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► **To cite this version:**

Bryan Treguer, Thierry Le Gougec, Pierre-Marie Martin, Rozenn Allanic, Cedric Quendo. Silicon Parallel-Plate Waveguide with Controlled Boundaries for Broadcast Applications in WiNoC Architecture. 2023 53rd European Microwave Conference (EuMC), Sep 2023, Berlin, Germany. pp.657-660, 10.23919/EuMC58039.2023.10290370 . hal-04290155

HAL Id: hal-04290155

<https://hal.science/hal-04290155>

Submitted on 16 Nov 2023

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Silicon Parallel-Plate Waveguide with Controlled Boundaries for Broadcast Applications in WiNoC Architecture

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Abstract — In this paper, a silicon parallel-plate waveguide dedicated to multicast signal propagation is studied around 60 GHz for Wireless Network-on-Chip (WiNoC) type interconnects. The aim is to maximize the bandwidth allowing broadcast communications. The suggested solution uses embedded dipole antennas permitting electromagnetic waves propagation on the silicon substrate between two metallic planes. First, a network of 4 dipole antennas is simulated and measured for an inter-element distance of 14 mm on a High Resistivity Silicon (HR-Si) substrate surrounded by a Low Resistivity Silicon (LR-Si) substrate. Secondly, the signal propagation for an array of 4 TSV antennas is studied to demonstrate the advantage of using isotropic antennas for broadcast communications. Finally, perspectives are presented for signal propagation for antenna network.

Keywords — Dipole, Electromagnetic propagation, Parallel-plate waveguide, Silicon, TSV, Wireless Network-on-Chip.

I. INTRODUCTION

Today the demand for data rates related to the Internet of Things (IoT) or Artificial Intelligence (AI) is growing due to the rapid expansion of digital technologies and connected devices. The 2021 IRDS (International Roadmap for Devices and Systems) report states that there will be more than 350 billion AI (Artificial Intelligence) + IoT (Internet of Things) electronic devices by 2030 [1].

The miniaturization of circuits and the increase in data rates are essential to meet the growing demands of these applications. Indeed, the complexity of electronic chips is increasing due to the ever-increasing number of transistors and the need to connect more and more electronic components within a single chip. This can lead to performance limitations, high power consumption and high space requirements for traditional internal communication architectures. Networks-on-Chip (NoC) have been developed to address these challenges by offering more efficient solutions.

Currently NoC technology is mainly wireline, and one of the main problems associated with Network-on-Chip (NoC) is the transfer of information between the different cores. The increase in throughput, coupled with an increase in the operating frequency of the circuits, can lead to several undesirable effects on signal transmission, such as crosstalk, latency and desynchronization problems. These problems can negatively affect the performance of the NoC. Several approaches have been explored in the literature to overcome these difficulties. These include guided RF, 3D and optical interconnections [2], [3].

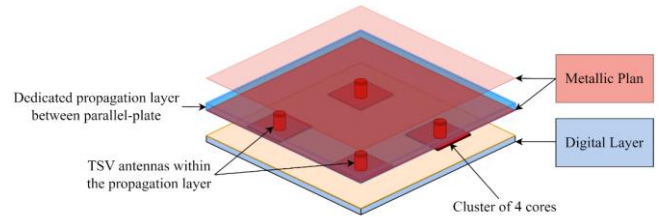


Fig. 1: WiNoC channel with 4-antennas, 16-cores topology

In the Complementary Metal-Oxide-Semiconductor (CMOS) context, Wireless Network on Chip (WiNoC) interconnections are promoted. They allow high reconfigurability with low routing complexity, multiple and simultaneous broadcast communication and a reduction of mutual coupling related to wired interconnections.

In most studies on WiNoC, the propagation of electromagnetic waves is considered in the air. Therefore, antennas were specifically designed to radiate in air [4]. Due to its high permittivity, antennas on silicon have a low efficiency. Thus, to overcome this problem and maximize signal transfer between cores, it is preferable to use a propagation medium, made of high-resistivity silicon, placed between two metal planes. The medium can be considered as a parallel-plate waveguide. The concept of an on-chip wireless network using this HR-Si propagation medium is illustrated in Fig. 1 for a case of 4 clusters of cores. Given the size of the chips, intra-chip propagation should be possible for an inter-cluster distance of 10 to 20 mm.

