Design of SiON-based grating-assisted vertical directional couplers

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Abstract: In this paper, we present the design of a SiON-based grating-assisted codirectional coupler for dissimilar waveguides, based on an accurate numerical method. All the design parameters, including coupling length and coupling efficiency, have been calculated at the free-space optical wavelength of λ =1.54 μm for both TE and TM polarisations as a function of grating height, thickness of the coupled slabs, gap thickness between the two coupled planar waveguides. It is shown that efficient (up to 70%) and polarisation independent vertical couplers can be realised.

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1. Introduction

Among the available integrated optical technologies that can be used to fabricate a number of functional guided-wave devices and circuits in optical telecommunications and optical signal processing systems, those based on high-index planar waveguides can achieve high performance, low cost and can be fabricated using standard fabrication processes. In

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particular, using silicon oxynitride (SiON) waveguides, active thermo-optic effect–based devices, arrayed waveguide gratings, high performance filters and other conventional passive optical components can be fabricated in a more compact and versatile way [1, 2].

Grating-assisted directional couplers (GADC) are basic guided-wave components for a number of applications, such as distributed feedback (DFB) and distributed Bragg reflector (DBR) lasing, optical wavelength filtering [3], wavelength division multiplexing, coupling between optical fibres and thin silicon waveguides [4], coupling between different planar waveguides etc.

In this work, the design criteria of GADC structures at the free-space optical wavelength λ =1.54 μm have been discussed by using a rigorous approach of the Floquet-Bloch theory (FBT) [5]. The method allows us to calculate, with high accuracy, all design parameters of the GADC, including the coupling length, coupling efficiency, power attenuation coefficient and total radiation loss, as a function of the gap thickness, grating depth, thickness of the coupled slabs, grating profile etc. It is well known that the FBT is more accurate than the coupled-mode theory (CMT) or the transfer matrix method (TMM) [6], especially for deeper gratings.

The design procedure has been applied to the vertical coupling between two planar silicon oxynitride waveguides. The silicon substrate is becoming a very attractive material for integrated optics because of its good quality and low attenuation losses. SiON films grown on a SiO_2 buffer layer over the Si substrate have been considered as a technological solution because of their high versatility, full compatibility with optical fibre technology and low propagation loss (0.2 dB/cm) [7].

2. GADC structure

The use of GADC to achieve efficient and polarization insensitive power coupling between SiON dissimilar waveguides can be suggested in many important applications. Vertical coupler filters, optical clock distribution in electronic systems, optical interconnections, vertically coupled passive or active ring resonators, vertical coupling wavelength multiplexer/demultiplexer are significant examples where high efficiency SiON-based GADC can find application. Another example can be an integrated optical architecture depicted in Fig. 1, where an optical fibre needs to be coupled to a photodetector with high efficiency through a planar optical waveguide.

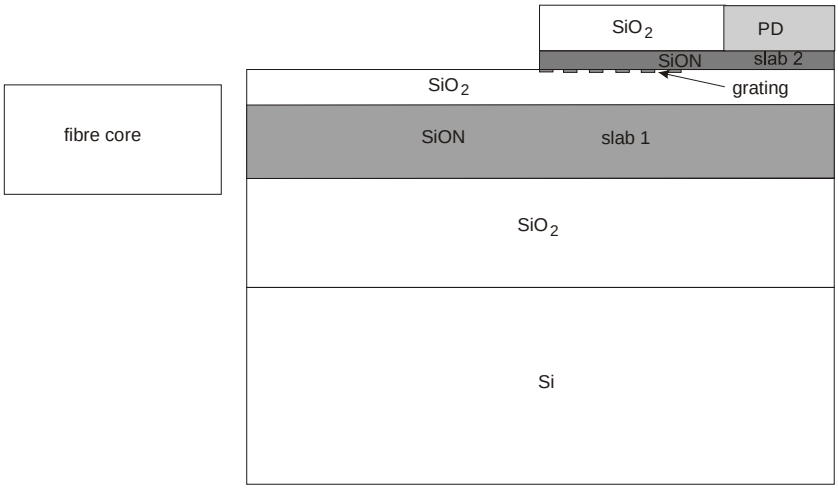

Fig. 1. GADC used for fibre-photodetector coupling in an integrated optical architecture.

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To this aim, a GADC structure can be used, in which the lower slab (slab 1) is coupled to the fibre, and the upper one (slab 2) to the photodetector (PD).

