Efficient coupling into polymer waveguides by gratings

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Investigations of highly efficient grating couplers for polymer slab and strip waveguides fabricated by electron-beam lithography are reported. A maximum input efficiency of 67% is achieved. The electron-beam direct-writing technique allows one to replicate the original gratings into polymer substrates by embossing. An all-polymeric optical chip with efficient grating couplers is demonstrated. Waveguide grating couplers with blazed profile and variable grating depth are investigated. Thus, the intensity distribution of the outcoupled light is matched to a Gaussian-like profile. A focusing blazed grating that couples the light with an efficiency of 42% into a polymer strip waveguide is reported. A curvature correction of the grating lines allows one to improve the focusing properties. © 1997 Optical Society of America

Key words: Waveguide grating, focusing grating, polymer waveguide, embossing.

1. Introduction

With the development of polymer waveguide devices, gratings have gained considerable interest for efficient coupling into polymer waveguides for use as passive components in optical communications and sensing. Polymers offer the possibility of replicating gratings by embossing, with a potentially high cost efficiency.[1]

Efficient grating couplers demand nanofabrication technologies such as electron-beam lithography.[2,3] In comparison with other fabrication technologies, electron-beam writing has several advantages, such as variation of the grating depth or the grating profile and realization of smooth, curved grating lines.

The use of poly(methyl methacrylate) (PMMA)-like polymers as waveguide layers allows corrugated gratings to be fabricated by electron-beam direct writing without a separate process of etching the grating pattern into the substrate.[4] Blazed structures are used to increase the coupling efficiency.[5–7] The original gratings are used as master gratings for the replication process. These master gratings can be directly characterized for their waveguide coupling qualities.

One can enlarge the field of applications for grating couplers by shaping the beam profile of the outcoupled light.[8,9] With variation of the grating depth along the grating, the leakage of a grating can be changed, leading to a Gaussian-like shaped beam profile.[10,11] Other applications, such as in-plane focusing elements or focusing couplers, require gratings with curved lines.[12–15] Here the investigations concentrate on the design and experimental results of focusing grating couplers for efficient coupling from free space to polymer slab and strip waveguides.

2. Fabrication Technology

The grating pattern is written directly into the waveguide layer by electron-beam lithography. The electron resist used for the grating fabrication acts as both the resist material and the waveguide layer. A thin film consisting of a copolymer of PMMA of less than 1-μm thickness is spin coated onto a quartz substrate to yield a monomodal waveguide at a wavelength of 632.8 nm. A thin metal layer (gold or aluminum) on top of the resist prevents charging up during exposure.

The grating patterns are drawn into the resist with two different electron-beam devices. Linear gratings with straight lines are written with a device that has a variable shaped beam (ZBA 23 Jenoptik). Increasing the electron dose across every grating period stepwise from one edge of the period to the other can accomplish an asymmetric energy deposition. Over

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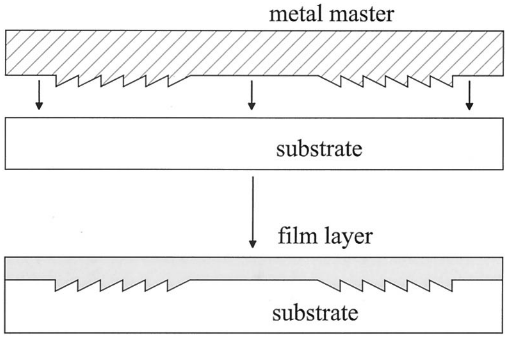

Fig. 1. Embossing of the grating structure into the substrate.

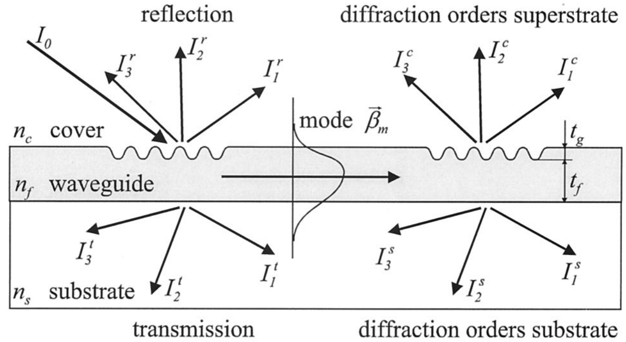

Fig. 2. General waveguide and grating configuration of the optical chip.

its whole grating length the pattern is drawn with a periodically repeating electron-dose distribution.