Through Silicon Via (TSV) antennas can be used as RF antennas to transmit the signal into a High Resistivity Silicon (HR-Si) substrate, enabling wireless multi-core links within the substrate at levels above -3 dB but with low transmission bandwidth [5], [6].

Several research works have been carried out on signal propagation on a silicon substrate showing the interest of using WiNoC interconnections on the widest possible bandwidths but without measurements [7]. These wide bandwidths were obtained by controlling the air-silicon boundaries ($\epsilon_{r_{Air}} = 1$ vs. $\epsilon_{r_{Si}} = 11.9$) by adding high losses thanks to a Low Resistivity Silicon (LR-Si) area on the periphery of the HR-Si substrate, attenuating reflected waves at interfaces [8]. This reduces multipath due to the permittivity differential and facilitates OOK demodulation techniques.

In this paper, the concept of LR-Si absorber applied to parallel-plate waveguide is taken up again with the aim of reaching the widest possible bandwidth at the intra-chip level at 60 GHz.

In the first step, a network of 4 dipole antennas is studied and measured in the V band (45-67 GHz). The shape of the absorber has been optimized to maximize the signal propagation. This substrate shape is innovative and allows to limit electromagnetic recombination. The influence of the resistivity of LR-Si on the scattering parameters is studied for different bias voltages. In a second step, a 2x2 TSV antennas array resonating around 60 GHz on a circular substrate is simulated. A comparison is made between the TSV and dipole simulations to determine the best solution for broadcast communications. Finally, perspectives are given on signal propagation for antenna arrays.

II. STUDY OF ELECTROMAGNETIC PROPAGATION ON SILICON IN V-BAND [45-67 GHz]

A. Network of 4 dipole antennas V-Band

In order to analyze the transmissions in the case of several antennas, a network of 4 dipole antennas on a HR-Si substrate is designed and studied, Fig. 2 (a). Equation (1) is used to calculate the cutoff frequency of the first parallel-plate waveguide upper mode TE₁₁, it is assumed that $W_{Sub} \gg H_{Sub}$:

$$f_{c11} = \frac{1}{2 * H_{Sub} * \sqrt{\mu_0 \epsilon_0 \epsilon_r}} \quad (1)$$

Where $\epsilon_r = 11.9$, the substrate width and height are $W_{Sub} = 16.1$ mm and $H_{Sub} = 350$ μm respectively. In our 60 GHz circuit, the cut-off frequency of the first higher mode is 124 GHz that means only a single mode TEM is propagated between 0 and 124 GHz. This figure shows the array of 4 antennas numbered 1 to 4, simulated and then measured using a 50 Ω coplanar waveguide (CPW) feed. The inter-element distances of facing antennas are 14 mm. The dipole antennas are placed at a distance corresponding to $\lambda_g/4$ at 60 GHz (i.e. 350 μm), from the doped areas. In this study a flat parallel aluminum metallization is defined in order to limit the radiation of the antennas in the air and thus maximize the bandwidth. The circuit Fig. 2 (b), was measured, as shown in Fig. 2 (c), using a probe station and a Rhodes & Schwarz ZVA67 network analyzer. All measurements were performed after calibration, using a SOLT (short, open, load and thru) calibration kit. At the periphery edge, a low resistivity silicon substrate is obtained by biasing an N⁺ (top side) P(substrate) P⁺ (bottom side) junction in the height of the substrate as it is illustrated Fig. 2 (d). The silicon substrate has a thickness of 350 μm corresponding to a guided wavelength $\lambda_g/4$ at 60 GHz. The N⁺ and P⁺ doped areas are deposited on the top and bottom side by sol-gel deposition and diffusion techniques respectively. These doped areas form an integrated N+PP+ junction in the substrate height and thus a LR-Si can be modeled by a diode as shown Fig. 2 (e). When bias voltage is negative, the diode is on and can be modelled by a resistance. When the bias voltage is 0 or positive, the diode is off and acts as a serial RC circuit. This technique allows the permittivity difference at the air-silicon boundaries to be controlled and thus reduces multipath. Indeed, the resistivity in

the junction can be reduced by applying a negative voltage [9]. Fig. 3 shows the S-parameters in matching and transmission for two bias voltages (0V and -1.2V). The simulation is performed for a 10 $\Omega\cdot\text{cm}$ resistivity in the LR-Si part, showing propagation in the real case (air-silicon interference) and ideal case (propagation in an infinite environment with radiation boundaries). Matching coefficients are presented in Fig. 3 (a).

