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On-chip Wireless Optical Communication: from Antenna Design to Channel Modelling

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ABSTRACT

Optical Wireless Networks on-Chip are promising solutions to overcome problems of miniaturization and energy consumption in a multicore on-chip environment. In this paper, we report the results of the design of an integrated plasmonic Vivaldi antenna fed by a silicon waveguide for on-chip wireless connection, which can be easily integrated into optical networks on-chip to achieve a hybrid wired/wireless signal transmission. Moreover, the optical wireless channel is modeled through a ray tracing approach, and the relationship between the optical antennas gain and the communication range in the on-chip propagation environment is investigated.

Keywords: Plasmonic Vivaldi antenna, Channel Modeling, Ray Tracing, Optical Wireless Network on Chip.

1. INTRODUCTION

Parallel computation through multi-processors architectures is likely to be a point of no return to cope with the increasing request for greater computation efficiency [1]. Nevertheless, the physical interconnection of many cores currently undergoes several technological impairments, to the extent that wireless network on chip are being investigated as a promising solution [2].

Although multi-processor chips are widely acknowledged as a promising solution for high-performance computing, prospects towards kilo-core architectures might be seriously thwarted by interconnects issues, e.g. in terms of complexity, high latency and power consumption [2]. These limitations heavily affect electrical network on chip (NoC), as well as optical NoC (ONoC), although to an overall lesser extent [3]. Wireless networks on-chip (WiNoC) have therefore gained consideration [2] as an effective way to overcome the bottleneck of the physical interconnection between many cores. To overcome the difficulties in antenna integration and energy consumption that obviously rise at UWB/millimeter frequencies, optical WiNoC (OWiNoC) have been recently proposed [3], to combine the advantages of both ONoC and WiNoC.

In this work, we report the results of the design of an integrated plasmonic Vivaldi antenna fed by a silicon waveguide for on-chip wireless connection. Since the antenna is efficiently coupled to conventional optical waveguides, it can be easily integrated into optical networks on-chip to achieve a hybrid wired/wireless signal transmission. Moreover, in this paper, we report the FDTD simulation results of on-chip wireless propagation in a point-to-point link. These simulations are reference cases to develop a Ray Tracing (RT) model [4] which can be used for investigating more complicated on-chip propagation scenarios, with noticeable savings in memory and CPU time. In fact, classical FDTD solution can become impractical if the propagation length, as desired, is hundred times larger than the wavelength. In the proposed simulation approach, the antenna radiation patterns are then calculated by the FDTD [5], while the link is modelled using the RT model.

2. INTEGRATED VIVALDI ANTENNA

Fig.1 (a) shows a scheme of the Vivaldi antenna fed by a silicon waveguide. The optical signal is launched into the Si waveguide and it is vertically coupled to a plasmonic slotted waveguide, made of silver. The plasmonic slotted waveguide opens up into a Vivaldi antenna and radiates the signal in the surrounding medium, i.e. SiO_2. In the coupling section, the Si and the Ag waveguides are vertically separated by a gap g=80 nm. The width and height of the Si waveguide are w=380 nm and h=220 nm, respectively, whereas the plasmonic waveguide width and the slot width are p=270 nm and s=30 nm, respectively. The thickness of the Ag layer is t=50 nm.

The length of the hybrid Si-plasmonic coupler, L_c=1.63 µm, was designed by applying the coupled mode theory (CMT) and the normal mode analysis [6] and by validating and optimizing the design through the three-dimensional Finite Element Method (FEM) [7]. Taking into account also the loss contribution, a 76 % coupling efficiency is achieved, between the Si and the slot waveguide, at the wavelength λ=1.55 µm.

The antenna behaviour was, therefore, optimized by varying the antenna length L_a. The optimal length value L_a=1.75 µm, corresponding to the maximum antenna gain G=9.9 dB, was found by the FDTD simulations. Further details on the coupler and on the antenna design can be found in [8].