The fabricated gratings were replicated into nickel by electroplating.[1] This ~300-μm-thick layer can be reinforced by ~3 mm of copper without a change in the quality of the master. The metal master was used for repeated embossing of the grating structures into polymer substrates. We used PMMA plates of ~2-mm in thickness as substrate material of the replica. The PMMA plates were heated to a temperature of 150 °C. Then the grating structures were molded under pressure into the polymer by the metal master.

After cooling down, the waveguiding layer consisting of poly(α)-methylstyrene was spin coated on top of the embossed grating structure (Fig. 1). This material has a refractive index of $n_f = 1.603$ at a wavelength of $\lambda = 633$ nm. In an experiment we used a film layer of 450-nm thickness.

Curved gratings are written with the second electron-beam writer (LION LV 1 Jenoptik) in the continuous path control mode, which allows the writing of smoothly curved lines by moving of the *xy* table across the writing area. One can vary the electron dose by using different table speeds, leading to an asymmetric triangular energy deposition in every period.

During the subsequent development process, the exposed regions of the resist are dissolved according to the varying electron dose, which results in blazed corrugated gratings. One can vary the depth of the gratings by changing the development time.

For fabrication of the strip waveguides by the direct-writing technique, at their right and left borders rectangular areas are exposed with a high electron dose. During the development process the resist of these areas is completely dissolved. Thus ridge waveguide structures are fabricated. The chosen width of 20 μm guarantees a strong decay of the evanescent field inside the rectangular areas.

3. Linear Waveguide Grating Couplers

A. General Grating Design and Parameters

The fundamental geometry of the realized optical chip is sketched in Fig. 2. It consists of an input and an output grating coupler with a 20-mm waveguide between.

The incoming beam I_0 is particularly reflected ($I_1^{\,r} \ldots I_n^{\,r}$) and transmitted ($I_1^{\,t} \ldots I_n^{\,t}$) into several diffraction orders by the input grating. The incoupled light propagates as a guided mode indicated by the propagation constant β_m. The chosen film thickness t_f and grating depth t_g allow only the coupling into the TE_0 mode ($m = 0$) at a wavelength of $\lambda = 633$ nm.

The coupling condition can be calculated from the well-known grating equation

$$n_{\text{eff}} = n_c \cos \phi_c + m \frac{\lambda}{\Lambda}, \tag{1}$$

where n_{eff} is the effective refractive index of the guided wave, n_c is the refractive index of the cover, ϕ_c is the coupling angle, m is the diffraction order, λ is the wavelength in free space, and Λ is the grating period. The guided wave is coupled out by the second grating into different diffraction orders in the cover direction ($I_1^{\,c} \ldots I_n^{\,c}$) and in the substrate direction ($I_1^{\,s} \ldots I_n^{\,s}$).

To calculate the efficiency of a grating coupler, we used a formalism developed by Tamir and Peng,[16] which is a first-order perturbation approach. This method considers several grating profiles, and the coupling quantity of the outcoupled light into every diffraction order, the leakage parameter α, can be calculated as follows:

$$P = P_0 \exp(-2\alpha z) \qquad \text{with} \quad \alpha = \sum_m \alpha_m^{\,c} + \alpha_m^{\,s}, \tag{2}$$

where P is the guided power and $\alpha_m^{\,c}$ and $\alpha_m^{\,s}$ are the leakage parameters of the mth diffraction order in the cover and substrate directions, respectively.

With this formalism the grating and waveguide parameters can be optimized with respect to the coupling efficiency.[7] Following the calculations, optimized parameters used in the experiments are given in Table 1. For a grating with the given arrangement, we calculated that the grating with a blazed profile couples the light into the different diffraction orders with a total leakage parameter of $\alpha = 1.16$ mm^{-1}, giving rise to efficient coupling.

Table 1. Parameters Used for the Grating Coupler

Parameters	Value
Grating parameters	
Grating period	$\Lambda = 800$ nm
Grating depth	$t_g = 250$ nm
Grating profile	blazed profile
Grating area	1×1 mm^2
Waveguide configuration	
Wavelength	$\lambda = 633$ nm
Refractive index of the substrate	$n_s = 1.457$
Refractive index of the film layer	$n_f = 1.498$
Refractive index of the cover	$n_c = 1$
Film thickness	$t_f = 800$ nm

B. Measurements and Results

An optical chip in conformity with Fig. 2 and with the given arrangement (Table 1) is realized. In addition to the input and output efficiency, the so-called throughput is an important parameter of the device. The throughput is defined as the ratio between the intensity of the light outcoupled into one (first) diffraction order in one (cover) direction and the intensity of the incoming light. This ratio includes all losses, such as in-coupling, waveguide, and scattering losses and losses by outcoupling into other diffraction orders.