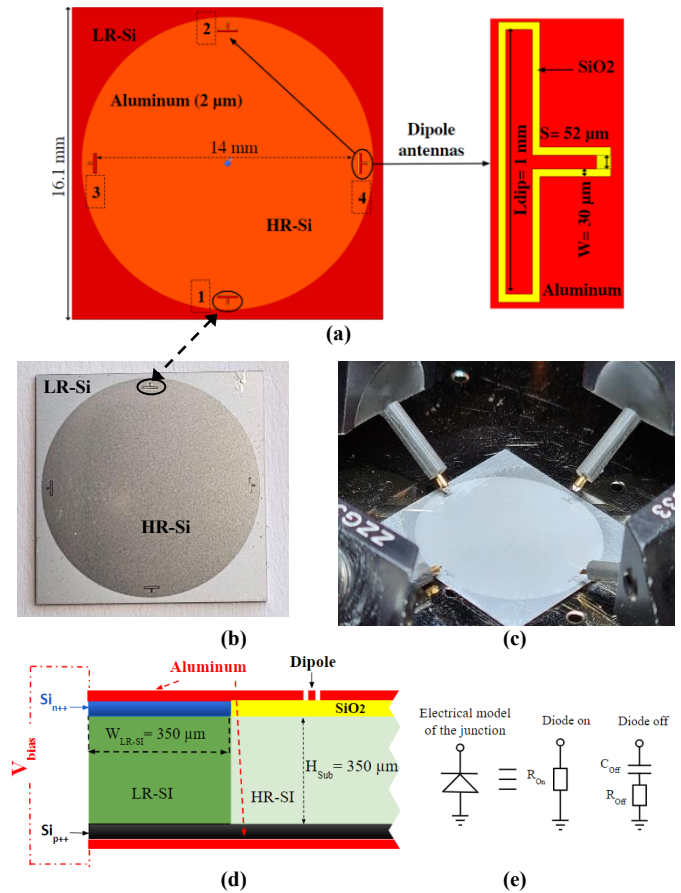


Fig. 2: Top view of 4 dipole antennas array for a 14 mm inter-element distance on circular silicon substrate (a); measured circuit (b); measuring device (c); Side view of the simulated structure (d); Electrical model with and without bias (e).

As the ideal case simulates an infinite medium, there is no reflection or recombination of waves, so the matching curve is smoother. Fig. 3 (b) shows the simulation and measurement results for face-to-face antennas. The maximum transmission level is higher in the real case than in the ideal case with respectively $S_{ij} = -16.5$ dB against $S_{ij} = -19.2$ dB. In the real case, constructive interferences at the HR-Si/LR-Si/air boundaries increase the signal level at several frequencies. However, in the ideal case, the propagation is assimilated to an infinite wave. In Fig. 3 (c), i.e. for antennas positioned 90° apart (S_{23} , S_{24} , S_{41} , S_{31}), there are destructive interferences in the real case, the propagation level is lower than in the ideal case, $S_{ij} = -30.6$ dB against $S_{ij} = -26.9$ dB. The ideal case shows that dipole antennas positioned 90° apart are not optimized for broadcast communications. Indeed, their radiation pattern is not uniform over the whole silicon substrate, which implies that the frequency response is lower than in the face-to-face case.

A high agreement between real cases simulation and measurement is observed, which validates the model simulated with the HFSSTM software.

