

# Size Influence on the Propagation Loss Induced by Sidewall Roughness in Ultrasmall SOI Waveguides

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**Abstract**—Silicon-on-insulator (SOI) optical waveguides with high electromagnetic field confinement suffer from sidewall roughness which is responsible for strong scattering effects. This letter reports a numerical investigation on the size influence of ultrasmall SOI waveguides on the propagation loss due to sidewall roughness. It is shown that for a size smaller than  $260 \times 260$  nm the roughness-induced propagation loss decreases. As the optical mode confinement is reduced, a very low loss light coupling from and to a single-mode fiber can be achieved with propagation loss as low as 0.5 dB/cm for a  $150 \times 150$  nm cross-sectional waveguide.

**Index Terms**—Optical interconnects, optical telecommunications, optical waveguide, propagation loss, roughness, silicon-on-insulator (SOI).

## I. INTRODUCTION

SILICON-ON-INSULATOR (SOI) material is of prime importance for integrated optoelectronic circuits offering the potentiality of monolithic integration of optical and electronic functions on a single substrate. As silicon is transparent at wavelengths larger than  $1.1 \mu\text{m}$ , including the optical communication bands, the silicon film of SOI substrates can be used to fabricate low-loss submicrometer optical waveguides [1], [2]. Silicon-silicon dioxide (Si-SiO<sub>2</sub>) waveguides benefit from a large refractive index difference, inducing a high electromagnetic field confinement in the silicon guiding layer which in turn allows reducing the waveguide size to submicrometer values [3]. Nevertheless, in order to use SOI waveguides for optical communications, both polarization insensitivity [4] and single-mode propagation have to be simultaneously fulfilled [5]. It has recently been shown that these conditions can be achieved by using deeply etched rib SOI waveguides with dimension of the order of  $1 \mu\text{m}$  [5]. Several compact systems are obtained with square-strip waveguides provided a square size smaller than  $320$  nm at  $1.55 \mu\text{m}$  to insure single-mode condition. It is important to stress due to the etching process [reactive ion etching (RIE)] those devices generally suffer from sidewall roughness. Such a random phenomena constitutes the dominant source of the propagation loss [6]. In order to predict the impact of the sidewall roughness on the propagation loss, a model based on a planar optical waveguide has been developed [6] showing that the propagation loss coefficient is linked both to roughness parameters and to the waveguide geometry. Taking into account the vertical confinement, this model has recently been extended to the case of two-dimensional (2-D) Si-SiO<sub>2</sub> structures [7]. The

propagation loss induced by sidewall roughness is calculated for  $500 \times 200$  nm rectangular cross-sectional Si-SiO<sub>2</sub> waveguides and the use of an oxidation step or anisotropic etching added to an RIE etching process to reduce the sidewall roughness has led to demonstrate the feasibility of low-loss SOI waveguides [3].

Based on the model described in [6] and [7], a numerical investigation of scattering loss induced by sidewall roughness is performed in this letter as a function of the size of SOI square strip waveguides with cross sections ranging from  $500 \times 500$  nm to  $150 \times 150$  nm. Propagation losses are strongly correlated to field confinement and are maximum for a  $260 \times 260$  nm waveguide. The smallest structures are quite useful for three-dimensional (3-D) tapers designed for low loss coupling between polarization insensitive microwaveguides and single-mode optical fibers [8].

## II. NUMERICAL MODEL

The planar optical waveguide used under study is made of a silicon core layer ( $n_c = 3.44$ ) surrounded by a silica cladding ( $n_{cl} = 1.44$ ). The waveguide width is  $2d$  and the propagation wavenumber is  $\beta = 2\pi n_{\text{eff}}/\lambda$  with  $n_{\text{eff}}$  the effective index and  $\lambda$  the operating wavelength fixed at  $1.55 \mu\text{m}$ . Calculations are performed for a transverse magnetic (TM) polarization of the incident fundamental mode. The sidewall roughness is obtained by a random variation of the waveguide width. Such a variation leads to local variations of the effective index corresponding to the formation of a pseudograting along the sidewall. Thus, the sidewall roughness acts as a dipole which can be excited by the incident waveguide mode. As a fraction of the dipole cannot be recovered, scattering loss effects take place [9]. Based on [6], the propagation loss coefficient due to scattering by surface roughness can be expressed as

