

Direct light-coupling to thin-film waveguides using a grating-structured GRIN lens

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Abstract: We present a novel coupling scheme using a collimating gradient-index (GRIN) element provided with a high frequency grating to couple light from a single mode optical fiber directly to planar thin-film waveguides. The waveguide devices are used, for example, for an efficient fluorescence excitation in biosensor applications. The external coupler can be multiply reused and supersedes the conventional internal gratings. FEM simulations and experimental results show that the new technique can provide similar coupling efficiencies as common internal grating couplers.

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1. Introduction

Planar optical waveguides consist of a layer of high refractive index material, usually a thin film of a metal oxide applied by an optical coating technique, on a transparent substrate. Some of the most interesting applications can be found in life science research [1]. For example, the waveguides are used as biosensors which enable a highly efficient and specific excitation of fluorescently labeled molecules on the waveguide surface by the evanescent field of the guided mode [2,3]. Other fields of application include telecommunication devices and material research.

To provide a strong and homogeneous evanescent field, the waveguide devices are usually designed to support a single mode only, resulting in a typical film thickness in the range of 100 - 200 nm. For these waveguide dimensions prism coupling or end face coupling are not applicable and grating couplers are usually applied to excite the waveguide mode [4]. They are based on the periodic modulation of the refractive index on the surface of the waveguide. Resonant coupling occurs when the wavevector of one of the diffracted beams (usually of first order) matches the wavevector of the guided mode. Since submicron periodicity is usually required for the gratings, lithography is often used to provide the surface patterning, followed by dry or wet etching of the surface relief [5]. While lithographic methods offer high precision, they are cost effective only in the fabrication of large quantities. Alternative techniques for the fabrication of the gratings include embossing [6] and direct laser-ablation [7,8]. The great flexibility of the laser ablation process allows to tailor the grating couplers to specific applications. For example, the spectral acceptance can be matched to the spectral width of ultrashort pulse lasers in applications requiring two-photon fluorescence excitation.

The refractive index modulation on the waveguide surface can also be induced by an external grating. Kocabas et. al. used an removable elastomeric grating made from polydimethylsiloxane (PDMS) to couple a He-Ne laser to a SiO_xN_y waveguide [9]. The reported coupling efficiency is of the order of 1%, limiting this coupling scheme to material research applications.

In this work, we present a technique that uses a collimating micro-lens, e.g. a gradient index (GRIN) lens, provided with a high frequency grating structure at the exit face to couple laser light from a single mode optical fiber directly to a planar waveguide. If positioned precisely on the waveguide, the external grating structure on the surface of the lens produces an effective index modulation on the surface of the waveguide and thus provides efficient coupling. We employ finite-element method (FEM) calculations to study the effect of experimental parameters on the coupling efficiency and demonstrate the feasibility of the approach using a grating structured GRIN lens. The grating with 500 nm period is fabricated on the lens end face by direct laser ablation with an F₂-laser at 157 nm wavelength.

Since the external couplers can be multiply reused, the conventional grating couplers, which induce a major part of the production costs of the waveguide devices, become dispensable. This is especially important in biosensing applications, where the waveguide chips are usually designed for single-use. Furthermore, certain restrictions like a minimum substrate thickness, which are imposed on the waveguide devices by the lithographic process, can be circumvented, thereby extending the range of applications.

2. Coupling scheme

The principle of waveguide coupling by an external grating-structured GRIN lens is illustrated in Fig. 1. Laser light emerging from a single-mode optical fiber is expanded and collimated by an 0.25 pitch GRIN lens. The exit face of the collimating lens is polished under the coupling angle and structured with a high frequency grating. If the structured surface of the lens is placed in close proximity or in contact with the waveguide surface, a part of the collimated beam can be coupled to and guided by the waveguide.

Resonant coupling occurs, when the wavevector of the diffracted beam of order r and the wavevector of the guided mode coincide:

$$k_m = k_0 n_i \sin \theta + r \frac{2\pi}{\Lambda} \quad (1)$$

where k_0 is the free-space wavenumber, n_i is the refractive index of the lens material, θ is the incidence angle of the collimated beam and Λ is the period of the grating structure. $k_m = k_0 n_{wg} \cos \theta_m$ is the propagation constant of the guided mode with mode angle θ_m and refractive index n_{wg} of the waveguide material. Here, a first order beam is used for the waveguide coupling. To meet the coupling condition, a precise adjustment of the beam angle can be achieved by a lateral translation of the fiber exit in the focal plane of the lens.

Since the waveguide coupling is solely governed by the characteristics of the external grating, a rod lens in a collimation configuration and with a microstructured end face can likewise be used in the proposed coupling scheme instead of the GRIN lens. Also, a simple micro-optical glass or quartz cylinder can be equipped with the grating structure and used as an external waveguide coupler. In this case, the collimation must be provided by an additional optical element between the output of the optical fiber and the structured element. The most appealing approach seems to be direct fiber to waveguide coupling using an optical fiber with an angle polished and grating structured end face and circumventing any further optical elements.

