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Rib sidewall scattering loss estimation for trapezoidal optical waveguide

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A new technique to estimate the scattering loss due to sidewall surface roughness amplitude and sidewall angle for trapezoidal cross section waveguide has been demonstrated. The proposed technique has been based on the modified Tien's formulation for scattering loss mechanism as a mathematical model and combination of effective index method and beam propagation method for problem solving tools. The simulated results have been compared with previous researchers and mutual agreement has been observed.

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1. Introduction

Optical waveguides are considered to be the most important bridging component in optical integrated devices. Hence, a low loss optical waveguides are essential for reliable and effective optical communications system. The researchers have put much effort on realizing a low loss optical waveguides, by applying and changing many parameters. However the basic idea of having the low-loss structure is to first understanding and modelling the optical losses as this may greatly reduce the processing cost and provide extra precautions during the fabrication process. To the first extent, losses of optical waveguides can be divided into three different mechanisms which are scattering, absorption and radiation. According to Van, *et al.* [1] and Chao, *et al.* [2], the predominant loss in a straight optical waveguide structure is caused by scattering due to surface roughness. Hence, concentration is being put on modelling this type of loss.

Study on scattering loss mechanisms have started more than two decades ago when Tien formulated his own model based on Rayleigh criterion to estimate the scattering loss from rough surfaces of a slab waveguide [3]. In this formulation, the structure is said to have uniform roughness amplitude throughout the structure. Although Tien's theoretical model for scattering loss is only an approximation, it provides a convenient closed-form expression for scattering based attenuation coefficient, α_s. Utilizing the Tien's formulation, Deri and Kapon [4] had further estimated the sidewall roughness loss of a rib waveguide by simplifying the two-dimensional (2-D) rib structure to one-dimensional (1-D) transverse index distribution using the effective index method. Further work by Deri, *et al.* [5] had produced a novel method for studying the dependence of scattering loss on rib waveguide structure. By applying the perturbation approach which is totally different than the Tien's formulation, they managed to obtain the differences in scattering due to changes in epilayer structure and rib sidewall slope. Furthermore, they utilized the numerical solutions for eigenmodes and simplifying assumptions regarding the surface roughness rather than just applying the analytical method as in their previous works on scattering loss. Apart from that, Hewson-Browne, *et al.* [6] and Stern, *et al.* [7] had produced a new formulation for scattering loss by considering the scattering of a guided mode into substrate radiation mode. The formulation is strictly for the limiting case of small etch depth and steady state roughness characteristics. Besides, Lacey and Payne [8] treat the waveguide as radiating antenna with random wall imperfections as equivalent current sources. By applying the conventional radiation methods, they managed to obtain the far field and thus the scattering losses, caused by the wall imperfections.

However, most of the works done is based on the rectangular rib waveguide structure. In contrast to the real situation of chemical wet-etching process, the trapezoidal cross section is the commonly obtained structure, as reported in our previous work [9]. This effect is mainly due to etching limitation together with diffraction effects associated with mask opening and film thickness. Motivated from this scenario, this paper is initiated towards modelling the sidewall roughness scattering loss for the trapezoidal waveguide structure, which is considered to be the first ever recorded work. Method of Tien's [4] is adopted and simulation results are shown to produce acceptable agreement with other methods for solid rectangular structure.

2. Mathematical formulation

Based on Rayleigh criterion for scattering which states that, if the incident beam at the surface has power P_i, the reflected beam from that surface will have the following amount of power [10]

$$P_r = P_i \exp\left[-\left(\frac{4\pi\sigma}{\lambda}\cos\theta_m^{'}\right)^2\right] \qquad (1)$$

where;

P_r = reflected power
σ = surface roughness
λ = signal wavelength
$\theta_m^{'}$ = incident angle

Tien [4] had then developed a scattering loss formulation for slab waveguide considering uniformity of surface roughness at the boundary. For symmetrical slab structure, the formulation can be written as:

$$\alpha = \frac{4\sigma^2 h^3}{\beta\left(t+\frac{2}{p}\right)} = \frac{2\sigma^2 k_o^2 h}{\beta}\frac{E_s^2 \Delta n^2}{\int E^2 dx} \qquad (2)$$

where;

σ = surface roughness
t = guide thickness
k_o = free space propagation constant
β = longitudinal propagation constant
h = transverse propagation constant in the guide
p = transverse propagation constant in the cladding
$\frac{E_s^2}{\int E^2 dx}$ = normalized optical intensity at guide-cladding interface
Δn = index difference between guide and cladding