In Fig. 2 the main parameters of the calculated GADC structure are shown. The lower SiON slab has thickness d_1 and refractive index n_1. The analogous parameters for the upper slab are d_2 and n_2. In all calculations, we have used n_1 =1.47 (allowing low insertion loss for coupling with optical fibres), d_2 = 2 μm, and n_2 = 1.51. The mono-modal condition [8] for each slab gives thicknesses of d_1 < 5.37 μm and d_2 < 2.08 μm at the wavelength of 1.54 μm. The other layers are all formed by SiO_2 with the refractive index of n = 1.463. We have already shown that the refractive index of SiON can be accurately tuned within this range using PECVD [9]. For example, parameters for the PECVD deposition of SiON layer with the refractive index of n = 1.470 are: SiH_4/N_2 gas flow = 155 sccm (standard cubic centimetre), NH_3 gas flow = 50 sccm, N_2O gas flow = 800 sccm, p = 1 Torr, T = 300 °C, P = 15 W. The geometrical and optical parameters of the structure are chosen, without any lack of generality, such to have only two leaky guided modes. This choice is similar to the TMM approach, in which only two local normal modes are considered at each grating section [6].

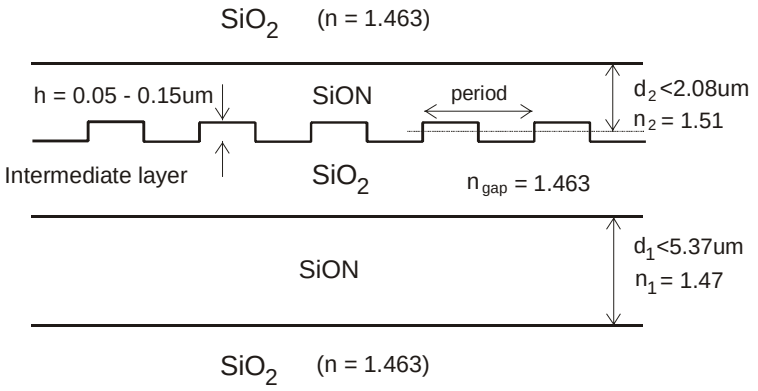

Fig. 2. Main parameters of SiON-based GADC.

The grating period Λ depends on the effective index difference between the two leaky guided modes (*A, B*) which exchange optical power along direction of propagation. It can be calculated by the FBT under the resonance condition as:

$$\Lambda = \frac{2\pi}{\min\left|\beta_A - \beta_B - 2\pi / \Lambda\right|} \tag{1}$$

where β_A, β_B are the propagation constants of the two modes, calculated in the presence of the grating. A good estimation of Λ can be also found by CMT only if the grating depth is small with respect to the slab thicknesses, as:

$$\Lambda = \lambda / \left[n_{eff}^{(even)} - n_{eff}^{(odd)} \right] \tag{2}$$

where $n_{eff}^{(even)}$ and $n_{eff}^{(odd)}$ are the effective indices of the even and odd modes of the unperturbed structure, respectively. A number of calculations in this paper have been carried out by considering FBT approach by using 23 space harmonics and double precision complex algorithms. The effective index difference between the perturbed GADC structure and the unperturbed structure (SiON layers without grating) was always <0.25 % giving very low theoretical insertion loss (<0.07 dB for TE and <0.06 for TM) at the interface between these

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two structures (i.e. structures with and without gratings). No significant difference has been found by comparing the FBT results with TMM predictions, as the grating depth is rather small (0.05 ÷ 0.15 μm). The rectangular grating profile with a 50% duty cycle has been considered. The bandwidth of the GADC, working as a filter, has been evaluated by CMT as:

$$\frac{\Delta\lambda}{\lambda_o} = 0.8\frac{\Lambda}{L}\Bigg/\left[1-\Lambda\frac{\partial\Delta N(\lambda)}{\partial\lambda}\bigg|_{\lambda=\lambda_o}\right] \tag{3}$$

where L is the coupling length, ΔN is the effective index change and the index dispersion has not been taken into account because it is negligible.

3. Numerical results

In Fig. 3 the coupling efficiency is shown as a function of the gap thickness for different grating depths (from 50 to 150 nm) and polarizations (TE, TM), and for d_1 = 3 μm. It can be seen that the best coupling condition occurs at mid range depths (0.1 μm) for gap thickness ≈ 2.5 μm.

