Birefringence Induced in Optical Rib Waveguides by Thermal and Mechanical Stresses

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Abstract:
In this paper a multiphysics approach to study the optical properties of integrated waveguides influenced by thermal and mechanical stress is presented. The heating and pressure effects are evaluated by means the Heat Transfer and Structural Mechanics modules respectively. Finally, the Electromagnetics Module is used in order to evaluate the optical eigenfunctions and eigenvalues.

Keywords: Integrated Optics, Silicon Photonics, Birefringence, Multiphysics Modeling.

1. Introduction
For decades, silicon has been considered the optimal material for electronics mass production. In the last few years, the possibility to realize highly performing active and passive photonic integrated devices using Silicon-on-Insulator (SOI) technological platform has been widely proved [1]. One of the most important aspects of any integrated optical technology for sensing or communication applications is the evaluation and control of the optical birefringence [2]-[6]. Generally speaking, the optical birefringence depends on the waveguide cross section, material and plasma dispersion effect [7], and mechanical stress. In this context, a detailed study has been proposed in [8], demonstrating that the stress engineering can be considered as an effective tool to modify or eliminate polarization dispersion in SOI waveguide devices, for a wide range of waveguide cross-section shapes and sizes. In addition, calculations and experiments proposed in [8] confirm that the SiO$_2$ cladding induced-stress can be used to eliminate the birefringence in SOI waveguides of arbitrary shapes for typical film stress values ranging from 100 to 300 MPa. Therefore, the goal of this work is to develop a self-consistent and integrated approach, in order to generalise the analysis presented in [8] including thermal and mechanical stress effects on guided-wave propagation in optical rib waveguides.

In practical applications, a rib waveguide is often in contact with a surface at higher temperature that causes heat flow into the device: this results in material strain and, ultimately, in an optical birefringence. Besides, in many applications of such components, strain is also produced by a pressure that acts on the device. The situation is illustrated in Fig. 1 (a), where $F$ is the force applied on the device and $Q$ is the heat propagating into it. A silicon-on-insulator rib waveguide is in contact with an aluminum layer through a silica layer; the heat flow is caused by the heated aluminum layer whose temperature is higher than that of the rib. The aluminum layer also transmits the pressure on the component. The stresses applied to the waveguide material structure cause each mode to be rotated. Thus, in this paper we use Comsol Multiphysics$^\text{TM}$ [9] to obtain a fully integrated simulations of SOI waveguides in order to estimate the birefringence effect.

Figure 1. (a) Domain structure; (b) SOI waveguide cross-section.

2. Physical Modeling

The goal of this section is to analyze the thermal and stress influence on the guiding properties of SOI waveguides. In this context, it is worth to briefly describe the procedure for the effective refractive index calculations for both quasi-TE and quasi-TM modes. With the aim to realize self-consistent simulations, we have implemented an integrated algorithmic procedure based on Finite Element Method (FEM) [9], in which the FEM electromagnetic module works together with
the FEM heat transfer and stress modules in order to take into account the thermal and stress effects on the material refractive index.

At the first step, the thermal distribution into the structure is evaluated considering the heat propagation from the aluminum layer towards the SOI waveguide, as described by the following partial differential equation:

\[
\rho C \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = Q
\]

being \( T \) the temperature variable, \( \rho \) the density, \( C \) the heat capacity, \( k \) thermal conductivity, and \( Q \) the heat source (or sink).

Thus, the solution of Eq. (1) is obtained by setting the temperature boundary condition at the interface between the aluminum layer and the adjacent layer. Fig. 2 shows the temperature distribution in all active domains and in steady-state regime, assuming the aluminum and room temperature \( T_{Al} = 350 \, \text{K} \) and \( T_{room} = 293 \, \text{K} \), respectively. Hereinafter, the simulations are performed considering a mesh with 76776 degrees of freedom.

\[
\begin{bmatrix}
T_x \\
T_y \\
T_z
\end{bmatrix} = \frac{E_l}{(1+\nu)(1-2\nu)} \begin{bmatrix}
1-\nu & \nu & \nu \\
\nu & 1-\nu & \nu \\
\nu & \nu & 1-\nu
\end{bmatrix} \begin{bmatrix}
\sigma_x \\
\sigma_y \\
\sigma_z
\end{bmatrix}
\]

\[
\alpha_{thermal}E_l \left( T_{ridge} - T_{room} \right)
\]

\[
F_y = 10^5 \, \text{N/m}^2
\]

\[
\begin{align*}
\sigma_x &= \left( \sigma_x - \sigma_0 \right)^2 + \left( \sigma_y - \sigma_0 \right)^2 + \left( \sigma_z - \sigma_0 \right)^2 \\
\sigma_x &= \left( \sigma_x - \sigma_0 \right)^2 + \left( \sigma_y - \sigma_0 \right)^2 + \left( \sigma_z - \sigma_0 \right)^2
\end{align*}
\]

Fig. 3 shows the Von Mises stress defined as:

\[
2\sigma^2 = \left( \sigma_x - \sigma_y \right)^2 + \left( \sigma_y - \sigma_z \right)^2 + \left( \sigma_z - \sigma_x \right)^2
\]

The plot represents the distribution \( \sigma_x (x,y) \) as induced by a temperature metal layer of 350 K and an applied external pressure \( F_y = 10^5 \, \text{N/m}^2 \). As it is evident, the stress field is mainly concentrated in the waveguide region confirming as the thermal and stress effect can strongly influence the optical modes propagating into the device.