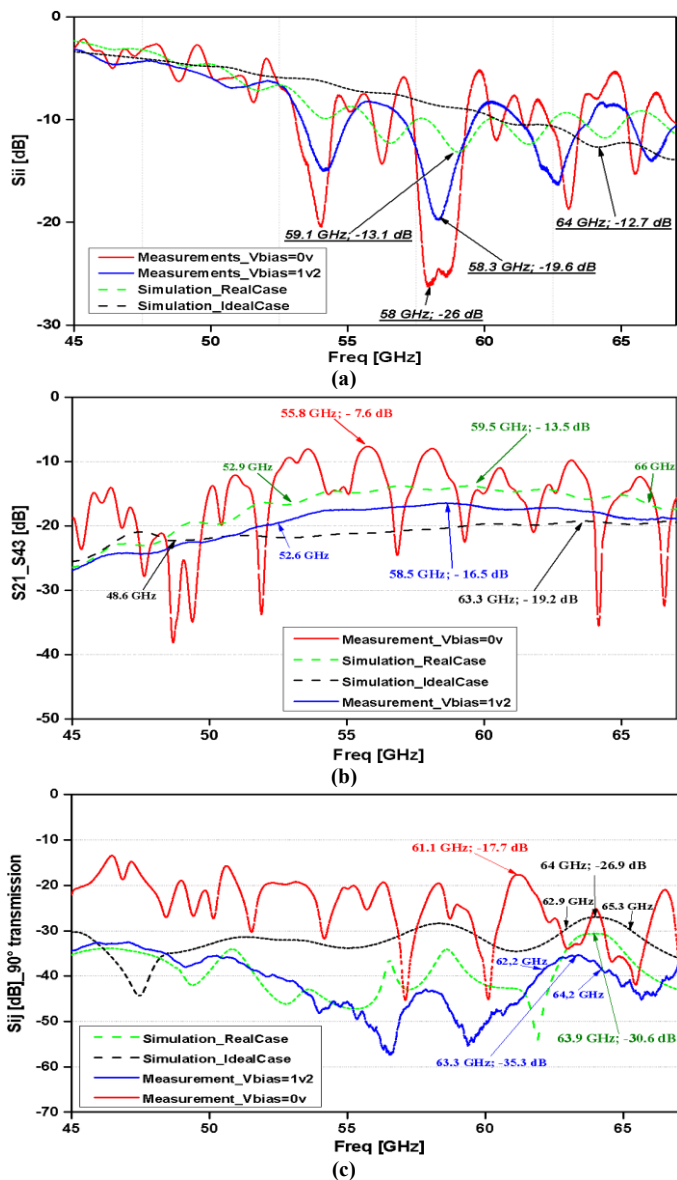


Fig. 3: Measurements and simulation (HFSSTM) of a network of four dipole antennas with a 14-mm inter-element distance (a) parameters S_{11} ; (b) parameter S_{21} , S_{43} ; (c) 45° transmission S_{ij} parameter.

Fig. 3 (b) shows that the bias voltage applied to the integrated junction leads to an increased bandwidth at -3dB. In fact, a bandwidth of more than 14.4 GHz is obtained for a maximum transmission level of $S_{ij} = -16.5$ dB with a bias voltage of -1.2V. Without bias, the substrate is considered to be entirely a high-resistivity one. Multipaths strongly degrade the signal propagation and many transmission zeros are observed.

Dipole antennas are directive in this 2x2 network. As shown in Fig. 3 (b), direct propagation (face-to-face) presents stronger results in terms of bandwidth than when antennas made 90° angle, Fig. 3 (c). For a bias voltage of -1,2 V, the -3 dB bandwidth is higher than 14.4 GHz, with a maximum transmission level $S_{ij} = -16.5$ dB for face-to-face antennas

whereas the -3 dB bandwidth is only of 2 GHz with a transmission level of $S_{ij} = -35.3$ dB for antennas positioned 90° apart. TSV antennas would be best suitable for multicast and broadcast communication as they would allow the electromagnetic signal to propagate uniformly, as it will be shown in the next part.

