Efficiency enhancement of grating couplers for single mode polymer waveguides through high index coatings

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Abstract - *High-index coatings on top of surface gratings strongly enhance the grating coupling strength in low-index contrast waveguide systems. This opens up new fields of applications for grating couplers such as coupling into single-mode polymer waveguides.*

Introduction

Polymers are an attractive material system for the realization of planar integrated optical waveguide devices in a wide range of applications [1]. Their fast and easy processing allows for cost-effective mass production using injection molding or hot embossing, while their tunable properties provide high flexibility in design. Beside data and telecom applications sensing is an important emerging market segment for polymer waveguide devices. Single mode behavior of waveguides is essential for sensing and for high performance telecom devices. Coupling into thin waveguides is a challenging task where grating couplers showed promising results for different material systems (gratings in polymers [2], silicon nitride (SiN) [3] or silicon (Si) [4]).
The coupling strength α of a grating for coupling out of a waveguide expresses the rate of leakage of the guided mode into the adjacent media [5]. In the case of input couplers, which are the focus of this paper, it determines the optimum spot size for an incident Gaussian beam at which maximum coupling efficiency is achieved. In high-index contrast waveguides systems such as silicon-on-insulator (SOI) α can be in the order of 0.05 μm^{-1} allowing for spot sizes as small as 10 μm [6, 7] without sacrificing coupling efficiency. In polymer waveguide systems, on the other hand, α only amounts to 0.0013 μm^{-1} even for a comparatively high index difference (n=1.46/1.65/1.52 for substrate/waveguide/cladding) leading to an optimum spot size of several hundred microns as illustrated in Fig. 1b). Behind gratings, lateral tapers are needed for coupling into single mode waveguides. The

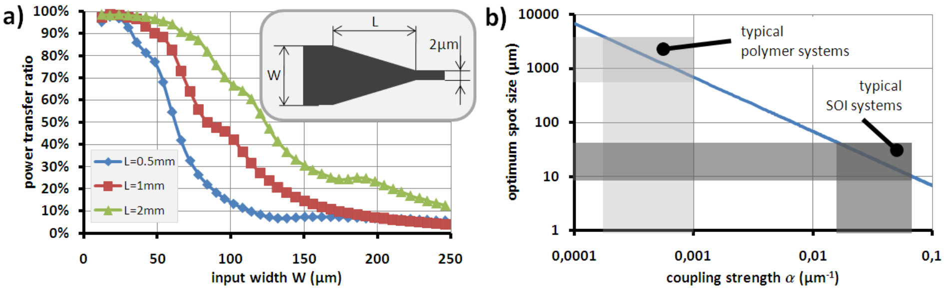

Figure 1: a) PTR of lateral polymer waveguide tapers. b) Optimum spot size of an incident Gaussian beam as a function of the coupling strength of a uniform grating.

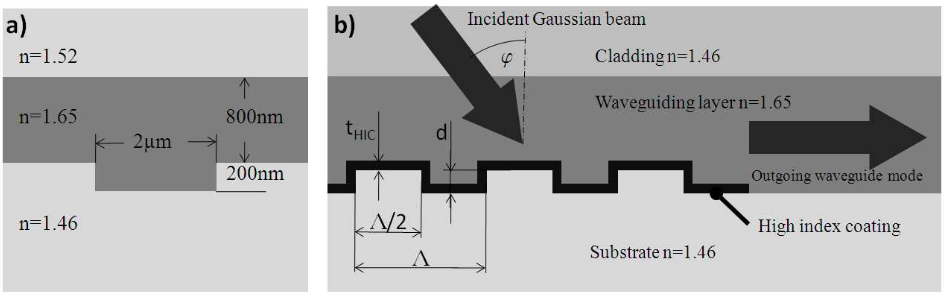

Figure 2: a) Cross section of single mode polymer waveguides and b) schematic view of the grating structures with high index coating investigated in this study.

power transfer ratio (PTR) of lateral tapers is a highly nonlinear function of the input width. Fig. 1a) shows the results of 2D beam propagation method simulations for the polymer system depicted in Fig. 2a). In the given example, tapering with a 1-mm long taper is possible for input widths up to 50 μm (PTR $>$ 90%). Thus, a spot size sufficiently small for low-loss lateral tapering results in a strongly reduced coupling efficiency of the grating and vice versa. In this paper, we show that this conflict can be solved by depositing a thin high-index coating (HIC) on the grating. Due to the strong dependence of α on the index difference [8] the higher index difference leads to a reduction of the optimum spot size for the grating, thus enabling efficient coupling via lateral tapers into single mode waveguides. In the following, simulations and experimental results illustrating the effect of an HIC on a polymer waveguide system is presented.

