Backscatter-Induced Transmission Noise and Length-Dependent Attenuation in Silicon Waveguides

Y. Xing,[1,2] A. Li,[1,2] R. Van Laër,[1,2] R. Baets,[1,2] and W. Bogaerts[1,2,3]

[1] Photonics Research Group, Ghent University-Imec, Technologiepark 15, Ghent, 9052, Belgium
[2] Center for Nano- and Biophotonics, Ghent University, Belgium
[3] Luceda Photonics, Dendermonde, 9200, Belgium

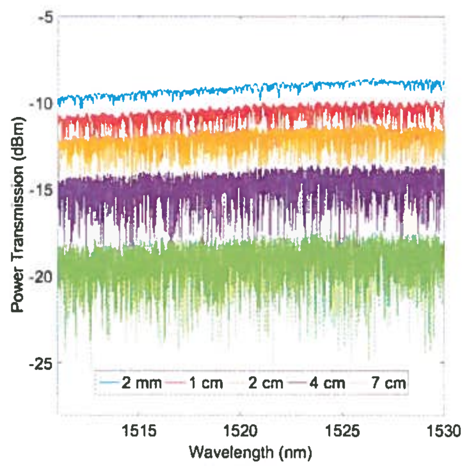
A SOI waveguide is considered well behaved and understood. Surprisingly, we observed in 7cm-long waveguides sharp fluctuations of more than 15 dB in transmission spectrum, which we attribute to the interference between the guided mode and multiple backscatters on waveguide sidewalls. To understand how the backscattering and the fluctuation are related, we built a lumped-circuit waveguide model in CAPHE that includes backscattering and recaptured sharp fluctuations as measured. A relation between fluctuation statistics and backscattering strength is found, facilitating a derivation of backscattering from transmission measurements. Using our CAPHE model, we found the transmission attenuation rate non-constant when backscattering is considered. Rather unexpected, it is waveguide length dependent. Using Coupled-Power Theory, we well explained and qualitatively revised the theory to calculate the average waveguide transmission.

Fluctuation in waveguide transmission

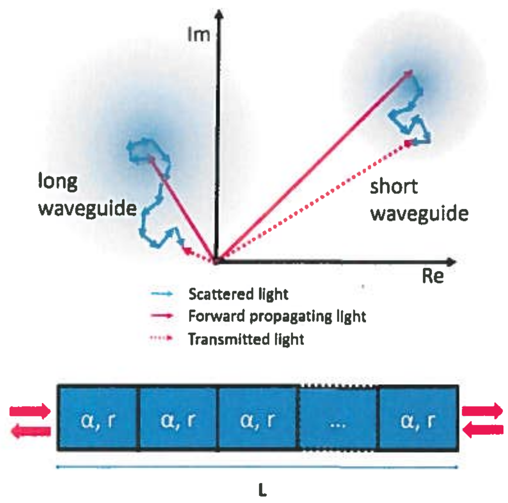
Si-on-insulator (SOI) waveguide is considered as a light guiding channel with exponential loss and linear phase change along light propagation. When having a small dispersion and little reflection on its two facets, its transmission is expected to be nearly flat over of the spectrum. However, we observed high random spectral fluctuations in the transmission of waveguides fabricated by the standard Imec 193 nm deep-UV lithography. A 7 cm long air-clad waveguide exhibits extreme fluctuations as large as 15 dB (Fig. 1a). The fluctuation might fundamentally kill the performance of a waveguide-based device.
We attribute the fluctuation to the backscattering on the rough waveguide sidewalls. The roughness sets up a large number of scattering centers, on each of which a small portion of light scatters with a random phase. The forward guided mode interferes with many small forward contributions that reflect at least twice on scatters. The interference explains the spectral fluctuation (Fig. 1b). When all the scatterings are out of phase with the guided mode, it leads to a sharp dip in the spectrum. As seen in the measurement, an increasing waveguide length leads to a larger number of scatters, therefore, stronger spectral fluctuations (a bigger uncertainty cloud on the phasor plot).

Lumped-circuit waveguide model

To understand how backscattering affects the waveguide transmission, we build a lumped-circuit waveguide model in the circuit simulator CAPHE. CAPHE describes each photonic block by scattering matrix and the connection between them by a netlist. In CAPHE, we divided a waveguide into multiple cascaded short blocks each of 25 μm. To incorporate scattering in our model, we build a block by two parts: a transmission section with



(a) Measured power spectral transmission of 2mm, 1cm, 2cm, 4cm and 7 cm waveguide with 1 pm resolution.



