Efficient and tolerant resonant grating coupler for multimode optical interconnections

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Abstract: More than 60% overall coupling efficiency is achieved in the demonstrator of an optical interconnect comprising an input grating coupler, a multimode slab waveguide section and an output grating coupler. The grating coupling strength is enhanced by means of a leaky mode resonance. The efficiency of the resonant grating coupler compares favourably with the performancs reported on mirror inserts.

OCIS codes: (050.2770) Gratings; (310.2790) Guided waves; (230.4000) Microstructure fabrication.

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1. Introduction

Although optical links have supplanted their electrical counterparts in long distance high rate transmission communications, the predicted transition to all optical interconnections at the board level has not happened yet. One of the reasons is that it turned out to be more difficult than expected to integrate optical interconnections in an easy and cost effective way into or onto a board. This is however very challenging and numerous works aim at integrating optical circuits in existing printed circuit board [1]. In short distance optical interconnections, coupling structures are key elements as they significantly limit the overall efficiency and represent the major part of the cost of an interconnection circuit. Diffraction grating couplers are bound to play an increasingly important role in miniaturised systems as they bring reduced weight and size, and have the advantage of being compatible with wafer or board scale batch planar manufacturing processes. Although they have been thoroughly investigated as a means of coupling light between free-space and single mode optical waveguides in the past [2, 3], their potential for short distance optical data communication involving multimode waveguides has not been widely considered yet. Grating coupling between a singlemode fiber and a singlemode all-silicon waveguide by means of a very small corrugated horn coupler is now considered in the telecom wavelength range were impressive coupling efficiencies have been obtained [4]. It is generally assumed that grating coupling to multimode waveguides has an inherently poor efficiency. It will be demonstrated here that a shallow diffraction grating can couple light very efficiently in a thick polymer waveguide layer. This paper presents a solution for coupling a free space optical wave under quasi-normal incidence into a highly multimode planar waveguide with minimum losses. The design of a resonant diffraction grating ensuring maximum coupling efficiency for a collimated and a weakly focused beam is described. The fabrication process and the characterization of a simple coated platform comprising two resonant gratings that allow light to propagate in a highly multimode polymer waveguide are described. Finally this approach is compared with currently used technologies.

2. Resonant grating design

The resonant structure used to couple light to and from a multimode optical waveguide is made of a shallow metal corrugation covered with a high index dielectric layer. It is placed at the substrate side of the multimode waveguide layer. The coupling between a guided mode and a free space wave by means of a grating is mainly governed by the radiation coefficient α [5] which expresses the rate of leakage of the guided mode in the adjacent media. The grating strength described by α is an increasing function of the refractive index contrast between the two media at either side of the corrugation, and of the normalized modal electric field in the corrugation. It is the weakness of the normalized modal field in the corrugation region which is at the basis of the common belief that grating coupling to and from a multimode waveguide is inherently small. In other words, the self-interfering zig-zagging plane wave associated with a waveguide mode bounces and gets diffracted at the corrugation at a zig-zag period which is proportional to the waveguide thickness, i.e., the thicker the waveguide, the smaller the bouncing rate. Efficient coupling requires that grating radiation occurs into one adjacent medium only. This imposes the use of a mirror at the waveguide side opposite the incidence medium. This mirror can be a multilayer stack reflecting the substrate radiated wave to the incidence medium if losses is a critical issue. It can also be a metal mirror if, as in optical interconnections, the application is not critically power limited.

The rationale behind high multimode coupling efficiency is best explained by considering the outcoupling diffraction event whereby the zig-zagging wave belonging to a waveguide mode impinges onto the grating located at the substrate and mirror side as sketched in Fig. 1. The objective is here to give rise to the largest possible α, i.e., to cancel the reflection