The results are presented in Table 2. More than 40% of the intensity of the incoming light could be coupled into the waveguide through the first diffraction order of the blazed grating. Thus the input efficiency could be doubled in comparison with a typical grating coupler with a symmetric grating profile.

Almost all the guided light is coupled out from the waveguide, which corresponds to a leakage parameter of $\alpha = 1.48$ mm^{-1}. Approximately 65% of the outcoupled light leaves the waveguide in the cover direction (blazing effect). The smaller than expected blazing effect is due to the nonideal sawtooth profile.[7] During the exposure process a second inclination of an approximately 200 nm in base length is formed.

The results achieved with the original gratings form the basis of the replication of the gratings into a PMMA substrate ($n_s = 1.489$) by an embossing technique. After the spin-coating process of a poly(α)-methylstyrene polymer as the waveguide layer ($n_f = 1.603$), an all-polymeric optical chip is produced.

With the replicated optical chip, the following results are achieved (Table 3). The measurements show that the replication of gratings into polymers does not affect the coupling efficiencies. The measured input efficiency is approximately 46%. The output efficiency of approximately 75% corresponds to a leakage parameter of $\alpha = 0.75$ mm^{-1}. Approximately 74% of the outcoupled light leaves the waveguide in the first diffraction order in the cover direction. This measurement represents a good proof of the blazing effect achieved by the asymmetric profile of the grating structure.

Table 2. Measurement Data of an Optical Chip Consisting of Two Blazed Gratings

Data	Value
Measured input efficiency	41%
Measured output efficiency	95%
Achieved blazing effect	65/35
Waveguide loss of PMMA	0.6 dBcm^{-1}
Achieved throughput	14%

Table 3. Measurement Data of the Replicated All-Polymeric Optical Chip

Data	Value
Measured input efficiency	46%
Measured output efficiency	75%
Achieved blazing effect	74/36
Waveguide loss of PαMS	1.2 dBcm^{-1}
Achieved throughput	12%

In summary, the input efficiency of a grating coupler that allows several diffraction orders is limited to a value lower than 50% for gratings with a blazed profile. The restriction of these gratings is in the nonideal asymmetric grating profile.

C. Grating Coupler with Only One Diffraction Order

For an input efficiency of more than 50% it is necessary to concentrate all the incoming light into one diffraction order. With the output grating in mind, this means that the number of diffraction orders has to be minimized. One can eliminate the part of the light outcoupled into higher orders by decreasing the grating period. The optimum can be achieved if the guided light can radiate away from the waveguide into only one diffraction order in only one direction (substrate, if $n_s > n_c$).

If the incoming light is directed onto such a grating, it is partially reflected and transmitted. Under the coupling condition [Eq. (1)] the remaining light is coupled into the waveguide without diffraction into higher orders. Such a grating is comparable with a prism coupler, but the grating supports the planar concept of waveguide elements.

In an experiment we realized a grating with a grating period of $\Lambda = 250$ nm and a corrugation depth of $t_g = 150$ nm. The grating profile is rectangular because the coupling efficiency does not depend on the grating profile.

When a grating with only one diffraction order is used, the light is coupled into the waveguide from the medium with a higher refractive index (here, the substrate). Therefore the light has to be transferred from air to the substrate, which is in the experiment a plate of approximately 2-mm thickness. It can be realized with a prism and an immersion liquid (Fig. 3).

The maximum achieved efficiency of this grating coupler has to be measured at 67%. Consequently, gratings with only one diffraction order allow highly efficient coupling into planar waveguides with a coupling efficiency of much more than 50%, which is

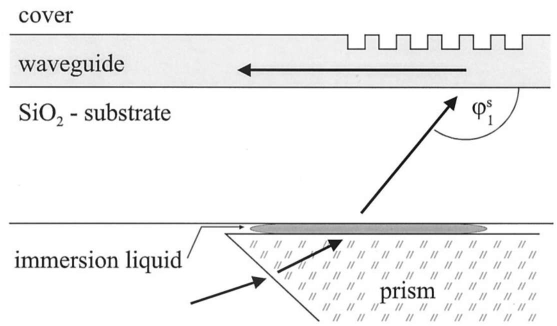

Fig. 3. In-coupling into a planar waveguide by a grating with only one diffraction order.