(b) Up: Random phasor model of light in a waveguide. Down: Lump-circuit waveguide model.

constant loss α and a fixed phase change and a reflector that reflects a fixed portion r of light with a uniformly distributed random phase change ϕ.
With the CAPHE model, we describe a waveguide by three parameters: unit length loss α, unit length reflection r and waveguide length l. By playing with these parameters, we reproduced the spectral fluctuations as measured, which is a validation of the model. [1]

Statistical model of transmission fluctuation

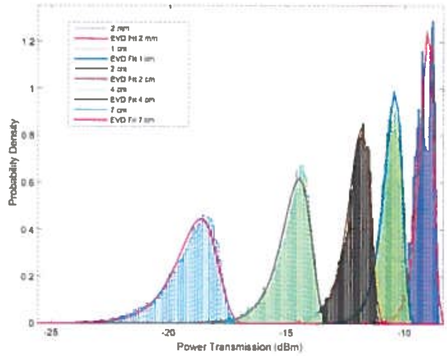
Severe fluctuations may stop light from passing through the waveguide. Therefore when we design waveguide-based devices, we want to know the possibility of severe fluctuations to avoid extreme fluctuations. The power transmission T is a random number that is manifested by spectral fluctuations. Both in measurements and in CAPHE simulation, the log-scale transmission follows an Extreme-Value distribution (EVD) and its probability density function (PDF) is expressed as:

$$p(x) = \frac{1}{\sigma_{EV}} \cdot e^{\frac{\mu_{EV}-x}{\sigma_{EV}} - exp\left(\frac{\mu_{EV}-x}{\sigma_{EV}}\right)} \tag{1}$$

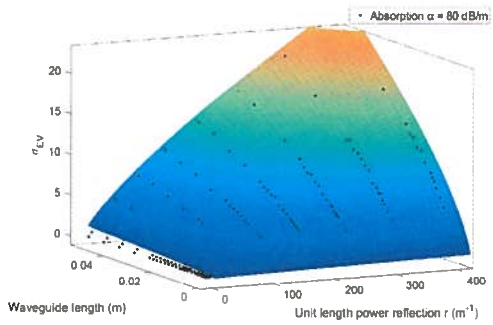
In CAPHE, we simulated waveguide transmission under a set of α, r and l. Then, we fit the simulated transmission spectrum with EVD and get μ_{EV} and σ_{EV}. We found the relation between waveguide fabrication parameters and statistical parameters μ_{EV} and σ_{EV} can be approximated as:

$$\begin{aligned} \mu_{EV} &= p_1 \cdot l^{p_3 \cdot \alpha} + p_2 \cdot l^{p_4 \cdot r} \\ \sigma_{EV} &= q_1 \cdot r^{q_2 + q_4 \cdot \alpha^{q_5}} \cdot l^{q_3 - q_4 \cdot \alpha^{q_5}} \end{aligned} \tag{2}$$

where α is the unit length loss, r is the unit length reflection and l is the waveguide length. $p_i (i = 1,2,3,4)$ and $q_j (j = 1,2,3,4,5)$ are constant. This relation tells the PDF of the transmission T of a specific waveguide. In turn, we can extract the reflectivity, loss by a set of measurements of waveguides of increasing length.



(a) Histograms of 2mm, 1cm, 2cm, 4cm and 7 cm waveguide power transmission in dBm. We fit each histograms using the Extreme Value Distribution (solid line).



(b) σ_{EV} vs. r and l at α = 80 dB/m. The Eq (1) (colored surface) fits well with simulated data using the CAPHE model.

Length-dependent transmission attenuation rate

A waveguide is considered to be a guiding structure with a constant linear attenuation rate along its propagation. So generally, we measure a short waveguide and a long one to get the attenuation rate that is assumed not waveguide length-dependent. However, when scattering induced reflection is involved, the attenuation rate is no longer a constant over an increasing waveguide length. When a waveguide has a 0.2 dB/cm absorption, CAPHE simulation shows that the transmission attenuation rate is not a constant. Instead, it becomes more waveguide length-dependent as reflectivity increases from 20 m^{-1} to 180 m^{-1}.

