ETRI Journal, volume 17, number 2, July 1995

3-Dimensionally Integrated Planar Optics for 100 Gb/s Optical Packet Address Detection

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ABSTRACT

We propose a novel planar optical interconnection scheme for 100 Gb/s optical packet address detection, which consists of waveguide grating couplers and a diffractive microlens integrated on a glass substrate 3-dimensionally. Length and duty cycle of the grating couplers have been determined on the bases of the ray-optic propagation-mode analysis in a slab waveguide and of the rigorous coupled-wave diffraction analysis for out-coupled radiation-modes. The 3-dimensionally integrated planar optics makes it possible to connect each address bit-signals of TE_0-waveguide mode to the detector with a power uniformity of 6.4 % and a total coupling efficiency of 72.3 %.

I. INTRODUCTION

Interests in optical packet switching networks have been ever increasing to fully utilize the enormous bandwidth of optics for future broadband multimedia communications. In packet (or cell) based optical switching networks [1], a header attached to each packet payload contains a destination address to route the payload to the proper destination. Since the speed of header detection process at each switching node affects the network throughput significantly, optical means have been sought to improve the header detection speed. The header processing schemes proposed so far are mainly based on fiber-optic loop-mirror configurations [2] and fiber-optic correlators [3]. Even though they utilize the enormous bandwidth of optical fibers, they may suffer from a large amount of optical loss higher than 12 dB due to a series of several 2×2 directional couplers.

In order to reduce the optical loss, we propose a novel scheme of 3-dimensionally integrated planar optics for 100 Gb/s packet address detection. Planar optic set-ups [4], [5] composed of free-space optical components integrated on a glass block make signal connections between 2-dimensional array of input and output optoelectronic devices through 3-dimensional glass space. Thus they can take the advantages of compactness, easy alignment and thermal/mechanical stability, and are regarded as a useful approach to realize an optical interconnection system in a practical way. The planar optics proposed in this paper consists of an array of waveguide grating couplers and a diffractive microlens fabricated on a surface of glass block, and makes it possible to connect 100 Gb/s, 10-bits packet address signals to a detector with an efficiency higher than 72 %. Therefore, we believe that the planar optics scheme can show much improvement in power requirement, signal processing speed, and component size. For a highly uniform coupling of each optical bit-signals to the detector, structures of the waveguide grating couplers are evaluated by using the ray-optic concept for propagation-mode analysis in a slab waveguide [6], and the rigorous coupled-wave theory [7] to calculate the out-coupling efficiency of radiation-modes.

II. BIT-SIGNAL COUPLING BY PLANAR OPTICAL INTERCONNECTIONS

Figure 1 shows a schematic illustration of the 3-dimensionally integrated planar optics for 100 Gb/s packet address detection. It consists of a glass substrate, a butt-coupled fiber for input signals, a waveguide layer with an absorption layer on the one edge, grating couplers (GCs) on the top of the waveguide layer, a detector, a diffractive microlens to focus the radiated beams from the GCs to the detector, and a mirror layer under the bottom surface of the glass substrate. As shown in Fig. 2, one of the GCs consists of line-shape gratings with

