workshop on Signal and Power Integrity (SPI), Baveno, 2017, pp. 1-4.

[5] D. Uebach, T. Kühler and E. Griese, "Efficiency Comparison of Directional Optical Couplers in Thin Glass Sheets Manufactured by a Field-Assisted Diffusion Process," 2020 IEEE 24th Workshop on Signal and Power Integrity (SPI), Cologne, Germany, 2020.

[6] R. Rogozinski, "Ion-exchange in Glass – The Changes of Glass Refraction", ion-exchange Technologies, 2012.

[7] Y. Sönmez, A. Himmler, E. Griese, and G. Mrozynski, "A ray tracing approach to model wave propagation in highly multimode graded index optical waveguides," Int. Journal of Applied Electromagnetics and Mechanics, vol. 17, no. 1-3, 2003.

[8] K. Kawano and T. Kitoh, "Introduction to Optical Waveguide Analysis: Solving Maxwell's Equations and the Schrödinger Equation," John Wiley & Sons, Inc., New York, USA, 2001.