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# Integration of carbon nanotubes in silicon resonators

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**Abstract**—This paper reports on recent results on the integration of carbon nanotubes on the silicon photonic platform. Light coupling from carbon nanotubes in a fully integrated silicon resonator will be presented.

**Keywords**— Carbon nanotubes, silicon photonics, light emission, ring resonator, CMOS fabrication.

## I. INTRODUCTION

Bandwidth-hungry applications such as video streaming, social networking, or web search relay on a large network of internet data centres, interconnected through optical links, to share huge amounts of information [1]. The ever-growing data rates and power consumption inside these data centres are pushing copper links close to their fundamental limits. Optical interconnects are expected to overcome these limitations, replacing electrical interconnects and becoming the preferred solution in the short link communication [2]. For instance, active optoelectronic cables are successfully commercialized by the company Luxtera since 2006 [3]. Besides, the increasing gap between the computational capacity and electrical bandwidth in high-performance computing systems is driving the development of rack-to-rack and even chip-to-chip optical links [4]. Silicon photonics [5], due to its compatibility with the CMOS platform, has been chosen by companies such as IBM [6], Intel [7] and Oracle [8] for the development of future generation photonic interconnects. However, the integration of all these photonic and optoelectronic building blocks in the same chip is very complex and is not cost-effective due to the various materials used: Ge, Si and III-V [9-11]. Indeed, the integration of a broad variety of materials on the Si platform leads to a very complex 3D integration scheme. Furthermore, III-V technology is not fully compatible with Si technology and new sophisticated processes have to be developed. The idea will be to integrate one material on the Si platform to perform all optoelectronic devices, including the source, the modulator and the photodetector. Carbon nanotubes (CNT) could be a viable solution. Indeed, CNTs are nanomaterials of particular

interest in photonics thanks to their fundamental optical properties including near-IR luminescence, Stark effect, Kerr effect and absorption. In consequence, CNTs have the ability to emit, modulate and detect light in the wavelength range of silicon transparency [12-16]. Furthermore, they are also considered as a future silicon compatible material because such a material is studied for transistor channel in the future integrated circuits.

Here, we report on the theoretical and experimental comparison of the light emission coupling from CNTs into optical resonators including strip and slot ring resonators. A theoretical and experimental analysis of the light interaction of CNTs according to the optical waveguide configurations were carried out.

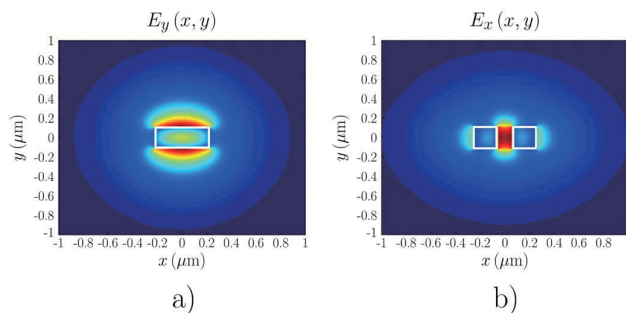


Fig. 1: a) TM mode (Electric field  $E_y$ ) of strip waveguide and b) TE mode (Electric field  $E_x$ ) of slot waveguide.

## II. ANALYSIS OF SILICON PHOTONIC WAVEGUIDES

We analyzed the modal properties of two silicon-on-insulator (SOI) photonic integrated waveguide configurations: the strip waveguide operating with transverse magnetic (TM) polarized light [17] and the slot waveguide operating with transverse electric (TE) polarized light [18]. These two waveguides support optical modes, represented in Fig. 1, and exhibit a very large evanescent field that maximizes light-matter

interaction outside the dielectric waveguide core. This ability to interact with the waveguide surroundings, together with their comparatively low propagation loss has made these kinds of waveguides the preferred solution in many silicon photonic biosensors [19] and an ideal platform for the investigation of the hybrid integration of CNTs onto photonic devices.