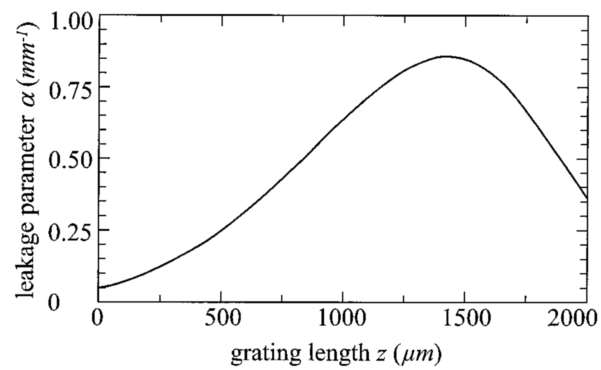

Fig. 4. Leakage parameter α versus grating length z.

comparable with the coupling efficiency of prism couplers.

4. Grating Coupler with Variable Groove Depth

A. Theoretical Treatment

For a grating coupler the change in the guided power $dA^2(z)$ is due to the light that radiates away from the grating $B^2(z)$:

$$-\frac{dA^2(z)}{dz} = B^2(z). \tag{3}$$

Grating couplers with a constant grating depth have a constant leakage parameter α:

$$\frac{dA^2(z)}{dz} = -2\alpha A^2(z). \tag{4}$$

The square of the electric field of the guided wave $A^2(z)$ (guided power) decreases exponentially with the constant leakage rate.

A grating with a variation in the corrugation depth produces a varying leakage parameter over the grating length:

$$\frac{dA^2(z)}{dz} = -2\alpha(z)A^2(z) \qquad \text{with} \quad \alpha = \alpha(z). \tag{5}$$

One can calculate the dependence of the leakage parameter α on the grating length by using Eqs. (3) and (5):

$$\alpha(z) = \frac{B^2(z)}{2\left[A_0{}^2 - \int_{z_0}^{z} B^2(t)dt\right]}, \tag{6}$$

where A_0 is the electric field of the guided wave at the beginning of the grating at z_0.

The electric-field distribution of the outcoupled light $B(z)$ represents a Gaussian beam profile:

$$B(z) = \frac{C_g}{\sqrt{2\pi}\sigma_g} \exp\left[-\frac{(z - z_m)^2}{2\sigma_g{}^2}\right]. \tag{7}$$

The maximum value of the field should be achieved after the half-grating length at z_m. At the beginning and the end of the grating the field should decrease to the $1/e$ of its maximum value. Additionally, the total power of the outcoupled light is the difference between the guided power at the beginning and the end of the grating.

Considering these conditions, the final dependence of the leakage parameter α on the grating length z is presented in Fig. 4.

To design a grating with varying grating depth, it is necessary to calculate a huge number of leakage parameters that are assigned to different corrugation depths. The dependence of the leakage parameter on the grating depth $\alpha(t_g)$ is calculated with the formalism by Tamir and Peng.[16]

Finally, we get the dependence of the grating depth versus the length of the grating $t_g(z)$ (Fig. 5, solid curve).

B. Experiment

The fabrication of blazed gratings with variable groove depth is realized in a similar way, as described in Section 2. The electron dose was varied across every period in order to yield a blazed grating profile. Additionally, the electron dose was changed over the whole grating length. The grating with a length of 2 mm was split into 25 subareas of 80-μm length. Inside every subarea the grating pattern was drawn

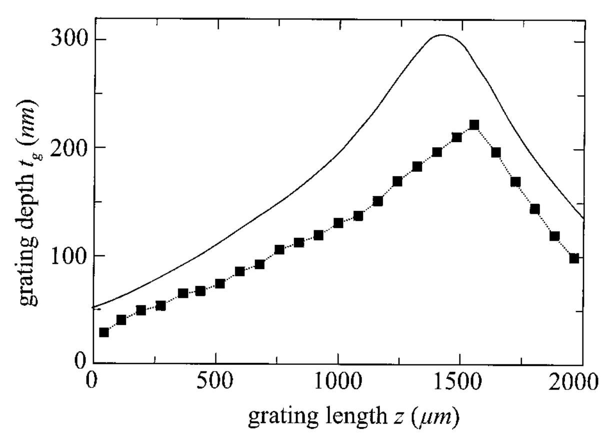

Fig. 5. Calculated (solid curve) and measured corrugation depth (squares) versus grating length z.

