FDTD Simulation of Stochastic Scattering Loss Due to Surface Roughness in Optical Interconnects

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***Abstract*—We investigate the scattering loss in optical interconnects comprised of dielectric slab waveguides operated at 1.54 μm source wavelength and exhibiting stochastic sidewall roughness, using the method of finite-difference time-domain (FDTD). Power degradation is numerically computed and compared against an existing analytical solution. Results show correlation between the proposed FDTD method and analytical model. A normalization is enforced based on input power to compensate for physical waveguide parameters.**

I. Introduction

In the optical regime, the silicon-on-insulator (SOI) optical interconnect is a crucial component. A planar analog in 2-dimensional (2D) space is the dielectric slab waveguide. Previous works have shown that, at the nano-scale, optical interconnects exhibit stochastic sidewall roughness with large per-unit-length power degradation due to scattering [2] [3] [4]. This paper continues the work in [5] by attempting to correlate the existing analytical solution [2] [3] for scattering loss due to sidewall roughness, by using the FDTD method via low-cost computer simulation of nano-scale optical interconnects.

II. Formulation

A. Analytic Expression

Equation (31) in [6] proposes an expression for the TE modal field amplitudes, based on physical waveguide parameters. Using it, we set A_e of equation (73) in [6], such that the normalization of equation (16b) in [2] is enforced, below

$$\int_{-\infty}^{\infty} \Phi^2(x)dx = A_e^2(d+\frac{1}{\gamma}) = 1, \qquad (1)$$

where the expression for loss is $\alpha = \Phi^2(d)M_W S_W$ (Np/m) [2], [3].

S_W represents the effects of the autocorrelation function. A common autocorrelation function (ACF) is the exponential ACF (2), where σ^2 is the variance of the random distribution and L_c is the correlation length [3].

$$R_{XX}(\zeta) = \sigma^2 e^{-\frac{|\zeta|}{L_c}} \qquad (2)$$

B. Simulation Setup

The FDTD method [7] is used to simulate a dielectric slab waveguide in 2D. The slab is operated in the *transverse-electric-to-z (TE^z) mode* with field components E_y, H_x, and H_z. The geometry for the simulation setup can be seen in Fig. 1. In this case the waveguide width $\delta = 2d = 200$ nm, the core refractive index $n_1 = 3.5$, and the cladding refractive index $n_2 = 1.5$. The refractive indices are chosen to correspond with the Si/SiO$_2$ interaction. The field excitation for each simulation setup is a Gaussian pulse modulated by a sinusoid with a frequency $f_0 = 194.8$ THz, and fields are absorbed at the boundary by 40 layers of the CPML [8] and 100 buffer layers of cladding. The spatial resolution is set by a maximum frequency $f_{\text{max}} = Hf_0$, where H is set to either 4 or 2 for generation of the tables. The temporal resolution is set at the Courant stability limit for 2D space.

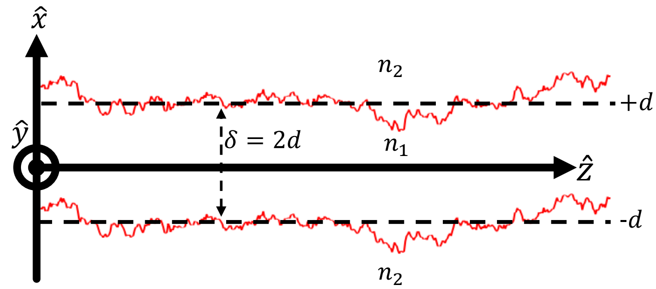

Fig. 1. FDTD simulation geometry.

Time domain E-field data are collected across $\hat{x}$ at two points separated by ℓ (cm) along $\hat{z}$. Power loss is calculated by (3), where $\tilde{V}_1$ is nearest to the source. $\tilde{V}_1$ and $\tilde{V}_2$ are calculated by performing a Fast Fourier Transform followed by a numerical integration over the interval $[-d, +d]$ on the E-field, where $\tilde{V}$ is the Fourier Transform of V [9].

$$\alpha = \frac{1}{\ell} 20 \log \frac{|\tilde{V}_2|}{|\tilde{V}_1|} \qquad \text{(dB/cm)} \qquad (3)$$

III. Results and Discussion

A. Effects of Discretization on Autocorrelation

Since computational systems are unable to run infinite spaces, some effects of truncation are unavoidable. This extends to the ACF experienced by the FDTD waveguide. A sample discrete ACF is compared against the ideal ACF in Fig. 2, and there are two notable differences. The most apparent deviation of the discrete ACF from the ideal ACF is the "ringing" for $\zeta > 1$ μm, and the second difference is the total

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overlap point, $|\zeta| < 10^{-2}$, having a value that is not exactly equal to the specified variance. These discrepancies may, in part, contribute to the difference between numerical simulation of finite length waveguides and the analytical model.

