# Comparison between different roughness shapes based on channel waveguide

M. SYUHAIMI AB-RAHMAN[a], F. ATER[a*], M. HASSAN[b] R. MOHAMMAD[c], I-SHYAN HWANG[d]
[a]*Spectrum Technology Research Division (SPECTEC), Faculty of Engineering& Built Environment, Department of Electrical, Electronic and Systems Engineering, University Kebangsaan Malaysia (UKM),*
*No. 43600, Bangi, Selangor Malaysia*
[b]*Asia Pacific University of Technology & Innovation, School of Engineering, Bukit Jalil, 57000 Kuala Lumpur Malaysia*
[c]*Faculty of Applied Sciences, Universiti Teknologi Mara (UiTM)*
*40450, Shah Alam, Selangor, Malaysia*
[d]*Computer Communications (Networks), Distributed Computing, Information Science,*
*Yuan Ze University, Taoyuan City 32003, Taiwan*

The present paper compares the effect of different roughness shapes on optical channel waveguides in terms of output power, insertion loss and attenuation coefficient. The analysis based simulation was performed using OptiBPM software which is adapted to simulate the performance of these waveguide structures. Varying-depths of roughness, $r_d$ ranging from 0 to 0.5μm and waveguide width variations from $w$ = 2μm, 4μm, and $w$ = 6μm are considered and numerical results are obtained for channel waveguide propagation losses due to roughness induced scattering. The results indicate that scattering loss increases as SWR depth increases, which leads to reduce the output power significantly especially for narrow waveguide ($w$ < 4μm) and high roughness depth ($r_d$ > 0.2μm). Accordingly, attenuation coefficient and insertion loss increases due to the corresponding reduction in output power. The propagation loss of the waveguide increases dramatically upon increasing the SWR of the channel. It can be concluded, that the sensitivity of propagation loss is more severely affected by the small waveguide width i.e. $w$ < 4μm and less by the large ones i.e. $w$ > 4μm. Finally it has been shown according to our typical values, it seems that sinusoidal-like SWR and triangular is more affected compared to random one due to the periodicity nature of shape which affects the overall phase interference. Further study should attempt to reduce the roughness of waveguide to lower the scattering loss.

(Received August 18, 2015; accepted September 9, 2015)

*Keywords*: Channel waveguide, Insertion losses, Output power, Roughness shapes, Scattering loss, Sidewall roughness

## 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. Losses of optical waveguides can divide 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 channel optical waveguide structure is caused by scattering due to surface roughness. Scattering loss is a major hurdle to performance improvement of photonic devices. Hence, concentration is being put on modeling this type of loss.

It is known that the channel waveguide is a basic optical device used in integrated optics for a variety of applications, such as Y-branch splitter, waveguide multiplexer and demultiplexer, waveguide laser, etc. For a particular type of coupler, the governing design parameters need to be determined accurately and to be controlled in the particular fabrication process.

For channel waveguides using etching and deposition techniques, roughness occurs on the interface between the core and cladding materials and contributes to attenuation through scattering of model power into radiation [3].

In channel waveguides, the major loss mechanism is sidewall scattering that arises due to residual roughness; as shown in Fig. 1. This Figure shows the effect of SWR on optical channel waveguide. As can be seen in Fig. 1(a) the SWR cerates scattering, which lead to out-of-plane losses, while Fig. 1(b) represents the propagation optical field along the channel waveguide subjected to SWR. Thus, efforts have been made to optimize processing to minimize roughness [3-5]. However, the optical losses may greatly reduce the processing cost and provide extra precautions during the fabrication process. The sidewall roughness (SWR) is formed in the manufacture process, so the scattering loss induced by the surface roughness is inevitably generated [6, 7].

