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Polarization analysis of antireflection coating for SOS material system

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Abstract: Using CAD tool Essential Macleod, MATLAB and Optimac-investigation is done on an antireflection coating for SOS material system. Here the polarization (TE & TM) effect of antireflection coating for SOS material system is mainly analyzed. No coating, single layer coating, optimized single layer coating and finally multilayer coating are used to investigate the polarization effect. It is observed that the mean transmission of 96.56%, 98.74% and 99.99% obtained for no coating, single layer coating and multilayer coating of a SOS material system respectively.

Keywords: Anti Reflection Coating, Silica on Silicon, TM, TE, Polarization

1. Introduction

Reflection is the optical phenomenon, which is born out of a transition in the medium, in which light is travelling. Any optical medium is characterized by the parameter known as refractive index (n) and quantifies the speed of light in the current medium with respect to that in vacuum. Normally a fraction of incident light reflected from the interface of an optical medium is measured by reflectance, and the rest transmitted (refracted) is measured by transmittance. The mathematical model to calculate the refractive index of a thin film is [1]-

$$n_{AR} = \sqrt{n_1 n_2}$$
$$physical\ thickness = \frac{1}{4} \cdot \frac{\lambda}{n_{AR}} \qquad (1)$$

Where, n_{AR} is the refractive index of the thin film, n_1 & n_2 are the refractive index of the related two mediums and λ is the wavelength of the light.

The first material system applied for fabricating commercial photonic integrated circuits for telecom applications on silicon was silica. Thanks to the very low loss of straight waveguides (0.03dB/cm) at a wavelength of λ= 1550 nm. The downside of this material system however is the low refractive index contrast of this material which implies huge bends.

To fabricate a waveguide in silica on silicon (Fig.1) is done by heavily doping a SiO_2 layer with germanium. This results a refractive index difference of about 0.75% with the undoped SiO_2. A waveguide is defined in the doped SiO_2 through an etching process, and afterwards an

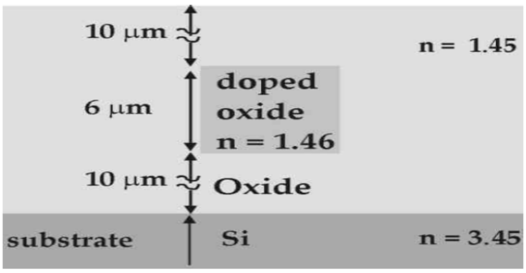

Figure 1. *Cross-section of a waveguide fabricated in silica on silicon.*

undoped SiO_2 cladding layer is deposited. Anti reflection coatings (ARC) are designed for different purposes [2], but here we considered the analysis to get a general polarization characteristic of the ARC.

We analyzed the transmission of the guided mode of the waveguide structure through the interface between the photonic integrated circuit and its surrounding medium (air). We wanted to maximize the transmission, to achieve this we used a single-layer coating, which we then optimized and finally we designed a multi-layer coating with the aid of the CAD tool Essential Macleod. We analyzed the transmission for Silica on Silicon (SOS) material system. In Essential Macleod we can only calculate the transmission through a stack of homogeneous layers [3],[4] so we modelled the cross section of the waveguide structure by one single number, the effective index n_{eff} of the guided mode of the structure. The transmittance can be increased using the ARC as explained in [8].

2. Simulation

By using the CAD software we can calculate the transmission of plane wave incident at an arbitrary angle. But the guided modes of the waveguide structures are approximated by Gaussian beam. The properties of this Gaussian beam are given in Table I. We solved this problem by decomposing the Gaussian beam into its plane wave components using the spatial Fourier Transform, calculating the transmission for each of these components. Afterwards using the inverse Fourier transform we obtain the transmitted beam.

Table 1. *Dimensions of the Gaussian field profile.*

Material System	λ_0 [μm]	σ_x [μm]	σ_y [μm]	n (n_{eff})
Silica on Silicon (SOS)	1.55	3.63	3.63	1.455

In Essential Macleod we calculated the transmission through a layer stack. This was built up of a semi-infinite substrate layer (in this case the waveguide), a number of thin films and another semi-infinite medium (in this case air). The thickness of each layer can be set by a physical thickness and by an optical thickness. The optical thickness is related with the wavelength and refractive index as-

$$\text{Optical thickness} = (\text{Physical thickness})/(\lambda/n) \quad (2)$$

3. Findings & Analysis

3.1. Without Coating

First we considered the transmission of light for the SOS material system without any AR coating. This transmission was conducted to consider it as the reference. The input field amplitude is shown in Fig. 3. This input field was used throughout the whole simulation, so that we can compare among all the results easily and effectively. Fig.4 represents the mean output field amplitude.