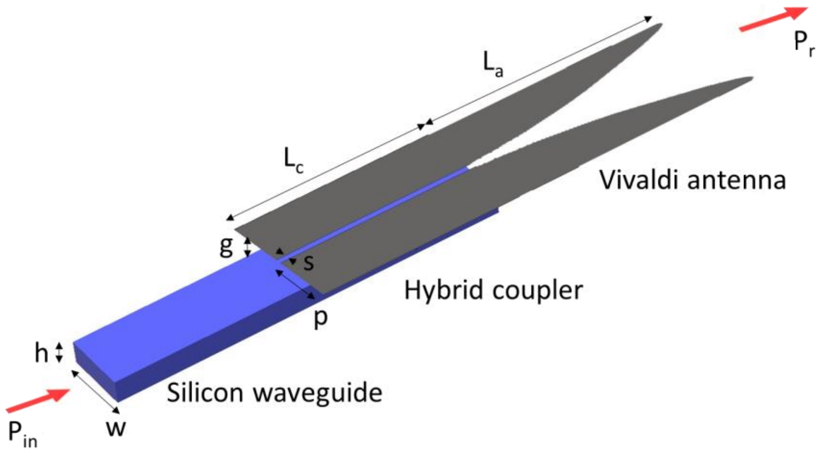

Figure 1. Scheme of the Vivaldi antenna coupled to the Si waveguide

In order to have reference cases for the development of the RT model, different point-to-point links between integrated Vivaldi antennas were simulated. As an example, Fig. 2 shows the electric field modulus (logarithmic scale) calculated by the FDTD for a point-to-point link between two integrated Vivaldi antennas in a multi-layered medium (Si-SiO_2-air layers). In this case, the antenna distance is d=50 µm and the calculated transmittance at the receiving waveguide is -36.5 dB.

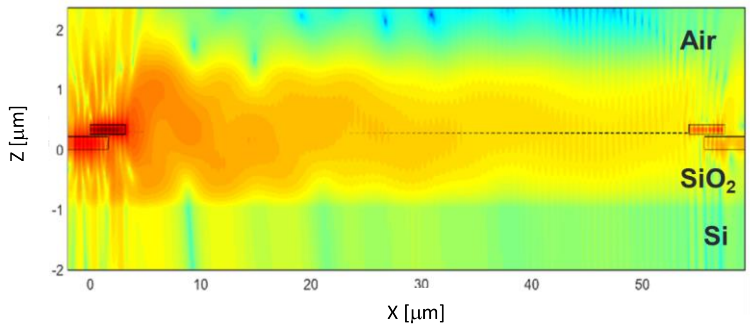

Figure 2. Electric field modulus (logarithmic scale) calculated by the FDTD for a point-to-point link between two integrated Vivaldi antennas in a multi-layered medium. The antenna distance is d=50 µm

3. RAY TRACING FOR OWINOC

Since the numerical evaluation of a complete wireless link is heavily limited by the required computational effort, ray tracing simulations is considered in the following as a reliable approach to channel modelling in OWiNoC.

The on-chip wireless channel is commonly sketched as a layered structure (Fig. 3a), where a plane dielectric slab including the transmitting (TX) and the receiving (RX) antennas is bounded by two different media on the upper and on the lower side. The electromagnetic properties of the materials are considered through their refraction index (values in Fig. 3a refer to the wavelength λ_0=1.55 µm). Planar interfaces are assumed perfectly smooth and infinitely wide at this stage of the work: wave propagation consists then of multiple reflections occurring in the xz plane (Fig. 3b).

