Effects of sidewall roughness on optical power splitter

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The effect of sidewall roughness (SWR) on the performance of 1×2 optical power splitter is investigated. For the sake of simplicity, the SWR, assumed to take a periodic triangle shape, is considered in different sections of waveguide. The impact of SWR on the output power ratio is analyzed in detail. The corresponding insertion loss and power penalty due to SWR are determined using OptiBPM. Simulation results show that the output power decreases as the roughness increases due to increasing of scattering loss. Accordingly, the insertion loss and the power penalty increase and this would lead to degrade the output power in the corresponding waveguide branch and hence, the output power ratio deviates from the designed value.

1. Introduction

Optical networks provide high-capacity telecommunications based on fiber optical technologies. Optical networks use an optical fiber as a transmission medium channel. A passive optical network (PON) is a point to multi-point, fiber to the premises network architecture in which passive optical devices are used to enable a signal optical fiber to serve multiple premises. Optical power splitter is widely used as a power combiner or divider. Its main function is to split the incoming light into multi paths where each path may carry same or different ratio of power. It can be considered as the best and simple approach to split light in a planar ligthwave circuit. Optical splitter plays a central role in passive optical distribution networks [1].

There are various types of optical power splitter such as 1×2, 1×3, 1×4, ….. and 1×N. In addition, there are many parameters that should be taken into account through the design of optical power splitters such as refractive indices, width of waveguide and branching angle. Additionally, many methods have been employed to fabricate optical waveguide splitter, for example: (i) The polymer optical waveguide with the dopant-free core made of perfluorinated amphorous polymer [2]. (ii) Developing of a perfluoropolymer Poly (perfluorinated butenyl vinyl ether) (PBVE) [3]. (iii) Adiabatic tapered 2×2 MMI splitters [4]. In addition, fabrication of planar optical waveguides by electrical microntanct printing (this splitter was fabricated by E-μCP) [5]. And (v) Various methods like effective index method (EIM), beam propagation method (BPM), finite element method (FEM) and method of lines, have been used for modeling of different geometries of integrated optic devices [6].

One of disadvantages of these methods is the "roughness" which is arises from less accuracy during fabrication process. Roughness in most types of planner optical waveguides is due to random deviations of the waveguide sidewalls from perfect uniformity and is caused by the deposition/etching process used during fabrication. Mainly, there are two main fabrication steps that introduce waveguide sidewall roughness. One is "photolithographic pattern transfer" where roughness is introduced due to imperfections in the photolithography mask and/or sample surface and irregularities created in the photoresist pattern. The other is dry etching, where roughness is introduced due to material degradation induced by high-ion energy and slow etching rates as can be seen in Fig. 1. In addition, SWR may occur due to various reasons; such as polishing of irregular waveguide structures, uneven surface coating or corrugation of surface while fabricating the waveguides Loss sources in the most common waveguides are material absorption and geometrical and physical discontinuities (as those induced by sidewalls roughness), which produce some radiated power. In bent waveguides, bending loss has to be taken into account too.

Among different contributions to propagation loss, scattering loss due to SWR is most difficult to estimate. Moreover, this contribution can be only minimized by appropriate design and technological strategies but it cannot be eliminated. Any optical devices often suffer from the losses, one types of this loss is SWR, which is the source of major optical loss. [7-14].
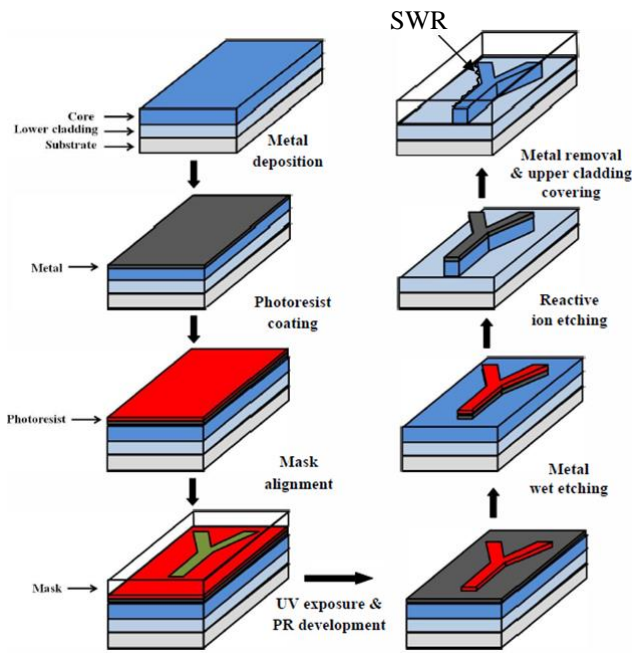
Fig.1. General procedure of photolithography technique