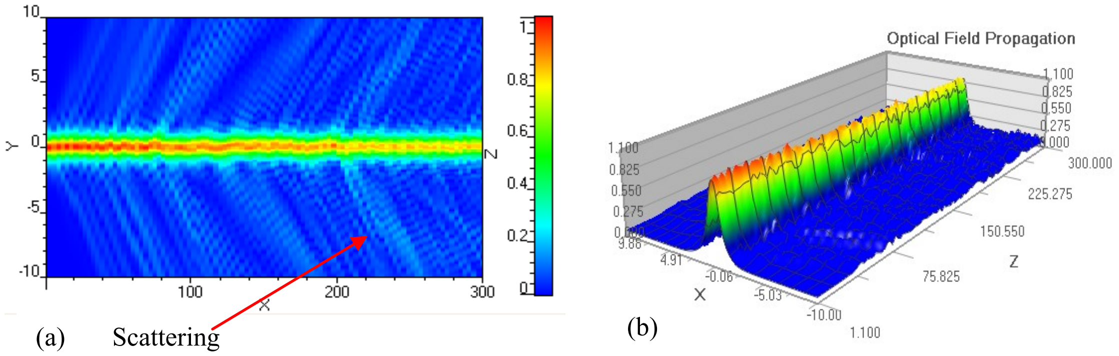


*Fig. 1. Effect of SWR on a channel waveguide: (a) Scattering of out-of-plane losses and (b) Optical field propagation.*

It is well known that scattering losses are smaller in wide and flat waveguides as the field overlap becomes smaller on the rough sidewalls [8, 9]. Thus, the waveguide scattering loss is determined by the sidewall roughness and the waveguide dimensions. The scattering loss is the fundamental factor that affects the performance of the optical waveguide devices [3-12]. SWR in optical waveguide is one of the paramount to the performance of microphotonic devices. Low propagation loss is critical to the performance of nearly all microphotonic devices and to the practical operation of microphotonic circuits of notable complexity. In order to figure out a highly optimized optical waveguide based design, it is important to precisely select the waveguide criteria and specifications. For example, all losses in the waveguide correspond to the material and geometry of the waveguide. There are three fundamental design principles which one should emphasise when selecting the material and geometry of the waveguide; Size, performance and fabrication.

Several techniques can be applied to fabricate waveguides [13, 14]. Among them, dry etching methods such as reactive ion etching (RIE) and an inductively coupled plasma (ICP) are often used because this technique can offer the excellent etching profile [15]. One of the disadvantages of this technique is its complicated process, and thus, not cost effective for mass production. Moreover, they suffer from optical loss because the scattering loss from the defect of sidewall [1, 16]. The roughness and the inhomogeneity are inherent in any integrated optics devices [17]. There has been a very limited amount of work devoted to SWR effect on optical waveguides. According to previous papers, the effect of SWR on channel waveguide with different roughness shapes has not been taken into account. In this paper, we identify a loss mechanism that we believe has not yet been reported in the literature.

This paper deals with the comparison between the effects of different roughness shapes i.e. triangular, sinusoidal and random on the channel waveguide. Performance analysis of optical channel waveguide subjected to the corresponding SWR shapes is performed. Thereby, optical output power, insertion loss and attenuation coefficient is determined for different values of waveguide widths and roughness depths.

The aim of this paper is to present comparison which gives a quantitative measure of the effect of each SWR shape on the optical channel waveguide in terms of output power, insertion loss and attenuation coefficient, which achieve the optimization of optical waveguide device. This measurement provides not only a visual assessment (i.e. a qualitative description) but also, an estimate of the roughness contribution to overall loss. This in turn, provides a feedback in the design of lower loss channel waveguides.

The benefit of this comparison is that the designer can predict and evaluate the performance of the channel waveguide subjected to SWR which is assumed triangular and sinusoidal SWR compared with the random SWR which occurs in practical case.

This paper is arranged as following. Section II describes the analysis of channel optical waveguides subjected to SWR for different roughness shapes. Section III presents the results and discussion. Finally, our conclusions are summarized in Section IV.

## 2. Analysis of channel optical waveguide subjected to SWR

In order to determine the effect of SWR on the optical channel waveguide, three main types of triangular, sinusoidal and random roughness shapes are considered, these three shapes are taken into account because they represent the basic components of most passive optical devices employed in optical integrated networks. Practically SWR is random. In this work SWR is considered as periodic and aperiodic. As shown in Fig. 2(a), (b) and (c) triangular, sinusoidal and random-like SWR shapes are considered, for channel optical waveguide, at both sides respectively.