For the purpose of two-dimensional (2-D) treatment of the lateral confinement structured waveguide such as rib structure, Deri and Kapon [5] had modified the Tien's formulation by treating the refractive index, n as effective index, n_{eff}. They first simplified the 2-D structure to 1-D transverse index distribution using the effective index approximation which is then treated as a slab waveguide. Using this approach, (2) can then be written as

$$\alpha = \frac{2\sigma^2 k_o^2 h}{\beta}\frac{E_s^2 \Delta n_{eff}^2}{\int E^2 dx} \qquad (3)$$

Value of attenuation coefficient, α in (3) is the scattering loss caused by the rib sidewall roughness having uniform distribution, σ. Interestingly, few papers had revealed the applicability of equation (3) by mutual comparison between the simulation and measurement results. Starting from [12], Deri and Kapon did some measurement of rib structured waveguide using the GaAs epilayer on AlGaAs buffer clad layer. Using two different rib heights and by changing the rib width, the loss measurement and simulation results were agreed to each other for 50 nm su rface roughness and 1.52 µm wavelength. Later works by Van, *et al.* [1] on GaAs-AlGaAs microring resonators had simulated the sidewall scattering loss for the straight waveguide using (3). By assuming the modal field integral in (3) as unity, simulation is done for single-mode structure at 1.55 µm with 4.6 nm uniform surface roughness which is obtained using SEM. Using the combination of cutback technique and Fabry-Perot method for the loss measurement, the results were nicely followed the simulation results for different rib widths. Similarly, works on microring devices which is exhibited by Chao and Guo [2] had verified that the sidewall roughness scattering loss using (3) was significantly agreed with the measurement results.

Based on this works, the applicability of (3) in modelling the sidewall scattering loss is verified. Hence, our proposed technique is to be based on equation (3) as described in the next section, in which we did some modification to suit our structural needs.

3. Proposed modelling technique

The structure that is going to be investigated here is a trapezoidal rib structure as shown in Fig. 1 which is practically observed when the chemical wet-etched fabrication method is utilized [9].

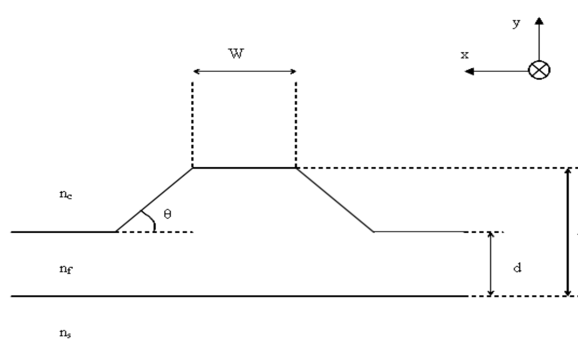

Fig. 1. Trapezoidal rib waveguide structure.

Our proposed approach is to be based on equation (3) that used to estimate the slanted rib sidewall scattering loss for trapezoidal structure. Based on this, the key idea is to estimate the value of β, using possible approach for particular structure. Recently, we had developed and tested the method of obtaining the β using the combination of effective index method and two-dimensional beam propagation method (2D-BPM) [11] and shown to produce tolerable results. Hence, this method will be applied in the process of obtaining α in (3). For validation, the scattering loss value obtained using this approach will be compared with previously reported work by Deri, *et al.* [12] using their solid rectangular structure and parameters. The comparison graph is shown in Fig. 2.

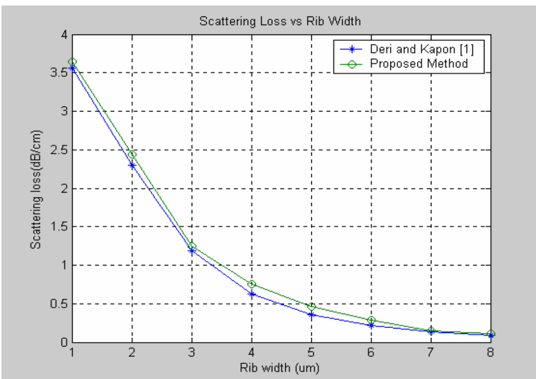

Fig. 2. Comparison graph between work by Deri et al. [12] and proposed method.

