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Study of an Array of Grating Couplers for Wireless Optical Communications

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ABSTRACT

An array of grating couplers is studied to be used for beam steering in a wireless optical communication system. This structure is designed using a rib waveguide with a silicon thickness of 220nm and an etch depth of 70nm using 2 μ m silica substrate. TE polarized input light with wavelength of 1550nm is coupled into the feed waveguide. The structure is optimized based on the angular coverage, directed power, and beam efficiency of the radiated main beam of an individual grating coupler. The main beam radiated by optimized grating coupler has a beamwidth of 10.3°×30.7°. The designed 1-D array of the fifteen grating couplers provides tunability in the range of around 30 degrees which is required for a point to point wireless optical communication transmitter.

Keywords: grating coupler, optical phased array, beam steering, point-to-point communications

1. INTRODUCTION

An optical wireless (OW) communication system, uses signals in optical frequencies to carry information through free space. OW links are intrinsically broadband and neither regulated nor licensed [1]. Wireless links in optical communications are classified based on mobility and configuration of transmitters and receivers. Furthermore, directionality is an important parameter for such structures, i.e. beam-angle and field of view (FOV) of transmitter and receiver [2]. However, there are still limitations and challenges for such communication systems concerning the coverage and tunability of optical beams.

An optical phased array (OPA) is similar to a microwave phased array, which the phase difference between array elements is used to change the beam direction. OPA enables rather accurate beam forming which could be resistant to external disturbances [3]. An OPA is fed by a laser source, divided into several dielectric waveguides using proper couplers, and fed to the emitters (grating couplers). Diffraction gratings have been widely used for various functionalities, i.e.; reflection, deflection, filtering, and input/output coupling of the beams to the waveguides. [4]. Grating couplers, which are able to convert waveguide mode to radiation mode, or vice versa, can largely be employed for point-to-point communications. Analysis of the tunable transceivers with rather wide angular coverage to obtain its limitations is the main objective of this paper.

Performance of an array of grating couplers for various applications has been studied by several researchers. Abediasl et al. have designed a 3×2mm² layout including 8×8 array of grating couplers, where each grating coupler is focused-shape. The distance between the elements is 33 μ m in this layout and results in 1.6° beam steering for each π phase delay. The total input-to-output loss of 23.6dB is reported [5]. An array of 4×4 silicon gratings to steer the main beam of about 22.5° with a footprint of less than 1mm² and an average optical loss of 1.8dB/cm has been realized by Aflatouni et al. [6]. A compact 2-D array (64×64) design is proposed by Sun et al. and realized in a foot print of 576 μ m² where each array element is a silicon grating coupler with 3 μ m length and 2.8 μ m width, consisting of only five grating teeth. Such structure is able to steer the main beam 6° in two directions. Doyle et al. have investigated a one dimensional coupler including 16 channels ending with grating couplers spacing 3.5 μ m edge to edge. Each grating coupler has 1 μ m width, 200 μ m length and 500nm height. Maximum beam steering for such structure is 20° in ψ and 14° in θ . Full-width half-maximum (FWHM) of the radiated power in main beam is 0.6°×1.6°. On-chip waveguide propagation loss in this design is 3.0 ± 0.2 dB/cm and the length of layout is 4mm [8].

In section 2, parameters of a single grating coupler, such as period, width, and length, are studied and optimized to achieve an efficient radiation. In section 3, based on the designed single grating coupler, an array of the couplers is

considered and performance trade-offs in terms of coverage and tunability are be discussed. Finally, in section 4 the paper is concluded.

2. DESIGN OF A SINGLE GRATING COUPLER

Thickness of the grating waveguide and etch depth is set to 220nm and 70nm accordingly. In order to achieve more efficient radiation duty cycle or filling factor, which is the ratio of width of grating tooth to grating groove, is treated to be 50% [8]. Outgoing beams of output couplers are directed in discrete angles in Theta direction as shown in Fig.1. These angles are determined by wavelength, material, and grating period [9]:

$$\Lambda = \frac{\lambda_0}{n_{eff} - n_t \sin \theta_n} \quad (n = 0, \pm 1, \pm 2, \dots) \tag{1}$$

where Λ is the period of grating, n_{eff} effective refractive index of waveguide, n_t refractive index of top cladding material, λ_0 the wavelength of the light in free space (here is 1550nm), and θ_n is the discrete angles in which light propagates into space. We will study the effect of period, width, and length of the grating during the next sub-sections to find an optimized design to be used for a one dimensional array of coupler.

Figure 1. 2-D cross section of single grating coupler in XY plane (a) and XZ plane and spatial coordinate system of study. Azimuth angle is the same θ in Eq. (1) and discussion. Elevation angle can also be called as ψ .