Roughness on a waveguide, which is shown in Fig. 2, can be modeled as a slight deviation from original waveguide such that the waveguide’s width i.e. deviations from the ideal waveguide.

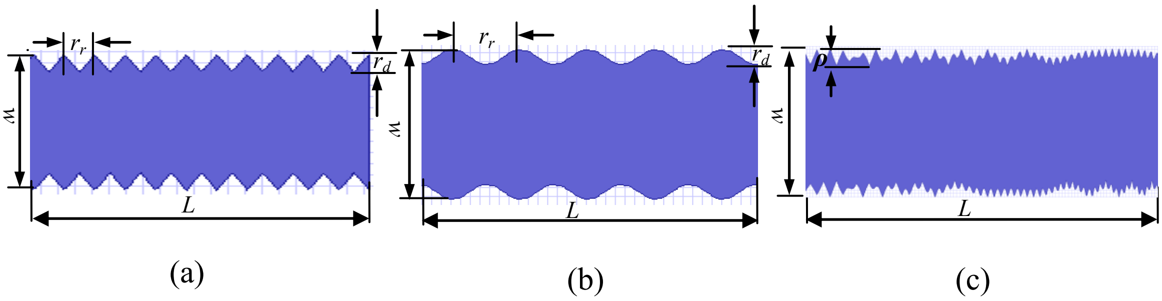


*Fig. 2. Channel waveguide with different SWR shapes: (a) triangular, (b) sinusoidal and (c) random-like roughness*

The values of roughness depth and roughness repetition rate are assumed as $r_d$ = 0.1µm to 0.5µm and $r_r$ = 0.6µm, respectively for waveguide length $L$ = 300µm.

Triangular $SWR_T$, Sinusoidal $SWR_S$ and Random $SWR_R$ are determined (mathematically) according to the following proposed equations respectively,

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

$$SWR_S(x) = \frac{1}{2}(w - r_d) + (r_d)\sin(x + \phi) \quad (2)$$

$$SWR_R(x) = \left(\frac{w}{2}\right) + \sin\left(\frac{x^2}{L} + K\right)\arcsin(\sin(x - \phi)) \quad (3)$$

where the $w$ is the waveguide width, $r_d$ is the roughness depth, $x$ is the distance and $L$ is the length of the waveguide section. $\phi$ is the phase shift of periodic shape. The value of latter can be tuned arbitrary in order to match the end of the corresponding waveguide section subjected to SWR with the other sections, $K$ is for controlling the random roughness shape of the waveguide. In addition, the SWR is considered to be occurred at both edges of channel waveguide section.

The scattering loss due different roughness shapes and waveguides widths are analyzed to determine the effect of sidewall roughness on the performance.

In order to investigate the influence of SWR on optical channel waveguide, equations (1) to (3), that describes mathematically triangular, sinusoidal and random-like SWR respectively. These equations are employed by using the OptiBPM in order to adapt it for the sake of evaluation of channel waveguide performance. In addition MathCAD software environment is used for calculation of optical output power, insertion losses and attenuation coefficient based on simulation measurements from beam propagation method (BPM) for the first time.

The values of the channel waveguide parameters used in the simulation can be found in Table1.

*Table 1 Parameters values used in simulation.*

| Parameters | Configurations |
|---|---|
| Substrate Length | 300µm |
| Substrate Length Width | 20µm |
| Refractive Index of waveguide substrate wafer, $n_1$ | 1.6 |
| Refractive Index of waveguide substrate wafer, $n_2$ | 1.5 |
| Wide guide wave | 2, 4 and 6µm |
| Wavelength | 1550nm |
| Medium | Gaussian |
| Display Number | 55 |
| Polarization | TE and TM |
| BPM Solution | Simple TBC |
| No of Mesh | 2000 |

## 3. Results and discussion

A simulation study was conducted to examine the impact of sidewall roughness on the propagation losses of a channel waveguide.