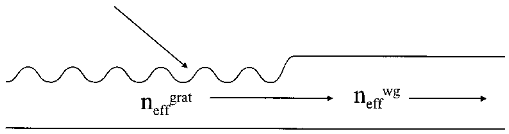

Fig. 6. Zero offset of approximately 80 nm in the grating region, which results in a difference of the effective refractive indices in the grating and the waveguide regions for corrugated grating couplers.

with a controlled electron dose into the resist. Thus each period of the grating remained a sawtooth, but the groove depth varied over the grating length, resulting in the required corrugation depths.

We realized gratings with a length of 2 mm. The other parameters are given in Table 1. The grating depth versus the grating length measured with a secondary electron microscope is shown in Fig. 5 (squares). The measured depths are in good agreement with the calculated depths, except for a difference of approximately 80 nm caused by the zero offset that is produced during the exposure process (Fig. 6).[7]

The measurement of the outcoupled near field of the beam was accomplished by the following setup. Light was coupled into the polymer waveguide by an input grating of constant grating depth. After the 20-mm waveguide the guided wave was coupled out by the variable-groove-depth grating coupler. The near-field intensity into the first diffraction order was reproduced by a CCD camera.

In Fig. 7 is shown the near-field pattern of the intensity distribution of the outcoupled light from the grating with variable groove depth and a curve fit to a Gaussian-like profile. The diagram represents graphically the cross-section analysis of the measured near-field intensity. The right-hand edge of the diagram corresponds to the beginning of the grating; the left-hand edge, to the end of the grating.

The grating couples the light away from the waveguide over a total grating length of 2 mm. The outcoupled light has its peak intensity in the vicinity of the center position of the grating. Changing the corrugation depth can enforce the leakage of the grating. In this way the peak intensity of the Gaussian profile can be shifted along the grating. The curve fit is in good agreement with the cross-section profile. The Gaussian-fit parameter reaches a value of approximately 0.9.

5. Focusing Grating Couplers

A. Design of the Curved Grating Lines

The focusing waveguide grating couplers represent a combination of a linear grating coupler and a focusing element in the waveguide plane. To design the focusing grating structure, we used a simple assumption.

The coupling condition can be calculated from the well-known grating equation

$$n_{\mathrm{eff}} = n_c \cos \phi_c + m \frac{\lambda}{\Lambda}, \tag{8}$$

where n_{eff} is the effective refractive index of the guided wave, n_c is the refractive index of the cover, ϕ_c is the coupling angle, m is the diffraction order, λ is the wavelength in free space, and Λ is the grating period of the basic linear grating, which corresponds to the grating period of the focusing grating at the center position in the lateral direction.

Additionally, the incoming collimated beam is focused on the waveguide plane. The grating lines must follow the condition of constructive interference:

$$q\lambda = zn_c \cos \phi_c - n_{\mathrm{eff}} (y^2 + z^2)^{1/2}, \quad q = 1, 2 \ldots, \tag{9}$$

where z is the coordinate in the propagation direction of the mode, y is the coordinate in the lateral direction, and q is the number of the grating line. The focal point is located in the origin of the coordinate system. This condition [Eq. (9)] is valid with the assumption that the effective refractive index in the grating and the waveguide region is constant:

$$n_{\mathrm{eff}}{}^{\mathrm{grat}} = n_{\mathrm{eff}}{}^{\mathrm{wg}}. \tag{10}$$

In the frame of the corrugated gratings, the condition in Eq. (10) is fulfilled only for shallow gratings. Then Eq. (9) represents an algebraic equation of the second order in y and z. Consequently, the grating

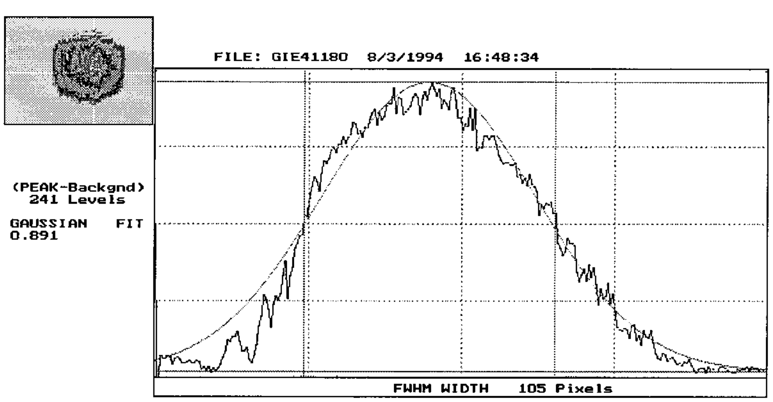

Fig. 7. Cross section of the near-field intensity pattern of a variable-groove-depth grating coupler.