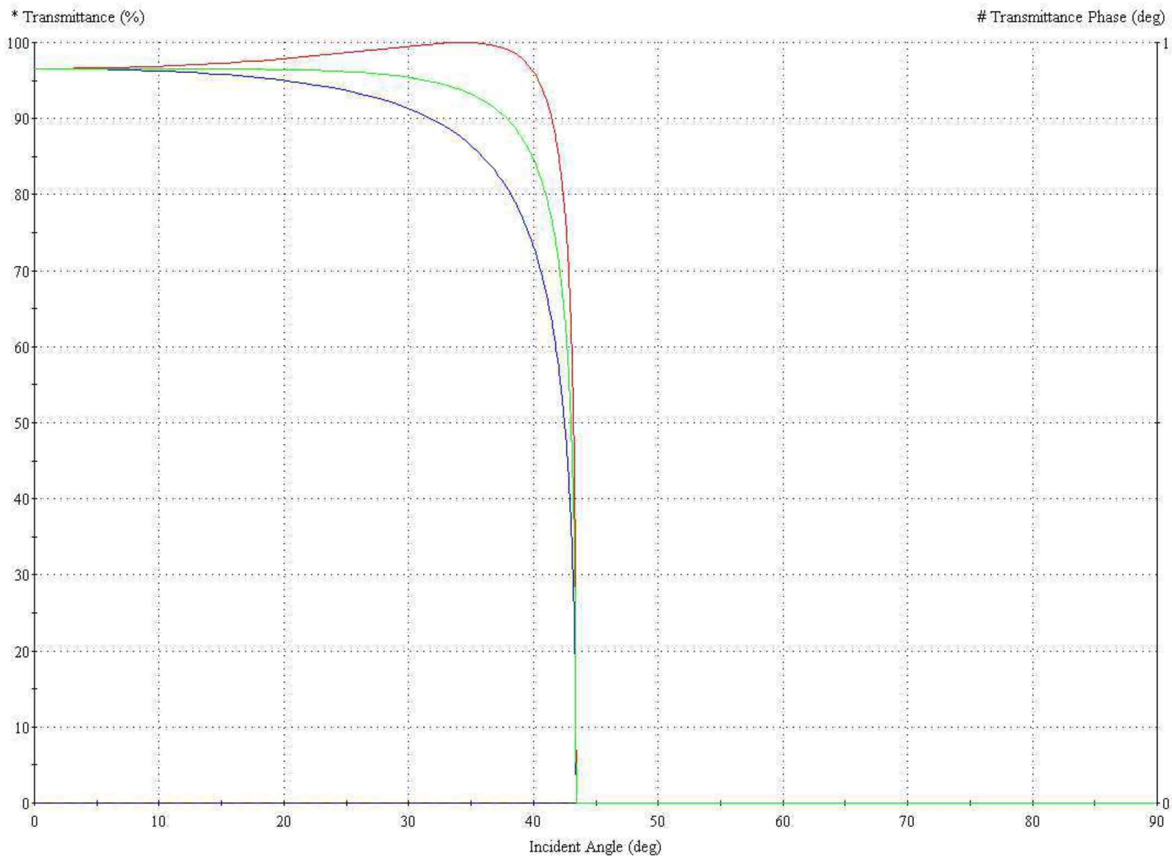

Figure 2. *Transmission for all polarisations when there is no coating: magnitude (solid lines) and phase (dashed lines). TM: Red, TE: Blue, Mean: Green. As there is no phase change so the dashed lines coincides with the incident angle axis.*

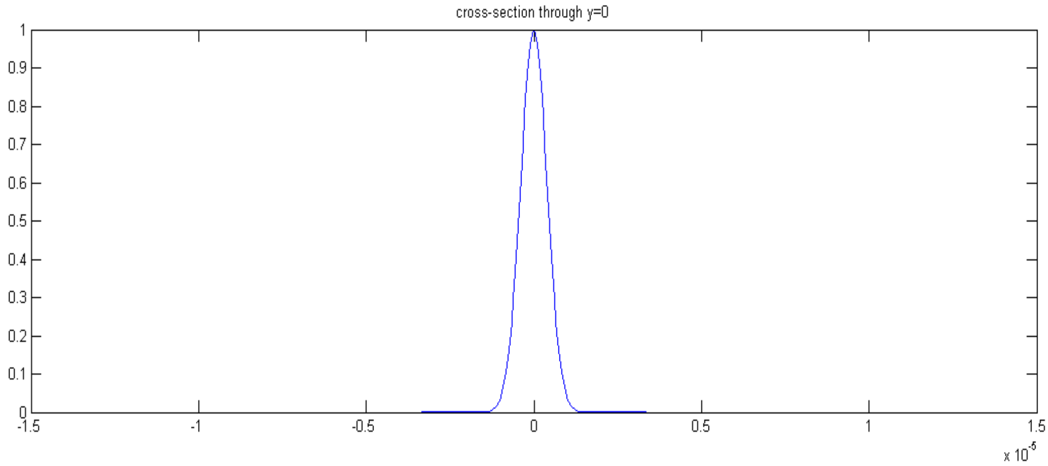

Figure 3. *Input field amplitude (cross-section through y=0, assuming arbitrary units along x and y axis).*