In general, it can be expected simulations revealed that the variation in the width of the waveguide, and to a greater extent, cause transmission losses especially at small waveguide widths.

In order to characterize for a waveguide loss, a channel waveguide with different roughness shapes has been adapted in the loss measurement. In this section, results were obtained based on simulation model using the commercial BPM-CAD software from Optiwave is employed for the analysis, to perform comparison purpose between different roughness shapes.

Fig. 3 depicts the normalized optical power of channel waveguide subjected to triangular, sinusoidal and random SWR for $w$ = 2, 4 and 6µm. The SWR is considered at both sides of waveguide. As shown in Fig. 3(a) for $w$ = 6µm, the optical output power is approximately the same for three shapes due to relatively large waveguide width i.e. $w >> r_d << 1$. When the width decreases to $w$ = 4µm (as shown in Fig. 3(b) and $w$ = 2µm (as shown in Fig. 3(c)) the optical output power decreases as the roughness depth increases especially for relatively small waveguide width as can be seen clearly in Fig. 3(c).

It is worth to mention that the difference in the corresponding curves can be ascribed to the interference between the internal reflected wave components through the waveguide channel due to the deviation in geometry of waveguide core subjected to SWR

It can be indicated, from Fig. 3, that a relatively high constructive interference occurs in optical waveguide subjected to random SWR compared with the periodic SWR. The results show that the sensitivity of propagation loss is more severely affected by the small waveguide width and less by the large ones.

Furthermore, Fig. 4 shows the insertion loss versus roughness depth for different roughness shapes and different values of roughness depth where the SWR was considered at both sides of channel waveguide for *w* = 2µm, 4µm, and *w* = 6µm. As shown in Fig. 4(a) for *w* = 6µm the effect of insertion loss is small for the three shapes due to large of waveguide width. Unlike when the width decreases to 4µm, and 2µm, as shown in Fig. 4(b) and (c) respectively, the insertion loss increases with the increasing of roughness depth due to increasing of scattering loss which reduces the output power.

The effect of sidewall roughness on the attenuation of the channel waveguides for the wavelengths of 1550nm was calculated and the results are shown in Fig. 5 waveguides widths for 6, 4, and 2µm were simulated.

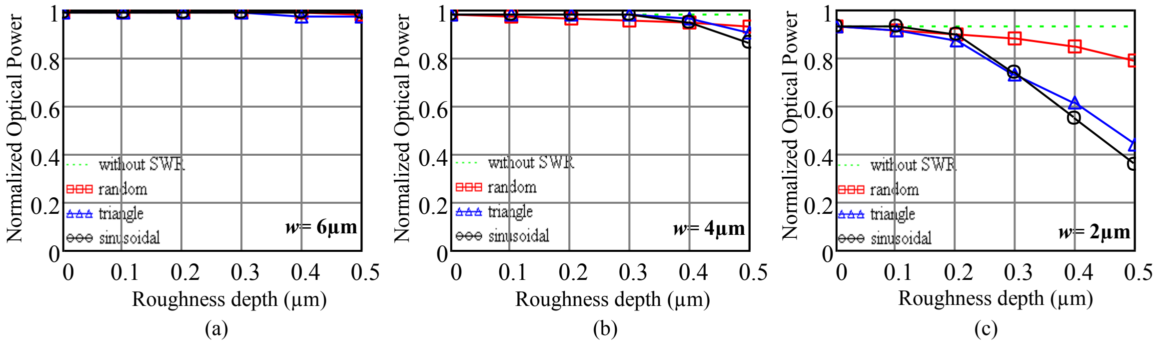


*Fig. 3. Normalized optical output power of channel waveguide subjected to random, triangular and sinusoidal SWR and different waveguide widths. (a) w = 6µm, (b) w =4µm and (c) w = 2 µm.*