Fig. 2 shows a schematic waveguide with SWR. As can be noted, roughness occurs at the edge between core and cladding region. Naturally, it takes random shape [15]. Roughness at the sidewalls of waveguides, in particular, can be a major cause of scattering loss. Therefore, SWR studies are significant for understanding the evaluation of performance of optical device based on optical waveguides. For instance, SWR is known to degrade the performance of optical device in terms of reduction of output power and fluctuation in corresponding splitting power ratio. Thus, a better understanding of the causes of SWR through simulation is useful in developing a process that improves device quality. BPM is most widely used propagation technique for modeling integrated photonic structure and most commercial software for such modeling is based on it [16]. Thereby, minimization of the scattering loss is one of the most significant challenges for their implementation in microphotonics. In addition, it is strongly believed that further improvements in design, fabrication and characterization aspects will increase the device performance.
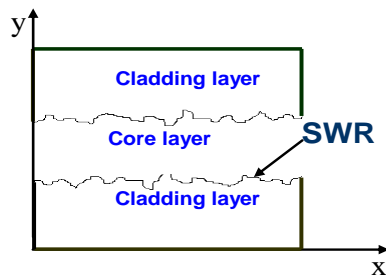

Fig.2. Schematic waveguide with rough sidewalls

2. Problem Formulation

SWR is an unavoidable defect caused by imperfection in the fabrication process. SWR is the source of propagation loss which attributed to scattering loss in optical power splitter and should be minimized as much as possible. The presence of SWR degrades the device performance and reduces the output optical power. Output optical power depends on various factors. An analysis of output optical power associated with different locations of SWR, waveguide dimensions, and sidewall depth is performed to investigate the effects of the investigated elements on output power of optical splitter.

3. SWR Design Model and Simulation

The effect of SWR on the performance of optical waveguide splitters was investigated. A 1×2 optical power splitter was considered because it is the basic unit of all other types. Roughness analysis was based on the assumption of a regular SWR shape. Although the true shape of SWR is random, an assumed geometry would simplify the analysis. Accordingly, a triangular periodic shape was assumed in consideration of roughness depth r_d, repetition roughness r_r, and spatial phase of the roughness shape. The effects of these SWR parameters on the optical splitter were analyzed for a specified value of waveguide width (i.e. $w = 6\mu m$). Analysis was performed with the commercial OptiBPM software [16].

Fig. 3 shows the optical power splitter device in consideration of SWR occurring in different sections. To generalize the analysis, different values of roughness depth, r_d is considered in each section. The corresponding output power is observed hence, the output power ratio is determined. The length of the entire device is 700μm, and the values of the core and cladding refractive indices are 1.6 and 1.5, respectively and the wavelength λ is =1.55 μm. The length of the linear section is 300μm, and S-bend waveguide is 400μm.
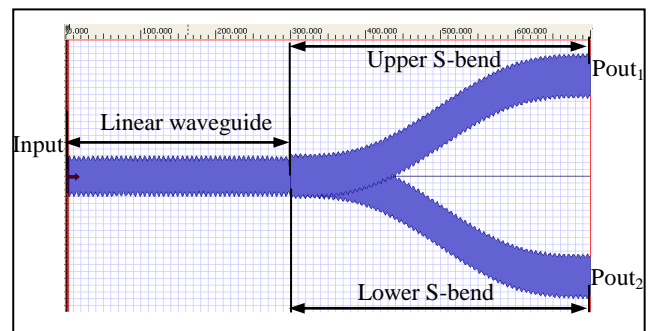

Fig. 3. Sidewall roughness in different sections and different values of roughness depth

The effect of SWR on linear and curved waveguides was analyzed first because these two types of waveguides are the building blocks of most optical power splitters and other passive devices. Therefore, the analysis in this study can be applied in the future to any type of passive devices with an optical waveguide as one of the components.

