Vertical Grating Coupler for Efficient Chip to Fiber Coupling in Silicon Photonics Technology

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***Abstract*—The design and analysis of vertical grating coupler in silicon photonics technology is presented in detail. The wavelength of operation is 1550 nm.The simulated structure has a 220 nm Silicon layer on top with a silicon on insulator box of 2 μm, an integrated input waveguide and vertical grating coupler. The structure was designed and optimized to improve the coupling efficiency from chip to fiber. The parameters that were optimised are grating period, depth of back reflectors and number of gratings. An efficient chip to fiber coupling is an important aspect of photonic integrated circuit that has been addressed in this article.**

***Index Terms*—silicon photonics, vertical grating coupler, coupling efficiency, grating period**

I. Introduction

Silicon photonics has become a full fledged technology which is used for large scale integration of optical devices such as modulators, photo detectors, waveguide couplers, arrayed waveguide etc on a single photonic chip [1]–[3] .Silicon photonics technology has found applications in next generation short reach data center interconnect, light detection and ranging (LiDAR), biosensing and various other technologies [4]–[6]. It has enabled low cost and mass scale producti, C. Lacava, A. Khokhar, X. Chen, I. Cristiani, D. Richard-tion of integrated photonic circuits and systems. The large index difference between Si and SiO^2 enables nanometer scale single mode waveguide configuration thereby enabling integration of large number of optical devices on photonic chip. On the downside the huge difference in mode areas of the fiber $(80\mu m^2)$and waveguide $(0.2\mu m^2)$ makes the chip to fiber coupling a challenging task [7]–[9]. Grating couplers and edge couplers are used to overcome the problem of chip to fiber coupling. The complications in post fabrication process of edge couplers such as correct alignment of optical fiber, clean facets in spite of having bandwidth larger than 100 nm and insertion loss lower than 0.5 dB, makes its ill suited for mass production and testing on wafer scale. Thus vertical grating couplers are a viable method that gives greater tolerance in terms of aligning the fiber on the chip and positioning error thus making chip characterization easier [10], [11].

In this manuscript we discuss the design and optimization techniques of vertical grating coupler having both one and two dimensional grating structure. Various techniques to improve the coupling effeciency of the vertical grating coupler have been discussed such as such as use of bottom reflectors and innovating the structural design of the the gratings. The wavelength diversity and the limited bandwidth issue has been discussed and methods have been suggested to improve the performance of the vertical grating couplers [12]. Another issue that occurs with high refractive index contrast between the core and cladding of the silicon on insulator (SOI) waveguide is the birefringence in the photonic circuits which leads to significant polarisation sensitivity [13]. When light from optical fiber having random polarisation enters the polarisation sensitive photonic circuits, it results in serious performance degradation. The grating coupler design has been optimized such that it makes the circuit polarisation insensitive.

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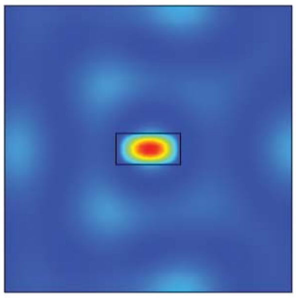

Fig. 1. Fundamental TE mode excitation in the waveguide

II. Grating Design

A grating structure is a periodic arrangement of certain material created by either etching or selectively depositing the material. In silicon photonics integrated circuits, its the silicon that is etched or deposited on silicon on insulator [14], [15]. The periodic variation in the structure results in variation in refractive index resulting in diffraction of optical signal. Optical signal is coupled in the direction variation of refractive index and thus the design of grating couplers are called one dimensional and two dimensional grating couplers depending on the number of directions in which the refractive index varies or the diffraction occurs. The working of a grating coupler can be understood using the concept of Bragg condition which gives the relation between the wave vector k_0 of the optical

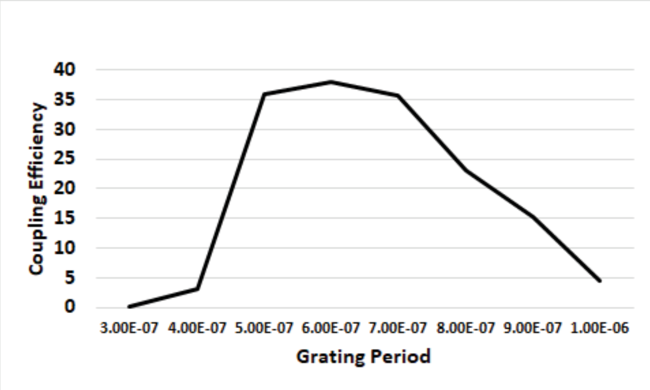

Fig. 2. Variation in Coupling Efficiency of one dimensional grating coupler with grating period from 300 nm to 1000 nm

