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# Development of Carbon Nanotube based Waveguide and Filters in W-Band

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**Abstract**—Demanding data rates and increasing data consumption requires matching electronic infrastructure which poses a key challenge. One of the solution to address this is by increasing the operational frequency and using higher frequency bands. In doing so the effective active component designing at higher frequencies is already being explored by researchers across globe. But for transmission of these signals using effective and suitable interposers at higher frequencies requires innovative approach in packaging design and technology. This remains a key challenge due to increasing number of components leading to more lateral area and heat dissipation. This article focuses on addressing the issue through three-dimensional integration using the carbon nanotubes(CNTs) based passive devices by focusing on waveguides, cavities and filters as their basic building block. We have designed the CNT based waveguides, cavities and filters in W band 75-110 GHz.

**Index Terms**—carbon nanotubes, waveguides, cavities, filters.

## I. INTRODUCTION

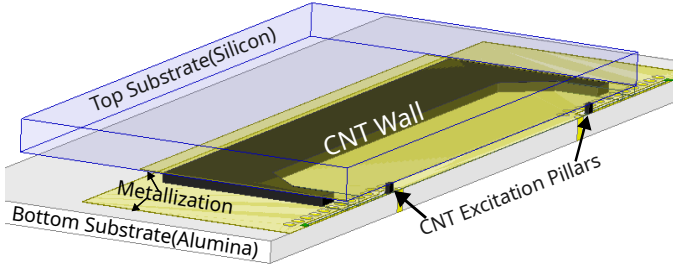
With rapidly increasing internet literacy and connectivity the demand of data at higher and higher data rates is increasing exponentially. According to one estimate the monthly average per capita data consumption globally will be 34 GB by 2026 [1]. The present 5G infrastructure seems to be insufficient to meet up this demand. In consideration with these challenges the focus on sub-millimetre(mm) wave technologies with terahertz spectrum is looked with great promise. As the higher data rates of the order of 1 petabit/second is achievable in 100 GHz channel [2].

Since most of the data has to be come through the processing units, the integration of these with passive trans-

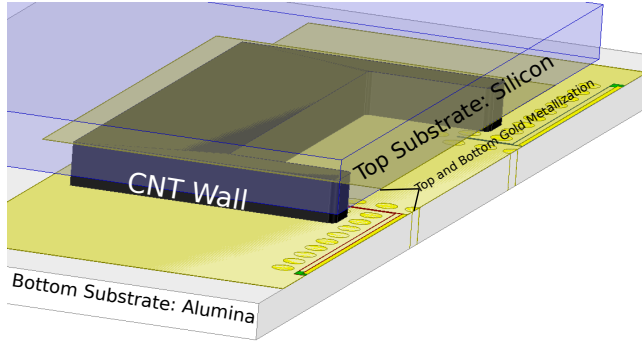
mission circuitry is key for effective data transmission. Due to this in an integrated circuit(IC) unit the integration between active and passive components becomes a crucial bottleneck. This integration has to be without or minimal parasitics(electromagnetic coupling) with high quality factor and low insertion loss devices. Another aspect which needs to be looked at is heat dissipation of an IC at higher frequencies which becomes a key challenge. These challenges are being addressed using various technologies such silicon micro-machining [3], LTCC technologies [4], III-V(GaAs type) material technologies [5] and many more.

Since in back-end-of-the-line(BEOL) technologies the aspect ratio is very critical to achieve with the fabrication technologies limitation with increasing number of layers. It becomes very important to look for alternates which can potentially solve these issues and in doing so we are looking towards CNT based passive devices and circuitry due to their exceptional intrinsic properties. For mm-wave technologies De Saxé et al have provided the proof of concept by designing and demonstrating waveguides [6] and interconnects [7] using CNTs.

Here we are presenting the preliminary study of CNT based waveguides, cavities and filters for frequencies in W-band. These studies are carried by doing full wave 3D simulations of W-band waveguide, its realisation and measurement and subsequently optimisation of cavity and filter designs using full wave simulations. A schematic design of CNT based waveguide and cavity is shown in Figure:1.



(a)



(b)

Fig. 1. Cross-sectional schematic view of a CNT-based (a) Waveguide (b) Cavity(Monopole Filter); The waveguide and cavity are delimited by side walls made of vertically aligned carbon nanotubes, and two metallized substrates are placed respectively above and below. Only half of the structure is displayed, the plane of symmetry intersecting the coplanar access lines is from the front.