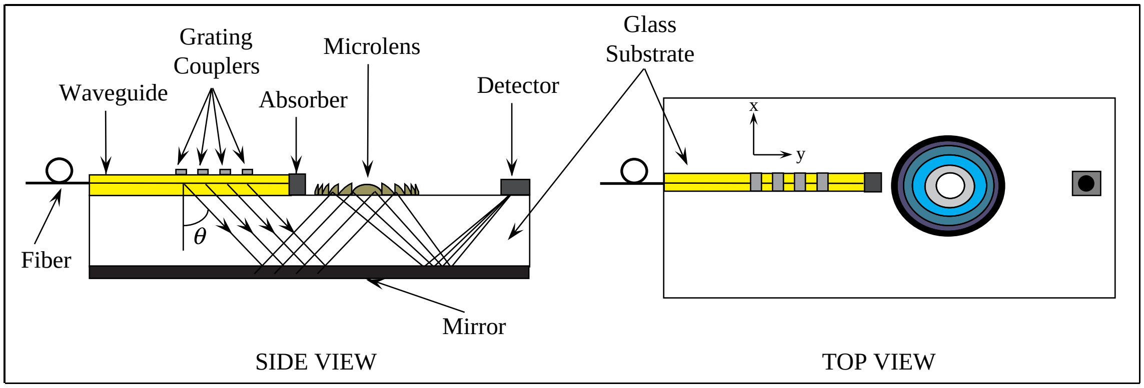

Fig. 1. Planar optical scheme for packet address detection.

the grating period of p, the grating thickness of t, and the width of d. The duty-cycle of the gratings is defined by g/p.

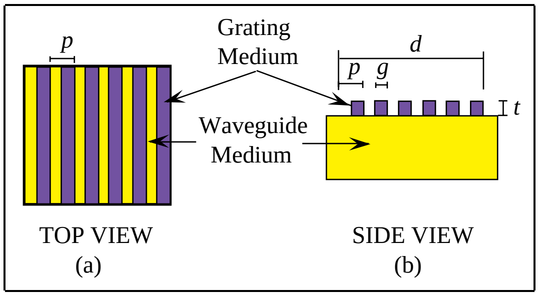

Fig. 2. Structure of a grating coupler. d: length, p: period of line gratings, t: thickness, and g/p: duty-cycle.

The signal flow is as follows. The input beams of optical packet signals are guided into the waveguide, and propagate in the direction of y-axis. Each of the guided bit-signals is then out-coupled, with an angle of θ, by the linear array of N GCs, resulting into N diffraction waves as radiation-modes. N is 4 in the Fig. 1. The diffraction waves are then focused onto the detector by the diffractive microlens. Output characteristics of the packet address detection process can be described as,

$$r(y_0) = \int_0^d \rho s(y_0 - y)\, f(y)\, dy, \qquad (1)$$

where ρ is the focusing efficiency of the microlens, $s(y)$ is an incoming packet address signal, and $f(y)$ is the impulse response function of the GC. If the incoming packet address is in a digital form with bit-interval of τ as described in Fig. 3(a), $s(y)$ with N address-bits and $f(y)$ are expressed as,

$$s(y) = \sum_{i=1}^{N} W_i A_i(y), \qquad (2)$$

$$f(y) = \sum_{j=1}^{N} \eta_j rect(y/\triangle y_j) * \delta(y - y_j), \qquad (3)$$

where W_i and $A_i(y)$ are the weighting factor and waveform of the i-th address bit, respectively. In (3), $*$ denotes the convolution and η_j, $\triangle y_j$ and $\delta(y - y_j)$ are the parameters for the j-th GC describing respectively the out-coupling efficiency, the width, and the delta function representing the center positions. If the code sequences of $s(y)$ and $f(y)$ are identical, the GCs generate an output of auto-correlation delta peaks. Otherwise, the GCs generate cross-correlation peaks. Figure 3 shows an example of $N = 10$ bits address detection, where $s(y)$ represented by the sequence (1011010011) is described in Fig. 3(a) and $f(y)$ given by the same sequence (1011010011) in Fig. 3(b). Therefore, under ideal circumstances the auto-correlation signal would be (1112213226223122111) as shown in Fig. 3(c). Since the central peak value, 6, of the auto-correlation signal is always higher than cross-correlation peak values, it can be easily decided whether the address of an incoming optical packet matches to a specific node address stored in the GCs by thresholding the correlation outputs with a level in between two values of the central auto-correlation peak and the highest cross-correlation peak.