2.1 Period of the coupler

In order to obtain single beam radiation into free space from the grating, periodicity of grating coupler needs to be properly selected. According to Eq. 1, the chosen period must satisfy grating diffraction order of $n=-1$ (see Fig. 1a). Since the second beam would radiate into the substrate, the period of the grating has been chosen in order to obtain maximum upward radiation and less leakage into the substrate. From the derived effective refractive index, the possible range for grating period to be in first order of diffraction and backward radiation is 420-580nm [9]. Behavior of grating coupler in this region is simulated to get the most efficient grating period. Consequently, grating coupler with a period of 500nm is taken into account based on the minimized side lobe level (SLL) (see table 1).

Table 1. Direction of upward and downward beams and side lobe level value for grating couplers with different periods in the range of backward radiation ($\theta<0$).

Grating Period	430 nm	450 nm	470 nm	500 nm	530 nm	550 nm	570 nm
Upward beam direction [°]	-68.6	-51.1	-33.1	-25.2	-17.1	-11.7	-5.3
Downward beam direction [°]	-109.0	-122.2	-142.4	-153.7	-162.7	-169.7	-175.2
Side Lobe Level (SLL) [dB]	-1.6	-0.6	-1.7	-3.7	-2.1	-0.9	-1.2

Figure 2. Far-field radiation pattern of three silicon grating couplers with (a) 1 μm , (b) 2 μm , and (c) 5 μm width.

2.2 Width of the coupler

Radiation properties of grating coupler by varying the width of the grating coupler are analyzed in this section. As shown in table 2, increasing the width of grating from 800nm to 5 μm , affects the gain of the radiated main beam and its width in elevation (or ψ) angle. As can be deduced from table 2, increasing the width of grating coupler generally results in the narrower beamwidth of elevation angle. However, in an exceptional case, where grating coupler width is narrower than wavelength (1550nm), instead of observing a main beam at elevation of zero, two mirrored beams can be observed (Fig. 2a). On the other hand, gain of the grating coupler could be increased by increasing its width, which could be expected since the effective area of the coupler has been increased. To satisfy the tradeoff between the performance and footprint, a width of 2 μm is chosen for further studies in the analysis of the array.

Table 2. Radiation properties of main beam in far-field pattern of a single silicon grating couplers with different width.

Grating Width	0.8 μm	1 μm	2 μm	3 μm	4 μm	5 μm
Realized gain [dB]	10.4	9.3	17.4	19.8	21	22
Main beam peak in θ [$^\circ$]	-46.1	-30.8	-27.6	-26.6	-26.2	-26.0
Main beam peak in ψ [$^\circ$]	18.8	5.2	0.0	0.0	0.0	0.0
3dB beamwidth in θ [$^\circ$]	9.2	8.1	10.3	10.5	10.5	10.5
3dB beamwidth in ψ [$^\circ$]	80.6	29.1	30.7	27.4	23.6	19.6
Side Lobe Level (SLL) [dB]	-2.1	-1.0	-2.9	-3.9	-4.0	-3.8

2.3 Length of the coupler

Effect of length on grating coupler performance is studied by increasing the number of periods. Gain of the grating coupler increases (from 15dB to 22.5dB) by increasing its length. However, this increase will be saturated after a certain length [10]. The (efficient) area of antenna increases with higher number of teeth, which results in higher radiated power. Increasing the length of grating coupler, also results in a narrower main beam, in both azimuth and elevation angles (Fig. 3b). For a silicon grating coupler with 500nm grating period, the light could radiate completely into free space after almost 80 periods as shown in Fig. 3a. Far-field pattern of grating coupler with 15 periods (Fig. 3b) shows that there are still radiations along the wave guide direction (x axis) while the radiations are significantly decreased in grating coupler with 45 periods.

Figure 3. Variation of maximum gain of silicon grating couplers with different lengths from 10 periods to 85 ones (a). 3dB beamwidth of radiated main beam for silicon grating coupler versus increasing its length from 10 periods to 85 periods. Besides, far-field pattern of two grating couplers owing 15 teeth and 45 teeth is presented (b).

3. STUDY OF THE GRATING COUPLERS ARRAY

An optical phased array can be used to steer the beam direction by varying the applied phase or alternatively delay to each arm of the radiating element [11,12].

3.1. Pattern analysis of the array

Pattern of an array is the product of each element pattern multiplied with array factor (AF). As it is shown in Fig. 4, grating couplers are localized in a 1-D array with equal spacing of d . The coupled light to each element has the same amplitude but a different phase (with a shift of β from each other).

Figure 4. Schematic view of a phased array of grating couplers for beam steering.