lines describe elliptical curved lines with one common ellipse focal point:

$$\frac{\left(z + \dfrac{q\lambda n_1 \cos \phi_c}{{n_{\text{eff}}}^2 - {n_c}^2 \cos^2 \phi_c}\right)^2}{\left(\dfrac{q\lambda n_{\text{eff}}}{{n_{\text{eff}}}^2 - {n_c}^2 \cos^2 \phi_c}\right)^2} + \frac{y^2}{\left[\dfrac{q\lambda}{({n_{\text{eff}}}^2 - {n_c}^2 \cos^2 \phi_c)^{1/2}}\right]^2} = 1. \tag{11}$$

For grating depths greater than approximately 50 nm we cannot assume the condition in Eq. (10). There is a difference in the effective refractive index of

$$n_{\text{eff}}^{\text{wg}} - n_{\text{eff}}^{\text{grat}} = \Delta n_{\text{eff}} \simeq 5 \times 10^{-3}, \tag{12}$$

owing to the zero offset as a result of the fabrication process during the electron-beam exposure (Fig. 6).[7] This difference causes aberrations of the light, which results in a larger spot size of the beam. By including a correction term, one can minimize the aberration errors. The improved condition of constructive interference now can be written as

$$\begin{aligned} q\lambda = n_{\text{eff}}^{\text{grat}}(y^2 + z^2)^{1/2} + n_c z \cos \phi_c + r(q_a) \\ \times (n_{\text{eff}}^{\text{wg}} - n_{\text{eff}}^{\text{grat}}), \end{aligned} \tag{13}$$

where $r(q_a)$ represents the correction term, which is weighted with the difference in the effective indices:

$$r(q_a) = q_a \lambda_f \frac{-z e_a (y^2 + z^2)^{1/2} + y^2 + z^2}{y^2 + (1 - {e_a}^2) z^2} \quad \text{with}$$

$$e_a = \frac{n_c \cos \phi_c}{n_{\text{eff}}}. \tag{14}$$

e_a is the numerical eccentricity of the inner ellipse. Equation (13) now represents an algebraic equation of the sixth order in y and z.

B. Experimental Realization

At first an optical chip consisting of a pair of gratings with a slab waveguide between is fabricated. Except for the area of the exposed grating pattern, the geometry and the grating and waveguide parameters are given in Subsection 3.A. For focusing gratings the pattern area is reduced because the writing time of the LION LV 1 electron-beam writer, which has a fine electron beam of only several nanometers, is much higher than the writing time of the variable shaped-beam writer ZBA 23.

The grating lines now represent curved lines. The gratings have a blazed profile. The distance between the two gratings is exactly twice the focal length of the focusing gratings (Fig. 8). The collimated light couples into the waveguide through the first grating and is focused on the waveguide plane after the focal length. Then the guided light becomes divergent and is coupled out from the waveguide through the second grating. The light coupled into the first diffraction order becomes nearly parallel.

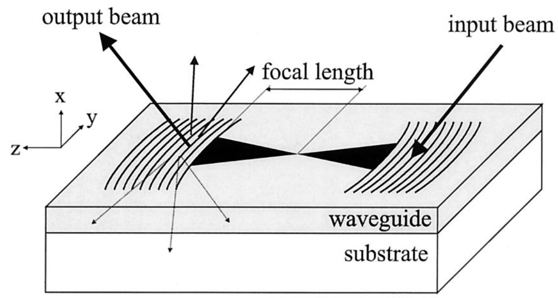

Fig. 8. Scheme of the focusing grating coupler with a slab waveguide.

For the purpose of checking the dependence of the focusing properties on the curvature of the grating lines, focusing grating couplers with identical parameters are structured into the slab waveguide (Table 1 in Subsection 3.A). One coupler is written by inclusion of the correction term; the other, without the correction. The focal length f was chosen to be 4 mm.

In addition to the input and output efficiencies, the spot size in the focal plane is an important parameter of a focusing grating. The theoretically minimum spot size (diffraction limit) can be calculated by

$$2\sigma = 2.44 \frac{f\lambda}{n_{\text{eff}} B} \left(1 + \frac{B^2}{4f^2}\right)^{1/2}, \tag{15}$$

where B is the width of the grating (lateral dimension). For the chosen parameters the spot size in the focal plane 2σ has to be 5.3 μm for $f = 4$ mm.