Therefore, the electromagnetic field radiated to the RX after n bounces (single reflections are for instance shown in Fig. 3b) can be expressed as:

$$\vec{E}_n = \vec{E}_{0n} \cdot \frac{e^{-j\beta r_n}}{r_n} \cdot \prod_n \tag{1}$$

being $\beta=2\pi n_0/\lambda_0$ the wave number, r_n the overall length of the ray, Π_n the product of the n reflection coefficients, and $\vec{E}_{0n}$ the TX antenna "emitted field" in the direction of departure of the ray (θ_d in Fig. 3b). It is worth mentioning that the path length r_n can be regarded as the distance between the RX and an "n_{th} virtual transmitter" (VTX in Fig. 3b) that is the 'mirror' image of the TX (if n=1) or of the $(n\text{-}1)_{th}$ VTX (otherwise) with respect to the reflecting plane (image principle). In the considered layered scenario, closed-form analytical expressions for the VTX locations can be easily achieved, meaning that the computation of both r_n and the incident angles (θ_i in

Fig. 3b) are straightforward. Then, the (Fresnel) reflection coefficients (and therefore the value of Π_n) are also immediately available. Finally, $\vec{E}_{0n}$ is computed as:

$$\vec{E}_{0n} = \sqrt{\frac{60 \cdot P_A \cdot g(\vartheta_d)}{n_0}} \cdot \hat{p}(\vartheta_d) \cdot e^{-j\beta} \tag{2}$$

where P_A is the overall absorbed power, $g(\theta_d)$ and $\hat{p}(\vartheta_d)$ are the antenna gain and polarization vector in the direction θ_d. As said before, the power P_A and the 2D angular description of the antenna gain and polarization, required by the RT engine as input data, are obtained by using the FDTD. Assuming the same antenna at the RX side for the sake of simplicity, the same input information can be exploited to transform the impinging fields into the corresponding received power, once the ray directions of arrival (θ_a in Fig. 3b) have been evaluated.

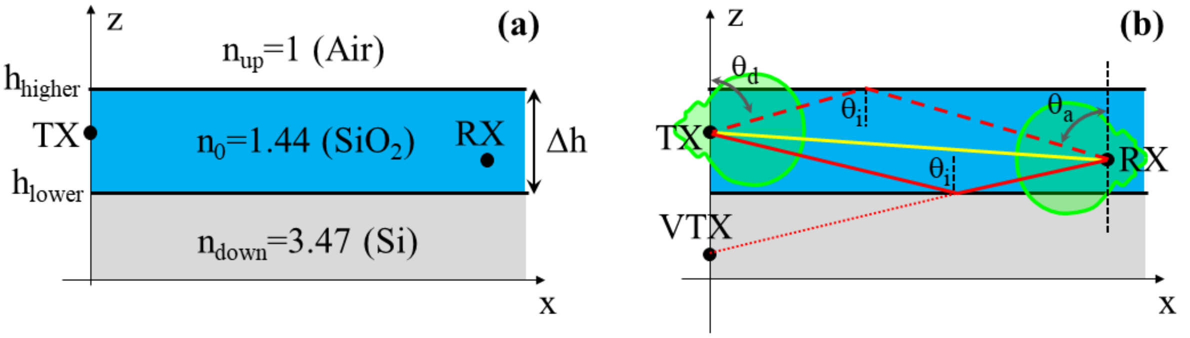

Figure 3. (a) Layered propagation environment; (b) Example: direct and double reflected rays between TX and RX.

The RT model has been tested for the double interface Si-SiO_2-Air with a layer thickness ranging from 4 µm up to 10 µm, and for different positions of the TX and the RX within the layer. Moreover, different antennas patterns with increasing gain value have been considered at the TX/RX side, assuming an RX sensitivity of -20 dBm and P_A = 0 dBm.

Fig. 4 shows that a guiding effect sets up within the layer, that is also visible in Fig.2. In fact, the received power is greater than in free space up to a breakpoint (BP) distance, which is strictly related to the layer width (the thinner the layer, the smaller the effect) and to the positions of TX-RX with respect to the lower interface (the closer the position, the weaker the effect). The guiding effect before the BP is mainly due to the overall constructive interference between the received field contributions. Beyond the BP, interference turns to become destructive, resulting in a received power weaker compared to the reference free space case.