$$\alpha_{\text{cm}^{-1}} = \varphi^2(d)(n_c^2 - n_{\text{cl}}^2)^2 \frac{k_0^3}{4\pi n_c} \int_0^\pi \tilde{R}(\beta - n_{\text{cl}}k_0 \cos \theta) d\theta \quad (1)$$

where  $\varphi^2(d)$  is a modal function only depending on the waveguide geometrical parameters and  $k_0 = 2\pi/\lambda$  is the wavenumber in vacuum. The integral term includes the power spectrum function  $\tilde{R}(\Omega)$  ( $\Omega = \beta - n_{\text{cl}}k_0 \cos \theta$  with  $\theta$  the scattering angle relative to the waveguide axis) which takes into account all the spatial frequencies  $\Omega$  induced by the sidewall roughness. Using the Wiener-Khinchine theorem [6] for the calculation of the total radiated power,  $\tilde{R}(\Omega)$  can be linked to the autocorrelation function  $R(u)$  through a Fourier transform [10]

$$\tilde{R}(\Omega) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} R(u) \exp(i\Omega u) du. \quad (2)$$

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The autocorrelation function  $R(u)$  takes into account the local variations of the effective index linked to the evolution of the sidewall roughness and corresponds to a measurement of the average correlation between one position along the waveguide with another set at a distance  $u$  further along. In the literature, the autocorrelation function is described either by an exponential or by a Gaussian statistic [10]. Experimental investigations have recently shown that an exponential statistic is well suited to characterize sidewall roughness of larger waveguides [11], [12], but to our knowledge, no experimental evidence has been yet reported for submicrometer ones. A sidewall roughness described by an exponential autocorrelation function is assumed in the following such as:

$$R(u) = \sigma^2 \exp\left(-\frac{|u|}{L_c}\right) \quad (3)$$

with  $L_c$  the correlation length and  $\sigma$  the standard deviation. Using (3), analytical calculations can then be carried out and the scattering loss coefficient in decibels per centimeter can be written as [7]

$$\alpha = 4.34 \frac{\sigma^2}{k_0 \sqrt{2} d^4 n_c} g(V) \cdot f(x, \gamma) \quad (4)$$

where  $g(V) = U^2 V^2 / (1 + W)$  is a function depending only on the waveguide geometry with the normalized coefficients  $U = k_0 d \sqrt{n_c^2 - n_{\text{eff}}^2}$ ,  $V = k_0 d \sqrt{n_c^2 - n_{\text{cl}}^2}$ , and  $W = k_0 d \sqrt{n_{\text{eff}}^2 - n_{\text{cl}}^2}$ . The function  $f(x, \gamma)$  is linked to the sidewall roughness

$$f(x, \gamma) = \frac{x \sqrt{1 - x^2 + \sqrt{(1 + x^2)^2 + 2x^2 \gamma^2}}}{\sqrt{(1 + x^2)^2 + 2x^2 \gamma^2}} \quad (5)$$

where the normalized expressions of coefficients  $x$ ,  $\gamma$ ,  $\Delta$ , can be written as

$$x = W \frac{L_c}{d} \quad (6)$$

$$\gamma = \frac{n_{\text{cl}} V}{n_c W \sqrt{\Delta}} \quad (7)$$

$$\Delta = \frac{n_c^2 - n_{\text{cl}}^2}{2n_c^2} \quad (8)$$

Equation (4) shows that the propagation loss coefficient is linked to the roughness parameters  $\sigma$  and  $L_c$ . However, this equation does not include the lateral field confinement. For strip waveguides, scattering mainly comes from the etched vertical sidewalls. In order to take into account the 2-D character of the SOI square waveguides, the effective index  $n_{\text{eff}}$  has been calculated using the film mode matching method which is well suited to high index contrast structures [13]. It is also worth noting that such a model does not take into account a 2-D sidewall roughness. Indeed, as the height of the waveguide is at most equal to 500 nm, the variations of the sidewall roughness along the vertical direction can be neglected. In the following, this numerical model is applied to SOI square strip waveguides with various widths.