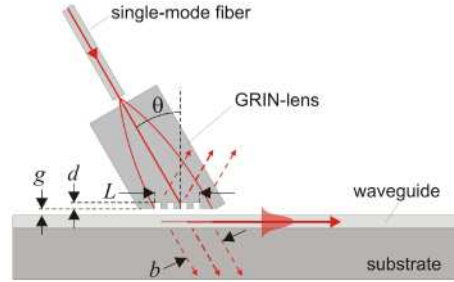


Fig. 1. Schematic illustration of the waveguide coupling scheme via a collimating GRIN lens with an angle-polished end face and structured with a high-frequency grating. Experimental parameters d : grating depth, g : gap width between waveguide surface and grating, L : grating length, b : diameter of collimated beam, θ : incidence angle.

3. FEM simulations

In order to determine the effect of experimental parameters on the coupling efficiency and to estimate the maximum efficiency that can be expected by the proposed coupling scheme, the coupling process is analyzed by calculations using the finite-element method (FEM). The COMSOL Multiphysics software package including the RF-module for electromagnetic field simulations is employed to this purpose. The model is set up in 2 dimensions to restrict complexity allowing TE wave propagation in the plane.

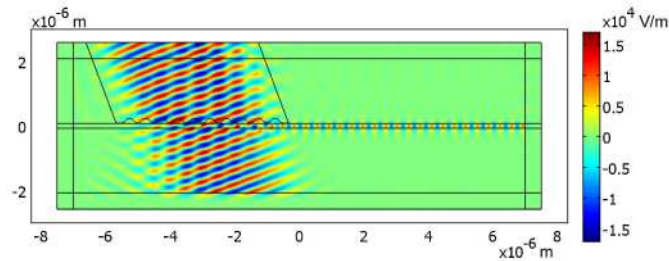


Fig. 2. Model used for the FEM simulation, depicting the out-of-plane component of the electric field in a false color representation.

The geometry of the model is illustrated in Fig. 2 for the example of a grating structured element of width $b = 5 \mu\text{m}$ which might represent the fused silica core of a single-mode fiber in a direct fiber to waveguide coupling approach. The grating with period 500 nm embedded into the end face is of sinusoidal shape and covers the full width of the element. The waveguide thickness is chosen to be 150 nm, the thickness of the substrate and air-layer over the free waveguide are 2 μm . The refractive indices of the structured element, the waveguide and the substrate are set to $n_i = 1.46$, $n_{wg} = 2.1$ and $n_{sub} = 1.52$, respectively. The incident beam with a free-space wavelength of 633 nm is simulated by a port excitation with cosine beam profile at the boundary of the structured element opposing the grating. The exact value of the beam angle is controlled by the port phase being a linear function of the position.

Except for the port, perfectly matched layers (PML) are used to terminate the computational domain. These PMLs match the optical index at the interface and attenuate the propagating fields exponentially to prevent fictitious reflections at the outer boundaries. An exemplary simulation of the out-of-plane component of the electric field is shown in Fig. 2.

The coupling efficiency is specified as the ratio between the power of the port excitation to the power that is directed into the waveguide. For a particular simulation of the electromagnetic field, the power guided by the waveguide is determined some distance from the edge of the external grating element by an integration of the power flow over the cross section of the waveguide, including the evanescent fields in the surrounding substrate and air layers. In the situation depicted in Fig. 2, using a grating depth $d = 150$ nm and a gap width $g = 20$ nm (defined as the distance between the elevations of the grating and the surface of the waveguide, see Fig. 1), a resonant coupling efficiency of 3% is obtained. The angular resonance has a width of approximately 6° (full width half maximum, FWHM). If the width of the grating element is kept at $b = 5$ μm , the coupling efficiency does not exceed 5%.

In analogy to internal grating couplers, the efficiency can be improved by increasing the coupling length. The beam waist must be increased respectively by a collimating element, e.g. a GRIN lens. Coupling is then simulated by extending the width of the grating structured element to $b = 250$ μm and setting its refractive index to $n_i = 1.5$. The thicknesses of the substrate and air layer over the free waveguide are limited to 1 μm with respect to computational resources. The length of the left aligned coupling grating (cf. Fig. 1) is initially set to $L = 220$ μm , covering 82% of the length of the angled end face. The dependence of the coupling efficiency on the beam angle is displayed in Fig. 3 for grating depth $d = 100$ nm and different gap widths. The resonance angle of maximum coupling increases with decreasing gap width. This is due to the fact that the proximity of the external element affects the effective index of refraction of the waveguide layer. The width of the angular resonance is rather small and amounts to approximately 0.15° (FWHM) in all cases.