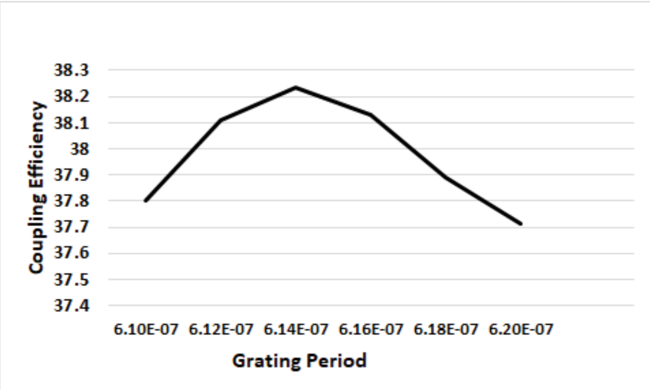

Fig. 3. Variation in Coupling Efficiency of one dimensional grating coupler with grating period from 610 nm to 620 nm

signal incident from the optical fiber and the propagation constant β of the signal propagating in the waveguide [14]. The Bragg condition is given as

$$n_eff - sin\theta_i = \frac{\lambda}{\Lambda} \tag{1}$$

where n_eff is the effective refractive index, θ_i is the angle of incidence, λ is wavelength of operation and Λ is the periodicity of the grating.

The coupling effeciency of the vertical grating coupler is defined as the fraction of power launched into the coupler that is coupled out to the fiber. The optical signal that enters the grating is partly reflected back, partly transmitted forward, partly leaked into the substrate and partly radiated from the grating coupler. An efficient coupler design is one that maximises the optical power radiated from the coupler and minimizes the reflected, transmitted and leaked component of the total power. It is the first order diffraction in the gratings that are radiated upward and the second order diffraction that are reflected backwards in to gratings. Using the Bragg's condition the diffraction order of the grating can be predicted. To minimise the second order diffraction and prevent back reflections, the gratings are detuned and the fiber is aligned at a small angle to the vertical. The power leaked to the

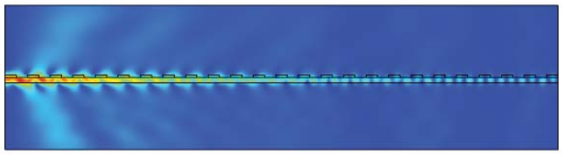

Fig. 4. Electric Field radiation from the vertical grating coupler for 614 nm grating period

substrate is minimized using the reflectors that reflected the leaked power back towards the grating surface. The grating coupler is designed using the Bragg's condition such that the effective refractive index of the grating satisfies the condition given in Equation (1). The grating consists of slab region and the etched region of width *w1* and *w2* , such that grating period $\Lambda = w1 + w1$. Thus, fill factor (*ff*) of the grating is defined as the fraction of the grating period that is slab region (not etched) or $ff = \frac{w1}{\Lambda}$. The effective refractive index of the grating is given as

$$n_eff = ff \times n_eff1 + (1 - ff) \times n_eff2 \tag{2}$$

where n_{eff1} is the refractive index of the slab region and n_{eff2} is the refractive index of the etched region of the grating period.

III. Results and Discussion

A vertical grating coupler in silicon on insulator platform has been simulated using COMSOL Multiphysics at 1550nm wavelength of operation. The grating coupler has a width of 15 μ m and length of 30 μ m and 25 grating teeth. The one dimensional grating was first optimised for the grating period and the fill factor. The width of the waveguide was 450 nm and height was 220 nm with etch of 70 nm for single mode excitation. Figure 1 shows the fundamental TE mode excitation in the waveguide.

The grating period was increased from 300 nm to 1000 nm with 50% fill factor and the coupling efficiency was calculated for the variation in grating period. As the grating period increased from 300 nm to 1000 nm the coupling efficiency increased initially from almost zero to approximately 37 percent for grating period of around 600 nm and thereafter decreased with further increase in grating period. So the coupling efficiency was further explored for variation of grating period from 610 nm to 620 nm. The graph again should an increase in coupling efficiency from 600 nm till 614 nm and then decreased further. Thus the maximum coupling of 38.23 $\%$ occurred at 614 nm grating period with 50 percent fill factor. Figure 2 and 3 shows the variation in coupling effeciency with grating period for the two conditions discussed above. Figure 4 shows the radiation from the grating coupler for 614 nm grating period with 50%