#87548 - $15.00 USD Received 14 Sep 2007; revised 1 Nov 2007; accepted 2 Nov 2007; published 4 Dec 2007

coefficient of the guided mode plane wave. To achieve this we will resort to a thin high index layer introduced between the multimode waveguide material and the metal mirror. As noted above the presence of a high index in the region of the corrugation increases the grating strength. Furthermore and most importantly it can have a major effect on the electric field in the grating region if its thickness is properly adjusted. As suggested in Fig. 1, the reflection of the zig-zagging wave field is the interference product between the wave directly reflected by the top high index layer interface and the wave refracted and trapped into the mirror-based high index layer and leaking into the multimode waveguide material. Usually this interference product is neither constructive nor destructive. However, if the high index layer thickness is such that it satisfies the dispersion equation of one of its leaky modes, both contributions to the reflection are real and, in addition, have opposite sign [5]. This property gives the key for a cancellation of the reflection by destructive interference: the corrugation is here to reduce the quality factor of the high index field trapping layer so as to balance the modulus of the two contributions, thus to set the condition for a destructive interference in the reflection direction, therefore to diffract the whole field in the direction imposed by the grating period [6]. Such condition is strictly valid for a definite mode of the multimode waveguide. However, most modes of a weakly guiding waveguide correspond to zig-zag plane waves which impinge on the diffraction grating under essentially grazing incidence where the first order leaky mode condition is very tolerant on the incidence angle. This implies that close to 100% diffraction efficiency essentially applies to most of the waveguide modes.

The dispersion equation of the leaky mode of order m is:

$$k_0 n_f h \cos\theta_f + \frac{\phi_m + \phi_c}{2} = m\pi \qquad (1)$$

where $k_0 = 2\pi/\lambda$ is the vacuum wave number, θ_f is the refraction angle in the high index layer of refractive index n_f, h is the average layer thickness, λ is the wavelength, ϕ_m is the reflection phase shift at the high index layer-metal interface and ϕ_c is the reflection phase shift at the layer-waveguide interface.

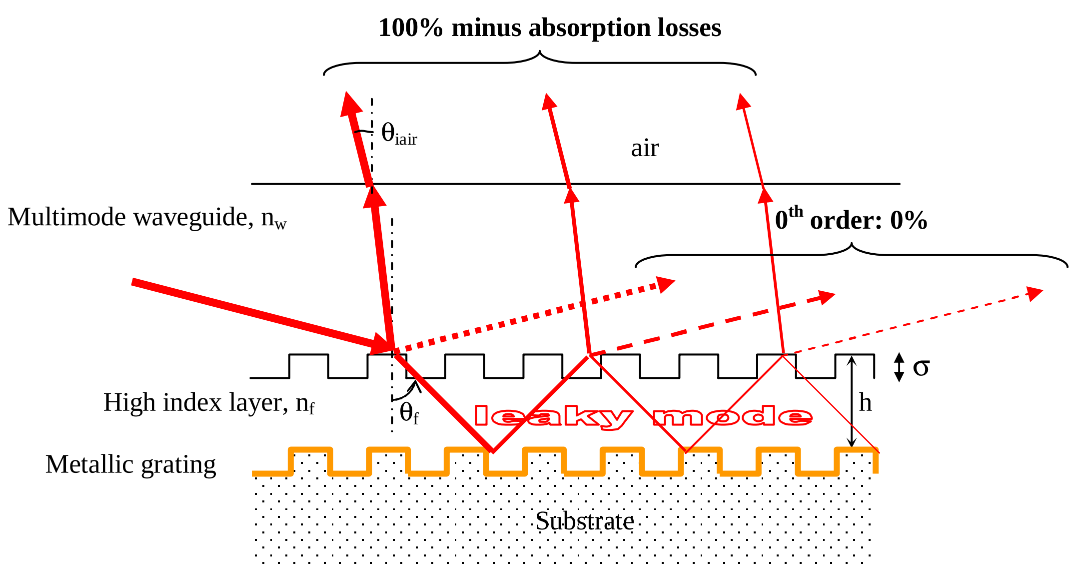

Fig. 1. Outcoupling resonant grating and scheme of the leaky mode mediated destructive interference of 0^{th} order reflection.

The above explanation relates to the outcoupling diffraction event. Reversing the light propagation direction implies that 100% incoupling is obtainable as well for a given mode. As