## II. METHODS

### A. Theory and Modelling

In our designs the metallic walls of the devices are made of vertically aligned CNTs as a dense forest with very high aspect ratio. So for accurate analysis we wish to apply a full wave 3D electromagnetic model. However this becomes a challenge due to involvement of various scales from quantum to micro as well as different physical models such as Maxwell's equations and density functional theory(DFT). The integration of various scales and various physical models has already been performed by Pierre Franck et. al. by proposing an equivalent bulk model and integrating with Ansys HFSS solver [8].

Above mentioned bulk equivalent model computes the complex conductivity( $\sigma_{axial}$ ) of CNT forest with a clear dependence on angular frequency( $\omega$ ) and density of single walled CNTs( $D_{CNT}$ ) as described in equation:1

$$\sigma_{axial} = \frac{8e^2\nu_F}{h(\nu + j\omega)} D_{CNT} \quad (1)$$

Here  $\nu_F$  is fermi velocity of CNT while  $\nu$  is relaxation frequency. This model considers the perfect alignment of CNTs as well as their single walled nature. But fabrication constraints does not allow the perfect alignment and type

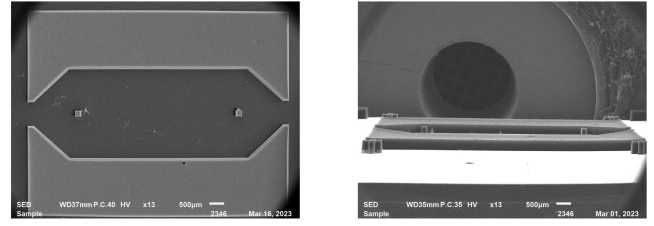


Fig. 2. SEM image of fabricated waveguide at CINTRA Singapore

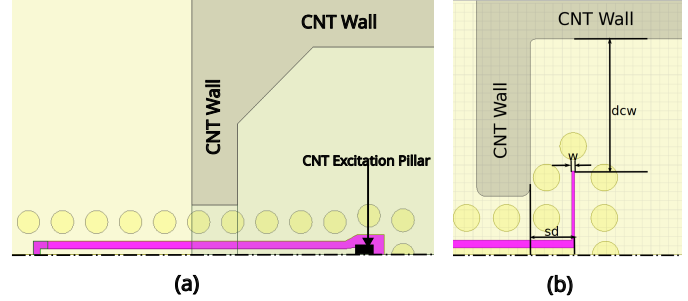


Fig. 3. Coupling parameters for (a) Waveguide (b) Cavity and Filter at 80 GHz: pink region is de-metallized part of modified CPW, broken line at bottom represents the symmetry plane.

of CNT so experimentally the effective conductivity gets degraded in comparison to model. However it can always provide a preliminary analysis as well as comparative study.

### B. Fabrication Methodologies

Optimized devices will be fabricated using conventional fabrication techniques of photo-lithography and material deposition. However the growth of vertically aligned CNTs brings a different challenge due to high temperature process and carbon residue. In this context we have developed a low temperature transfer process for the realisation of CNT based 3D structures [9], [10]. In our case we have grow the CNTs on a different substrate and transfer them on desired pattern using flip-chip technology [11]. This will help in achieving low temperature fabrication process with lesser carbon residue. The CNTs are grown on iron patterned catalyst using the chemical vapor deposition and subsequently transferred on patterned device designs on alumina substrate. Scanning electron-microscopy(SEM) images for fabricated waveguide(without top cover) are shown in Figure:2

## III. DESIGN OF WAVEGUIDE AND FILTERS

### A. Waveguide

The waveguide has the three key components namely as input/output access lines for excitation mechanism with an CNT excitation pillar, vertical CNT walls and enclosing top metallization with silicon substrate. The dimension of CNT excitation pillar as well as CNT wall height plays a crucial role in effective waveguide design.

In our 6.9 mm long and 2.7 mm wide waveguide design we have used the wall height of 100  $\mu\text{m}$  and excitation pillar of

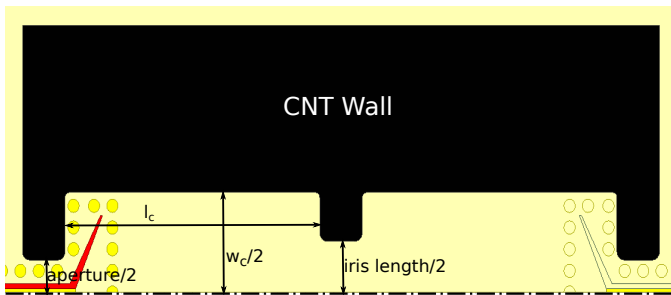


Fig. 4. Schematic view of 2-pole filter, broken line at bottom represents the symmetry plane.