3.1 Linear Waveguide Analysis

Fig. 4 shows two simple forms of waveguide considered in the analysis. Figure 4(a) shows a linear waveguide without SWR, and Figure 4(b) shows a linear waveguide with periodic triangular SWR. The values of roughness depth and roughness repetition rate were assumed to be r_d = (0.1μm to 0.5μm) and r_r = 0.6μm respectively, for waveguide length L = 300μm. Roughness shape was modeled according to the following equation:

$$SWR(x) = r_d \arcsin(\sin(x + \phi_r)) + \left(\frac{w}{2} - r_d\right) \quad (1)$$

where x is the distance and ϕ_r is the phase of the periodic shape. Its value can be tuned arbitrarily to match the end of the corresponding waveguide section subjected to SWR with the other sections. Equation (1) represents SWR in the upper edge of the linear waveguide section.

A similar equation was considered for the lower edge, and the waveguide width was maintained at w = 6μm. Roughness depth r_d would be more affected if its value is relatively larger than the waveguide width. The corresponding propagation power is shown in figures 4(c) and 4(d). As shown in Figure 4(c), the output power is almost constant with distance for the waveguide without SWR. In addition, the attenuation caused by propagation can be neglected because of short distance. When SWR occurs (Fig. 4(d)), a degradation in propagated light can be clearly observed because of SWR. Consequently, the scattering loss increases.
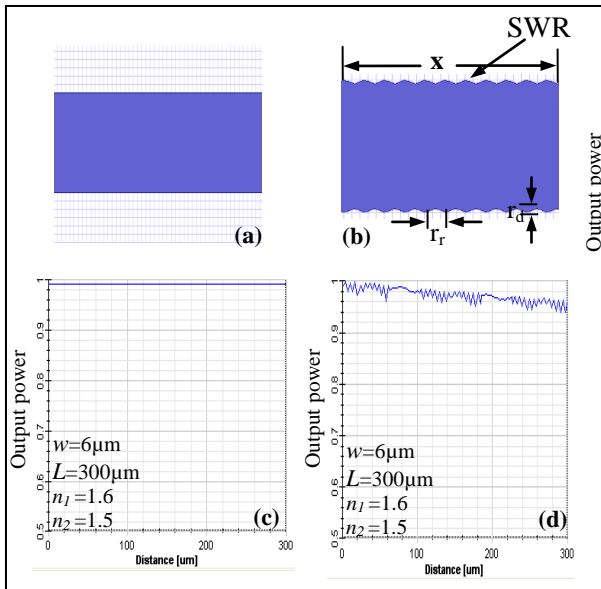

Fig.4. Top view of a waveguide (a) without and (b) with SWR; (c) and (d) show the corresponding output power, respectively

3.2 S-bend Waveguide Analysis

Fig. 5(a) and 5(b) show the geometry of an S-bend curve waveguide with and without SWR, respectively. The corresponding propagated power is shown in figures 5(c) and 5(d). To form the S-bend curve in OptiBPM software (figures 5(a), and 5(b)), the upper edge of the S-bend waveguide section to SWR is considered according to the equation:

$$SWR(x) = h\left[r_d \arcsin\left(\frac{x - \phi_r}{L}\right) - \sin\left(\frac{2\pi x}{L}\right)\bigg/2\pi\right] \quad (2)$$