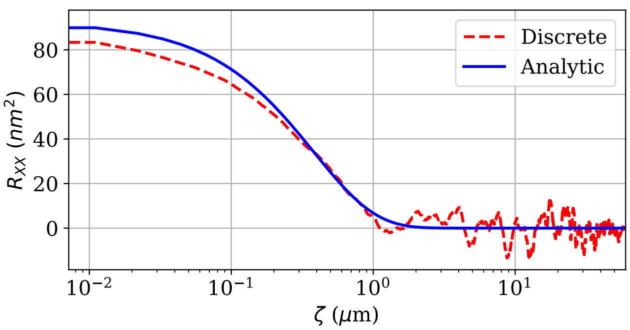

Fig. 2. Right half of a sample ACF vs. the ideal ACF.

B. Numerical Experiments

The FDTD method is used to solve a discretized dielectric slab waveguide with stochastic sidewall roughness, where the upper and lower roughness profiles are identical (correlated). Correlated profiles are used to reduce numerical noise and show setup changes more distinctly. This setup is tested with $\sigma = 9$ nm and $\sigma = 15$ nm over a range of correlation lengths. The nominal loss value for each setup is calculated and converted to have units of (dB/cm) by multiplying (1) by 0.08686. This value is then compared against the computed loss value from FDTD. The minimum, mean, and maximum percentage difference from the expected loss value for each test-case is shown in Tables I and II. In order to reduce some errors resulting from the stochastic nature of the problem, ten simulations are run for each setup. For each setup, a unique rough profile is generated, discretized, and evaluated for proximity to the desired setup conditions. Each profile is considered *valid* if the computed discrete parameters (σ, L_c) are within $\pm 10\%$ of the desired value. The evaluated discrete parameters are then used in the analytical calculation for each individual simulation, dependent on the true roughness profile experienced by the FDTD simulation.

σ = 9 (nm)

	Analytic	Error (%)		
Lc (nm)	α (dB/cm)	Min	Mean	Max
400	407.0	-11.19	11.60	23.51
500	339.2	-8.16	0.78	19.96
600	289.3	-21.82	-7.67	11.09
700	251.6	-29.20	-8.56	3.65
800	222.3	-15.19	0.99	12.06
900	198.9	-25.30	6.24	42.85
1000	179.9	-24.79	-1.91	22.53

TABLE I

α IS THE ANALYTICAL VALUE FOR THE CORRESPONDING SETUP. MEAN OF MEAN ERRORS IS: 0.21%

The average of the mean of the mean errors across L_c for both $\sigma = 9$ nm and $\sigma = 15$ nm is approximately -0.38%,

σ = 15 (nm)

	Analytic	Error (%)		
Lc (nm)	α (dB/cm)	Min	Mean	Max
200	1726.0	11.18	19.01	25.70
300	1390.2	2.30	12.61	25.70
400	1130.4	-11.28	6.78	20.83
500	942.2	-25.01	3.97	15.73
600	803.7	-23.74	-5.34	16.17
700	699.0	-27.69	-3.94	11.33
800	617.5	-45.18	-13.05	17.17
900	552.5	-40.71	-15.51	15.88
1000	499.7	-30.64	-13.18	12.02

TABLE II

α IS THE ANALYTICAL VALUE FOR THE CORRESPONDING SETUP. MEAN OF MEAN ERRORS IS: -0.96%

showing a reasonable correlation between the numerical experiments in FDTD and the analytical solution. It may be noted that while ten simulations per setup can provide a rough trend, adding many more simulations for each test case would help increase statistical confidence in the correlation between analytical and FDTD results.

IV. Conclusion

A dielectric slab waveguide exhibiting stochastic sidewall roughness was simulated in 2D FDTD, where the surface roughness exhibited randomness according to an exponential autocorrelation function. The FDTD simulation results were compared against a known analytical solution and showed statistical error near -0.38%. Work is currently underway to explore ways to further reduce the error and to extend the work into 3D space.

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