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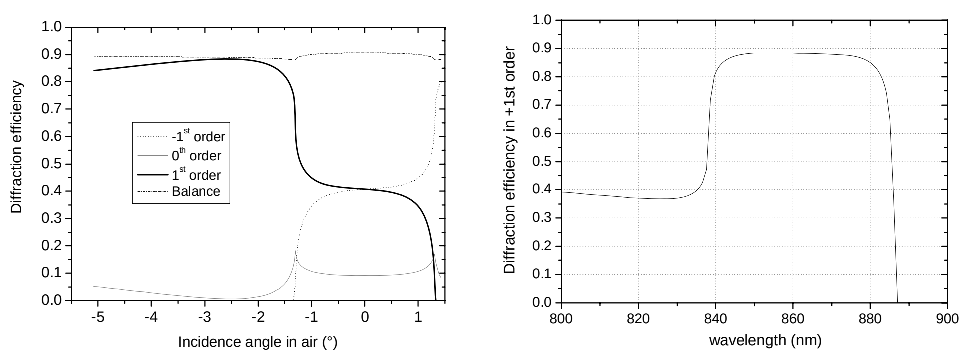
in practice the waveguide excitation and outcoupling are by far not symmetrical, there is a need for a careful geometrical and numerical modelling to best exploit the described high efficiency feature. This will be made hereafter as well as in the analysis of the experimental results.

The optimisation of the resonant grating parameters was performed by means of a commercial code based on the C-method for the calculation of the diffracted field [7]. Unlike in the phenomenological explanation of high efficiency resonant diffraction, the numerical optimisation will be made on the input coupler which is more critical than the output coupler. The structure is designed to operate under TE incidence in the 850 nm wavelength range where vertical-cavity surface-emitting lasers (VCSEL) are available and commonly used in board-to-board optical interconnections. The substrate side corrugation is covered with a reflective gold layer of refractive index 0.198+ j 5.634 in the simulation. The refractive index of the thin dielectric layer n_f is chosen equal to 1.9 corresponding to sputtered HfO_2.

The refractive index of the waveguide n_w is 1.568 and its thickness h_w is 50 µm. The corrugation is assumed to be rectangular with rounded edges and has a period of 550 nm. The waveguide supports 68 modes which can be excited by the $+1^{st}$ diffraction order when adjusting the incidence angle in air θ_{iair} between -5° and 1.29°; the low order modes are excited under positive incidence angles in co-directional coupling and the higher order modes are excited under negative angles in contra-directional coupling. The grating depth σ and the thickness h of the thin dielectric layer are two parameters optimised to reach the maximum diffraction efficiency in the useful angular range [-5°, 1.29°]. The best values found are σ = 166 nm and h = 176 nm; they lead to the diffraction efficiencies shown in Fig. 2. The efficiency in the $+1^{st}$ order reaches 88.3% near -2.5° and levels off over a wide angular range between -1.6° and -5°. This plateau allows to expect an efficient coupling of a focused incident beam in the waveguide as will be demonstrated in the experimental part. At smaller incidence angles the diffraction efficiency falls to about 40% because of the appearance of the -1^{st} order in which part of the energy is uselessly diffracted, and cancels at 1.3°. The power balance curve, which is the sum of all diffraction efficiencies allows to estimate the losses to about 11.5%; in the useful angular range about 6.4% of the incident light is absorbed by the gold layer and about 4.9% is reflected at the air-waveguide interface. Fig. 2(b) shows that the resonant grating structure is also very tolerant spectrally with a 40 nm wide band. The sensitivity of the diffraction efficiency to some opto-geometrical parameters of the structure was evaluated in a previous paper [8].



(a) (b)

Fig. 2. (a)Theoretical diffraction efficiencies in the waveguide versus θ_{iair}. (b) Spectral variations of the diffraction efficiency of the $+1^{st}$ order for -2.5° incidence angle in air.

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3. Technology and experimental results

The fabricated device is an elementary demonstrator including two resonant diffraction gratings to couple light to and from a multimode optical waveguide of 30 mm length. The two diffraction gratings were fabricated by a single step holographic exposure. Photoresist was deposited on 50 mm x 50 mm square pyrex slides and was exposed to the interference pattern of a HeCd laser at 442 nm wavelength through two 5 mm x 40 mm apertures separated by 30 mm made in an opaque mask (see Fig. 3(a)). After development, the pattern was transferred into the substrate by reactive ion-beam etching. The period of the gratings (550 nm) was measured under a Littrow mount at 633 nm and the groove depth (around 165 nm) was measured by AFM. A reflective gold layer was evaporated on top of the two gratings followed by a high refractive index HfO_2 coating that was sputtered. The final step was the spin-coating of a commercially available epoxy-based polymer (Epoclad, Microresist Technologies), as the multimode optical waveguide (thickness h_w = 50 µm, refractive index 1.5443 @ 850 nm), on the whole pyrex plate. A SEM analysis of the sample cross-section was performed to control the geometrical characteristic of the corrugated layers. The cross-section preparation was uneasy due to the large difference in ductility between the different materials that resulted in the peeling off of the polymer layer from the substrate. In the grating regions, the HfO_2 layer and part of the gold layer peeled off with the polymer layer, leaving only gold in the pyrex grating grooves. Figure 3(b) shows a SEM picture of the gold and HfO_2 corrugations attached to the polymer layer. The polymer appears in black on the top of the picture, the first corrugation below corresponds to the HfO_2-polymer interface and the top of the gold lines appears lighter. One can observe a widening of the HfO_2 lines as compared with the gold lines. From Fig. 3(b), one can infer two different grating profiles for the gold and the HfO_2 layers. In order to perform simulations (see section 4), these profiles have been described by 21 and 15 Fourier components respectively and have been drawn in red on the SEM picture. The two grating depths are kept equal to about 165 nm and the measured HfO_2 layer thickness is 200 nm, i.e. more than the optimised 176 nm. The dashed blue line on the picture points out the location where the layers peeled off from the substrate.

