Si/SiO$_2$ Interlayer Coupler Based on Cylindrical Resonant Cavities

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***Abstract*—A grating-assisted-cylindrical-resonant-cavities (GARC) coupler consisting of three cavities and made of Si/SiO$_2$ is designed. An interlayer optical coupling efficiency of 71% for TE polarization at 1.55 μm is simulated.**

***Index Terms*—resonant cavity, circular grating, interlayer coupling, optical interconnect.**

I. INTRODUCTION

As emphasized by the Integrated Photonic Systems Roadmap International (IPSR-I) [1], [2], photonics are destined to have a central role in the high-density integration of silicon chips that are needed to meet the growing needs of high-speed computing, parallel image processing, 5G wireless communication, etc. 2.5D and 3D integration technologies are inherent in these future systems. Fully integrated photonics within these systems will enable denser and more complex designs without the problems of waveguide crossings and crosstalk. As more 2.5D/3D IC technologies are applied to the heterogeneous multi-die integration, a key barrier to energy-efficient computing and signal processing is the loss in interlayer optical connectors. 1D/2D rectangular gratings are potential candidates for these optical couplers because they can achieve relatively large interlayer distances and their planar geometries make them compatible with IC wafer-scale fabrication and testing. Methods to increase the single-grating diffraction efficiencies η_s of rectangular gratings include engineered materials and profiles [3], [4] as well as applying additional elements such as poly-Si overlayers, DBR or metal reflectors, apodized or chirped gratings, in-plane grating reflectors (see [5] and references therein), dual grating layers [6], and novel subwavelength structures [7]. Despite of all these efforts, relatively small grating periods ($\sim$ 100 nm for SOI gratings at 1.55 μm) need to be defined in order to achieve high diffraction efficiencies (η_s >70%), which requires relatively high-cost high-resolution fabrication techniques, such as e-beam lithography. The methods used to increase the directionality, e.g. applying reflectors or depositing overlayers, also add complexity to the fabrication process. Furthermore, rectangular grating couplers are sensitive to misalignment [8], which greatly impacts the cost and complexity of the assembly, integration, and packaging processes as well as the overall photonic interconnect performance.

In the present work, we propose a fundamentally different approach, the Si/SiO$_2$ grating-assisted-cylindrical-resonant-cavities (GARC) interlayer coupler, to achieve efficient interlayer coupling. The GARC coupler consists of a pair of circular gratings together with a high-index via. The via plays a significant role as a cylindrical resonant cavity in the vertical direction, and the outer circular gratings serve as distributed Bragg reflectors (DBR), forming another set of resonant cavities in the horizontal direction and enhancing the fields which are reinforced by the inner circular gratings. The fundamental principles that GARC couplers follow are constructive interference and evanescent coupling instead of the Floquet condition of rectangular gratings, and thus relatively wide grating ridges can be used and there is no need to incorporate adjacent-layer reflectors which would increase the fabrication cost. At 1.55 μm wavelength, the simulated coupling efficiency obtained from an optimized Si/SiO$_2$ GARC coupler (interlayer coupling efficiency is η_c = 71% or -1.5 dB, single-layer efficiency is η_s = 84% or -0.76 dB) are relatively high compared with those obtained from the conventional SOI rectangular gratings with adjacent-layer reflectors (e.g. η_s = 69% with reflectors, η_s = 50% without reflectors [9]). Perhaps the most significant benefit of the GARC coupler is the wide spectral bandwidth, e.g. 270 nm 1 dB bandwidth for the Si/SiO$_2$ GARC coupler, which can't be achieved by conventional rectangular gratings. Other advantages are the flexibility in choosing interlayer separations and the grating periods, which are based on the resonant condition of the cylindrical via and the interference condition in the circular waveguides, respectively. To the best of the authors' knowledge, this is the first treatment of combining cylindrical resonators in both horizontal and vertical direction to achieve interlayer optical coupling.

