Abstract

There is a need to the development of hybrid simulation concepts to describe the light interactions with polymers. Usually, in order to develop comprehensive a description, a multi physics approach is required, i.e., to take into account all relevant parameters such as polymerization, mechanical properties and temperature. The aim of this thesis was to develop a multi-scale and multi-physics simulation approach to simulate the formation of polymer-based photonic components and their optical properties as function of ambient parameters such as temperature. In particular, the case of self-written waveguides which are the interconnects written by light itself was examined. The material interaction with light, the induced polymerization process in monomer/polymer material sample and the influence of temperature on the optical properties was investigated.

The research activities presented in the thesis involved optical simulations, parameter studies, experimental validations and thermo-mechanical simulations of polymer based optical waveguides to be used as interconnects in integrated photonic circuits. The motivation behind confining the research to polymer class material is its processability, high flexibility and ultimately lower cost than corresponding glass counterparts. A very simple and reliable technique by means of self-written waveguides was applied to fabricate and simulate such couplers. Initially, a custom research code for the optical simulation of polymer self-written waveguides (SWWs) was developed. A Crank-Nicholson(CN) based finite difference scheme beam propagation method (BPM) in conjunction with transparent boundary conditions (TBCs) was implemented by applying paraxial approximations to the Helmholtz equation. Other bench-marking photonic components, such as, Y-branch, straight waveguide, bent waveguide and Mach-Zehnder interferometer were simulated using the CN-BPM approach. Furthermore, the photonic components were simulated using the commercial tool RSOFT and the obtained results are compared to the CN-BPM approach for validation purposes. The parameter study was carried out for bench-marking the calculation of insertion loss, mode-mismatch loss, effective refractive indices

and the number of guided modes. Two kinds of material models, named as phenomenological model and diffusion model, were implemented to exactly describe the refractive index modulation within the material sample. These material models are further linked with the CN-BPM scheme to obtain the evolution of SWWs during their writing mechanism.

A comparative study on the theoretical predictions from two kinds of material models for simulating straight and bent SWWs was carried out. Further, a series of numerical investigations were performed on a bent coupler using the diffusion based material model. The temporal dynamics of refractive index modulation along with the corresponding intensity distributions during the curing mechanism of bent couplers are reported. Apart from this, the possibility of misalignment compensation with the increase in length of the bent coupler, regulation of the curvature and curing time of a coupler by controlling specific model parameters in the simulation are presented.

Another interesting aspect of the research involved the validation of the obtained experimental results from the one polymer approach with the theoretical predictions from the diffusion material model. Optical interconnects of various length scales between two multi-mode fibers were fabricated. Their corresponding attenuation coefficient was calculated and compared with the theoretically predicted attenuation coefficient. In general, a good agreement between the attenuation coefficients was observed which demonstrated a successful application of the diffusion material model to the epoxy based acrylate SWW. The transmittance from an SWW interconnect during the writing process was recorded from both simulation and experiment. The evolution of the shape of the SWW at different time steps during simulation and experiment were compared. Also, attenuation measurements between optical fibers with SWWs as interconnects and one without SWW, i.e. with an air gap in between, were performed.

Finally, the research activity was focused on combining the thermo-mechanical and optical simulations and to carry out a comprehensive analysis of planar polymer waveguides. The finite element approach was followed for stress/deformation and thermal simulations. The results of the finite element analysis were coupled back to the CN-BPM results, so the optical simulation as a function of temperature was obtained for polymer waveguides.

This thesis is organized as follows: Chap. 1 presents the introduction and motivation that emphasizes the adaption of optical interconnections in various domains and then signifies the growth of the emerging photonic market. Chap. 2 addresses waveguiding fundamentals to describe the function of optical waveguides. The classifications of optical waveguide, waveguiding design methodology and their propagation techniques are reported. Furthermore,

polymer waveguides are introduced as the research work presented in the thesis revolves around the polymer material class system. In Chap. 3, the implemented numerical method, Crank-Nicolson (CN-BPM) finite difference scheme in conjunction with transparent boundary condition, to carry out optical simulations of various photonic structure is described. The obtained simulation results were validated against a commercial software RSOFT by comparing the simulations results of benchmarking photonic structures. Chap. 4 investigates two implemented material models named phenomenological model and diffusion material model. It introduces the concept of self-written wave-guides. Further details on coupling material models equations with the CN-BPM scheme to demonstrate the change the SWW formations is described. The theoretical predictions by simulating a straight and bent SWW from two kinds of material models are presented. In Chap. 5, the employed diffusion material model to perform various numerical investigations on bent SWW couplers is presented. The investigations are carried out to find an adequate temporal dynamics of refractive index modulation that supports the movement of maximum focus points of intensity. Further investigations on the increased misalignment compensation with respect to coupling or gap length, and the influence of propagation distance on bending and width of a bent SWW are reported. Chap. 6 examines various experimental as well as theoretical studies of polymer base SWWs with respect to the evolution of intensity profiles of SWWs and their transmittance during the writing mechanism. Furthermore, the attenuation was calculated for many fabricated polymer waveguides in experiment and then compared with the predicted attenuation from simulation models. A combined simulation approach that focuses on the thermo-mechanical and optical study of planar polymer waveguide structures is employed. First, two waveguide models are designed with implanted polysilicon microheater to report the impact of induced temperature gradients on refractive index modulation. The optical simulations as a function temperature gradients and the deformation analysis to find corresponding elongations in waveguide dimensions are discussed. Finally, in Chap. 7, the results obtained in this thesis are briefly summarized and an outlook towards future directions is given.