For both gratings the input efficiency was measured to be approximately 40% and the output efficiency, approximately 85% (Table 4). It can be established that the curvature of the grating lines does not affect the coupling efficiencies. Additionally, the input efficiency of approximately 40% corresponds to those results achieved with linear blazed gratings. The measured output efficiency corresponds to a leakage parameter of $\alpha = 1.2\ \text{mm}^{-1}$. The asymmetric blazed grating profile causes an asymmetric outcoupling behavior (blazing effect) of the light: approximately 65% of the outcoupled light leaves the waveguide in the cover direction.

The spot size of the light in the focal plane depends on the written grating pattern. In the measurement the beam in the focal plane was photographed by a CCD camera. Whereas gratings without an aberra-

Table 4. Measurement Data of Focusing Gratings without and with the Correction

Data	Grating Correction	
	No	Yes
Input efficiency	40%	40%
Output efficiency	85%	85%
Blazing effect	65/35	65/35
Spot size	12 μm	7 μm

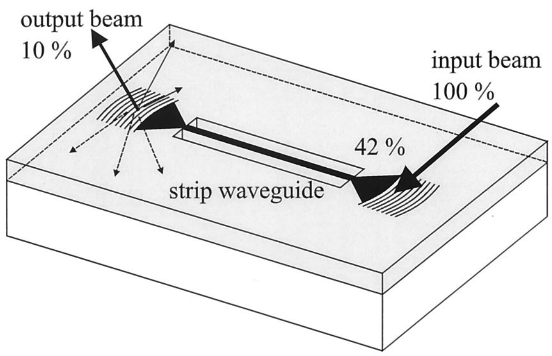

Fig. 9. Focusing grating coupler with a strip waveguide between. The distance of the end faces of the strip waveguide to the gratings is the focal length.

tion correction have a spot size of approximately 12 μm, which is approximately 2 to 3 times greater than the diffraction limit, the measured spot size of focusing gratings with the correction can be decreased to a value of approximately 7 μm, which is only approximately 1.5 times greater than the diffraction limit.

An optimized spot size is required if the incoming light should be coupled into a strip waveguide.[17] Using the following experimental setup, we investigated the coupling behavior of the light into a strip waveguide.

An optical chip consisting of a pair of gratings with a strip waveguide in between was fabricated. For the new chip we used the same parameters as those given in Table 1. The strip waveguide had a width of 15 μm and a length of 2 mm. The two gratings were placed on the waveguide in such a way that their focal points coincided with the beginning and the end of the strip waveguide (Fig. 9). In the experiment the first grating acted as an input coupler, focusing the in-coupled light in the waveguide layer. The second grating coupled the light out from the waveguide. Additionally, in the first diffraction order the divergent light of the waveguide was transformed into a collinear beam.

Optical chips, one with and the other without an aberration correction, were fabricated. For the coupling devices that couple the incoming light into the strip waveguide by focusing gratings with a blazed grating profile, the following results were achieved (Table 5). The maximum input efficiency was measured to be 42% and the output efficiency, approximately 85%. Approximately 70% of the outcoupled light was concentrated in the cover (air) direction. This value characterizes the blazing property of the grating. These results are in accordance with the measurements above.

Table 5. Measurements of the Focusing Grating Coupler with a Strip Waveguide Between, without and with Aberration Correction

	Grating Correction	
Data	No	Yes
Input efficiency	42%	42%
Output efficiency	85%	85%
Blazing effect	70/30	70/30
Spot size	12 μm	7 μm
Throughput	5%	10%

The spot size of the light in the focal plane depends on the written grating pattern. Gratings without an aberration correction have a larger spot size than gratings with a correction, which leads to a lower in-coupling efficiency of the focused guided light into the strip waveguide, owing to higher scattering losses. The measured throughput for those gratings is smaller than it is for gratings with an aberration correction. The maximum throughput we measured was approximately 10% for the corrected grating couplers.

Experiments with other grating coupler elements with strip waveguide widths of 10 and 5 μm show a throughput for these devices of less than approximately 3% and 1%, respectively. This fact corresponds to the measurements of the spot sizes.

6. Summary

Gratings are well suited for efficient coupling into polymer slab and strip waveguides.

One can increase the input efficiency of gratings to more than 40% by using asymmetric triangular (blazed) grating profiles. Such gratings can be fabricated by electron-beam lithography by means of electron-dose control across the grating period. These high-quality master gratings allow one to replicate the grating structures into polymer substrates by an embossing technique. An all-polymeric optical chip consisting of an input and an output grating coupler with a 20-mm waveguide between has been demonstrated. The input efficiency was measured to be 46%, and the measured efficiency of outcoupling into one diffraction order in the cover direction (blazing effect) was 74%.