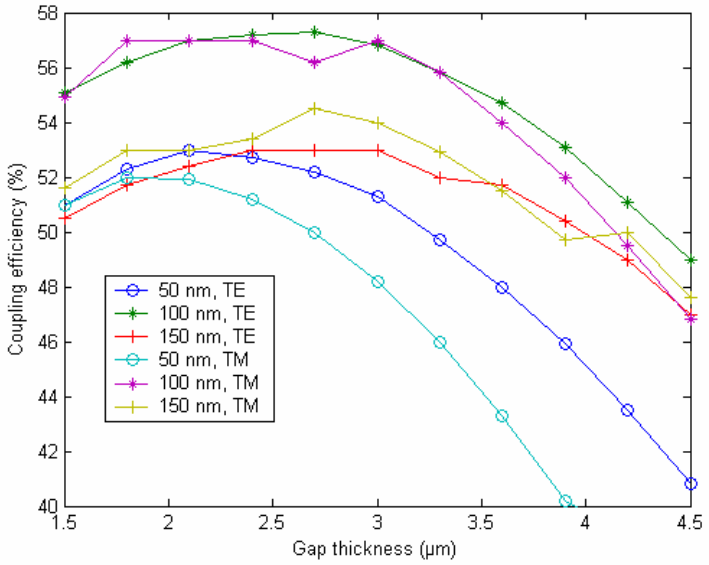

Fig. 3. Coupling efficiency versus gap thickness for d_1= 3μm.

Figure 4 shows the coupling length for the same parameters. It increases for larger gap thicknesses with a parabolic law, because the power transfer becomes less efficient by increasing the separation between the two slabs. However, deeper gratings can significantly reduce the coupling length (Fig. 4). In Fig. 5, the resonance grating period is shown as a function of the gap thickness. Its value is relatively constant, Λ_{TE} ≈ 56.4 μm and Λ_{TM} ≈ 57.8 μm for TE and TM polarisation, respectively. It is important to note that the dependence on grating depth is not significant. For the average grating period of ≈ (Λ_{TE} + Λ_{TM})/2 it would be so possible to obtain polarisation independent devices at the expense of some reduction of the coupling efficiency, however less than 10%.

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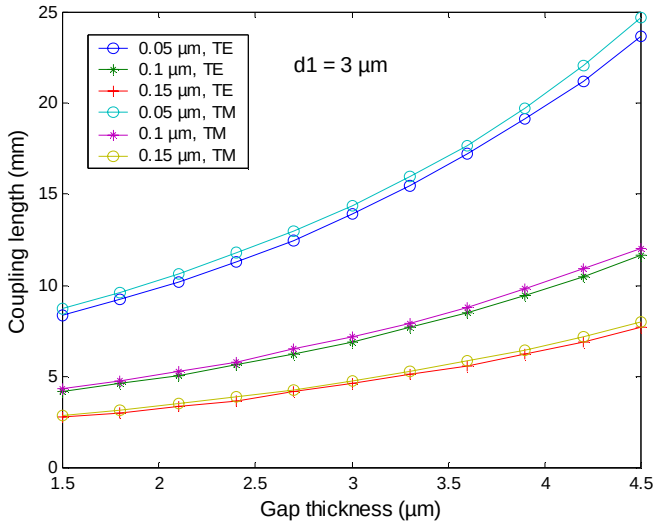

Fig. 4. Coupling length versus gap thickness.

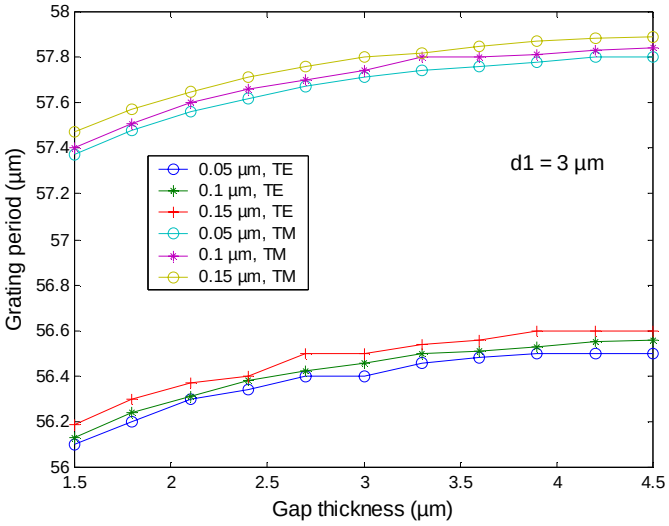

Fig. 5. Grating period versus gap thickness for various grating depths.

When we consider the coupling efficiency/length ratio versus the gap thickness, as in Fig. 6, we see that deeper gratings (0.15 µm) are to be chosen to optimize the GADC length without a significant decrease of efficiency. However, fast decrease of the ratio with respect to the gap thickness is revealed for increasing grating depth.