The solution of Eq. (2) (see Fig. 3) is then used to evaluate the stress-induced material anisotropy as described by the following relations [8]:

\[
\begin{align*}
n_x - n_0 &= -B_1 \sigma_x - B_2 \left( \sigma_y + \sigma_z \right) \\
n_y - n_0 &= -B_1 \sigma_y - B_2 \left( \sigma_x + \sigma_z \right)
\end{align*}
\]

being \( n_0 \) the refractive index of the material without stress (Si or SiO2), and \( B_1 \) and \( B_2 \) the stress-optical constants dependent by the material photoelastic tensor \( (P_{ij}) \), defined as in [8].
Finally, optical mode field distributions propagating within the device and their effective indices $n_{eff}$ can be calculated as eigenfunctions and eigenvalues of the following equation:

$$\nabla \times \left( \varepsilon_{zz}^{-1} \nabla \times H_t \right) - \varepsilon_{zz} \nabla \cdot \left( \mu_{zz}^{-1} \nabla \cdot H_t \right) - \left( k_0^2 \mu_t - \beta^2 \varepsilon_0 \right) H_t = 0$$

(4)

where $\varepsilon_{zz}$, and $\mu_{zz}$ are the z-components of relative permittivity and permeability tensors, respectively. The terms $\varepsilon_{zz}$, and $\mu_{zz}$ represent the 2-by-2 tensors in the transversal x-y plane.

It is worth to note that, for accuracy reasons, the calculation window for the stress module is 40 times larger than the window require for the calculation of the waveguide modes.

3. Numerical Results

For the following simulations, we consider two different SOI waveguides, named Wg1 and Wg2, characterized by the following dimensions properly named according to the schematic shown in Fig. 1(b):

- Wg1: $H_d = 0.22 \mu$m, $W = 1 \mu$m, $H = 1 \mu$m, $H_R = 0.78 \mu$m;
- Wg2: $H_d = 0.22 \mu$m, $W = 0.5 \mu$m, $H = 0.61 \mu$m, $H_R = 0.39 \mu$m.

For both waveguides considered the first and the second mode are always aligned as a quasi-TE, and a quasi-TM mode, respectively. Figs. 4 and 5 show the dominant component of the electric field for quasi-TE and quasi-TM modes respectively, and assuming $T_{al} = 350 K$ and $F_y = 10^5$ N/m$^2$.

Performing a number of simulations based on the multiphysics approach described before, we evaluate the thermal and stress dependence of the effective refractive index. The results for the waveguide Wg1 are shown in Figs. 6 and 7, where the effective refractive index is plotted as a temperature and pressure function, respectively. The curves indicate that the effective refractive index for quasi-TE, and quasi-TM modes increases by increasing the temperature with a thermal slope ($S_{th}$) of $5.92 \times 10^{-7}$, and $4.33 \times 10^{-7}$ RIU/K, respectively. The opposite trend is observed in the case of pressure changes (see Fig. 7) where a negative pressure slope ($S_p$) of $-2 \times 10^{-12}$, and $-5.67 \times 10^{-12}$ RIU/(N/m$^2$) are obtained for quasi-TE and quasi-TM modes, respectively.

Similar simulations have been performed for the waveguide Wg2 as shown in Figs. 8 and 9. Our investigations indicate that the Wg2 presents a $S_{th}$ coefficient of about $6.31 \times 10^{-7}$ and $4.51 \times 10^{-7}$ RIU/K for quasi-TE, and quasi-TM modes, respectively.

On the contrary, observing Fig. 9, the pressure slope $S_p$ assumes values of $-2.85 \times 10^{-10}$, and $-8.23 \times 10^{-11}$ RIU/(N/m$^2$) for quasi-TE and quasi-TM modes, respectively.
4. Conclusions
In this paper a fully integrated multiphysics model, involving heat transfer, mechanical stress and electromagnetic modules, has been used for SOI waveguides. Physical effects induced by heating and external pressure acting on the waveguide structure have been investigated. Effective refractive index changes for quasi-TE and quasi-TM optical modes have been calculated for SOI waveguides with micro and nano-scale cross section.
Through this calculation, a thermal and pressure slope has been estimated in order to realize an useful tool for the design of optical waveguides under different temperature and pressure conditions.

5. References