The coupling efficiency can also be increased if the grating period is decreased to a value in which only one diffraction order exists. For such a grating coupler an input efficiency of 67% was achieved.

Blazed gratings with variable grating depths across the grating length have been demonstrated. A beam-shaping grating giving rise to a Gaussian intensity profile of the outcoupled beam was realized.

Another possibility of beam shaping in the form of focusing gratings has been investigated. An input efficiency of more than 40% reaches a value comparable with linear grating couplers with similar grating parameters. It could be shown that it is possible to couple the light into a strip waveguide by a focusing grating in an efficient way. By including a correction term, one could minimize the aberration. A spot size of less than the one and a half times the diffraction limit was measured. An optical chip consisting of a pair of gratings with a strip waveguide between with a measured throughput value of 10% of the incoming light has been realized.

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References

1. P. Dannberg, E. B. Kley, R. Waldhäusl, A. Bräuer, and W. Karthe, “Passive polymeric components fabricated by embossing technique,” in *Proceedings of the 19th European Conference on Optical Communication* (Swiss Electrotechnical Association, Zurich, 1993), pp. 437–440.
2. T. Suhara and H. Nishihara, “Integrated optics components and devices using periodic structures,” IEEE J. Quantum Electron. **QE-22,** 845–867 (1986).
3. H. Nishihara, M. Haruna, and T. Suhara, *Optical Integrated Circuits*, Optical and Electrooptical Engineering Series, R. E. Fisher and W. J. Smith, eds. (McGraw-Hill, New York, 1987).
4. T. Fujita, H. Nishihara, and J. Koyama, “Blazed gratings and Fresnel lenses fabricated by electron-beam lithography,” Opt. Lett. **7,** 578–580 (1982).
5. R. Moshrefzadeh, X. Mai, C. T. Seaton, and G. I. Stegeman, “Efficient grating couplers for polymer waveguides,” Appl. Opt. **26,** 2501 (1987).
6. Q. Gong, G. Assanto, R. Zanoni, G. I. Stegeman, R. Burzynski, and P. N. Prasad, “Efficient grating coupling to poly-4BCMU optical waveguides,” Appl. Opt. **29,** 3887–3890 (1990).
7. R. Waldhäusl, P. Dannberg, E. B. Kley, A. Bräuer, and W. Karthe, “Highly efficient blazed grating couplers in planar polymer waveguides,” Int. J. Optoelectron. **8,** 529–536 (1993).
8. K. A. Bates, L. Li, R. L. Roncone, and J. J. Burke, “Gaussian beams from variable groove depth grating couplers in planar waveguides,” Appl. Opt. **32,** 2112–2116 (1993).
9. L. C. West, C. Roberts, J. Dunkel, G. Wojcik, and J. Mould, Jr., “Nonuniform grating couplers for coupling of Gaussian beams to compact waveguides,” in *Integrated Photonics Research*, Vol. 3 of 1994 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1994), pp. 302–304.
10. S. Miyanaga and T. Asakura, “Intensity profiles of outgoing beams from tapered grating couplers,” Radio Sci. **17,** 135–143 (1982).
11. M. Lipovskaya and A. A. Lipovskii, “Study of an integrated optical grating coupler with a varying ripple depth,” Sov. Phys.—Tech. Phys. **28,** 503–504 (1983).
12. D. Heitmann and C. Ortiz, “Calculation and experimental verification of two-dimensional focusing grating couplers,” IEEE J. Quantum Electron. **QE-17,** 1257–1263 (1981).
13. S. Ura, T. Suhara, H. Nishihara, and J. Koyama, “An integrated-optic disc pickup device,” J. Lightwave Technol. **4,** 913–918 (1986).
14. M. Fujimura, T. Suhara, and H. Nishihara, “Integrated acousto-optic correlator using a biaxial focusing grating coupler,” Int. J. Optoelectron. **8,** 7–12 (1993).
15. S. Ura, T. Kimura, T. Suhara, and H. Nishihara, “An integrated-optic device using electrooptic polymer waveguide on Si substrate for modulating focus spot intensity distribution,” IEEE Photon. Technol. Lett. **5,** 1291–1293 (1993).
16. T. Tamir and S. T. Peng, “Analysis and design of grating couplers,” Appl. Phys. **14,** 235–254 (1977).
17. R. Waldhäusl, B. Schnabel, E.-B. Kley, and A. Bräuer, “Efficient focusing polymer waveguide grating couplers,” Electron. Lett. **33,** 623–624 (1997).