The overall efficiency η of the device is defined as the ratio of the power coupled out by the second grating to the power incident on the first grating. It is measured using a titanium-sapphire laser tuned at 850 nm and focused on the first grating. The polarization is perpendicular to the incidence plane and parallel to the grating lines. The coupling grating is placed in the focal plane of a lens of 60 mm focal length which produces a divergence close to 1°. The sample is mounted vertically on a rotating stage (positioning accuracy $\pm$0.01°) in order to perform the measurements as a function of the angle of incidence θ_{iair}. The power extracted by the second grating is measured with a thermopile probe. A reference signal picked up from the reflection of the incident light on a beam splitter was monitored to account for the laser power fluctuations. Measurements were performed both with a focused incident beam and a collimated incident beam by removing the lens. The incident beam had to be positioned accurately as close as possible to the edge of the first grating to minimise the de-coupling of the light as discussed later. The normal incidence position can be determined to within 0.02° with the collimated beam and to within 0.8° when the lens is added in front of the coupling grating.

The results obtained with the focused and collimated incident beams are shown in Fig. 4. The main result is that η exceeds 60% with a focused beam in a reasonably broad angular range. This overall efficiency is the product of the out-coupling efficiency by the in-coupling efficiency times the transmission of the 30 mm long multimode waveguide section. Assuming equal input and output coupling efficiencies and zero waveguide loss, one can estimate the efficiency of one grating coupling event as the square root of the overall efficiency, i.e., 77%. This is actually a worst case estimate since considering waveguide propagation losses would lead to a larger figure.

A more detailed analysis shows that the shape of the envelope of the focused and collimated beam curves (Fig. 4) is similar with two maxima roughly at the same angles for

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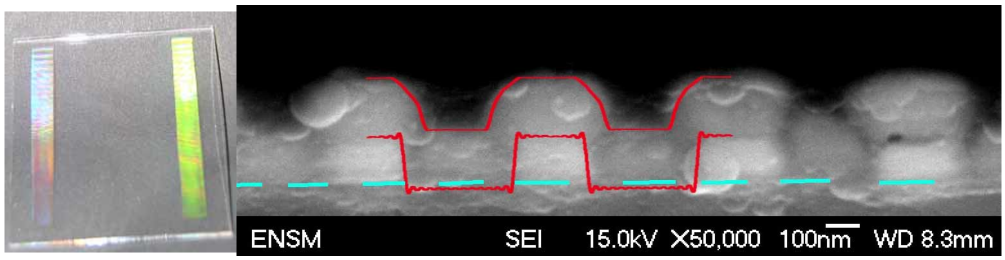
both curves: whereas η reaches 61% at –3.6° with a focused beam, it only reaches 31% and at 0.9° with a collimated beam. Moreover, in the latter case reproducible oscillations with an amplitude of about half the maximum values are observed. The period of the oscillations slightly increases as the incidence angle decreases. This feature as well as the comparison between the experimental and the theoretical data will be discussed in detail in the next section.



(a) (b)

Fig. 3. (a) Top view of the 5x5mm² pyrex plate with two resonant gratings (colored bands). (b) SEM picture of the grating cross-section: the red curves are the fitted profiles of the gold (bottom) and HfO_2 (top) corrugations considered in the simulations shown in section 4. The blue dashed line shows the location where the gold layer peeled off from the substrate.

