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# Design of an Erbium-Organic Slot Waveguide on Silicon on Insulator for C-Band Optical Amplification

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## Introduction

Photonic Integrated Circuits represent a key topic to overpass the frequency limits of the current microelectronics tecnologies and keep the pace of the Moore's Law. Exploiting the technologies and materials developed for the optical communications and integrating them on a shared substrate working as a platform allow to benefit of the potential THz bandwidth of photonic frequencies. Therefore, wavelengths of the near infrared, grouped mainly in the O-band (1260 nm - 1360 nm) and the C-band (1530 mm- 1565 nm) are used as ranges of interest for signal transmission within the PICs. Silicon photonics technology [1], aiming at implementing all the main optical functions on a shared Silicon platform, is the most appealing technology for the industry given the Silicon-based CMOS technology to be the current pervasive technology in the microelectronics industry. Silicon Organic Hybrid technology [2] is a branch of silicon photonics that exploits the properties of organic materials on Silicon on Insulator (SOI) substrates to achieve optical functions integrated on Silicon such as over 100 GHz modulation [2] and electroluminescence [3]. The availability for solution processing of organics [4] on SOI enable low cost fabrication of SOH technology, making it more appealing for industrial processing.

Nevertheless, waveguiding through an organic material laying on Silicon is made hard by the negative index contrast between the low index organic (eith $n$ typically between 1.3 and 1.6) and Silicon ($n$=3.48 at the wavelengths used in the optical communications). Slot waveguides [5], consisting of two silicon rails surrounded by dielectric material, are the solution to the negative index contrast as because of the strong field discontinuity at the interface Silicon/dielectric and the following field displacement continuity imposed by Maxwell equations, there is a strong field enhancement within the slot of a factor $n_{Si}^2/n_{slot}^2$, with $n_{Si}$ the refractive index of Silicon and $n_{slot}$ the refractive index of the dielectric material into the slot. Therefore, the field enhancement results in optical field to be confined in the spatial slot region between the rails, i.e. in the low refractive index dielectric material.

If the dielectric material is light-emitting, then the slot waveguide has the potential to work as a waveguide amplifier, with light confined and propagating into the active medium that provides optical amplification [6]. Optimization of the slot waveguide requires the basic condition of light confinement to be achieved and optimized, before dealing with further steps as optimization of single mode propagation with maximized power transmission, device incoupling and strip-to-slot mode conversion. The work described in this paper is aimed to optimize the design of a slot waveguide based on SOH technology, with an Erbium-doped organic coating as infrared emitter in the afore mentioned C-band, in terms of maximization of the optical field confinement into the slot region. In order to design a device that has a practical use and consider the possible effects on the optical field distribution, side n-doped silicon strip contacts were included into the design. Moreover, the features of the SOI wafers available on-the-shelf, in particular in terms of SOI thickness, were considered.

## Methods

The maximization of the optical field confinement into the slot is a mandatory target to achieve the waveguiding and the amplification ability of the slot waveguide. The optical confinement factor $\Gamma$ is given by:

$$\Gamma=\frac{\iint_{D_{int}} |E|^2 dxdy}{\iint_{D_{tot}} |E|^2 dxdy}$$

with $D_{int}$ the organic slot region spatial domain and $D_{tot}$ the whole domain of the model. Therefore, the optimization of the optical confinement factor depends on the geometrical features of the device and the Re($n$) of the involved materials, as shown in Figure 1.

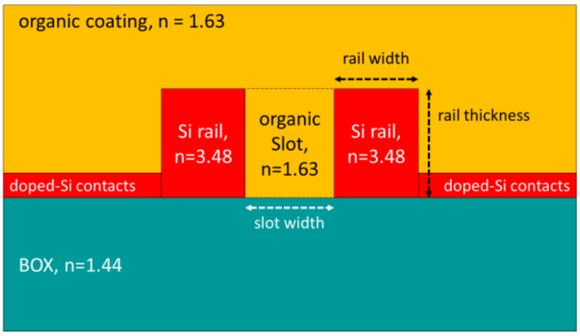

**Figure 1:** Device layout with materials distribution and geometrical parameters used for the study

The *Electromagnetic Waves, Frequency Domain* interface of the Wave Optics Module was used to derive the optimal set of geometrical features of the device layout able to maximize the Γ factor into the slot. Geometrical parameters rail width and slot width were used for parametric sweep based study, considering rail thickness imposed by the maximum SOI thickness values available in the market, namely 220 nm, 260 nm, 340 nm and 400 nm, with 220 nm SOI thickness being the most used substrates type both in R&D and in the industry. Materials Library of the Wave Optics Module provided the refractive index values of Silicon and Buried Silicon Oxide (BOX), whereas the Re($n$) of the Erbium-doped organic material was derived by ellipsometry in the infrared range (800 nm – 1700 nm), resulting in n=1.63 at 1550 nm.