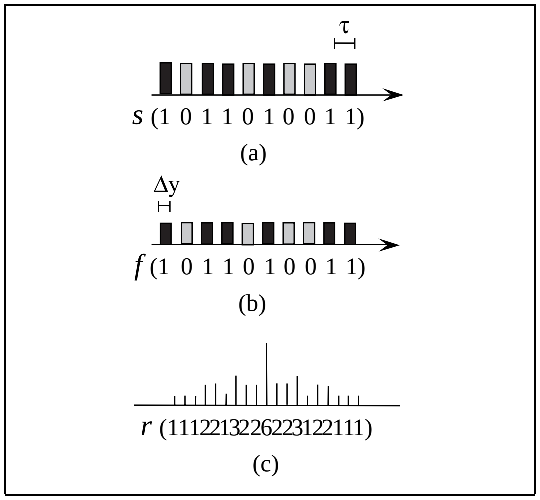

Fig. 3. (a) A 10-bits optical packet address signal, (b) 6 grating couplers placed at the positions corresponding to the bit-values of ‘1’, (c) the detector output of auto-correlation peaks. Black or gray boxes represent respectively existence or absence of the bit-signals.

Speed of the packet signal detection is only limited by the spacing between the GCs. If the spacing is 2 mm and the refractive index of the waveguide layer is about 1.5, then the time interval between the bit-signals, τ, is given by 10^{-11} second. Therefore, it is possible to get a detection speed of packet address bit-signals in the range of 100 Gb/s.

III. DIFFRACTIVE FRESNEL-TYPE MICROLENS

In order to produce large peak values of the auto-correlation, it is desirable to make the ρ and the sum of η_j for all j to be high. We have designed the diffractive microlens as an off-axis Fresnel-type lens, in which the phase profile is described by the following equation:

$$\begin{aligned}\phi_m(x,\ y) = {} & \frac{2\pi(n_s - n_0)}{\lambda} \\ & \times \{\sqrt{x^2 + y^2 + F^2 - 2yF\sin\theta} - F\} \\ & -2\pi m, \end{aligned} \tag{4}$$

where n_s and n_0 are the refractive indices of the substrate and the air, respectively, and F is the focal length. Since the phase profile is continuous and has the maximum height of 2π, the diffractive microlens can take its focusing efficiency of ρ more than 80 % under ideal circumstances, and the efficiency of 78 % was achieved in experiment [8]. In the special case of $\theta = 0^\circ$ in (4), Fig. 4 shows a part of the microlens that we have fabricated by the laser writing technique [9]. The F-number of the microlens was 10 with the diameter of 250 μm. The sample substrate of optical glass covered with 0.2 μm thick positive-photoregist (S1400) layer was exposed by the raster-scanned laser beam, and was developed with the solution of AZ351 developer. Based on the gamma curve of the photoregist layer, the continuous surface-relief micro-structure was fabricated as it was designed. The spot size of the writing laser-beam was measured to be 2.3 μm.

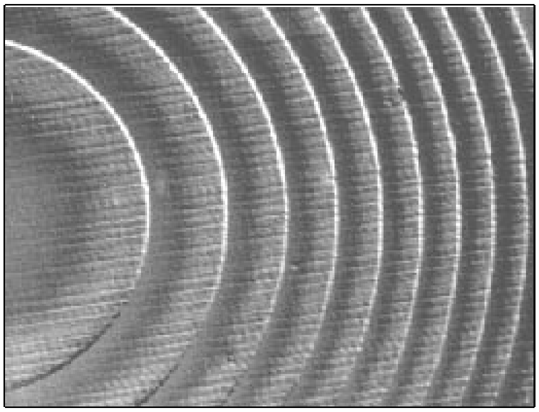

Fig. 4. Fresnel-type diffractive microlens fabricated by the laser writing technique.