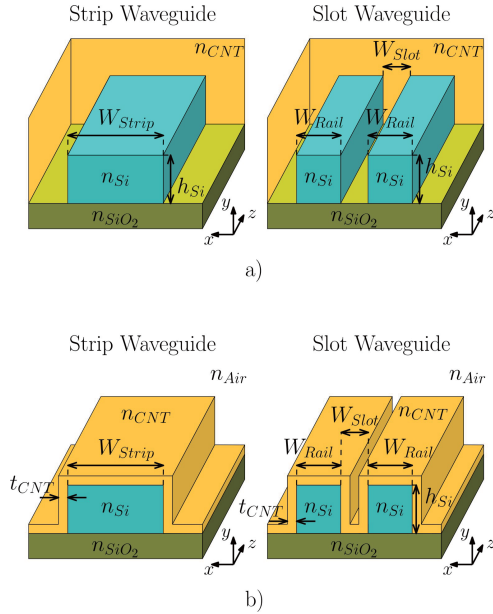


Fig. 2: Schematic views of strip and slot waveguides in a) bulk scenario, corresponding to drop casting CNT deposition and b) surface scenario, corresponding to spin coating CNT deposition.

Here, we theoretically compared the light-matter interaction capability of the strip and slot waveguides considering two different scenarios that model two different CNT deposition techniques. On the one hand, we considered a bulk scenario, where we assumed that the waveguide is surrounded by a thick (semi-infinite) layer of CNTs, corresponding to drop casting deposition. On the other hand, we analyzed a surface scenario, being the waveguide covered with a thin ( $t_{CNT} = 10$  nm) CNT layer that assessed the spin coating deposition technique. In both cases the CNTs (surrounded by polymer for chirality selection purposes [20]) were modeled as a homogenous medium with refractive index of  $n_{CNT} = 1.5$ . As a figure of merit we used the bulk ( $S_B$ ) and surface ( $S_S$ ) sensitivity parameters as usually defined in photonic biosensors [21]:

$$S_B = \frac{\partial n_{eff}}{\partial n_{CNT}} [RIU / RIU] \quad (1)$$

$$S_S = \frac{\partial n_{eff}}{\partial t_{CNT}} [RIU / nm] \quad (2)$$

where  $\partial n_{eff}$  is the variation in the effective index of the waveguide mode produced either by a modification of the refractive index of the surrounding media ( $\partial n_{CNT}$  in bulk scenario) or a change in the thickness of the waveguide covering layer ( $\partial t_{CNT}$  in surface scenario). High sensitivities are directly related to strong interaction with surrounding media [21], which corresponds to the CNT-rich layer in this case.

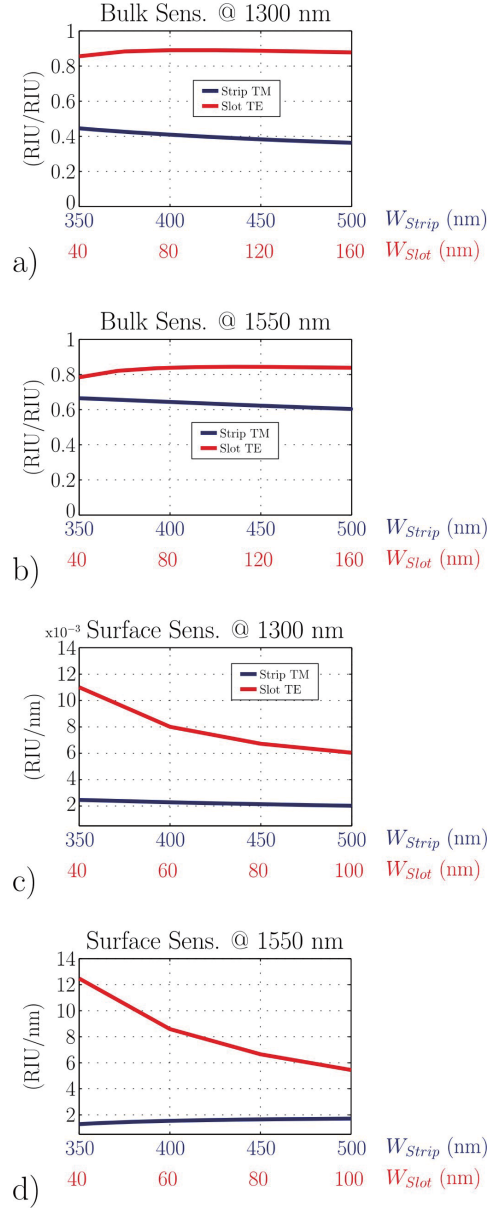


Fig. 3: Calculated sensitivity of strip and slot waveguides for bulk scenario (drop casting CNT deposition) at a) 1300 nm and b) 1550 nm wavelength and surface scenario (spin coating CNT deposition) at c) 1300 nm and d) 1550 nm wavelength.