B. Network of 4 TSV antennas V-Band [45-67 GHz]

TSV antennas offer an alternative to traditional planar interconnects [8]. In order to realize wireless links within a multilayer substrate, a network of 4 TSV antennas is simulated on HFSSTM, as typical disc-loaded monopole antenna, in the [45-67] GHz frequency band. The inter-element distance is 14 mm, which will allow a comparison between the dipole and TSV antenna arrays. The simulated structure is shown in Fig. 4 (a). It follows the same concept as in part A with an integrated junction forming a LR-Si layer on the periphery of HR-Si. The conductive parallel-plate is aluminum. The 50 Ω access is simulated with a lumped port. As the name suggests, the TSV is a through-port, which has the advantage of propagating the signal directly into the silicon layer. Its height therefore depends on the height of the substrate, below, $H_{\text{substrat}} = H_{\text{TSV}} = 350 \mu\text{m}$. The height (350 μm) and radius (20 μm) of the TSV define its resonant frequency. It is possible to play with the matching by adjusting the diameter of the discs at the ground level, Fig. 4 (b).

Ideal and real cases simulation results of TSVs environment are analyzed and compared to dipole cases. As shown in Fig. 5 (a), the matching frequency is similar between the dipoles and TSV cases, whether in ideal or real, we obtain respectively $S_{11} = -13.1$ dB at 59.1 GHz and $S_{11} = -25.7$ dB at 59.4 GHz. The TSV antennas show a higher matching level due to the adjustment of the disk radius at the ground level. For these simulations $R_{\text{disc}} = 70 \mu\text{m}$.

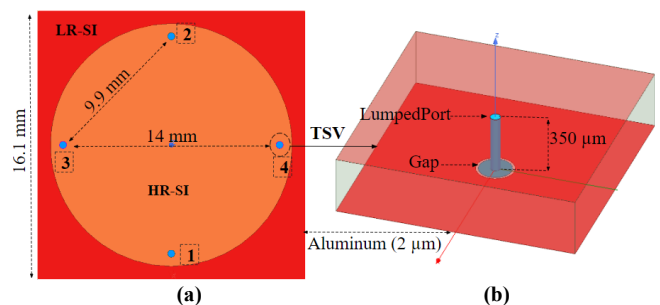


Fig. 4: HFSSTM simulated structure of 4 TSV antennas, top view (a); 3D view (b)

As shown in Fig. 5 (b), the bandwidths and transmission levels, when the antennas are face-to-face, are higher for dipole antennas. This difference is mainly due to the directivity of the antennas. TSV antenna is isotropic, radiating uniformly in all directions, whereas dipole is more directional. The small radius of TSVs (20 μm) compared to the size of the silicon substrate cavity can explain the parasitic effects on the propagated signal. The bandwidth obtained for TSVs in the ideal case is similar to the dipoles with $B_{W,-3dB} = 20.5$ GHz. The bandwidth of TSV antennas in the real case is lower than for the dipoles with $B_{W,-3dB} = 7.7$ GHz versus $B_{W,-3dB} = 13.1$ GHz. There are several areas of improvement that could be made to maximize this bandwidth

and thus get closer to the infinite medium case, including increasing the width of the LR-Si.