IV. OUT-COUPLING EFFICIENCY OF GRATING COUPLERS

For a higher sum of η_j we have designed the GCs to radiate the guided beams only toward the glass substrate [10] with the condition that only a TE_0 mode can be guided in the waveguide structure. Another important parameter in the packet address detection is the uniformity of light intensities out-coupled from the GCs. Therefore, the out-coupling efficiencies of GCs, η_j for all j, must keep the relation of

$$\eta_j = \frac{\eta_1}{\{1-(j-1)\eta_1\}}, \quad \textit{for } j=1,\ 2,\ \cdots,\ N. \tag{5}$$

In our design, two parameters have been evaluated, namely the width d and the duty-cycle g/p of square gratings in a GC. The design is based on the ray-optic concept for propagation-mode analysis in a waveguide, and the rigorous coupled-wave theory has been used to calculate the out-coupling efficiency of the radiation-modes. Figure 5(a) shows the schematic diagram to describe the ray-optic concept. Assume that there is only a fundamental TE mode (TE_0) in the waveguide. The propagation angle of TE_0 mode is θ_0 and the effective thickness T_{eff}. The incident ray to the GC is then diffracted into several substrate-modes with the diffraction efficiencies of S_q for q = -1, -2, ..., and air modes (C_q) higher than the first order diffraction. The un-diffracted zeroth-order beam with the efficiency, f, propagates with the initial guiding direction. The total number of bounces to the GC layer with the length of d is

$$M = \frac{d}{2T_{eff}\tan\theta_o}. \tag{6}$$

The diffraction efficiencies, η, of S_q, C_q, and f, have been calculated by the rigorous coupled-wave theory, and the results are shown in Fig. 5(b), as a function of the grating thickness, t. In the calculation, the GC with a square-shaped grating was estimated with the refractive indices of glass substrate ($n_s = 1.46$, quartz), waveguide medium ($n_f = 1.52$, ThF_4), grating medium ($n_g = 1.49$, PMMA), and air ($n_c = 1.0$). The other parameters used are the duty-cycle of 0.5, $\lambda = 633$ nm, glass thickness of 3mm, waveguide thickness of 1.0 μm for guiding only a TE_0 mode, effective waveguide thickness of 1.38 μm, effective waveguide index of 1.62, θ_0 of 80.7 degree, p of 2.14λ, and θ_{-1} of 45 degree. It can be found from the result that C_{-1} is always zero, because the condition of

$$\frac{n_c}{n_s} < \sin\theta_{-1} < 1 \tag{7}$$

is satisfied. Therefore, only a substrate-mode obtained from the first-order diffraction can give us the higher η_j for all j. Since the relation of p and θ_0 is out of the Bragg condition, most of the diffraction efficiencies of substrate- and air-modes are lower than 20 %, and the efficiencies in the range of t less than 0.1 μm are negligible except for the first-order of substrate-modes, S_{-1}.

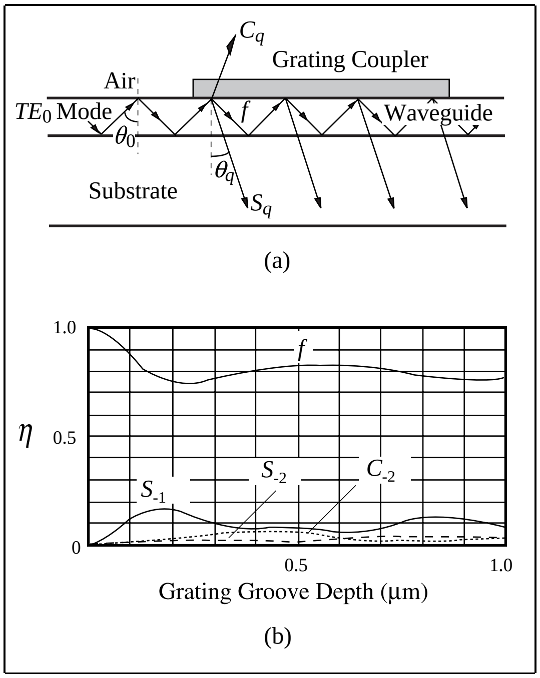

Fig. 5. (a) Ray-optic concept for radiation-mode analysis showing that the zigzag wave of TE_0 mode in the waveguide is out-coupled by multiple-diffraction from the grating coupler, (b) diffraction efficiency of radiation-modes when the duty-cycle of grating is 0.5.

