Modeling Multivariate Dependencies for Manufacturing Single-Mode I/O Structures of Integrated MMI-Based Splitters in Glass Sheets

Jan-Philipp Roth, Thomas Kühler and Elmar Griese
Theoretical Electrical Engineering and Photonics
University of Siegen
Siegen, Germany
jan-philipp.roth@uni-siegen.de

***Abstract*—For the realization of integrated optical interconnect systems, optical waveguide components are needed. A promising approach to manufacturing graded-index waveguide components is their embedding in thin glass sheets by ion-exchange processes. In this work, constraints imposed by the multivariate manufacturing process for the realization of single-mode input and output structures in multimode-interference-based (MMI-based) optical splitters are elaborated. Corresponding correlations between these constraints and the according modeling of the devices are established.**

I. Introduction

Increasing data rates have challenged electrical on-board communication. To address related physical constraints, research has focused on optical chip-to-chip interconnect systems [1]. The embedding of optical waveguide components in thin glass sheets by ion-exchange processes is a feasible approach [2] since the integration in common PCB manufacturing processes can be accomplished efficiently [3]. For the realization of photonic integrated circuits, waveguide components are needed. MMI-based couplers can be used for the realization of 1×N optical splitters [4]. While the general functionality of these splitters is not limited to a specific choice of input and output waveguides, many properties of the device will fundamentally benefit from single-mode input and output waveguide structures. The main aspect to be considered is the quality of the transversal n-fold images in the MMI-section [5], [6]. An improvement thereof will advance the optical properties and most importantly reduce the splitting losses. However, the geometry, the materials and the multivariate manufacturing process introduce complex dependencies, which are to be elaborated in this work.

II. Manufacturing Process

For the manufacturing of integrated waveguide components by diffusion, a metallic mask is grown on the substrate material. The shape of the mask can be designed arbitrarily. By the application of a diluted salt melt at a specific temperature, Ag^+ ions diffuse into the substrate replacing Na^+ ions in the glass. The manufacturing process of integrated components can be divided into four basic steps accordingly: (1) Metallic coating, (2) Mask structuring, (3) Application of the diluted salt melt and (4) Mask removal and surface treatment. With a given set of process parameters, the ion-exchange process can be accurately described by Fick's law

$$\frac{\partial c}{\partial t} = \nabla(D\nabla c), \qquad (1)$$

where t is the diffusion time, D is the self-diffusion coefficient of Ag^+ ions in the glass substrate and c is the Ag^+ concentration in the substrate. Figure 1 shows a resulting index profile of an MMI-based splitter with single-mode input and output waveguides. The mask structure of the diffusion process is illustrated qualitatively as a red border.

III. Results and Discussion

The specific challenge in realizing single-mode I/O waveguide structures lies in correlating the macroscopically observed optical properties of the device with the different parameters of the manufacturing ion-exchange process. More specifically, the initial concentration c_0 of silver ions in the salt melt, diffusion times t_{in} and t_{out} and the temperature can be chosen arbitrarily within appropriate ranges. With respect to MMI-based splitter, the process temperature has been set to $250°C$ to prevent internal reflections, because then the

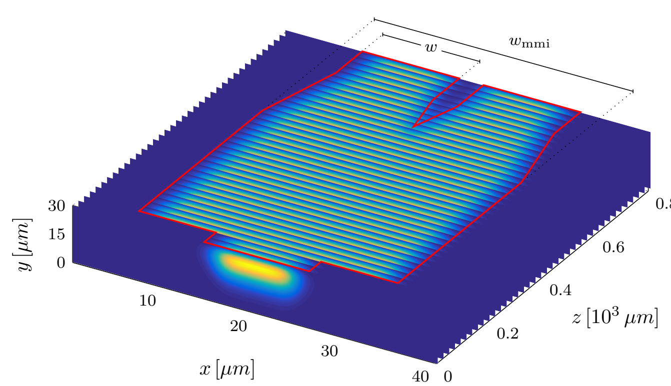

Fig. 1. Index profile of an MMI-based splitter. Mask structure of the diffusion process is illustrated qualitatively as a red border. Since the substrate material is a three-dimensional block, it has been sliced for a better visualization. The number of slices was chosen arbitrarily.