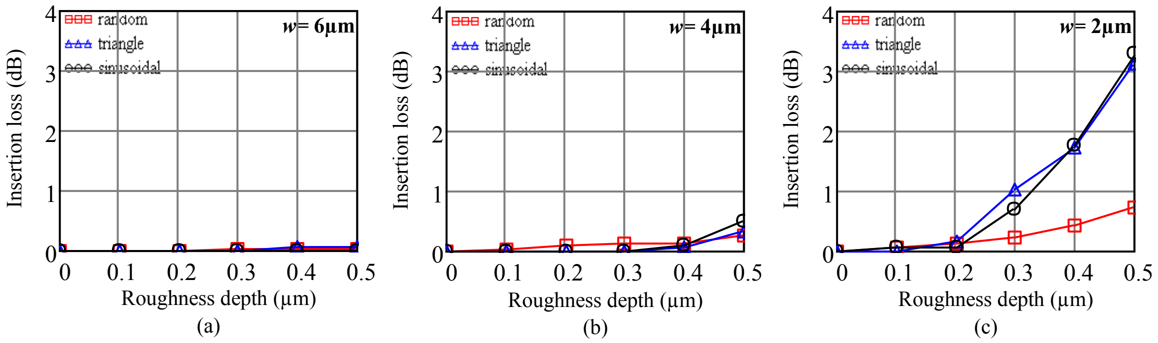


*Fig. 4 Insertion loss versus roughness depth at both sides, of channel waveguide for (a) w = 6µm, (b) w = 4µm, and (c) w = 2µm.*

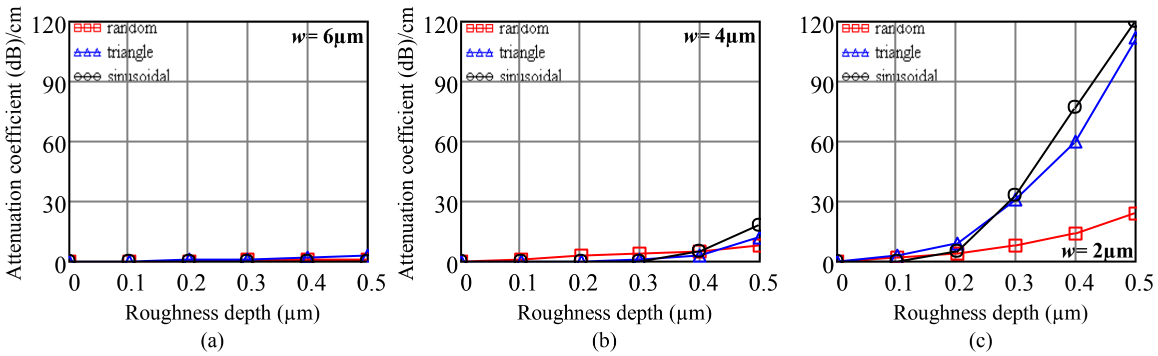


*Fig. 5. Attenuation coefficients versus roughness depth at (a, b, c) both sides, of channel waveguide for (a) w = 6µm, (b) w = 4µm, and (c) w = 2µm.*

As can be noted, the effect of periodic SWR i.e. triangular and sinusoidal is more affected than random one. The reason can be explained as follows, due to the asymmetric shape of SWR at the upper and lower sides, the constructive interference between internally reflected wave components is high which results in a relatively high output power compared with symmetric SWR shapes i.e. triangular and sinusoidal especially at narrow waveguides.

The difference in the corresponding curves can be related to the interference between the internal waves components reflected through the curved waveguide channel. In particular, the structure of waveguide core subjected to periodic/non-periodic (random) SWR gives different waviness behaviour.

Thereby, optical field intensity resulted in form internal reflection of propagated wave components will affected according to the SWR shape.

Finally, it has be concluded that: according to the aforementioned analysis the more affected SWR shape is the sinusoidal and triangular compared to the random one due to the periodicity nature of shape which affects the overall phase interference. Results of the comparison between the applied different roughness shaped on the performance of channel waveguide are summarized in Table 2.