The scattering losses of the whole component have been roughly estimated to be quite low: summing up the overall efficiency, the reflection coefficient of the in-coupling grating and the transmission coefficient of the small part of the incident beam which impinges past the in-coupling grating area (about 5% of the Gaussian incident beam impinges on the waveguide outside the grating area in the condition of optimized efficiency) practically amounts to 1 minus the theoretically estimated metal absorption. Moreover, very little scattering is observed when looking at the propagation track in the 3 cm waveguide with an IR viewer.

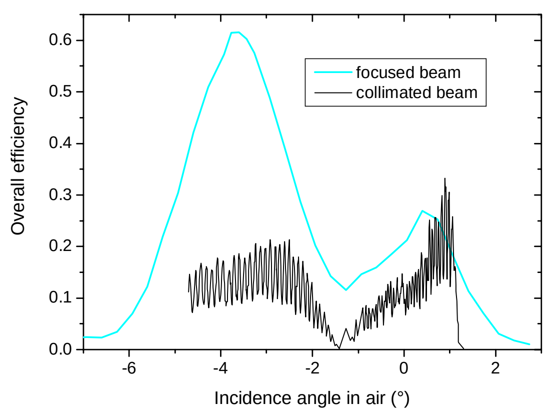


Fig. 4. Overall efficiency η measured with a focused and a collimated beam at 850 nm wavelength under TE polarization versus the incidence angle in air θ_{iair}.

4. Discussion

The oscillations observed in the output power of the collimated incident beam are attributed to the selective excitation of the guided modes of the waveguide. The calculation of the effective

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index $n_{em} \cong n_w - \frac{1}{8n_w}\left(\frac{(m+1)\lambda}{h_w}\right)^2$ of the guided modes of order m of the step index multimode guide shows that the angular interval between two adjacent modes varies monotonically between 0.003° and 0.18° from the low order to the high order modes and that about 68 modes of each polarization propagate in the polymer waveguide. The modes angular position is qualitatively in agreement with the experimental data of Fig. 4 which have been measured to within only 0.01°. The right-hand part of the angular spectrum of Fig. 4 corresponds to co-directional coupling where the K-vector of the grating couples the incident beam to low-order modes of narrow angular spacing. The left-hand part corresponds to contra-directional coupling to higher-order modes of smaller effective index and broader angular spacing. Although it is not possible to identify each waveguide mode, the line structure of the collimated beam curve can be interpreted as follows. A maximum is observed in the out-coupled power when the axis of the incident Gaussian beam is diffracted into a guided mode. Outside these particular coupling angles the coupling into adjacent guided modes is less efficient and the output power decreases. The modes being very close to each other, and the incident laser beam being slightly divergent (1 mrad i.e. about 0.06°), a fraction of the angular spectrum of the diffracted beam can always be partially coupled into a mode.

The highest overall efficiency measured with a collimated beam is significantly smaller than that measured with a focused beam. This can be explained as follows. When the incident beam impact zone on the grating is wide (about 1 mm for the collimated beam), part of the beam cross-section diffracted in the 1st order bounces more than once against the waveguide wall and gets re-diffracted by the grating. Re-diffraction is added to the reflection coefficient rather than to the coupling efficiency. This effect can be roughly accounted for by a ray tracing model of the modes propagating in the waveguide. The fraction of the incident light which is actually coupled into the guide can be estimated from the position of the ray from the grating edge. As sketched in Fig. 5, when the minimum distance L needed for a ray (i.e. a mode) to bounce twice on the grating is smaller than the width of the beam D, the contribution to the coupling efficiency falls from η_1 to the product $\eta_1\eta_0$, where η_1 is the diffraction efficiency of the resonant grating in the 1st order and η_0 is the diffraction efficiency in the 0th order. When L < D/2, the contribution falls to $\eta_1\eta_0\eta_0$, etc. Assuming a beam width D = 1 mm and the waveguide parameters described above, part of the incident beam is re-diffracted up to three times by the first grating. Only the modes of order above 18 undergo a double, a triple or a quadruple diffraction. The result of this simple modelling is given in Fig. 6(a) considering a wavelength of 850 nm, a TE polarization, n_w = 1.568, n_f = 1.9, h = 200 nm and the two grating profiles fitted from the SEM picture. This calculation doesn't take into account the coupling in the different waveguide modes; only the envelope of the experimental curve is compared. The agreement between the experimental and the calculated curves is very good.