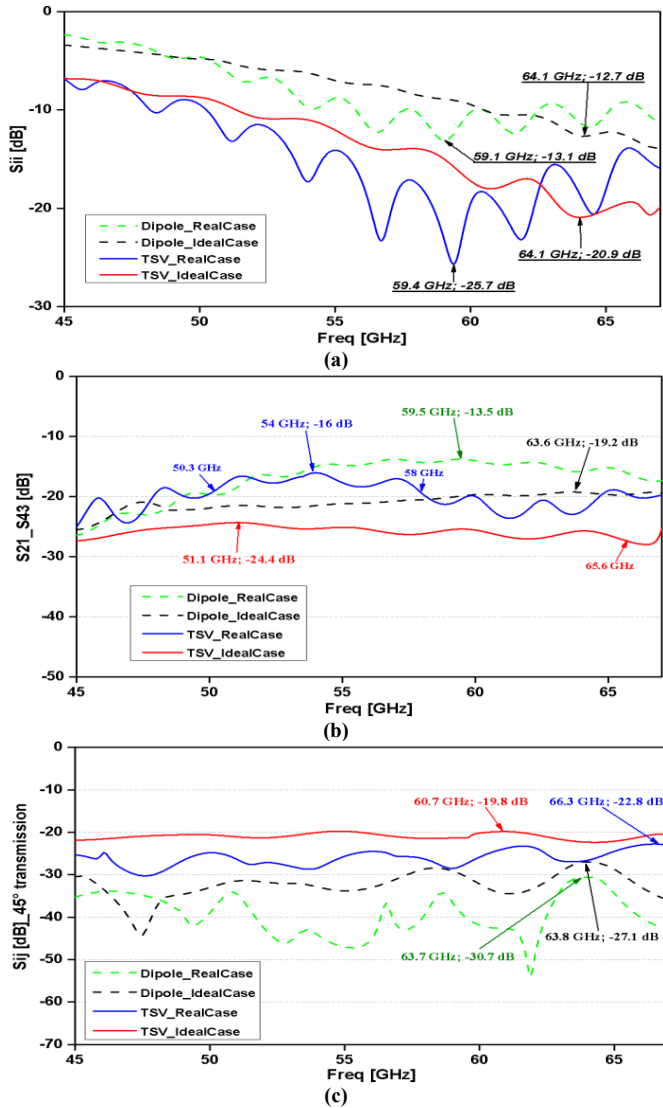


Fig. 5: Measurements and simulation (HFSS™) of a network of four dipole antennas with a 14-mm inter-element distance (a) parameter S_{ii} ; (b) parameter S_{21} , S_{43} ; (c) 45° transmission S_{ij} parameter.

Table 1. TSV vs Dipole simulations comparisons for an LR-Si of $10 \Omega \cdot \text{cm}$.

S parameters	TSV				Dipole			
	Ideal Case		Real Case		Ideal Case		Real Case	
	S_{ij} (dB)	Bw at -3dB (GHz)	S_{ij} (dB)	Bw at -3dB (GHz)	S_{ij} (dB)	Bw at -3dB (GHz)	S_{ij} (dB)	Bw at -3dB (GHz)
S_{ij} Face-to-face Transmission	-24.4	20.5	-16	7.7	-19.2	18.7	-13.5	13.1
S_{ij} 45° Transmission	-19.8	>20	-22.8	2.9	-27.1	2.4	-30.7	1.9

Fig. 5 (c) shows the interest of using isotropic antennas for broadcast communication. In the ideal case, the bandwidth is greater than 20 GHz for TSVs compared to 2.4 GHz for

Dipoles. In air-silicon medium, simulations with TSVs show that the propagated signal has less multipath, which results in a smoother signal shape. The results of the simulations can be summarized in Table 1. It compares the -3 dB bandwidth and the propagated signal levels of the two networks studied in this article.

III. CONCLUSION

In conclusion, WiNoC topology using a silicon parallel-plate medium offers an alternative solution to traditional wired NoCs. In this paper, the advantage of using dipole or TSV antennas to excite the parallel-plate waveguide, for wireless communication applications has been discussed. A 2×2 dipole antenna network with an inter-element distance of 14 mm was simulated and measured in the [45-67 GHz] frequency band. The propagation channel is controlled by a bias voltage on the peripheral edge of the LR-Si substrate. The results of the measurements allowed the evaluation of the -3dB bandwidth in face-to-face transmission of more than 14 GHz, which represents one of the largest bandwidths in the literature. As dipole antennas are directive, they are not the most suitable for broadcast communications. This is the reason why a network of TSV antennas [2×2] has been proposed. TSV antennas allow the signal to be propagated inside the silicon. Moreover, they have the advantage of being isotropic, facilitating communications in all directions. The simulation of the TSV network in the case of propagation in an infinite medium demonstrates the great interest of this kind of antenna. Bandwidths of 20.5 GHz for face-to-face transmission and greater than 20 GHz for 45° transmissions are obtained. In the future, prospects are envisaged for obtaining better transmission characteristics in real structures. For example, the absorbing boundary shape between HR-Si and LR-Si can be optimized to enlarge the -3dB bandwidth.

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