100  $\mu\text{m}$  X 100  $\mu\text{m}$  lateral dimensions. In this case the lateral dimension of CNT pillar is of crucial importance to have an aspect ratio which allow effective coupling. The excitation mechanism for waveguide is shown in Figure:3(a).

### B. Filters

To design an effective 2-pole filter we decided to proceed with designing of a resonant cavity at 80 GHz as this will act as basic building block for an iris-based 2-pole filter. In doing so our first challenge was to devise an effective CNT pillar free excitation mechanism to avoid fabrication complications. As shown in Figure:1(b) the design of cavity is similar to waveguide with truncation of length. The pillar free coupling was achieved with modified CPW input/output access lines of gold embedded in bottom alumina substrate with an extended de-metallized region as shown in Figure:3(b) and same was used for 2-pole filter as well. Here the optimized resonant cavity is 2.86 mm long and 2.4 mm wide, with a CNT wall height of 330  $\mu\text{m}$  and aperture of 0.79mm.

After optimization of cavity the 2-pole filter design optimization was achieved by placing two resonant cavities side by side of desired central frequency with iris based coupling as shown in Figure:4. In case of filter the resonant cavity dimensions remained same with an iris of 1.03 mm.

Modified input and output CPW access lines were optimized to achieve low losses and high quality factor. The vias are placed along it to avoid leakage of the field and filleting of corners is done to avoid concentration of field distribution at particular points. Extension of de-metallized region with optimized dimensions and orientations have played a key role for optimizing effective coupling.

Here important to note is that, all the designs were optimized for primary dominant mode of  $\text{TE}_{101}$ . Also the bulk equivalent conductivity for CNT walls is kept at  $10^5$  S/m for an equivalent density of  $10^{15}$  with a minimum wall thickness of 300  $\mu\text{m}$  to avoid any skin depth effects.

## IV. RESULTS AND DISCUSSION

The optimized device structures were used for computing S-parameters, specifically  $S_{11}$  and  $S_{12}$  for estimation of return loss and insertion loss. The unloaded quality factor for cavity

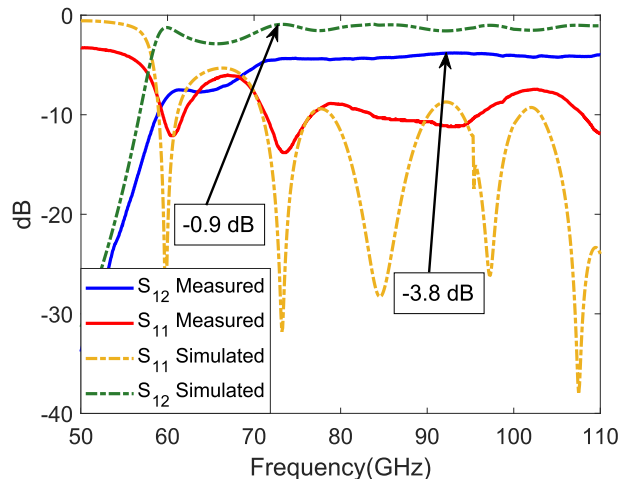


Fig. 5. S-parameters of waveguide for measured and simulated designs

TABLE I  
RESONANT CAVITY QUALITY METRICS

Frequency	Insertion loss(<)	Quality Factor
80 GHz	3.19 dB	270

was computed using an equivalent lumped model. The s-parameters for the optimized waveguide were compared with measurement result of fabricated device in Figure:5.

The insertion loss and quality factor for cavity are mentioned in Table:I while key figure of merits for 2-pole filters in terms of return loss and bandwidth are summarized in Table:II. The S-parameter characteristics for cavity and filter are shown in Figure:6

As we can see from waveguide s-parameters shown in Figure:5 that minimum insertion loss for simulated design is -0.9 dB while the measured one is -3.8 dB. This discrepancy can be attributed to fabrication challenges leading to reduced effective CNT conductivity causing poor coupling. In addition to this the attenuation constant extracted from measured data for the waveguide is around 0.5 dB/mm.