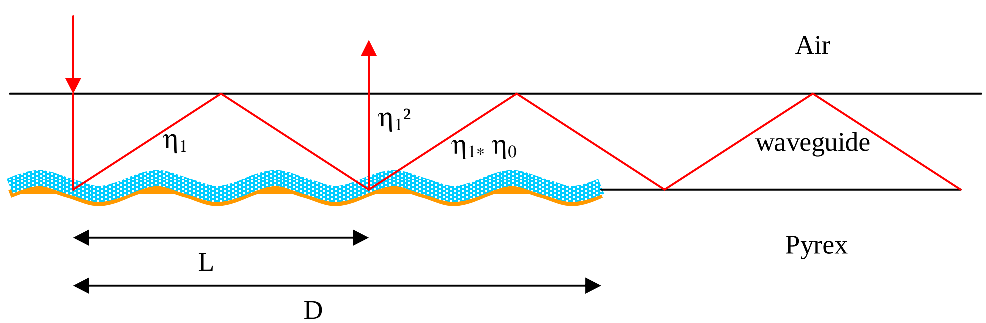

Fig. 5. Sketch of a double interaction of a diffracted ray with the coupling resonant grating.

The simulation of the focused beam efficiency was made by calculating the square modulus of the diffraction efficiency of the resonant grating shown in Fig. 2 (two gratings are

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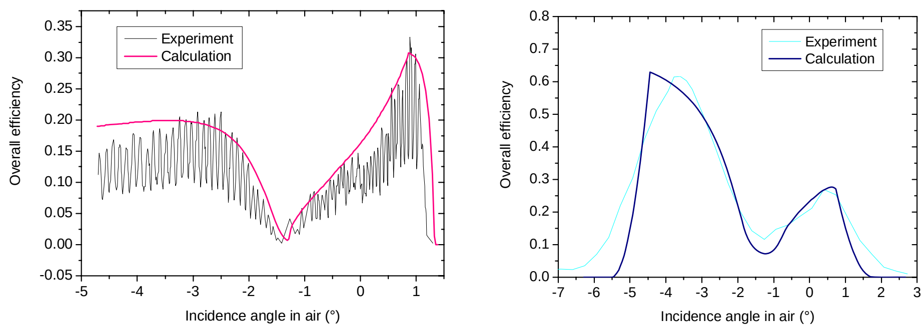
involved for coupling and decoupling light) convoluted by an angular window of 1° width (divergence of the incident beam in air). The diffraction efficiency is set to zero for incidence angles in air larger than 5° since guided modes only propagate the coupled power to the out-coupling grating. The size of the focused beam on the grating is estimated to be about 32 μm which is largely inferior to the minimum value of L corresponding to the highest order mode (about 244 μm). Thus re-diffraction effects need not be considered in the present optogeometrical configuration. The result of the calculation with the parameters used for the calculation of Fig. 6(a) is sketched in Fig. 6(b). As previously, it is very close to the experimental data.

These very encouraging results demonstrate that resonant gratings can couple light into thick waveguides with high efficiency for a TE polarized incident beam. Nevertheless, improvements are clearly possible in order to experimentally reach more than 70% overall efficiency with a focused or even a collimated beam. In the latter case another optimisation will maximise the diffraction efficiency for the first 20 modes to avoid the multiple diffraction effect.



(a) (b)

Fig. 6. Comparison of the experimental and the theoretical overall efficiency assuming a collimated incident beam (a) and a focused beam (b).

5. Comparison with currently used technologies

As the interest in optical interconnections integrated in boards is increasing, several solutions to couple light in and out of the optical layers are being envisaged. Comparing the solution presented in this paper with other waveguiding currently studied is clearly showing and highlighting the advantages of the grating coupler described here. Other solutions for coupling light in and out of the optical layers can be divided in 2 main categories, namely the use of deflecting mirrors and the use of pin-like inserts.