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maximum concentration does not depend on the geometry of the mask structure. Several challenges need to be addressed, which are related to the component class itself and to the nature of the manufacturing process. On the one hand, the low index contrast needed for single-mode waveguide structures can be accomplished by using diluted salt melts with silver ion concentrations of as low as 10^{-4} [7]. This also effectively reduces the formation of silver clusters at the diffusion interface and keeps diffusion times short. Additionally, non-linear concentration dependencies can be neglected in the modeling. On the other hand, short diffusion times result in waveguide structures closer to the surface of the substrate. Therefore, the optical properties are sensitive to the specific choice of process parameters, especially with respect to single-mode input and output waveguide structures of MMI-based splitters.

Figure 2 illustrates how the maximum concentration $c_{\max}$ depends on the diffusion times t_{in} and t_{out}. Increasing diffusion time t_{out} decreases the influence of t_{in}. The two lines indicate the level of maximum concentration for which the input and output structures are still single-mode waveguides - shown exemplarily for a mask width of $w = 8\mu m$ and $w = 15\mu m$. Obviously, multiple combinations of diffusion times are possible. While lower diffusion times support the economical scaling of the manufacturing process, the burial depth of the waveguides is significantly decreased. Another point to be taken into account is the dependency on the initial concentration c_0. Figure 3 shows the total number of propagating modes depending on the initial concentration c_0 versus the diffusion time t_{out}. For higher concentrations, the dependency on t_{out} decreases as the maximum concentration in the substrate is limited and corresponds to the chemical composition of the glass substrate. For low concentrations, it is easy to ensure single-mode operation. However, significantly reducing the concentration potentially leads to stirring issues of the diluted salt melt solution during manufacturing. Consequently, the choice of a set of process parameters implies balancing the need to realize specific characteristics against the ability to fully control the manufacturing process.

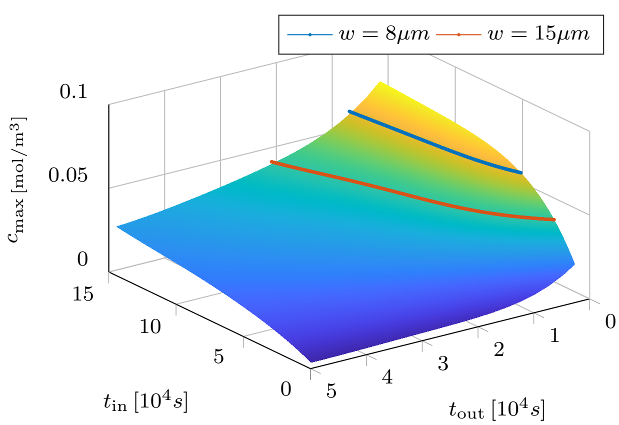

Fig. 2. Maximum concentration $c_{\max}$ after the ion-exchange process versus both diffusion times t_{in} and t_{out}. The two lines indicate the level of maximum concentration for which the input and output structures are still single-mode waveguides - shown for a mask width of $w = 8\mu m$ and $w = 15\mu m$.

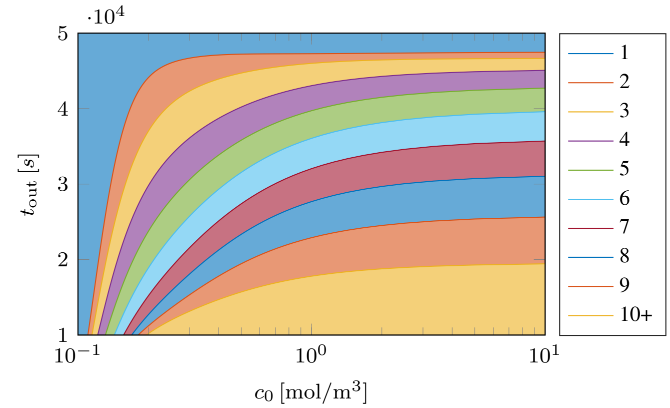

Fig. 3. Total number of propagating modes depending on the initial silver ion concentration c_0 in the diluted salt melt solution versus the duration of the second process step t_{out}.

IV. Conclusion

Realizing input and output structures of MMI-based splitters as single-mode waveguide elements by ion-exchange processes is very promising with respect to splitting performance. The low silver ion concentration improves the kinetics of the diffusion and the choice of temperature supports an economical point of view. While the general goal is to keep diffusion times short, there are limitations, which are imposed by requirements of burial depth and the stirring of the diluted salt melt solution during the manufacturing process. Ultimately, the exact choice of a set of process parameters implies balancing the need to meet requirements with respect to geometrical or optical waveguide characteristics against the ability to entirely control the manufacturing process.

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