Figure 5. Radiation pattern of three configurations of 1-D array of silicon grating couplers in planes ($\psi=0^\circ$) and ($\theta=28.3^\circ$). d is the center-to-center distance between array elements.

Single grating coupler with a width of $2\mu\text{m}$ and a length of $45\mu\text{m}$ (85 periods) is considered in our analysis to be used as a single element for the phased array. Three configurations took into account: 5, 10, and 15 elements with center to center distances of 9, 4.5, and $3\mu\text{m}$ accordingly. Radiation patterns of these configurations are shown in Fig. 5. As expected, array of grating couplers changes neither the beam direction in azimuth (θ) angle (see Fig.5a) nor the half power beamwidth (see table 3).

Table 3. Main beam properties of single antenna and array of them based on designed silicon grating on a platform of $45\times 45\mu\text{m}^2$

Grating Width	2 μm			
Main beam peak in θ [°]	-28.3°			
Number of elements	1	5	10	15
Space between elements [μm]	-	9	4.5	3
Main beam gain [dB]	23.4	30.4	33.5	34.8
3dB beamwidth in θ [°]	3.1	3.1	3.1	3.1
3dB beamwidth in ψ [°]	25.6	1.8	1.7	1.6
Side lobe level (SLL) [dB]	-19.8	-1.5	-11.5	-13.2
Beam efficiency [%]	22	10	20	27

The beam forming in elevation angle is shown in Fig.5b. Increasing the number of elements results in higher radiated gain of main beam, whereas decreasing the distance between the elements results in the narrower beamwidth and less number of side lobes. In other words, by increasing the distance between the elements, secondary beam is amplified and getting closer to the main beam which results in a narrower field of view. FOV is the angle through which transceivers are sensitive to radiated wave [1]. Widest FOV is observed for 15-element array which is around 60 degrees. SLL values in table 3 confirm that decreasing the distance, would weaken the secondary beam dramatically from -1.5dB for 5-element to -13.2dB in 15-element design. The other parameter reported in table 3 is beam efficiency, which is the ratio of the accumulated power in the main beam angular range, $[\theta_1, \theta_2]$ and $[\psi_1, \psi_2]$, to the whole radiated power (Eq. (2)).

$$B.Eff(\Delta\theta, \Delta\psi) = \frac{\int_{\theta_1}^{\theta_2} \int_{\psi_1}^{\psi_2} \mathcal{G}(\theta, \psi) d\theta d\psi}{\int_0^{2\pi} \int_0^{2\pi} \mathcal{G}(\theta, \psi) d\theta d\psi} \quad (2)$$

3.2 Beam steering

Beam steering capability of an array with 15 elements and 3 μ m spacing is considered in this section. Variations of elevation angle in plane of $\theta = -28.3^\circ$ (the azimuth angle in which maximum peak power occurs) is considered here. Beam steering of about 14.8° is obtained by applying around π phase shift between elements (table. 4).

Table 4. Radiation properties of array of Silicon grating coupler under applying different phase shifts.

Array design	15 elements and 3 μ m spacing				
Main beam peak in θ [$^\circ$]	-28.3°				
Phase shift	0	$\pi/3$	$\pi/2$	$5\pi/6$	π
Main beam direction in ψ [$^\circ$]	0	-4.9	-7.4	-12.3	-14.8
Main beam gain [dB]	34.8	34.7	34.5	32.7	30.8
Side Lobe Level (SLL) [dB]	-13.2	-12.9	-12.7	-4.8	0

By increasing the phase shift between elements, especially more than $\pi/2$, SLL is dropped dramatically, which means that the secondary lobe is enhanced [13]. In this study, a maximum beam steering of $\pm 14.8^\circ$ is obtained for the array of grating couplers (Fig. 6).

Figure 6. Radiation pattern of single (a) and array of 15 Silicon grating couplers in plane of ($\theta = -28.3^\circ$) and its beam formation by applying 0 (b), $\pi/3$ (c), $\pi/2$ (d), $5\pi/6$ (e), and π (f) phase shift between elements.

4. CONCLUSION

An array of silicon grating couplers has been studied to be used for optical wireless communication system in telecom wavelength. Grating periods of 500nm is investigated due to radiate single upward beam and less leakage into the substrate. Increasing width of grating lead to narrower width of main beam in elevation angle Length of grating coupler is increased to investigate the saturated point where no more radiation occurs. Main beam reached its maximum power and narrowest FWHM after 85 grating periods. Various arrays of optimized grating couplers (i.e. 5, 10, and 15 elements with distances of 9, 4.5, and $3\mu\text{m}$ accordingly) are studied due to either power amplification or beam steering ability. The designed 1-D phased array with 15 elements is able to steer the main beam around 30 degrees in elevation direction (ψ angle).

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