Mode analysis modeling of optical waveguide scattering losses

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1. Abstract

In this work, we investigate a method for modelling scattering losses in optical waveguides using absorption layers in Finite Difference Method (FDM) mode analysis simulations. To test the model we compare calculated losses to experimental results using a practical geometry: pedestal Anti-resonant Optical Waveguides (ARROWs).

Pedestal waveguides have the property that no etching of the core material is required, which makes it less prone to scattering losses. For this reason, novel materials that would be difficult to etch using conventional microelectronics techniques are feasible with the pedestal process.

2. Introduction

In waveguides fabricated with planar technology the main source of propagation loss is scattering in the etched sidewalls due to transfer of roughness of the masking material during the etching process. This problem is so evident that many solutions have been proposed such as resist reflow and using alternative processes where the waveguides sidewalls are defined in such a way that the light propagating through the waveguide's core is not directly in contact with any etched surfaces. In [1] for example, Q factors as high as 5 million were achieved in micro-disk resonators by using resist reflow technique. Shallow rib waveguides are an alternative for reducing the interaction of light with etched surfaces, but result in largely delocalized modes, which cannot be used in devices where there are curves with small bending radii.

An effective solution is the etchless process, where a mask of lower index material is defined over the core of the waveguide and the sidewalls of the waveguides are defined by thermal oxidation. In this process, although the waveguide sidewalls end up not being perfectly vertical, which is not detrimental to the guiding characteristics, much smaller losses are achieved. In [2], losses as low as 0.3 dB/cm are achieved at 1.55 μm wavelength. With very similar processes, ring resonators with quality factors as high as many hundreds of thousands were demonstrated [3, 4]. Unfortunately the etchless process can only be used for materials that can be thermally oxidized. Sidewall scattering, being the most important source of propagation losses in the majority of photonics technologies, requires special care with respect to numerical modelling in order to assert the properties of waveguides precisely. In the present work we use absorption layers to model losses at sidewalls and interfaces between media with different refractive indices.

2. Structure under test: pedestal ARROWs

Lossy surfaces with complex refractive index n_{C1} were positioned on each side of the core (Abs. Layer 1) were used in order to model the scattering losses due to sidewall roughness, [5]. To model absorption and scattering from density fluctuations another absorbing area in the top of the waveguide core was defined (Abs. Layer 2) with complex refractive index n_{C2}. Three values of pedestal height (h) were used: 3, 4 and 5 μm. The pedestal width was varied between 2 and 20 μm in steps of 1 μm. The core height was 4 μm and the thicknesses of the first and second ARROW layers (h_{A1} and h_{A2}) were 93 nm and 2 μm, respectively. The core side width and core side height (w_{CS} and h_{CS}) were dependent upon the core width and height and were modelled accordingly by using SEM micrographs to estimate their exact dimensions. The thickness of all absorption layers (Figure 1) was set to 20 nm.

FIMMWAVE software package was used to iteratively find the value of the extinction coefficients of the absorption layers that matches the ones measured experimentally. The attenuation coefficient measured from the 20 μm width waveguide was used to adjust the value of n_{C2}. This waveguide, which has the largest width, the electric field of the fundamental mode interacting with the core sidewall roughness is very weak and so, losses are mainly due to absorption and scattering from material imperfections.

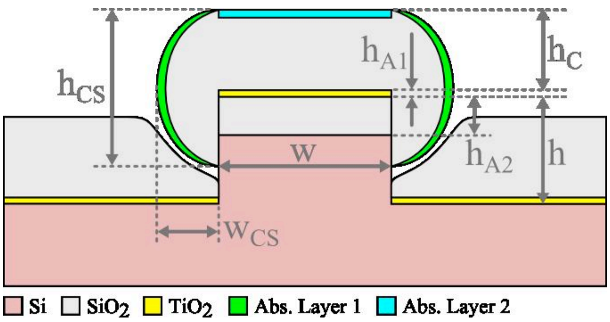

Fig.1. *Waveguide cross-section model used in the FDM simulations.*

The value of the complex refractive index of the sidewall absorption layer n_{C1} was found using the attenuation coefficient of a 5 μm-wide waveguide as reference. By varying the imaginary part of the refractive index of the layers that represent scattering at interfaces and bulk losses, we were able to match the behaviour of propagation losses as a function of pedestal width quite reasonably. Even more important, we were able to estimate the relative importance of each of these losses.