Without any coating the critical angle was found as 43.42^0. Angle consideration of ARC for the telecom wavelength can be found in [10]. It is clear from the Fig.2 that there is no transmission above the critical angle. We also noticed, there is 100% transmission for TM-polarisation at Brewster angle [11]. i.e.-

$$Brewster\ angle = \tan^{-1}\left(\frac{1}{1.455}\right) = 34.50^o \quad (3)$$

It is observed that the calculated and the simulated Brewster angle is the same. Next we considered the transmission for incident angle = 0° (perpendicular incidence):

$$r = \frac{n_{eff} - 1}{n_{eff} + 1} = 0.19$$
$$T = 1 - R = 1 - r^2 = 97\% \quad (4)$$

So the transmission for perpendicular incidence was 97% and this also matched with the simulated result as shown in Fig.2. In this case the phase is zero everywhere in the Fig.2. There was no coating so no phase shift occurred for the transmission. This results no interference. Because of the Brewster angle the TE-transmission is slightly lower than TM-transmission but has similar amplitude profile. No interference fringes around the edges of the Gaussian beam were observed because the beam width was large compared to the wavelength.

Global transmission was calculated using the Table-1 parameters and MATLAB simulator.

Global *transmission:*

TM Polarized light	TE Polarized light	Mean
96.5871	96.5428	96.5650

As expected, the mean value is slightly lower than the value for perpendicular incidence because the Gaussian beam has also plane wave components with a more oblique incidence (referring to Fig.2).

3.2. Single Layer Coating

Using (1) we can get the theoretical values for single layer coating:

$$n_{AR} = \sqrt{1.455} = 1.206 \quad (5)$$

We considered a material with n close to this value- Na_3AlF_6: n' = 1.35; n'' = 0 (n' for real; n'' for imaginary)

Results from the simulation were as follows-

Critical angle when $\theta_{air} = 90°$ or $\theta_{AR} = 90°$:

$$\theta_{SOScrit} = \min\left\{\arcsin\left(\frac{n_{air}}{n_{SOS}}\right), \arcsin\left(\frac{n_{AR}}{n_{SOS}}\right)\right\} = \arcsin\left(\frac{n_{air}}{n_{SOS}}\right) = 43.42^o \quad (6)$$

Phase change was different for TE & TM polarization. The phase change is observed due to the interference of the different plane wave components of the Gaussian beam. This results a lower transmission.

TM-transmission was slightly higher than the TE-transmission because of smaller phase shift for TM than for TE (referring to Fig.5). i.e. less interference of the plane waves.

Global *transmission:*

TM Polarized light	TE Polarized light	Mean
98.7524	98.7329	98.7427

These transmission values are better than the ones for silicon on insulator (SOI) [5]. This is because the beam width of the Gaussian beam relatively larger compared to the wavelength, which results the plane wave decomposition spread out. The critical angle was also much larger than for SOI. So less plane wave components were completely lost. Single layer reflectance can also be calculated using [6] for comparison purposes. The result shown in Fig.5 can be compared with the reflectance in [7][12].

3.3. Optimized Single Layer Coating

We optimized the transmission through the coating by changing the thickness of the layer using Simplex. The optimization leads to a thickness very close to the theoretical value, and there was no difference in the transmission values of the Gaussian beam.

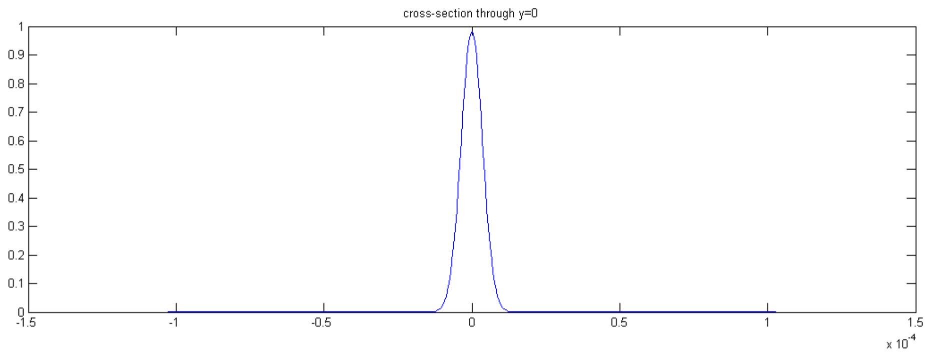

Figure 4. *Mean output field amplitude (cross-section through y=0, assuming arbitrary units along x and y axis).*