Simulation results

The numerical model of the simulation tool used for the calculation of grating input couplers employs a rigorous Floquet-Bloch (FB) approach [9, 10, 11]. For the computation of the 1D grating layer eigenmodes [10] an efficient and numerically extremely stable high-order finite-element approach is applied. The polymer waveguide system studied in this paper is assumed to consist of a polymethylpeptene (PMP) substrate (n=1.46), a polyimide (PI) waveguide core layer (n=1.65) and an Ormoclad (OC) cladding (n=1.52). The surface grating at the substrate/waveguide core interface (see Fig. 2b)) comprises hundred periods of Λ=1.75 μm, *i.e.*, the coupling condition is fulfilled for an angle of incidence φ of about 45deg in air at λ=1.55 μm. The grating has a duty cycle of 0.5 and the diameter of the incident TE-polarized Gaussian beam is 30 μm. Fig. 3 shows the calculated PTR of input gratings with a 1 μm thick polymer waveguide layer as a function of the etch depth d for a SiN (n=2) and an amorphous Si (n=3.48) HICs with different thicknesses. The PTR increases with the HIC thickness. The termination condition of the simulation was the excess of the effective index of the waveguide mode over the refractive index of the waveguide core layer. The simulations were verified with 2D-FDTD simulations. These FDTD-simulations indicated that a further increase of the HIC thickness has a negative effect on the PTR.

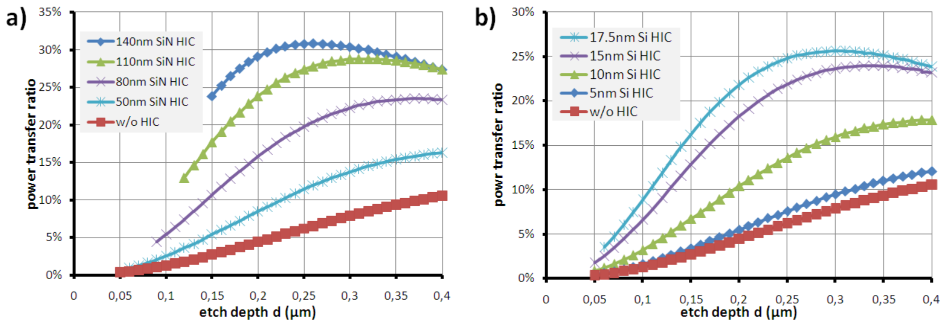

Figure 3: Calculated PTR of a 1 μm thick polymer waveguide as function of the etch depth d for a) a SiN (n=2) and b) amorphous Si (n=3.48) HICs.

Fabrication and experimental results

In order to experimentally verify the positive effect of a HIC on grating couplers in low index contrast waveguides samples were prepared on silicon wafers. Instead of PMP, SiO_2 was used as lower cladding, which matches the refractive index of PMP in the near infrared. A 210nm SiN anti-reflection layer and a 3 μm thick SiO_2 layer were deposited on a silicon wafer via PECVD. The gratings and the inverse rib waveguides were patterned using standard photolithography and etched into the SiO_2 layer with an SF_6 RIE process. The etch depth varied slightly between 200 nm and 250 nm over the sample due to variations in the RIE process. The SiN HIC was deposited using PECVD and selectively removed outside the grating area employing a RIE etch step. A 1-μm thick layer of a spin-coatable PI from HD Microsystems was used as waveguide core layer material. After spin-coating of Ormoclad as cladding the samples were cleaved to enable fiber butt coupling for the output waveguides.
Four series of samples were prepared with different thicknesses of the SiN HIC. For each series eleven gratings with and eleven without HIC were measured. The enhancement of the input coupling efficiency induced by the HIC could be confirmed. Despite

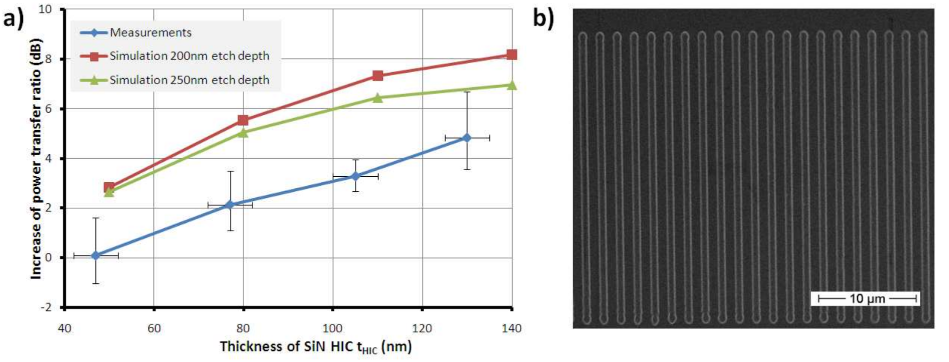

Figure 4: a) Calculated and measured PTR increase as a function of the SiN HIC thickness and b) SEM picture of a 30 μm width grating with 140-nm HIC.

a nearly 5-dB increase in the coupling efficiency with a 135-nm SiN HIC, the measured enhancement is not as high as in the simulation. This mismatch and the comparatively large variations between gratings of the same HIC thickness can be most likely attributed to imperfections of the fabricated grating structures such as non-vertical side walls, and variations of the duty cycle and the thickness of the waveguide core layer.

Conclusion

The coupling strength of polymer waveguide grating couplers can be significantly increased by applying a HIC. This technique allows for compact grating couplers with optimum spot sizes of several tens of microns, which facilitate the coupling to single mode waveguides using adiabatic tapers in low index difference material systems. A wide range of materials is suitable to act as HIC. Since the HIC is only present in the comparatively small grating area the optical quality and absorption losses of the HIC have only minor influence on the PTR. Therefore, low-temperature thin film deposition techniques usually not used for optical waveguide fabrication because of lower optical layer quality such as sputtering could be employed for the HIC deposition on polymers waveguides.

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