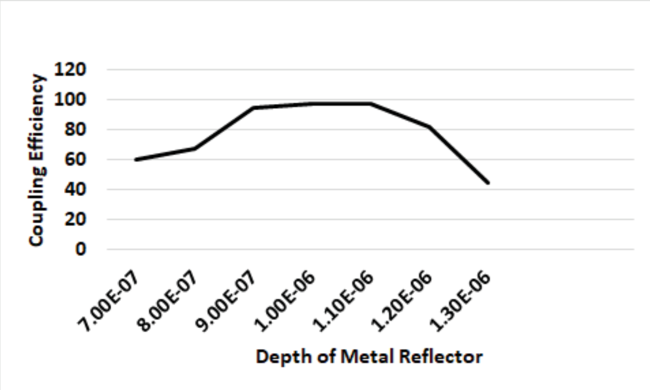

Fig. 5. Variation in Coupling Efficiency of one dimensional grating coupler with depth of Metal Reflector

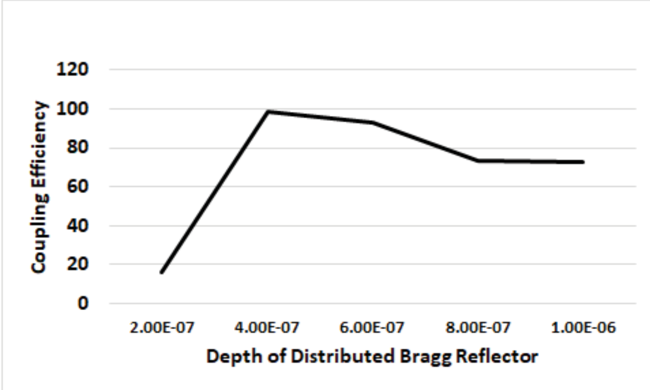

Fig. 6. Variation in Coupling Efficiency of one dimensional grating coupler with depth of Distributed Bragg Reflector

fill factor.

The coupling efficiency of the grating can be further improved by using reflectors at the bottom of the grating to reflect the downward radiated wave back towards the top of the grating so that the optical signal can be coupled with the optical fiber. Two types of bottom reflectors were explored to improve the coupling efficiency. One method was the use of metal reflectors and other was the use of Distributed Bragg reflector. When metal reflectors were used at the bottom of the grating coupler the coupling efficiency improved from 38.6 percent to almost 97 percent. Figure 5 shows the variation in coupling effeciency of the grating coupler with the variation in the depth of the metal reflector from 0.2 μ m to 2 μ m. It was observed that maximum coupling efficiency occurred at the depth of 1 μ m depth of the metal reflector. But depositing metal at while fabrication is a complicated process and hence the alternative method of use of Distributed Bragg Reflector was explored. In Distributed Bragg Reflector alternate layer of silicon and silicon dioxide was deposited in the bottom of the grating to improve the back reflections. Figure 6 shows the variation in coupling efficiency with depth of the Bragg reflector from the grating. It was observed that maximum coupling of approximately 98 percent occurred when the depth of the distributed Bragg reflector was approximately 0.4 [um] from the grating. Thus from the above analysis we can conclude that the coupling efficiency of the vertical grating coupler improved with the use of back reflectors. Though the fabrication of metal reflectors and distributed Bragg reflector are challenging process, nonetheless the increase in coupling efficiency is very high.

Once the grating coupler was optimised for one dimension then the periodic grating in two dimension was optimised for coupling efficiency. The grating period and the fill factor in both the dimensions varied to study the effect on grating period. Similarly metal reflectors and Distributed Bragg Reflectors were used to decrease the back reflections and improve the coupling efficiency of the two dimensional grating coupler. Figure 7 shows the field propagation in two dimensional grating coupler. There were nine and thirteen grating respectively in x and y directions. The grating period was 610 nm in both x and y directions with fifty percent fill factor.The coupling efficiency of 2D grating was investigated by varying the number of gratings and the grating period in x and y direction.