The influence of the lower slab thickness (d_1) has also been investigated (Fig. 7). Assuming a grating 0.15 µm deep, the best efficiencies are obtained by using large slab 1

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thickness and reduced gap thickness (2 μm). It is important to note the behavior of TE and TM polarisations is very similar in these SiON-based structures, although usually any grating-based component is strongly polarization-dependent.

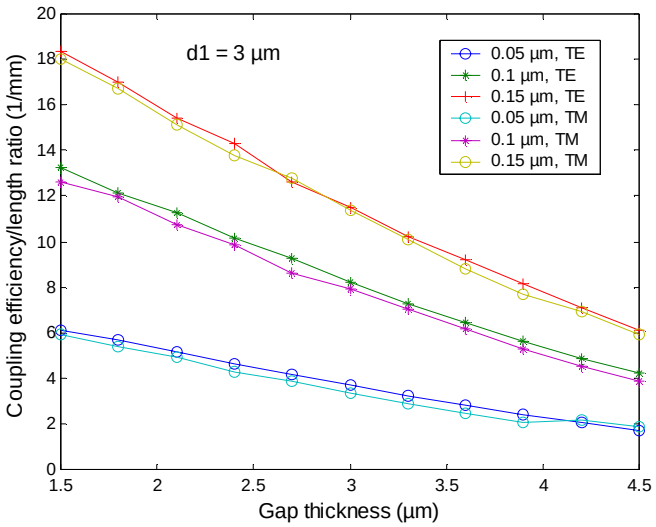

Fig. 6. Coupling efficiency/length ratio versus gap thickness.

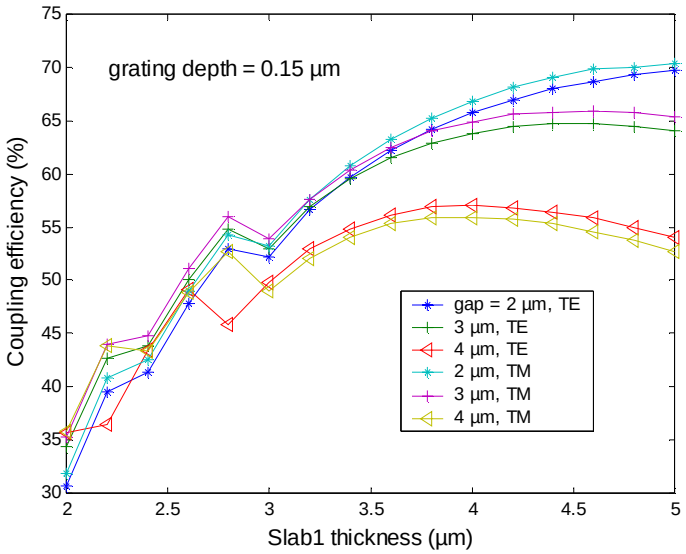

Fig. 7. Coupling efficiency versus slab 1 thickness.

In Fig. 8 the coupling length is depicted versus the slab 1 thickness. Similar to its dependence on the gap thickness, the behaviour is again parabolic, and a small gap must be chosen for minimizing the length. The resonance grating period is shown in Fig. 9 by changing the slab 1 thickness. The period significantly depends on the slab thickness

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according to a quasi-linear dependence. Figure 10, which shows the coupling efficiency/length ratio versus the slab 1 thickness, confirms that small gaps are preferred for the optimization of the GADC performance.

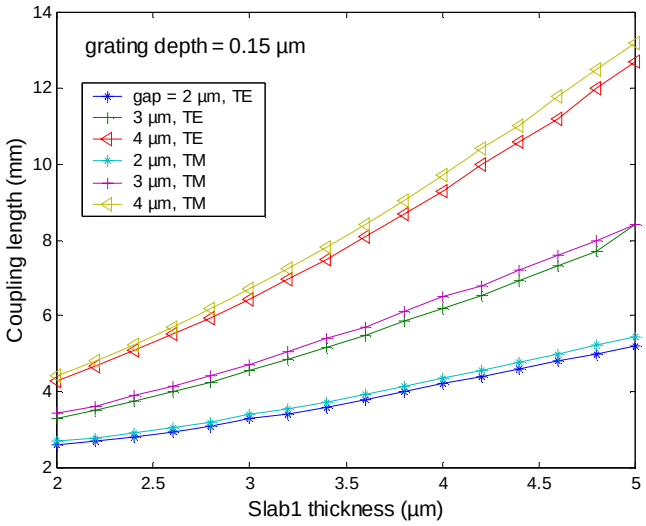

Fig. 8. Coupling length versus slab 1 thickness.