## Simulation Results

The results of the parametric sweep on the geometrical features are shown in Figure 2, related to SOI thickness of 340 nm.

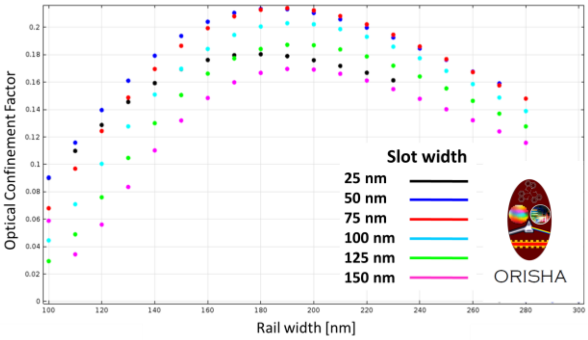

**Figure 2:** Plot of Γ for rail width and slot width combinations, with rail and slot thickness set at 340 nm

As shown in Figure 2, the maximum confinement of the optical field into the slot is achieved with slot width at 50 nm and rail width at 190 nm. The optical field distribution related to the maximum confinement condition is shown in Figure 3.

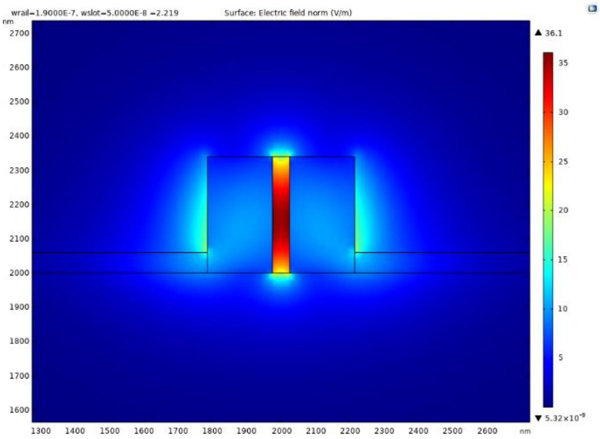

**Figure 3:** Optical field distribution of the layout providing maximum Γ in Figure 2

Table 1 resumes the maximum achievable optical confinement into the slot for each of the four SOI thickness values used for simulations. It is clear, as expected, that increasing the thickness of SOI leads to a thicker slot, resulting in a larger portion of optical filed that is confined into the slot.

| SOI thickness (nm) | Maximum Γ factor (%) | Slot width (nm) | Rail width (nm) |
|---|---|---|---|
| 220 | 13.74 | 50 | 210 |
| 260 | 16.70 | 50 | 200 |
| 340 | 21.33 | 50 | 190 |
| 400 | 24.25 | 75 | 180 |

**Table 1:** Maximum Γ factor vs slot width, rail width and SOI thickness

## Conclusions

Parametric analysis allowed for optimization of the design of the slot waveguide in terms of maximum achievable optical confinement into the slot, considering the features of SOI wafer available on-the-shelf for device processing by Electron Beam Lithography. Figure 4 shows the SEM image of a first prototype fabricated by CNR-IFN Rome Unit (Dr. Annamaria Gerardino), that is under optical characterization. Future works will consider the optimization of the optical propagation along the designed slot waveguides, the optimization of the fiber-to-strip light incoupling (inverted tip) and the following strip-to-slot mode conversion. All of these targets will be studied by mean of the Beam Envelop Method (BEM) included in the Wave Optics Module, *Electromagnetic Waves, Beam Envelop* interface.

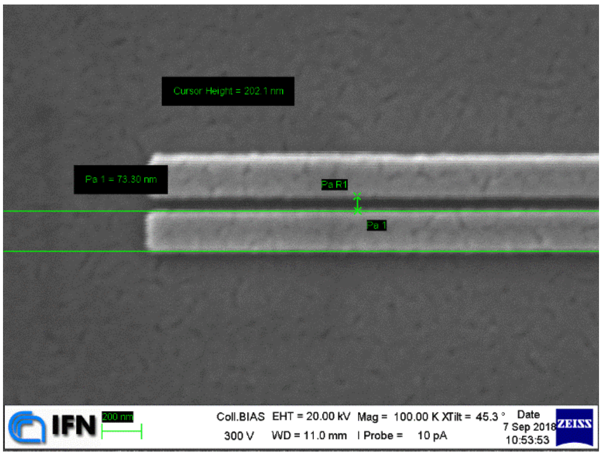

**Figure 4:** Top view of the uncoated slot waveguide at SEM imaging, with 75 nm slot width and 200 nm rail width (courtesy of Dr. A. Gerardino, CNR-IFN)

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