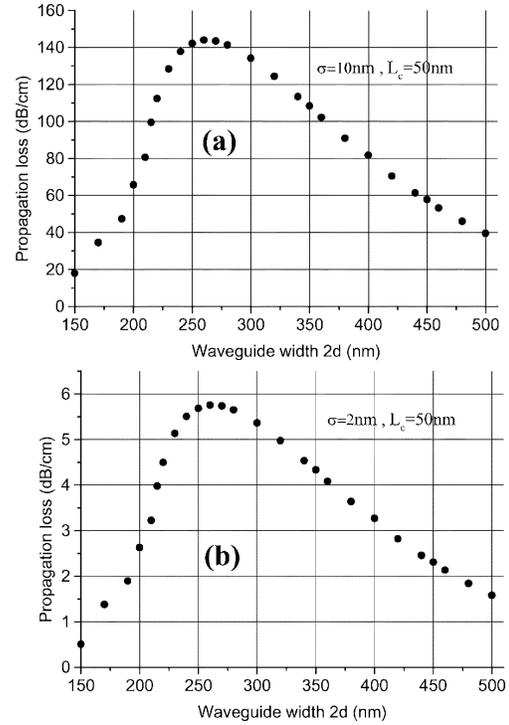


Fig. 1. Calculated propagation loss versus the waveguide width ( $150 \text{ nm} < 2d < 500 \text{ nm}$ ) for the following roughness parameters: (a)  $\sigma = 10 \text{ nm}$  and  $L_c = 50 \text{ nm}$ ; (b)  $\sigma = 2 \text{ nm}$  and  $L_c = 50 \text{ nm}$ .

### III. NUMERICAL RESULTS

An SOI strip waveguide with a square cross section  $2d_x = 2d_y = 2d$  in the range from 500 to 150 nm is assumed for the calculations. The corresponding effective index varies from  $n_{\text{eff}} = 2.90$  (for  $2d = 500 \text{ nm}$ ) to  $n_{\text{eff}} = 1.44$  (for  $2d = 150 \text{ nm}$ ). For each  $d$  value, the propagation losses are calculated from (4). Results are plotted in Fig. 1, where the variation of the calculated propagation loss versus the waveguide size  $2d$  is reported for a correlation length  $L_c$  of 50 nm and a standard deviation  $\sigma$  either equal to 10 [Fig. 1(a)] or 2 nm [Fig. 1(b)]. The roughness parameters have been chosen according to recent measurements obtained on similar structures [3]. In the first case,  $\sigma = 10 \text{ nm}$  corresponds to a usual situation encountered when an RIE pattern process is used [3]. The second example with  $\sigma = 2 \text{ nm}$  can be reached if an oxidation or anisotropic etching step is added to the RIE process [3]. In both situations, two regions can be clearly distinguished in the graphs. When the waveguide width decreases from  $2d = 500 \text{ nm}$  to  $2d = 260 \text{ nm}$ , the sensitivity to sidewall roughness is strengthened since the mode confinement increases. Propagation losses are enhanced from 1.58 to 5.68 dB/cm for  $\sigma = 2 \text{ nm}$  and from 39.55 dB/cm to more than 140 dB/cm for  $\sigma = 10 \text{ nm}$ . It is also important to note single-mode propagation is no more insured if  $2d > 320 \text{ nm}$ . The propagation losses are always calculated for the fundamental mode. As no coupling with higher order modes is taken into account, the propagation losses are underestimated. Loss reaches a maximum value for  $2d = 260 \text{ nm}$  for the structures under consideration, for both  $\sigma$  values. The numerical simulations show that when  $260 \text{ nm} > 2d > 150 \text{ nm}$ , the propagation loss decreases. At the same time, the effective

