Effect of multilayer substrate interference in planar waveguide scattering loss

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Introduction

Scattering loss due to a nanoscale interface roughness has been an unavoidable effect limiting planar waveguide performance, especially when the evanescent field at the core-cladding interfaces is strong, such as in waveguide-based sensors. Extensive theoretical work has been carried out to quantitively understand the scattering loss, among which Payne's approach [1] has been widely accepted. Following this work, Schmid et al [2] proved that the scattering loss is changed by interference between the two interfaces of a planar waveguide to a great extent, which is omitted in Payne's model. Since the loss can be significantly reduced due to interference, we have developed a theoretical model for scattering loss that takes account of the multilayer interference effect by extending Schmid's model. We have also fabricated a number of different Ta_2O_5 planar waveguides of different thicknesses deposited on Si wafers and compared the measured propagation loss to theory, showing a very good agreement.

Model and experiment

The analytical expression for scattering loss from TE modes is given as [2]

$$\alpha_{TE} = \frac{k_0^3}{4\pi n_{\text{eff}}}\left(n_2^2 - n_1^2\right)^2 \left(\mathrm{E}_0^x\right)^2 \int_0^\pi \left[\left(1 + r_s(\theta)\right)^2 + t_s^2(\theta)\right] \tilde{R}\left(\beta - n_2 k_0 \cos\theta\right) \mathrm{d}\theta$$

where E_0^x is the normalized TE mode modal field at the interface, n_{eff} is the effective refractive index of the waveguide mode, r_s and t_s are the total reflectivity and transmittance of the complete three-layer structure, $n_{2/1}$ is the refractive index of cladding/core. $\tilde{R}$ is the correlation function of the roughness and is proportional to the mean square of the surface fluctuation, σ^2. The expression for TM modes has a similar but more complicated form than TE and is also given by Schmid [2]. In our work, the transfer matrix method [3] is incorporated to calculate the r_s and t_s for waveguides with multilayer substrate.

To experimentally validate the model, Ta_2O_5 thin films with different thicknesses are deposited on silicon wafers as the waveguide core. The silicon wafer has a $2\mu m$ oxidized layer, so the planar waveguides are four-layer structures of cladding - Ta_2O_5 core- SiO_2- Si. Compared to the standard three-layer waveguide, the extra SiO_2/Si interface provides extra reflection, which has to be taken into account. The theoretical and experimental results are shown in Fig. 1. The theoretical values are calculated for a mean-square-roughness of one nanometer and the experimental values are normalized to the measured mean square of the surface fluctuation. In Fig. 1(a), by comparing Payne's and Schmid's model in the three-layer waveguide it is shown that the interference effects reduce the scattering loss significantly. In Fig. 1(b), the loss coefficients for the four-layer structure are calculated with our extended model and agree well with the experimental results. It is shown that the additional SiO_2/Si interface, while not affecting the field distribution of the guided modes, has a positive effect on the scattering loss. The experimental results have proven the accuracy of our extended model and imply that scattering loss could be reduced even further via interference effects in a purpose-designed multilayer substrate.

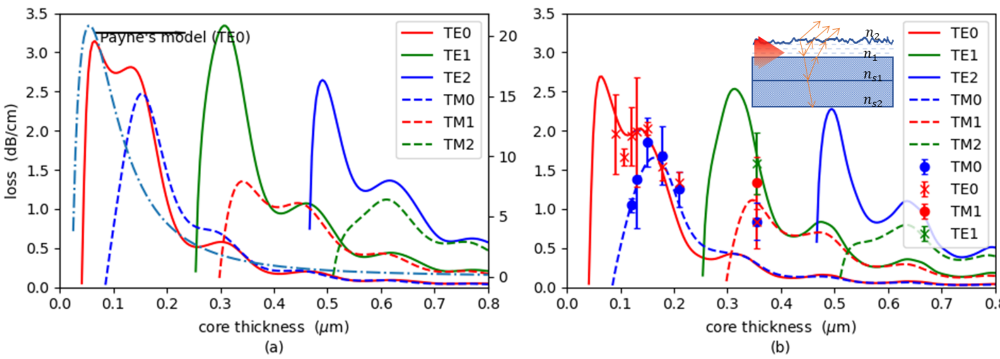

Fig. 1 Theoretical scattering loss coefficient for (a) three-layer air - Ta_2O_5 core - SiO_2, planar waveguide (the dash-dot line is scattering loss from Payne's model that omits the interference effect – plotted on the right Y-axis). (b) four-layer structure and the experimental results (the silica substrate layer is 2μm thick). The operation wavelength is 633nm.

References

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