The lower edge follows a similar equation but deviates with a value equal to the width of the waveguide. In equation (2), the value of offset (h) is estimated to be 15μm; the roughness depth and repetition rate are similar to those in figure 5. The value of r_d is equal zero for the waveguide without roughness. As shown in figure 5(c), the output power diminishes slightly because of bending loss. The output power diminishes even more when SWR in the S-bend section is considered as shown in figure 5(d). Bending loss is also expected to contribute but with low impact because the radius is relatively large.
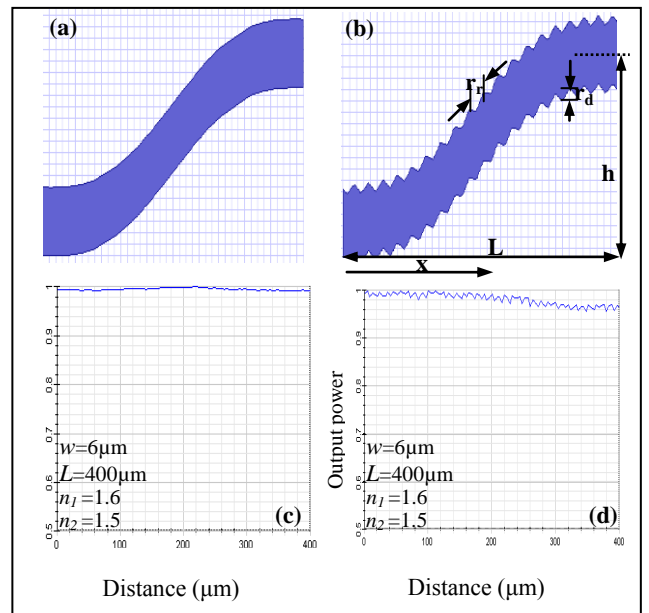

Fig.5. Geometry of S-bend section waveguide (a) without and (b) without SWR; (c) and (d) show the corresponding output powers.

Fig. 6 shows a scanning electron microscope (SEM) effect of the roughness on the fabricated waveguide. It shows the aspect of an etched waveguide with the presence of the SWR.
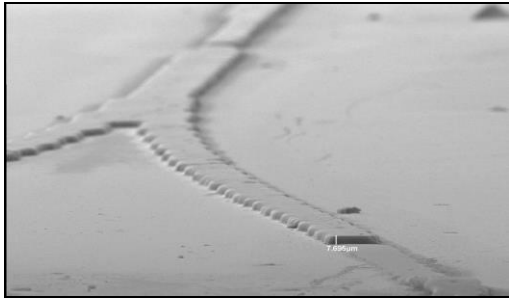
Fig.6. Microscope photograph showing a cross section of the SWR waveguide structure.

Fig.7. Effect of roughness depth on the output power ratio of the optical power splitter. SWR is considered in the linear waveguide

4. Results Analysis and Discussion

The overall performance of the optical power splitter is examined in this section and evaluated using output power level achieved at ends, insertion loss, and penalty.

Insertion loss can be determined through the following equation:

$$I.L.(dB) = 10\log_{10}\left(\frac{P_{out}}{P_{in}}\right) \quad (3)$$

Furthermore, we define the penalty according to the following equation:

$$Penalty(dB) = 10\log_{10}\left(\frac{P_{out}^{roughness}}{P_{out}^{ideal}}\right) \quad (4)$$

As the power penalty that compares the output power of the optical splitter, namely, the upper and lower S-bend sections.

Fig. 7 presents the output power of the two output ports of the optical splitter at different values of roughness depth. The value of the repetition rate is assumed to be $r_r = 0.6\mu m$. SWR is considered in the linear waveguide section. As shown in the figure, SWR is not significantly affected at roughness depth $r_d = 0.1\mu m$ to $0.4\mu m$. The reason is that roughness depth is very small compared with the waveguide width ($w = 6\mu m$). However, when the roughness depth increases to $r_d = 0.5\mu m$ the output power from P_{out1} is lower than that from P_{out2}. This phenomenon would change the output power ratio's designed value, i.e., approximately 50%.
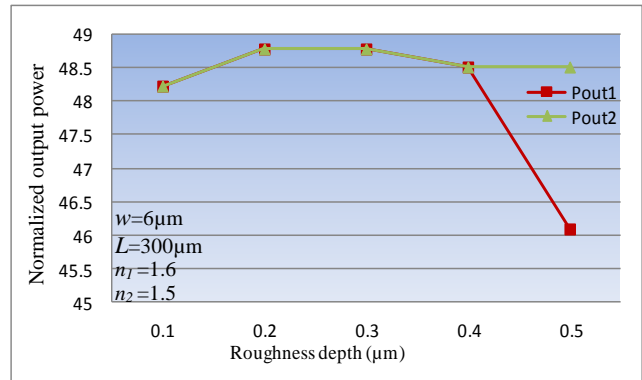
Table 1 shows the simulation measurements obtained for the output power of the optical splitter assuming that SWR occurred in linear, upper S-bend, and lower S-bend waveguides.

Table1. Simulation measurement of roughness depth= 0.3μm and various roughness locations.