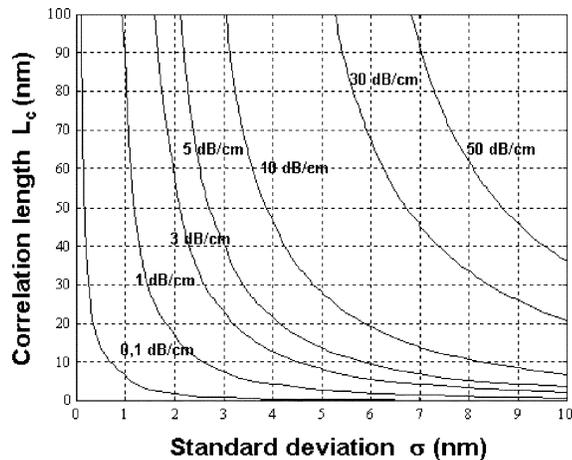


Fig. 2. Contour lines of the propagation loss in the  $(\sigma, L_c)$  plane. The strip waveguide has a  $200 \times 200$  nm cross-sectional dimension.

index decreases from 1.70 to 1.44 [8] and becomes very close to the refractive index of the silicon oxide cladding. This is accompanied by a significant deconfinement of the optical mode which is favorable to the loss reduction. As an example, for  $2d = 150$  nm and  $\sigma = 2$  nm, the predicted mode diameter is  $4 \mu\text{m}$  at  $1/e^2$  and the calculated propagation loss does not exceed 0.50 dB/cm. Such a result is of prime interest for optical telecommunications since a 3-D tapered waveguide ended by a small strip section with low mode confinement can provide an efficient coupling with a single-mode optical fiber [8] with negligible scattering loss. Although for narrow waveguides the expanded field increases the minimum distance avoiding coupling to nearby waveguides or leakage toward the substrate, a compromise can be found around 200 nm which corresponds to a mode diameter of the order of  $0.4 \mu\text{m}$ . Further investigations have been made to estimate the propagation loss for large variation ranges of the roughness parameters  $\sigma$  and  $L_c$ . Assuming that  $0 \text{ nm} \leq L_c \leq 100 \text{ nm}$  and  $0 \text{ nm} \leq \sigma \leq 10 \text{ nm}$ , contour lines of the propagation loss are reported in the  $(\sigma, L_c)$  plane for a  $200 \times 200$  nm cross-sectional waveguide (Fig. 2). On one hand, when  $L_c$  is fixed, the propagation loss increases monotonically with the standard deviation  $\sigma$ . For example, for  $L_c = 20$  nm, when  $\sigma$  varies from 0.5 to 10 nm, propagation loss is enhanced from 0.1 up to 30 dB/cm. On the other hand, when the standard deviation  $\sigma$  is fixed, the propagation loss is less affected by a change in the correlation length. For instance, for  $\sigma = 2$  nm the propagation loss remains smaller than 5 dB/cm over the whole  $L_c$  variation range, from 0 to 100 nm. These simulation results point out the importance of an accurately controlled fabrication process since a variation of the standard deviation induced by a larger fluctuation amplitude at the core-cladding interfaces leads to stronger scattering effects. These results also demonstrate that, for a  $200 \times 200$  nm cross-sectional strip waveguide, although the mode diameter is not affected, remaining close to  $0.4 \mu\text{m}$  at  $1/e^2$  [8], the propagation loss is fairly lower than for a  $320 \times 320$  nm cross-sectional strip waveguide, i.e., close to 30 dB/cm for  $\sigma = 7$  nm,  $L_c = 50$  nm, to be compared to 65 dB/cm.

