# Simulation of Nonlinear Optical Absorption in Silicon Optical Waveguide

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**INTRODUCTION**: From the perspective of nonlinear silicon photonics, the strong light confinement in sub-micron sized silicon waveguides increases the effective nonlinearity. However, the high optical power density in the waveguide core also increase nonlinear absorption and hence the device self-heating [1]. In this work, effects of two photon absorption (TPA) and TPA-induced free carrier absorption (FCA) are investigated at the 1550nm telecom wavelength (C-band) in continuous-wave light scenario.

**3D Simulation:**

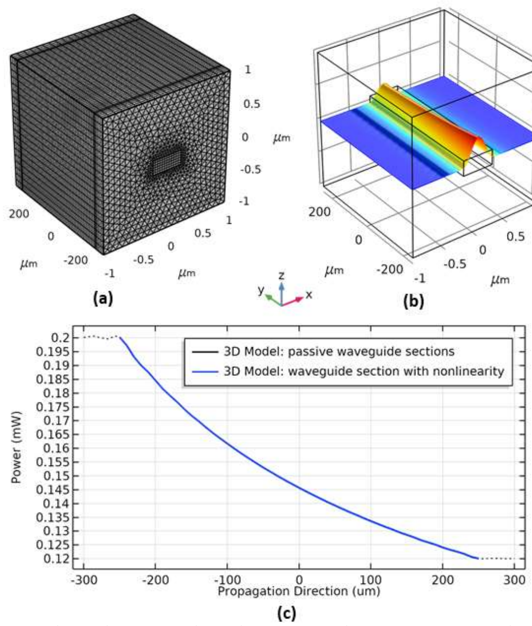


**Figure** 1 Three-dimensional nonlinear optical transmission simulation for a silicon waveguide. (a) Swept Meshing for a 0.5mm long waveguide. (b) Norm of E-field of light in the horizontal cross section of waveguide. (c) Optical power (Integrated optical power flux) along propagation direction.

The first principle nonlinear loss definition is introduced to the imaginary part of silicon refractive index, which is a function of the spatial electric field strength. Buffer regions with linear silicon refractive index are used to facilitate boundary optical mode computations. As shown in Fig.1, it is feasible to simulation a first principle 3D nonlinear optical transmission through a 0.5mm long silicon waveguide. Linear discretization is used to make this 3D simulation run possible on a laptop with 8GB free memory. Given adequate computational resources, the coupled TPA-induced free carrier effects and self-heating in silicon may be simulated in full dimension.

**1D Effective Model Along Propagation Direction:**

One-dimensional nonlinear propagation equation of optical power P along propagation direction z is widely used in nonlinear optics community.

$$\frac{\partial P}{\partial z} = -\frac{\beta}{A_{eff}}P^2 - \sigma\frac{\tau\beta}{2\hbar\omega}\frac{P^2}{A_{eff}^2}P \qquad Eq.(1)$$

Here $\beta$ is TPA coefficient. $A_{eff}$ is effective cross section area of TPA. $\sigma$ is FCA cross section. $\hbar\omega$ is photon energy.

**REFERENCES**:

1. Minhao Pu, Yaohui Chen, Kresten Yvind, Influence of thermal effects induced by nonlinear absorption on four-wave mixing in silicon waveguides, IEEE conference on Group IV photonics, 2014.

**2D+1D segmented Simulation** (2D cross section and 1D propagation direction) has been used to downscale the overall computational cost and time. And a computationally lite application is built for web-based Comsol server usage scenario.

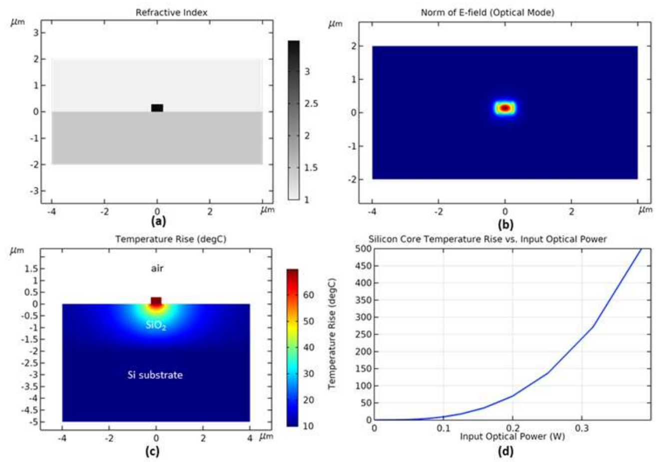


**Figure** 2 Two-dimensional opto-thermal simulations for a silicon waveguide. (a) Refractive index of a Silicon Waveguide (450x285nm$^2$) with 2um buried oxide layer. (b) Optical waveguiding mode profile. (c) Temperature distribution profile due to nonlinear absorption in the presence of 200mW optical power (1000W/m$^2$/K heat transfer coefficient at the bottom of 500-um-thick Silicon substrate) (d) Temperature rise in silicon waveguide core as a function of input optical power.

The two-dimensional opto-thermal simulations are shown in Fig.2. Wave optics module is used to simulate the optical waveguiding mode in the 2D cross section of waveguide. Optical energy density (correlated to optical power flux density) is used to approximate first principle nonlinear optical absorption (TPA and FCA) with the relevant effective area value. Here all absorbed light power density (in unit of W/m$^3$) is assumed as spatial heating source in the core of silicon waveguide. Heat transfer module is used to simulate the thermal problem in this 2D cross section of waveguide. For realistic estimation of silicon-on-insulator structure, the thermal problem considers stacks of a 500um-height silicon substrate and a 2um-height silicon dioxide layer. A realistic heat transfer coefficient is defined at the bottom of silicon substrate to emulate cooling effects by a heat sink.

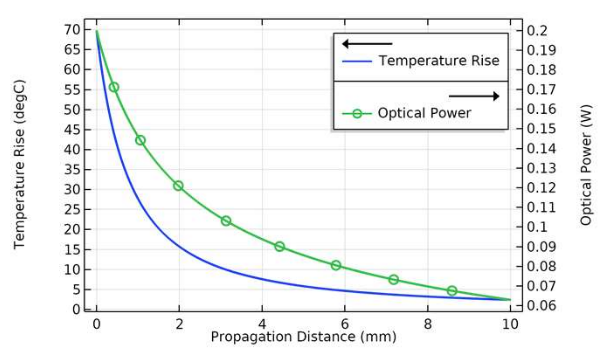


**Figure**.3 1D opto-thermal simulations for a silicon waveguide based on 2D cross-section solutions. Optical power and the corresponding temperature rise in a 10mm-long strip waveguide.

One-dimensional opto-thermal simulation are shown in Fig.3. Two-dimensional solutions from optical and thermal solvers (shown in Fig.2) are projected into parameters used in a 1D effective propagation equation of optical power along waveguide propagation direction, which is implemented in general PDE form. The approximated temperature rise is interpolated as function of optical power based on pre-calculated 2D solution.