After the M times diffraction from the j-th GC, the out-coupling efficiency of each radiation-mode can be calculated by

$$\begin{aligned}\eta_j &= S_q + S_q f + S_q f^2 + \cdots + S_q f^{(M+1)} \\ &= S_q \frac{(1-f^M)}{(1-f)}\,, \end{aligned} \tag{8}$$

and the optical power remaining in the waveguide is given by f^M, for the incidence of unit optical power. By equating η_j in (8) to that in (5), we can obtain an optimized width of each GC as follows:

$$d_j = \frac{1}{2\alpha_r}\ln\left(\frac{S_{-1}}{S_{-1}-(1-f)\eta_j}\right), \tag{9}$$

where α_r is the radiation decay coefficient (or coupling coefficient) of grating coupler, and it is obtained by

$$\begin{aligned}\alpha_r &= -\frac{M}{2d}\ln(f) \\ &= \frac{1}{4T_{eff}\tan\theta_0}\sum_{m=1}^{\infty}\frac{(1-f)^m}{m} \\ &\approx \frac{(1-f)}{4T_{eff}\tan\theta_0}, \qquad for\ f << 1. \end{aligned} \tag{10}$$

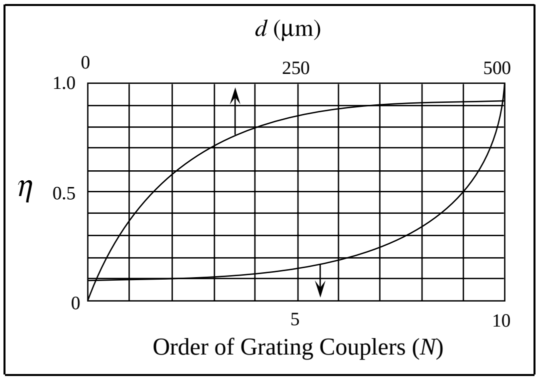

Fig. 6. Dependence of the out-coupling efficiency on the width of GC, and the efficiency distribution for generating 10 uniform beam.

Figure 6 shows the out-coupling efficiency, η, of 10 GCs required to generate 10 uniform out-coupled beams in the lower curve. The grating thickness and duty cycle were 50 nm and 0.5, respectively. The upper curve in the figure shows that the out-coupling efficiency can be adjusted from 0 % to 92 % by increasing the width of a GC from 0 μm up to 500 μm. Also the lower curve shows that the efficiencies required for the first 5 GCs are less than 20 %, resulting that the width of each GC becomes shorter than 20 μm. If the path length from a GC to the microlens is several millimeters, the diameter of the diffracted beam may be too large to fit into the microlens. Therefore, it is required to make the GC width wider than 100 μm in general cases. Increasing the duty-cycle makes it possible to enlarge the GC width given by (9). From our calculation results, we have found that the efficiency can be still less than 20 % in the case of 0.9 duty cycle, even though the GC width reaches to 500 μm. Since the GC width in y-direction is defined by the total number of grating lines, the GC width can be controlled with an accuracy of less than 1 μm, which gives us the designing accuracy of the efficiency within 0.1 %. Therefore, the duty-cycle of each GC is first chosen as a coarse-adjustment parameter, and then the GC width can be determined for a fine-adjustment of the out-coupling efficiency.

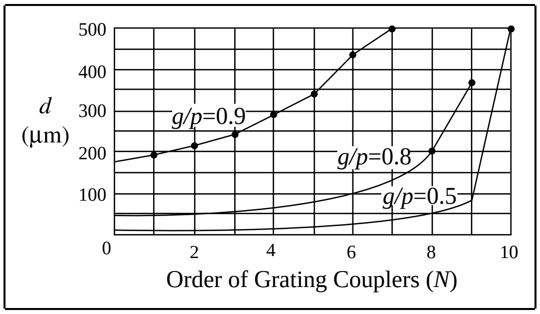

Fig. 7. Design result of the widths and duty-cycles of 10 grating couplers for 10-bits packet address detection.