#### IV. CONCLUSION

A numerical study has been performed to evaluate the propagation loss induced by sidewall roughness in square SOI strip waveguides. Propagation loss strongly depends on the size of the cross section and decreases when the size is reduced, due to a lower optical confinement. It has been shown that for a  $150 \times 150$  nm cross section and with roughness parameters such as  $(\sigma, L_c) = (2 \text{ nm}, 50 \text{ nm})$ , propagation loss as low as 0.5 dB/cm is expected. Those results may have interesting applications for optical telecommunication since 3-D tapered waveguide ended by a strip section with lower confinement can insure very low insertion loss for light coupling between a sub-micrometer single-mode waveguide and a single-mode optical fiber. It has also been shown it may be advantageous to use  $200 \times 200$  nm waveguides instead of  $320 \times 320$  nm as the propagation loss are reduced by a factor larger than two without a significant widening of the guided mode.

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#### REFERENCES

- [1] A. Layadi, A. Vonsovici, R. Orobitchouk, D. Pascal, A. Koster, Y. Tohmori, Y. Itaya, and H. Toba, "Low-loss optical waveguide on standard SOI/SIMOX substrate," *Opt. Commun.*, vol. 146, pp. 31–33, 1998.
- [2] J. Schmidtchen, A. Splett, B. Schuppert, and K. Petermann, "Low loss single-mode optical waveguides with large cross-section in SOI," *Electron. Lett.*, vol. 27, pp. 1486–1488, 1991.
- [3] K. K. Lee, D. R. Lim, L. C. Kimerling, J. Shin, and F. Cerrina, "Fabrication of ultralow-loss Si/SiO<sub>2</sub> waveguides by roughness reduction," *Opt. Lett.*, vol. 26, no. 23, pp. 1888–1890, 2001.
- [4] P. D. Trinh, S. Yegnanarayanan, F. Coppinger, and B. Jalali, "Silicon-on-insulator (SOI) phased-array wavelength multi/demultiplexer with extremely low-polarization sensitivity," *IEEE Photon. Technol. Lett.*, vol. 9, pp. 940–942, July 1997.
- [5] L. Vivien, S. Laval, B. Dumont, S. Lardenois, A. Koster, and E. Cassan, "Polarization-independent single-mode rib waveguides on silicon-on-insulator for telecommunications wavelength," *Opt. Commun.*, vol. 210, pp. 43–49, 2002.
- [6] F. P. Payne and J. P. R. Lacey, "A theoretical analysis of scattering loss from planar optical waveguide," *IEEE Proc. Optical and Quantum Electron.*, vol. 26, pp. 977–986, 1994.
- [7] K. K. Lee, D. R. Lim, H. C. Luan, A. Agrawal, J. Foresi, and L. C. Kimerling, "Effect of size and roughness on light transmission in a Si/SiO<sub>2</sub> waveguide: Experiments and model," *Appl. Phys. Lett.*, vol. 77, no. 11, pp. 1617–1619, 2000.
- [8] L. Vivien, S. Laval, E. Cassan, X. Le Roux, and D. Pascal, "2-D taper for low-loss coupling between polarization-insensitive microwaveguides and single-mode optical fibers," *J. Lightwave Technol.*, vol. 21, pp. 2429–2433, Oct. 2003.
- [9] W. Boagarts, P. Bienstman, and R. Baets, "Scattering at sidewall roughness in photonic crystal slabs," *Opt. Lett.*, vol. 28, pp. 689–691, 2003.
- [10] F. Ladouceur, J. D. Love, and T. J. Senden, "Effect of side wall roughness in buried channel waveguides," *Proc. Inst. Elect. Eng., Optoelectronics*, vol. 141, no. 4, pp. 242–248, 1994.
- [11] —, "Measurement of surface roughness in buried channel waveguides," *Electron. Lett.*, vol. 28, no. 14, pp. 1321–1322, 1992.
- [12] F. Ladouceur, "Roughness, inhomogeneity and integrated optics," *J. Lightwave Technol.*, vol. 15, pp. 1020–1025, June 1997.
- [13] FIMMWAVE Software, Photon Design [Online]. Available: www.photon.com