When there is backscattering, there are two modes in a waveguide: a forward propagating mode ϕ_f and a backward mode ϕ_b, where the reflection on scatters couples two modes. Given that the ϕ_f and ϕ_b are power of forward and backward modes along waveguide direction z, we can calculate power transmission $\phi_f(l)$ of waveguide with l length using Coupled Power Theory (CPT) as:

$$\begin{aligned} \frac{d\phi_f}{dz} &= -(\alpha+r)\phi_f + r\phi_b \\ \frac{d\phi_b}{dz} &= +(\alpha+r)\phi_b - r\phi_f \end{aligned} \tag{3}$$

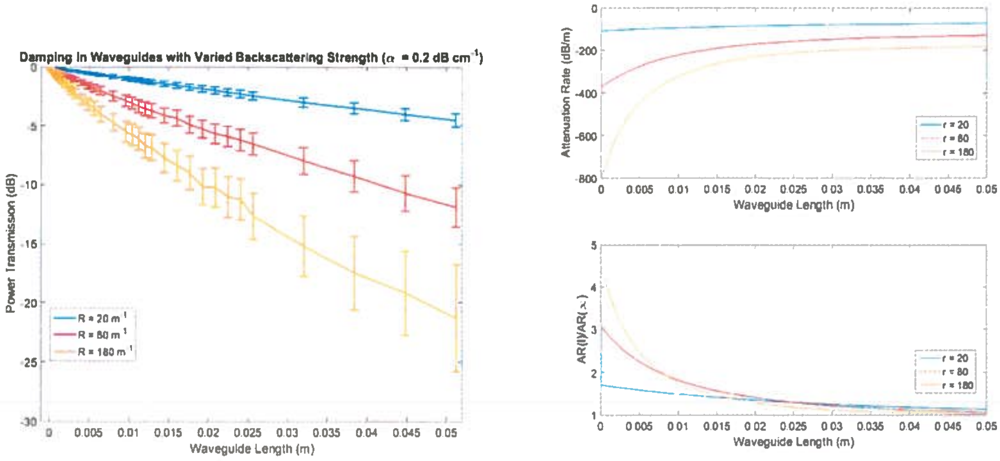
where α is the unit length power absorption in waveguide, and r is the unit length power reflection. Under boundary condition $\phi_f(0) = 1$ and $\phi_b(l) = 0$, the power transmission of the waveguide with length l is:

$$\phi_f(l) = \frac{2\sqrt{\alpha}\sqrt{\alpha+2r}e^{\sqrt{\alpha}\sqrt{\alpha+2r}l}}{(\alpha+r)\left(e^{2\sqrt{\alpha}\sqrt{\alpha+2r}l}-1\right)+\sqrt{\alpha}\sqrt{\alpha+2r}\left(e^{2\sqrt{\alpha}\sqrt{\alpha+2r}l}+1\right)} \tag{4}$$

The derived solution fits the CAPHE model generated transmission well. With the CPT solution, we calculate the attenuation rate of waveguides over increasing length. Notice that, the attenuation rate is higher in shorter waveguides and approaches a constant value in longer waveguides, which is because there are two sources of attenuation: absorption and reflection. When light travels in a waveguide, initially it suffers both absorption and reflection. As it goes further, more forward power couples into the backward mode. The backward mode also couples into forward mode on scatters thus partially compensating the attenuation in the forward mode. The coupling between both modes reaches an equilibrium as waveguide length increases. For an infinitely long waveguide, its attenuation rate can be calculated by Eq. (4) as:

$$AR(\infty) = \sqrt{\alpha} \cdot \sqrt{\alpha + 2r} \tag{5}$$

As shown in Fig. 3b, when $\alpha = 0.2dB/m$ and $r = 180/m$, attenuation rate can be more than 4 times as high as the infinitely long waveguide.



(a) Measured power spectral transmission of 2mm, 1cm, 2cm, 4cm and 7 cm waveguide with 1 pm resolution.

(b) Up: Attenuation rate (AR) vs. waveguide length. Down: Ratio of AR of l long waveguide by AR of infinitely long waveguide.

References

[1] Y. Xing, A.Li, R. Van Laer, R. Baets and W. Bogaerts. "Backscatter Model for Nanoscale Silicon Waveguides." in *Optical Wave & Waveguide Theory and Numerical Modelling, 24th International Workshop*, 2016.