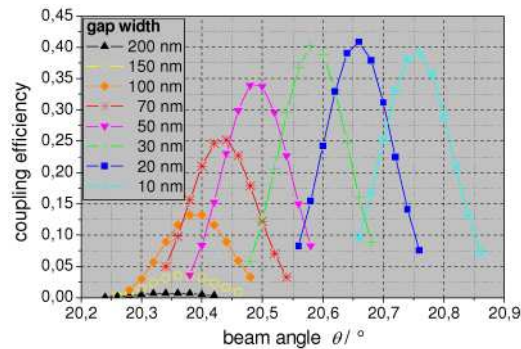


Fig. 3. Coupling efficiency vs. coupling angle for different gap width between the end face of the external grating coupler and the waveguide surface. The grating depth is $d = 100$ nm.

The calculated data reveal that an approximation between the external grating element and the waveguide surface of 100 nm or less is necessary to achieve coupling efficiencies above 10%. The maximum coupling efficiency is obtained for a gap width of 20 nm and amounts to 41%. The relationship is displayed in Fig. 4 in more detail, where the dependence of the coupling efficiency at the resonance angle on the gap width is depicted for different grating depth. The shown curves basically reflect the exponential decay of the evanescent field of the waveguide mode which has a penetration depth of 97 nm into a glass superstrate.

From Fig. 4 it can be seen that increasing the grating depth from 50 nm to 100 nm increases the coupling efficiency substantially. However, a further increase of the grating depth does not improve the coupling. Rather, regarding gap width of 20 nm and below, the coupling efficiency starts to decrease with increasing grating depth. This decrease can be interpreted as part of the guided wave already being out-coupled by the external grating due to strong coupling.

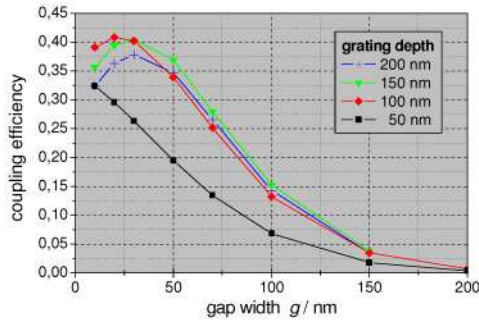


Fig. 4. Coupling efficiency at resonance vs. gap width for different grating depth of the external grating coupler.

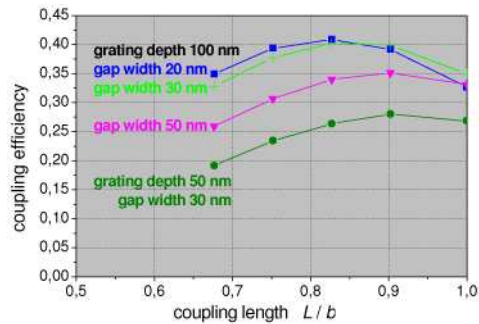


Fig. 5. Coupling efficiency vs. grating coupling length given as a ratio of the beam diameter for different grating depth and gap width.

The dependence of the coupling efficiency on the grating length L is depicted in Fig. 5. In case of strong index modulations on the waveguide surface (large grating depth, small gap width), the maximum efficiency is found for a coupling length of approximately 80% of the beam diameter. Moderate index modulations shift the optimum towards larger coupling lengths. Note that internal grating couplers likewise require the incident beam to extend over the edge of the grating for maximum efficiency with a theoretical optimum of 85% overlap between beam and grating [10].

4. Experimental realization

A GRIN lens made from SELFOC® glass (Newport) with pitch length 0.25, diameter 1 mm, physical length 2.58 mm and designed for a wavelength of 630 nm is polished at one end face at an angle of 20° and a relief grating of 500 nm period is produced in the central part of the angle polished surface by direct laser ablation with an F₂-laser at 157 nm wavelength. The F₂-laser processing system consists of a F₂-laser (Lambda Physik LPF 220i), a 157 nm beam-shaping and -delivery system (MicroLas Lasersystem), a nitrogen purging system, high precision target positioning stages, and beam and sample-alignment diagnostics. Ablative processing of materials is performed in a mask projection configuration at 25x demagnification using a Schwarzschild objective of 0.4 numerical aperture (NA). The target field size used in the experiment is 200 x 120 μm². A detailed description of an equivalent processing system and a discussion of the general characteristics of F₂-laser processing at 157 nm are given in Ref. 11. Due to the short wavelength in combination with the high NA of the Schwarzschild objective the depth of field is very limited. The structuring of gratings with submicron periodicity usually requires a control of the focal plane position within ± 0.5 μm. This is accomplished by the integration of an optical coherence tomography (OCT) module into the sample-alignment optics of the F₂-laser processing system [12].