II. GARC INTERLAYER COUPLER MODEL

Figure 1 shows the structure in which relatively high-index waveguides and a via, made of Si, are configured to couple optical signals between layers otherwise separated by an air gap. The low-index layers, made of SiO$_2$, are sandwiched between the via and the grating layer, enclosing the resonant via cavity. The necessity of the via, which is used for evanescent coupling, and the definition of the circular gratings, which is based on the interference conditions, are explained in our previous work [5]. By setting the parameters $p = 2$, $s = 3$, and $t = 2$, the minimum groove width for the reported Si/SiO$_2$ GARC coupler is 414.5 nm (period 829 nm), which can be readily fabricated by photolithography. Wider grating grooves can also be chosen provided that the interference conditions explained in [5] are satisfied. The interlayer separation d, or the via height, is optimized as 2 μm, though other values are

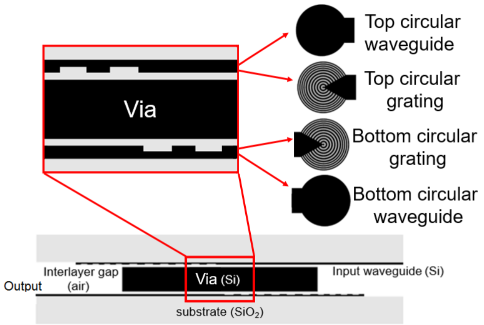

Fig. 1. Cross-sectional view of the compact GARC interlayer coupler. Inner and outer circular grating diameters are 14.08 μm and 20.72 μm, respectively.

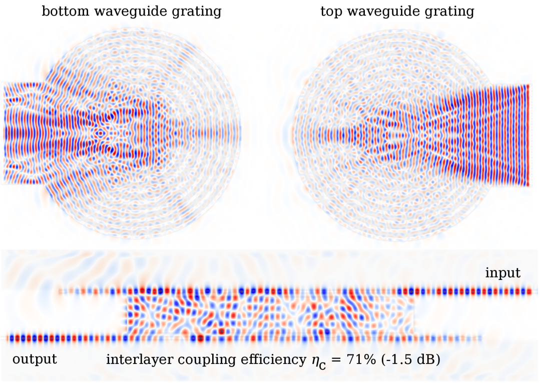

Fig. 2. Cross-sectional views of the H_z field distribution of top and bottom waveguide gratings as well as the vertical interlayer via (efficiency η_c = 71 % or -1.5 dB).

also possible provided the relation of d and the via radius R satisfies [10]

$$\lambda_{lm} = \frac{2\pi}{\sqrt{\left(\frac{\omega_l}{R}\right)^2 + \left(\frac{m\pi}{d}\right)^2}}, \tag{1}$$

where l and m indicate the resonant mode order in the radial and longitudinal directions, respectively, $\lambda_{lm} = 0.5526\ \mu m$ is the wavelength in the radial direction in the via, and ω_l is the lth zero of the 1st-order Bessel function derivative $J_1'(x)$. The combination $R = 7.04\ \mu m$ and $d = 2\ \mu m$ result in the $(l = 26,\ m = 5)$ resonance.

The cross-sectional H_z field patterns are shown in Fig. 2. A TE-polarized (E_r, E_θ, H_z) optical signal is launched from the top waveguide and 71% of that power is coupled into the bottom waveguide. The field pattern exhibits inversion symmetry about the via center which produces reciprocal top-to-bottom and bottom-to-top performance. The spectral response of the designed structure is shown in Fig. 3. The 1 dB bandwidth is about 270 nm, which is much wider than that of conventional SOI gratings, e.g. 40 nm bandwidth at 1 dB [9]. The oscillations in the single-layer and interlayer curves are apparently due to constructive and destructive interference effects. The efficiency eventually decreases at wavelengths much different from the design wavelength (1.55 μm). Rotational misalignments are less likely to occur due to the presence of the via which provides a mechanical support between layers.

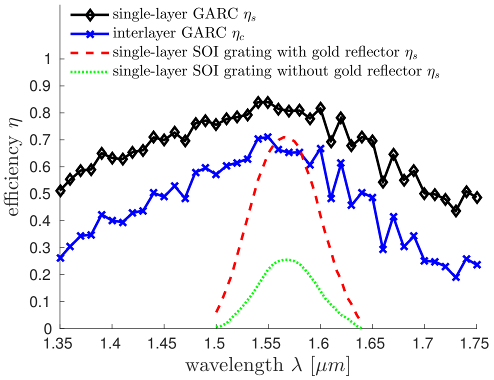

Fig. 3. Spectral response showing the broadband characterisitc of the Si/SiO$_2$ GARC coupler; for comparison, the rectangular gratings reported in [9] show much narrower bandwidth.

III. CONCLUSION

A vertical interlayer coupling structure (GARC) that uses circular gratings and a high-index via has been designed. A Si/SiO$_2$ GARC coupler is optimized to achieve 71% interlayer coupling efficiency (84% single-layer efficiency). The coupling structure is broadband (270 nm 1dB bandwidth), compact (20 μm in diameter), reciprocal, CMOS compatible, and relatively straightforward to fabricate due to the wide grating grooves and the absence of adjacent-layer reflectors.

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