3. Results and discussion

Figures 3 shows a micrograph of a pedestal waveguides with pedestal height of 4 μm. This pedestal was fabricated by growing a 2 μm-thick thermal oxide layer on a clean p-type silicon wafer. After chromium deposition and photolithographic process, the pedestals were etched using Reactive Ion Etching (RIE) with chromium as a hard-mask.

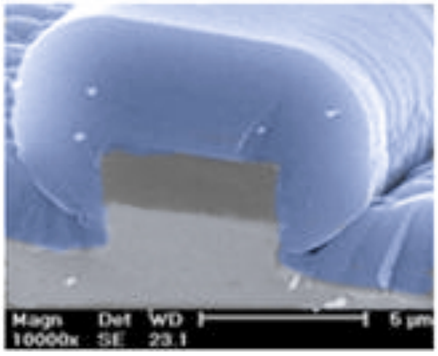

Fig.3. *SEM micrographs of pedestal ARROWs with pedestal height h = 4 μm.*

The optical losses measured in dB.cm-1, as well as losses calculated in simulations, are plotted as a function of waveguide width, for the pedestal ARROW with height of 5, 4 and 3 μm in Figure 4. The minimum optical loss obtained was 0.45 dB cm-1, corresponding to a 9 μm waveguide. As it can be seen, he losses modelled using the absorption layer discussed in the previous section fit the experimental results reasonably well.

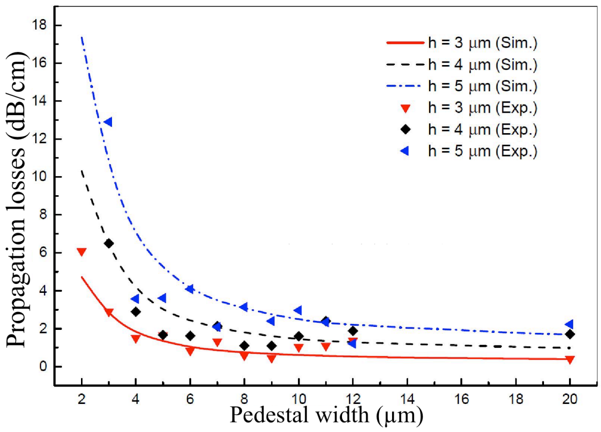

Fig.4. *Simulated and experimentally measured propagation losses for waveguides with pedestal height of 3, 4 and 5 μm and widths ranging from 2 to 20 μm.*

The core of the waveguide was deposited over the pedestal, consisting of a 4 μm-thick Plasma Enhanced Deposition (PECVD) silicon dioxide layer. It is important to point out that the contribution of Absorption Layers 1 and 2 to the simulated losses shown in Figure 4 are very different. The imaginary part of the refractive index of Absorption Layer number 1 (on the sidewalls) was 10 times larger than that of Absorption Layer 2. This indicates that the scattering losses on the sidewalls are at least one order of magnitude larger than losses due to material imperfections and absorption, and the losses due to scattering on the sidewalls predominate.

4. Conclusions

We have modeled the propagation losses due to scattering in the sidewalls of pedestal waveguides fabricated using ARROW waveguides. Experimentally, ropagation losses as low as 0.45 dB cm-1 were obtained for multimode waveguides. The pedestal height studies indicate an optimal value at around 3 μm, for a 4 μm thick core ARROW. It is noteworthy that the technique proposed here is specially useful for the calculation of losses with waveguides where the scattering at interfaces predominate. By fitting the propagation losses as a function of geometric parameters, namely the pedestal width, it is possible to estimate the contribution of different types of losses. With this technique we found that sidewall scattering is responsible for producing 10 times more losses than bulk absorption in the dielectric materials for this particular waveguide.

Acknowledgments

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