V. DESIGN CONSIDERATIONS OF GRATING COUPLER ARRAY

An example of our design results is shown in Fig. 7, when $N = 10$ and the grating thickness is 50 nm. The 10 dots in the figure represent the 10 designed values of the widths and duty-cycles for the 10 GCs. In order to make the beam size reaching the microlens smaller than the microlens diameter, d must be large enough, so that in the example we chose the width in the range from 180 μm to 500 μm. The first 7 GCs have the duty-cycle of 0.9, the 8th and 9th GCs with the duty-cycle of 0.8, and the last GC of 0.5. The grating coupler with the duty-cycle of 0.9 has the minimum feature size of 0.12 μm in the example, which can be obtained by the direct electron-beam writing technique. The out-coupling efficiency of each GC has a value from $\eta_1 = 9.91$ % up to $\eta_{10} = 91.93$ %, respectively, in accordance with (7). The total out-coupling efficiency defined by the ratio of the total optical power coupled out of the 10 GCs to the incident power, is 99.1 %.

VI. DISCUSSION

From the Fig. 7, it can be mentioned that the fabrication tolerance is more tight for the duty-cycle than for the width. For example, using a GC with $g/p = 0.9$, $d = 500$ μm and $t =$ 50 nm, one may find that a 10 % increase in the grating groove width , which means the change of duty-cycle from 0.9 to 0.89, produces a 3.1 % change $(\triangle\eta_d)$ in the GC's efficiency. However, even though the width deviates with 1 μm from the designed value, it makes just a 0.1 % change $(\triangle\eta_w)$ in the efficiency. Since the accuracy of line width fabricated by the direct electron-beam writing is normally given by 10 nm, one can achieve the non-uniformity of optical powers radiated from the 10 GCs to be about $2(\triangle\eta_d + \triangle\eta_w) = 6.4$ %, and the total out-coupling efficiency (η_{GC}) of the 10 GCs to be about 92.7 %. Consequently, taking the value of 78 % reported in [8] as the focusing efficiency (ρ) of the microlens, one can mention that the overall coupling efficiency obtained from the grating couplers and the diffractive microlens would be $(\eta_{GC} \times \eta_{dm}) = 72.3\%$.

Fabrication accuracy of the grating thickness is not so critical, since the 10 % error in the thickness from 50 nm makes just 0.5 % change in the efficiency. Therefore, the grating layer could be fabricated by spin-coating process, but, it is not easy to make a very thin spin-coated-film because many pin-holes may appear on it. The Langmuir-Blodgett (LB) film-deposition technique, on the other hand, is one of the accurate techniques to make thin polymer-layers with the thickness accuracy of 1 nm [11]. By using the LB technique, an e-beam resist as the grating layer can be deposited very accurately on the wave-guiding layer without any pin-holes generating problem. Mass production of the GC arrays proposed here can be possible by replication technology, which is already well developed for diffractive optical elements [9]. After the e-beam fabrication of the original grating structure, a metal shim by electroplating the surface of the structure can be used as a master replication shim and it makes use of GC arrays practically.

VII. CONCLUSION

We have proposed a novel scheme of planar optical interconnections for 100 Gb/s packet address detection. The planar optics consisting of an array of waveguide grating couplers and a diffractive microlens fabricated on a surface of glass block can make the connection of 100 Gb/s, 10 bits packet address signals to a detector with an efficiency higher than 70 %. For a highly uniform coupling of each optical bit-signals to the detector, structures of the waveguide grating couplers have been evaluated by using the ray-optic concept for propagation-mode analysis in a slab waveguide and the rigorous coupled-wave theory to calculate the out-coupling efficiency of radiation-modes.

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