Categories	Output power	Ideal	Linear	Upper S-bend	Lower S-bend
Roughness Length (μm)		-----	300	400	400
Insertion Loss (dB)	P_{out1}	-3.13	-3.54	-5.02	-2.35
	P_{out2}	-3.13	-3.43	-2.35	-5.02
	P_{Total}	-0.12	-0.47	-0.47	-0.47
Output power (%)	P_{out1}	47.91	43.39	30.99	57.41
	P_{out2}	47.91	44.47	57.41	30.99
	P_{Total}	95.82	87.86	88.40	88.40
Penalty (dB)	P_{out1}	0	-3.43	-4.89	-2.21
	P_{out2}	0	-3.32	-2.21	-4.89
	P_{Total}	0	-0.36	-0.34	-0.34

As shown in Fig. 8, when the upper side of the S-bend waveguide is subjected to SWR, the output power at the corresponding P_{out1} is reduced and output power at P_{out2} in the lower side of the S-bend section is increased. This result can be attributed to the relatively high scattering loss caused by SWR in the upper S-bend. Hence, the power propagated through the lower S-bend increases at the expense of the power in the upper part. This phenomenon would cause the output power ratio to deviate from the optimum value, i.e., $\approx 50\%$.
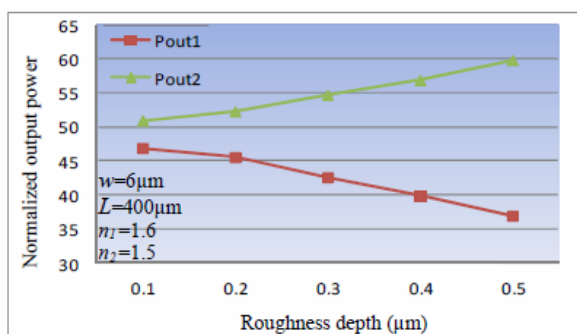
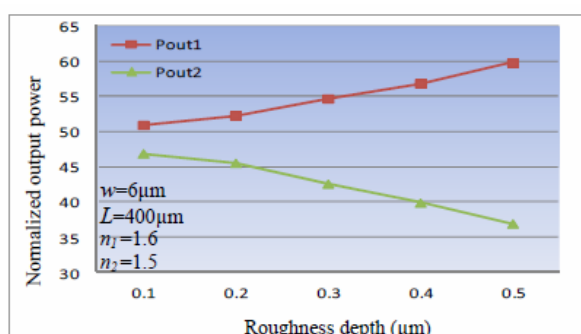*Fig.8. Effect of the variation in roughness depth on the upper S-bend waveguide*

Fig.9. Effect of the variation in roughness depth on the lowerS-bend waveguide

When SWR is considered at lower S-bend section, as shown in figure 9, the output power at the corresponding P_{out2} is reduced because of increase in scattering loss.

Figs. 8 and 9 show that the occurrence of SWR in the S-bend waveguide sections significantly affects the output power ratio. In addition, the propagated power in the S-bend section without SWR increases at expense of the power in the S-bend section with SWR. Hence, the output power ratio which represents the amount of power delivered to the any branch in the optical network is affected.

5. Conclusion

The effect of SWR on the performance of an optical power splitter was analyzed. The main parameters of SWR are roughness depth and repetition rate. The effect of SWR on the output power of the optical splitter was also investigated at different roughness depths. The latter is affected when its value is relatively large compared with waveguide width.

Our simulation results show that SWR has a significant value at a roughness depth of $r_d \geq 0.5\mu m$ and waveguide width of $w = 6\mu m$. In addition, the effect of SWR is more significant in the S-bend waveguide section than in the other sections because of the combined effect of bending and scattering losses. This phenomenon affects the power distribution in each output branch, and consequently, the output power ratio. The analysis performed provides useful detailed information for designers the when dealing with an optical power splitter in an optical network. Therefore, low-loss optical waveguide etching technologies that produce high and smooth sidewalls are required. Such technologies are important for designers in predicting the quality (i.e., performance) of devices subjected to SWR and in evaluating devices in optical networks before real fabrication. Additionally, determining the limiting loss contributions of these devices is necessary to establish novel fabrication processes for reduced scattering loss.

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