*Table2.Comparison between the different roughness shapes at narrow waveguide width (w = 2μm)*

| Roughness depth | Parameters | SWR shapes | | |
|---|---|---|---|---|
| | | Random | Triangular | Sinusoidal |
| ($r_d > 0.2\mu m$) | Output power | low | medium | high |
| | Insertion loss | low | medium | high |
| | Attenuation coefficient | low | medium | high |
| ($r_d < 0.2\mu m$) | Output power | low | low | low |
| | Insertion loss | low | low | low |
| | Attenuation coefficient | low | low | low |

## 4. Conclusion

SWR in optical waveguides represents a severe impairment for the proper functionality of photonic integrated circuits. A simulation study has been performed to evaluate propagation loss in channel waveguides arising from sidewall roughness. The effect of SWR on the performance of optical channel waveguide subjected to triangular, sinusoidal and random-like SWR has been analyzed and compared for various waveguide channel widths. Based on the simulated measurement and results have shown relatively high loss arises when the roughness depth is comparable to the waveguide width. Hence, the output power decreases significantly and leads to increase the insertion loss and attenuation coefficient. Finally, it turned out that the sinusoidal-like SWR and triangular is more affected compared to random one. In addition the different between the corresponding curves becomes more pronounced when the roughness depth $r_d$ larger than 0.2μm. As a conclusion, this qualitative analysis illustrates the influence of the waveguide dimensions opens the way for designing and optimizing a wide range of microwaveguide geometries. These moicro-waveguides used both for optical communications and for future optical interconnects definitely require a quantitative evaluation of the scattering loss before processing.

**Acknowledgments**

This work is sponsored by the National University of Malaysia (Universiti Kebangsaan Malaysia – UKM) through grand no. UKM-AP-ICT-17-2009.

## References

[1] V. Van, P. P. Absil, J.V. Hyrniewicz, P. T. Ho, Journal of Lightwave Technology, **19**, 11 (2001).
[2] CY Chao, LJ Guo, Photonics Technology Letters, IEEE **16**, 6 (2004).
[3] F. Ladouceur, J. D. Love, T. J., Senden, IEE Proceedings-Optoelectronics, **141**, 4 (1994).
[4] Ladouceur, F., Love, J. D., Senden, T. J. Electronics Letters 28, (1992).
[5] M. S. Ab-Rahman, F. S. Ater, R. Mohamed, J. Optoelectron. Adv. Mater. **17**, (5-6) (2015).
[6] K. K. Lee, D. R. Lim, H. C. Luan, A. Agarwal, J. Foresi, L. C. Kimerling, Applied Physics Letters, **77**, 11 (2000).
[7] P. Y. Kuan, D. Andre, L. Jean, L. Boris, H. S. Jens, W. Philip, A. S. Barry, J. Siegfried, J. of Lightwave Technology, 27, (2009).
[8] T. Barwicz, H. A. Haus, Journal of Lightwave Technology **23**, 9 (2005).
[9] F. Grillot, L. Vivien, S. Laval, D. Pascal, E. Cassan, J. IEEE Photonics Technology Letters, **16**, 7 (2004).
[10] Kehinde, Latunde-Dada, F. P. Payne, Optical and Quantum Electronics, **40**, 11-12 (2008).
[11] B. Huang, J. Chen, W. S. Jiang, J. of Infrared Milli Terahz Waves, **30** (2009).
[12] M. S. Ab-Rahman, F. S. Ater, R. Mohamed, Optical Engineering, **54**, 5 (2015).
[13] U. Streppel, P. Dannberg, C. Wächter, A. Bräuer, L. Fröhlich, R. Houbertz, M. Popall, Optical Materials, **21**, 1–3 (2003).
[14] R. Yoshimura, M. Hikita, S. Tomaru, S. Imamura, Electronics Letters **33**, 14 (1997).
[15] M. Kagami, H. Ito, T. Ichikawa, S. Kato, M. Matsuda, N. Takahashi, Applied Optics, **34**, 6 (1995).
[16] S. J. Choi, K. Djordjev, S. J. Choi, P. D. Dapkus, J. Vac. Sci. Technol. B. **20**, 1 (2002).
[17] F. Ladouceur, Journal of Lightwave Technology **15**, 6 (1997).

*Corresponding author: aterfoze@yahoo.com