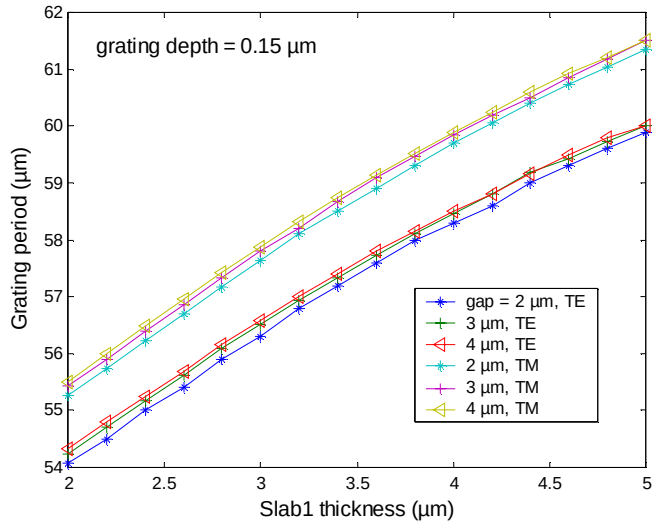

Fig. 9. Resonance grating period versus slab 1 thickness.

Fabrication tolerances have been also evaluated. We have considered some changes of slab 1 and slab 2 refractive indices and calculated the corresponding changes in coupling efficiency and length. Results are summarized in Tables 1 and 2. They demonstrate that slab 1 index (n_1) changes (up to 0.2%) have a strong influence on both the efficiency (up to 20%)

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and length (up to 26%), while slab 2 (upper slab with grating) index has a more moderate influence (up to 15% and 13%, respectively). However, we have already shown [9] that this refractive index tolerance can be kept within the ± 0.05% range.

Table 1. Fabrication tolerances for slab 1 index.

Slab 1 index relative change	Coupling efficiency relative change	Coupling length relative change
+ 0.05%	+ 6%	+ 6%
- 0.05%	- 4%	- 6%
+ 0.1%	+ 11%	+ 12%
- 0.1%	- 20%	- 11%
+ 0.2%	+ 16%	+ 26%
- 0.2%	- 34%	- 20%

Table 2. Fabrication tolerances for slab 2 index

Slab 2 index relative change	Coupling efficiency relative change	Coupling length relative change
+ 0.05%	~ 0	~ 0
- 0.05%	~ 0	~ 0
+ 0.1%	+ 2%	+ 7%
- 0.1%	- 1%	- 7%
+ 0.2%	+ 4%	+ 13%
- 0.2%	- 15%	- 2%

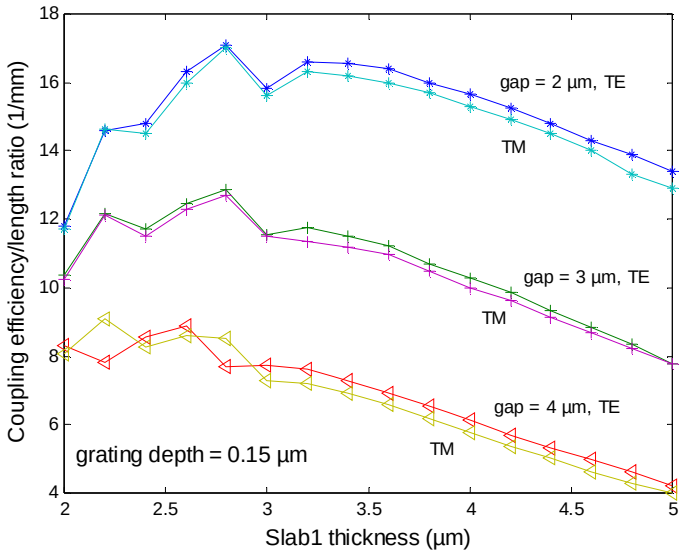

Fig. 10. Coupling efficiency/length ratio versus slab 1 thickness.

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4. Conclusion

In this paper the dependence of the SiON-based GADC performance on the design parameters has been investigated. Thicker SiON input waveguides (≈ 5 μm) are preferable because of the increase in coupling efficiency and reduction of the insertion loss for a butt coupling with optical fibres. On the other hand, the gap thickness should be around 2 μm to increase the coupling efficiency and reduce the coupling length, and consequently propagation losses. Maximum coupling efficiency of 70% can be achieved for coupling to 2 μm thick SiON waveguide and as the optimum grating periods for TE and TM polarisations are very similar, polarization independent devices can be realized for a large number of applications.

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