Besides the obvious beneficial effect of the layer, which acts as a guide, our analysis shows that the link performance is also heavily affected by layer width and antenna gain and position. This is shown in Fig. 5, where the maximum link distance, corresponding to a received power equal to the RX sensitivity, is plotted for different gain values. If the gain is too low, a large amount of power is lost because of the large refraction losses of the rays far from grazing incidence, while the guiding effect is not important for large gain, since the antenna radiation lobe is narrower.

In both cases, the link distance turns out to be impaired, to an extent which also depends on the layer thickness (Figs. 5a and 5b) and on the TX-RX positions within the layer (different curves in each figure).

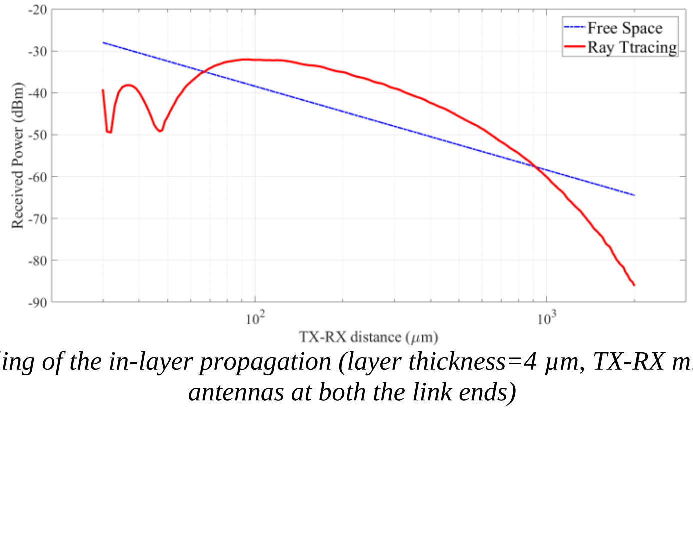

Figure 4. RT modeling of the in-layer propagation (layer thickness=4 µm, TX-RX middle placed, Vivaldi antennas at both the link ends)

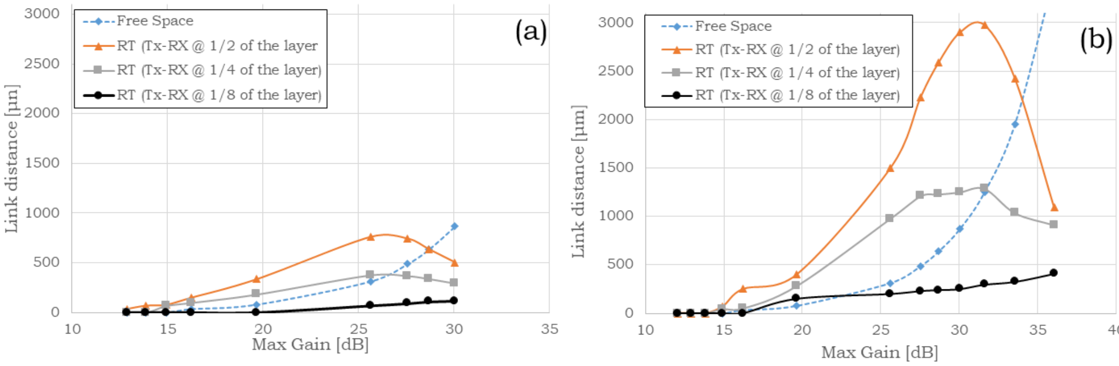

Figure 5. Link distance vs. antenna gain for different layer thicknesses: (a) 6 µm; (b) 10 µm.

4. CONCLUSIONS

The design of a Vivaldi antenna coupled to a silicon waveguide has been reported. Moreover, electromagnetic propagation for optical wireless network on-chip has been investigated using a ray-tracing approach. It has been found that, if the link is in a layered structure, which is reasonable for multi core chips, grown in a multilayered structure, the maximum link length does not increase simply increasing antenna gain, but also depends on the thickness of the layer and the position of the antenna in the layer. This requires a strong interaction between the e. m. link and the electronic layout designers to find the optimum balance among all these design parameters.

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