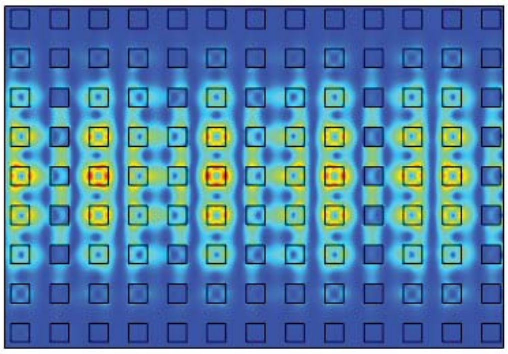

Fig. 7. Electric Field propagation in two dimensional grating coupler

When the grating number was increased in x direction it was found that the coupling efficiency increased initially and reached the maximum value for fifteen gratings and then decreased further. Similarly in y direction, coupling efficiency was maximum at fifteen gratings and then decreased thereafter. But another peak was observed for grating in y direction at twenty five gratings. Thus when number of grating is same in both x and y direction and equal to 15 the coupling efficiency is maximum. Another factor that was investigated was the grating period of the two dimensional grating. It was found that when the grating period was increased from 610 nm to 620 nm, coupling efficiency increased to approximately 70 percent for a grating period of 618 nm. The grating period was same in both x and y directions.

IV. Conclusion

A robust packaging scheme for silicon photonics integrated circuit is an essential requirement for making the product commercially successful. Thus packaging of silicon photonics IC has gained significant interest in recent times. Once a

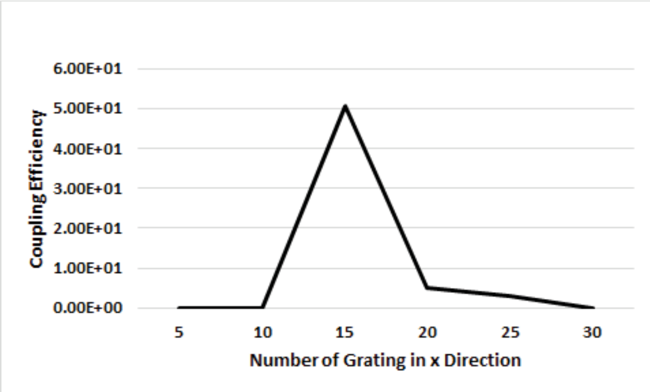

Fig. 8. Variation in Coupling Efficiency of two dimensional grating coupler with number of gratings in x direction

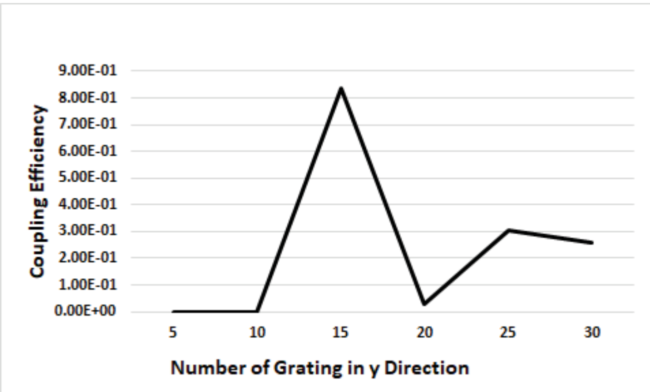

Fig. 9. Variation in Coupling Efficiency of two dimensional grating coupler with number of gratings in y direction

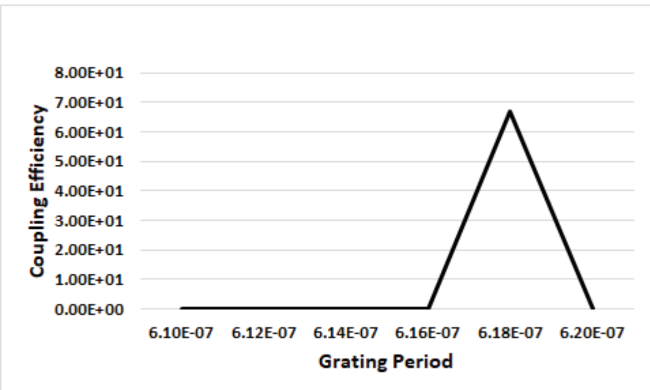

Fig. 10. Variation in Coupling Efficiency of two dimensional grating coupler with Grating Period

low cost and large scale packaging options are available for silicon photonics ICs then the technology will achieve its full potential. The packaging of photonic ICs is a much complicated process compared to electronic ICs because it requires precise alignment of fiber and large scale integration of optical components. The accurate alignment of fiber over the chip is challenging due to mismatch between the core and waveguide dimension. Thus grating couplers play an important role in solving this problem. This paper analyses the performance of one dimensional and two dimensional vertical grating couplers for grating period, back reflectors and number of gratings. The optimum solution has been suggested on the basis of the performance evaluation. The results would be useful in designing highly efficient vertical grating coupler for chip to fiber coupling.

Acknowledgment

The author would like to acknowledge SERB TARE Project No. TAR/2018/000227 for funding the work.

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