As can be seen from Fig. 2, the results obtained using the proposed approach for $\theta = 90^o$ which is equivalent to solid rectangular structure exhibit the same qualitative behaviour as compared to [12] which is based on effective index approximation. Thus, the proposed method is supposed to work well in estimating the surface roughness scattering loss for slanted rib structure. Section IV will describe further on this issue.

4. Results

Two distinct structures will be utilized for the purpose of evaluating the effectiveness of our proposed method. The first structure is to be based on simulation work by Deri, *et al.* [5] for trapezoidal rib structure. From [5], λ = 1.52 μm, W = 3 μm, t = 1.45 μm, d = 1.10 μm, n_s = 3.40, n_f = 3.44 and n_c = 1.0 with 50 μm and 30 μm surface roughness magnitudes. Further simulation will occupy the simulated structure by Benson, *et al.* [13] to confirm the qualitative behaviour as obtained from the first structure. In [13], the following parameters are chosen, t = 1 μm, W = 3 μm, n_c = 1.0, n_f = 3.44, n_s = 3.40 and wavelength, λ = 1.15 μm. Likewise, surface roughness magnitude is set to 50 μm. The rib height (t-d) is varied to further investigating the behaviour of our proposed method. The result for the first structure is shown in Fig. 3, while Fig. 4 exhibits the results for the second structure.

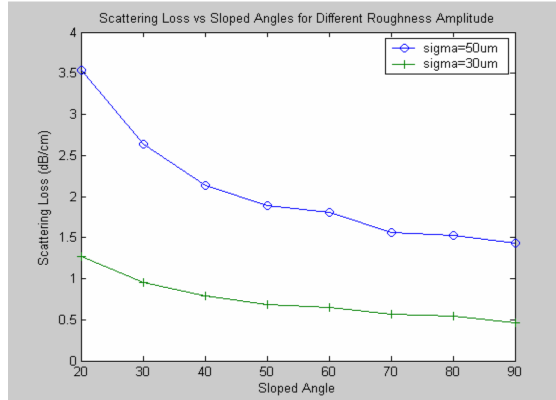

Fig. 3. Scattering loss at different sloped angles for different roughness amplitude.

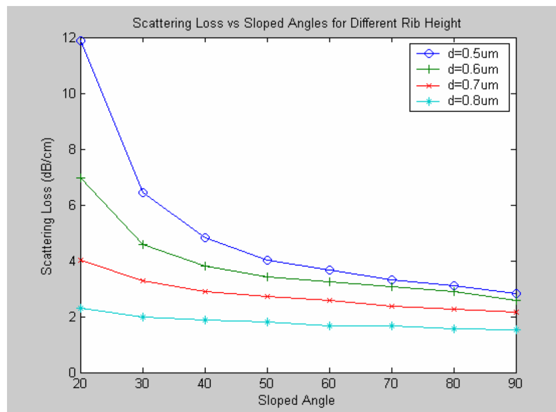

Fig. 4. Scattering loss at different sloped angles for different rib height.

As compared to the work in [5], our proposed method exhibits the same qualitative behaviour for both surface roughnesses. The second simulation also proven to exhibit the same qualitative behaviour for all slanted rib heights. It can be clearly seen from the results, the significant of surface roughness and the rib height on the scattering loss values. As can be deducted from equation (3), the increment in surface roughness magnitude will further increase the loss value. Having smaller rib height, means less surface area being exposed to the wave eigenmodes. Hence, less amount of wave will be scattered for the case of smaller rib height and further reduction in waveguide loss. Furthermore, it was observed that for smaller slope angle, losses will be higher. This phenomenon can best be described by adopting previous deduction of exposed surface argument, whereby smaller slope angle will reflect to longer slanted length and greater exposed area. As a result, higher losses value will be recorded as proven in our simulation results.

4. Conclusions

The modelling of scattering loss is very essential as it reflects the quality of optical waveguide. Thus, having a proper scattering loss model will then assist us in improving the waveguide fabrication techniques in order to produce good waveguide quality. We have successfully demonstrated the applicability of modified Tien's formulation in modelling the rib sidewall scattering loss for trapezoidal structure. The effect of surface roughness amplitude and rib sidewall angle have been signified and bound to be agreeable to the previous recorded work. These simulation results evidently give us strong insight on the applicability of the proposed method in modelling the rib sidewall scattering loss for trapezoidal structure.

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