Doctoral dissertation

Light-coupling diffraction gratings for planar optics: design, fabrication, and characterization

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Abstract:

Efficient and controlled coupling of light from a laser source into waveguide structures via an optical fiber is one of the key challenges in the advancement of the planar optics technology and the implementation of novel material platforms. Currently, there are two primary coupling schemes, distinguished by the orientation of the fiber with respect to the waveguide: horizontal coupling, based on mode conversion, and vertical coupling, which relies on exciting propagating waveguide modes by using a periodic structure. Vertical couplers, also referred to as grating couplers, are increasingly applied, as they enable light coupling at arbitrary locations on the surface of even complex integrated photonic circuits. This dissertation addresses the design, fabrication, and experimental characterization of periodic structures for coupling light into planar waveguides, with particular emphasis on grism fabricated on the end-face of single-mode optical fibers.

The first part of the dissertation reviews state-of-the-art solutions developed in mature technology platforms such as SOI and Si_3N_4, and presents methods to enhance coupling efficiency. Based on numerical modeling, a rapid optimization procedure for coupler geometry and its alignment with respect to the fiber was developed, employing the finite element. These computational procedures were applied to the design of grating couplers for waveguides fabricated from SiO_2:TiO_2 ceramics ($n = 1.8$). The maximum theoretical coupling efficiencies for simple structures reached 25%. However, it should be emphasized that the fabricated couplers exhibited lower efficiencies, which was attributed to technological limitations (defects and inhomogeneities) as well as to the shallow waveguide height (a phenomenon confirmed numerically). Nevertheless, the results demonstrated the feasibility of efficient light coupling into SiO_2:TiO_2 waveguides using grating couplers.

The second part of the dissertation focuses on the development of a fabrication process for grating couplers integrated directly onto the end-face of a single-mode fiber. This approach offers two fundamental advantages: it allows coupling at arbitrary wavelengths by designing and fabricating a dedicated grating, and it enables light coupling at any location along a straight section of a waveguide. The structures were fabricated using nanoimprint lithography and different materials where tested. The

best results were obtained with ionic liquids, which enabled the formation of grism with angles up to 45° and grating periods ranging from 1 μm to 4 μm. The fabricated gratings exhibited high reproducibility and quality, and their parameters were evaluated using atomic force microscopy and far-field intensity distribution analysis. As part of the experimental work, a coupler was fabricated for waveguides made of SU-8 photoresist. The measured coupling efficiency reached 4.5%, which showed good agreement with numerical results ($\eta \approx 5\%$). Furthermore, the fabricated coupler was successfully employed to estimate the propagation losses of the tested waveguides, while additional finite-element-based simulations of transmission losses in SU-8 waveguides confirmed the validity of the experimental findings.

In summary, this dissertation demonstrates that periodic structures fabricated on the end-face of optical fibers using nanoimprint techniques can be effectively applied for coupling light into waveguides. The results broaden the knowledge base in photonic integration technologies and may serve as a foundation for the further development of miniaturized photonic devices. The results of this work have been published in four scientific articles and presented at five national and international conferences.