The first category, the deflecting mirrors, can be split up into mirrors fabricated integrated in the optical layers themselves or inserts in which the deflecting mirrors are integrated. Currently, the use of integrated 45° micro-mirrors is being studied by a number of groups [10]. The advantages of these mirrors are that they can be fabricated with a number of technologies, they are wavelength and polarization independent and they have a very good reproducibility. Both 45° micro-mirrors based on total internal reflection and metallized 45° micro-mirrors can be considered. Unlike the former, the metallized mirrors can be used in multilayer structures, which allows for flexible routing schemes and high interconnection densities. Integrated structures, where the mirrors are directly integrated with the waveguides can be fabricated using laser ablation or laser direct writing. The mirrors can be accurately aligned with respect to the waveguides with use of alignment marks. Compatibility with printed circuit board (PCB) manufacturing and soldering is required here, which puts high temperature and pressure demands on the used polymer materials. Laser ablation is fully compatible and nowadays used for the drilling of micro-vias in high density boards. If a

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choice is made for discrete configurations , the mirrors are fabricated in or on the surface of an insert which is placed into a cavity into the optical layer [11]. This solution requires passive or active alignment in order to get a good alignment between the mirror and the waveguide end facet. The discrete mirrors can for instance be made with deep proton writing or with a mechanical process and subsequent polishing step. Compatibility with existing PCB and soldering processes is not required since they can be placed in a very late stage of processing.

The second category of solutions to couple light in and out of the optical layers is the use of pin-like structures or submounts on which the photodetectors, light emitters or any other structure is mounted and positioned in a hole in the optical layer, directly but-coupled to the end facet of the integrated waveguide. This solution is generally considered as easing the fabrication of the optical path (no deflecting structure needed, no micro-optical parts required, …) but puts extra requirements on the electrical interconnections and, especially, requires a stable and accurate assembly of this electrical submount on the board, in front of the optical waveguide.

Comparing the grating coupler described in this paper with the alternative coupling schemes shows that the solution proposed here combines some of the advantages of the integrated character of the deflecting mirrors, as well as some of the advantages of pin-like structures as the deflecting functionality is kept in the optical path, loosening the requirements on the electrical assembly.

6. Conclusion

This paper demonstrates that a resonant diffraction grating can couple light in and out a multimode waveguide with an overall efficiency exceeding 60% when the incident beam is focused, TE polarized and the incidence is close to normal. This means that the losses, which include the light reflected at the air-waveguide interfaces, absorbed by the metal layers and scattered on the diffracting structures, do not exceed 1.1 dB. These low losses compare favourably with losses reported on alternative coupling concepts and technologies. In comparison, the 45° deflection micro-mirror has coupling losses, depending on the fabrication process, in the range from 3.6 dB [9, 10] to 6.5 dB [11, 12] although much lower losses can be obtained with silver coated mirrors [13].

Mirror inserts have the advantage of wavelength and polarization independence. However, the wavelength dependence of the present grating coupling mechanism is very weak for two reasons. Firstly, the resonance used to enhance the coupling efficiency is very broad. Secondly, a variation of the laser wavelength or the dispersion of the nominal wavelength of different lasers will not noticeably alter the coupling efficiency since the angular acceptance of the multimode waveguide is much wider than the angular spectrum of the in-coupled beam. Therefore any variation of wavelength will simply amount to the coupled power to be propagated by the neighbouring set of waveguide modes. The polarization dependence of the resonant coupling mechanism is a more serious concern. If a non polarized source must be used or if the source polarization fluctuates or else if the multimode waveguide cross-section has an aspect ratio sufficiently close to 1 to give rise to polarization coupling, there are ways to decrease and possibly suppress the polarization dependence. A further problem which remains to be solved is that of keeping high unidirectional coupling efficiency under strictly normal incidence. Here too, known concepts developed in integrated and diffractive optics during the past decade can be resorted to. One advantage of grating coupling which could become decisive in the perspective of an industrial production technology is its compatibility with all-planar batch technologies. Ways of improving the current overall efficiency are foreseen with optimized opto-geometrical parameters of the structure: better control of the refractive indices of the materials and optimised corrugation shape.

Acknowledgements

The Region Rhône-Alpes is gratefully acknowledged for the financial support of J. Franc. This work was carried out in the framework of the Network of Excellence on Micro-Optics

(NEMO) supported by the European Commission through the FP6 Program (FP6/2003/IST/2/contract no. 003887). The authors thank Paul Jouffrey from the Centre Science des Matériaux et des Structures, Ecole des Mines de Saint-Etienne (France) for performing the SEM measurements. Nina Hendrickx would like to thank the Flemish IWT (Institute for the Promotion of Innovation by Science and Technology) for financial support. The authors thank J.-C. Pommier from the Laboratoire Hubert Curien for the grating etching.

#87548 - $15.00 USD Received 14 Sep 2007; revised 1 Nov 2007; accepted 2 Nov 2007; published 4 Dec 2007