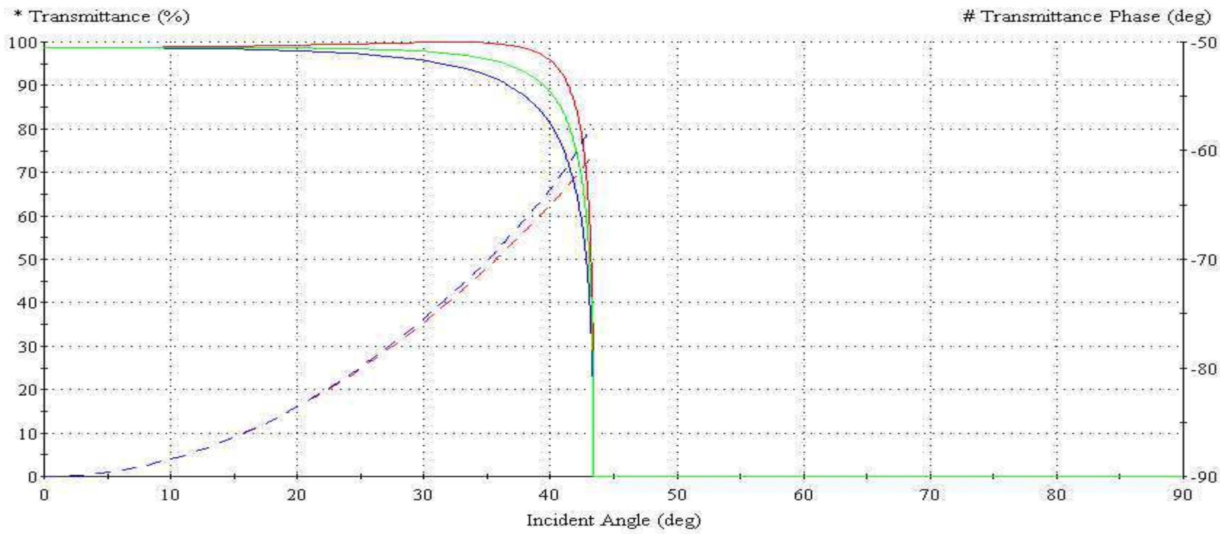

Figure 5. *Transmission for all polarisations for a 1 layer coating: magnitude (solid lines) and phase (dashed lines). TM: Red, TE: Blue, Mean: Green.*

Table 2. *Multilayer coating design parameters for SOS.*

Layer	Material	Refractive Index	Extinction Coefficient	Optical Thickness	Physical Thickness (nm)
Medium	SOS	1.45500	0.00000	-	-
1	Na_3AlF_6	1.35000	0.00000	0.23865533	274.01
2	MgF_2	1.37600	0.00000	0.04876160	54.93
3	Al_2O_3	1.64974	0.00000	0.08543824	80.27
4	MgF_2	1.37600	0.00000	0.11674291	131.51
5	Na_3AlF_6	1.35000	0.00000	0.23325150	267.81
Substrate	Air	1.00000	0.00000	-	-
-	-	-	0.00000	0.72284958	808.52

Incident Angle: 0^0; Reference Wavelength: 1550 nm

3.4. Multilayer Coating

Next we optimized the transmission with multiple layers (maximum 5) using Optimac. We did not use metals in the coating because metal absorbs the field, nor do we use water because it is impossible to fabricate a liquid coating. We set the targets to a wavelength of 1550 nm, and 100% transmission for 0°-10° angle. Design details are given in Table 2. There was almost no reflection of the Gaussian beam when we used this coating. The wave characteristics in multilayered structure can be analyzed using [9].

Global *transmission:*

TM Polarized light	TE Polarized light	Mean
99.9952	99.9947	99.9949

4. Conclusion

Results in general are better for SOS because the refractive index contrast is lower than for SOI. We expected a better performance of the multilayer coating compared to the single layer coating. For SOS this is true, for SOI however, the optimized single layer coating gave the best result. The mean transmission 2.1777% and 3.4299% are increased by using single layer and multilayer coating respectively using SOS material system comparing with the reference (without coating).

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