Calculated sensitivity as a function of the main geometrical parameters of strip and slot waveguides, implemented on a 220 nm thick silicon SOI platform, is represented in Fig. 3. This analysis was performed at wavelengths of 1300 nm and 1550 nm in the center of the O and C bands of the optical fiber, typically used in telecom applications. Note that these two bands correspond to the maximum photoluminescence (PL) region of HipCo/PFO and Laser/PFO-A [22], respectively. In all studied cases slot waveguides operating with TE polarized light exhibited larger sensitivity than strip waveguides with TM polarized light. This phenomenon can be qualitatively understood looking at the strip and slot mode field distribution (Fig. 1). The optical mode in the slot waveguide is much more localized outside silicon (i.e. in the CNT-rich layer), while for strip waveguides, the mode is more confined inside the silicon core. In terms of light interaction with the CNT-rich layer, slot waveguides are thus more promising to enhance the light coupling from CNTs. However, in terms of propagation loss, strip waveguides exhibit lower loss, which induces better resonator behavior (i.e. higher  $Q$ -factors).

### III. EXPERIMENTAL CHARACTERIZATION CNT INTEGRATION ON SILICON PHOTONIC MICRORESONATORS

We have integrated CNT-rich layers onto silicon photonic micro-ring resonators, implemented with strip and slot waveguides. This way we can experimentally compare the ability of such photonic structures to interact with CNTs by monitoring resonance-enhanced photoluminescence. First, silicon waveguides were fabricated using e-beam lithography followed by ICP etching process. The technology developed here was optimized in order to reduce the optical propagation loss of the waveguides [23]. Figure 4 shows a scanning electron microscope (SEM) image of fabricated slot waveguides. Highly pure semiconducting HipCo CNT solution, prepared using polyfluorene-based extraction techniques [20], was deposited by spin coating. The total thickness of the PFO/CNT layer was thick enough to ensure optical mode symmetry.

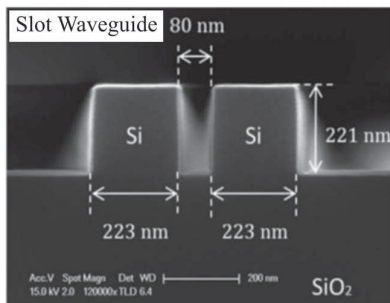


Fig. 4: Scanning electron microscope (SEM) image of fabricated slot waveguides.

PL of the CNTs integrated on photonic micro-resonators is measured pumping the samples with a 735nm wavelength titanium-sapphire laser, using a microscope objective to focus the pump within the region of interest and to collect emitted PL [12]. Figure 5 represents measured light emission from CNTs coupled in strip slot waveguide resonators. We noticed that the resonances from the CNTs' PL are more intense for the slot ring resonator approach in comparison with the emission obtained in the strip ring one. This effect can be explained by the fact that the light interaction in slot waveguides is stronger than what it can be achieved with strip waveguides. Quantitatively, this characteristic is thus in good agreement with simulation results (Fig. 1) with a stronger light interaction with slot waveguides.

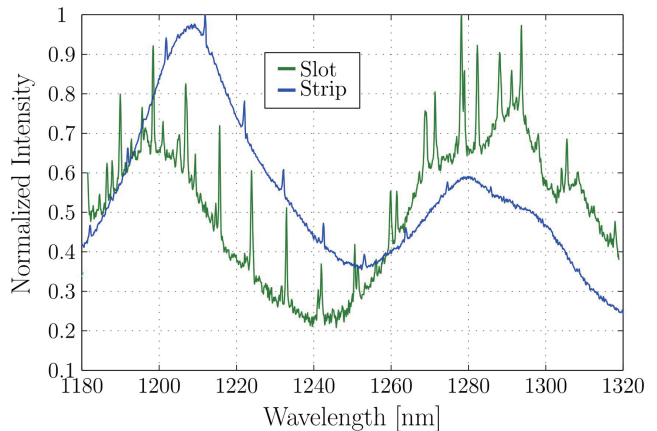


Fig. 5: PL intensity as a function of the wavelength for strip and slot waveguide ring resonators. The pump wavelength was 735nm.

### IV. CONCLUSIONS

In conclusion, CNTs have some remarkable optical properties which could be exploited to develop a new kind of hybrid photonics on silicon platform for a large range of applications including on-chip optical communications. We presented the latest results on the experimental demonstration of the light coupling from CNTs photoluminescence into slot waveguides and its comparison under the same measurement conditions with a strip waveguide configuration.

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