Figure 6 shows a microscope image of the processed GRIN lens mounted in a micro V-clamp (Thorlabs). For the grating fabrication, an on-target fluence of 1.25 J/cm^2 and two pulses per position (nine positions in total) were used. The processed area exhibits a strong diffraction of

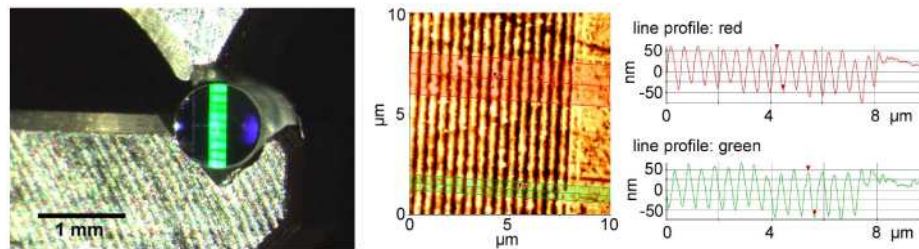


Fig. 6. Left: microscope image of the end face of a grating structured GRIN lens; center: AFM measurement of the grating relief in a false color representation; right: selected line profiles.

green light in the figure and has a width of $200 \mu\text{m}$. AFM measurements of the grating relief reveal an almost sinusoidal grating with a depth of $100 \pm 15 \text{ nm}$ (Fig. 6, right).

Waveguide coupling by the processed GRIN lens as schematically depicted in Fig. 1 is realized by coupling the beam of a HeNe laser operating at 633 nm wavelength into the far end of a single-mode fiber (Newport, F-SV). The state of polarization at the fiber exit is adjusted to transversal electric (TE) polarization with respect to the coupling plane by a fiber polarization controller. At the fiber exit the beam is expanded and collimated by the structured GRIN lens. The numerical aperture of the fiber (specified NA 0.10 - 0.14) results in a collimated beam of approx. $250 \mu\text{m}$ diameter. The structured side of the GRIN lens is placed on the surface of a waveguide chip, consisting of a 159 nm thick layer of Ta_2O_5 with an index of refraction of 2.1 on AF45 glass substrate (Oerlikon Balzers). The waveguide supports only a single TE polarized mode at 633 nm wavelength.

Figure 7 shows images from the experimental setup. In the left image the laser is turned off. The image in the center depicts a slightly misaligned coupling angle. For the image on the right hand side, the coupling angle is adjusted to maximum coupling efficiency by adjusting the lateral position of the fiber end. The trace of the coupled beam is guided to the next internal grating coupler of the waveguide chip over a distance of 5 mm . The intensity of the outcoupled beam under resonance conditions is measured as 9.5% of the intensity at the fiber exit. Accounting for the attenuation of the waveguide layer of 3 dB/cm yields a coupling efficiency of 13.4%. The FEM calculations from the previous section suggest that a gap width of $\sim 100 \text{ nm}$ between the GRIN lens grating and the waveguide has been achieved.

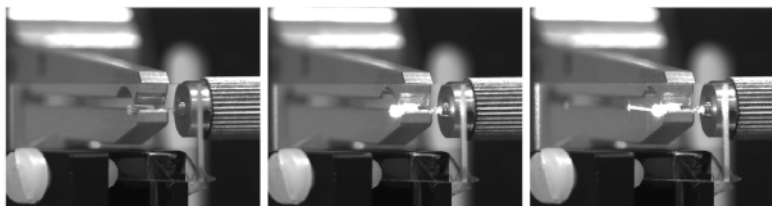


Fig. 7. Experimental demonstration of waveguide coupling by an external GRIN lens showing the waveguide chip, the GRIN lens mounted in a V-clamp and the fiber chuck. Left: laser off; center: misaligned coupling angle; right: resonant coupling.

5. Conclusions

We presented a new technique for coupling laser light from a single mode optical fiber directly to the guided mode of a thin-film waveguide by using a collimating micro-optical element with a grating structured end face. The external grating coupler can be multiply

reused and eliminates the need for internal couplers on the waveguide chips, which induce a major part of the production costs and impose certain restrictions on the waveguide devices.

The feasibility of the approach was demonstrated with an 0.25 pitch GRIN lens that has been equipped with a relief grating of 500 nm period, yielding an experimental coupling efficiency of 13%. FEM simulations of the coupling process suggest that efficiencies as high as 40% might be accessible in the present experimental configuration, provided a close approximation between external grating and waveguide can be achieved. For comparison, internal grating couplers can attain coupling efficiencies up to a theoretical value of 80% [13]. In practical applications their efficiency is also usually much lower.

Concerning the most direct approach of fiber to waveguide coupling using the grating structured end face of a single-mode optical fiber as the external coupler, the FEM calculations predict coupling efficiencies to be restricted to a few percent. This coupling scheme might still be valuable in special applications.

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