## V. CONCLUSION

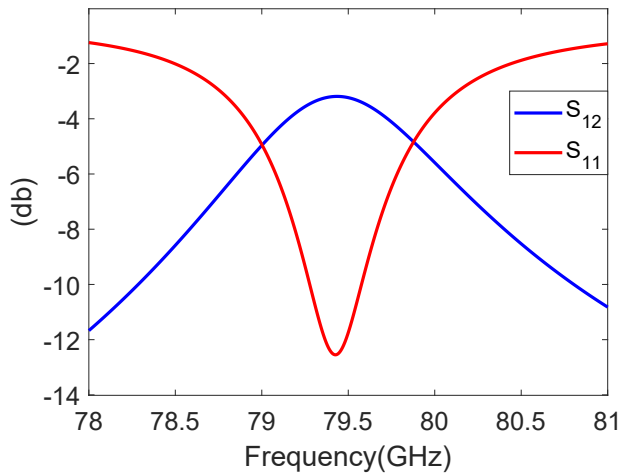
We have designed and optimized the waveguide and 2-pole filter by performing full wave simulations using Ansys HFSS. The preliminary results of fabricated waveguide are promising with CNT based technology which brings additional advantage of better electromagnetic shielding, heat dissipation and very high aspect ratio which will play a crucial role in nano-packaging with effective interposer designs. A better estimation can be made once the fabrication and measurements

TABLE II  
FIGURE OF MERITS FOR 2-POLE FILTERS

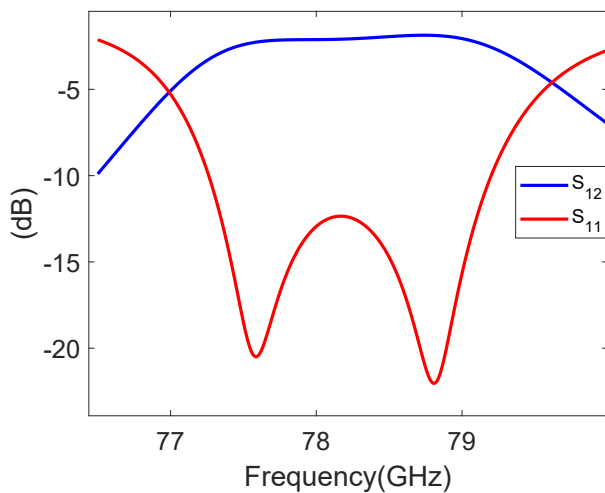
Frequency	Return loss(>)	Bandwidth(%)
80 GHz	12.34 dB	2.4(1.8 GHz)

## REFERENCES

- [1] "Ericsson Mobility Report November 2020" [Online]. Available: <https://www.ericsson.com/4adc87/assets/local/mobilityreport/documents/2020/november-2020-ericsson-mobility-report.pdf>.
- [2] T. S. Rappaport et al., "Wireless communications and applications above 100 GHz: Opportunities and challenges for 6G and beyond," in *IEEE Access*, vol. 7, 2019.
- [3] J. Campion et al., "Toward industrial exploitation of THz frequencies: Integration of SiGe MMICs in silicon-micromachined waveguide systems," in *IEEE Transactions on Terahertz Science and Technology*, vol. 9, 2019.
- [4] A. Kumar et al., "150 GHz band-pass filter using LTCC technology," in *IEEE Microwave and Wireless Components Letters*, vol. 19, 2009.
- [5] L. A. Samoska, "An overview of solid-state integrated circuit amplifiers in the submillimeter-wave and THz regime," in *IEEE Transactions on Terahertz Science and Technology*, vol. 01, 2011.
- [6] P. L. Doan et al., "Potentialities of air-filled substrate integrated waveguides based on carbon nanotubes in e-band," in *2020 IEEE MTT-S International Conference on Microwaves for Intelligent Mobility (ICMIM)*, IEEE, 2020, pp. 1–4.
- [7] J. M. de Saxcé et al., "Millimeter wave carbon nanotube based flip chip coplanar interconnects," in *2020 IEEE 22nd Electronics Packaging Technology Conference (EPTC)*, IEEE, 2020, pp. 81–84.
- [8] P. Franck et al., "Mesoscopic model for the electromagnetic properties of arrays of nanotubes and nanowires: A bulk equivalent approach," in *IEEE Transactions on Nanotechnology*, vol. 11, 2012.
- [9] Wang J., Coquet P. and Tay B.K., "Nanostructure Transfer Method," Singapore Patent 10201807403V, 29 August 2018.
- [10] C. F. Siah et al., "Development of a CMOS-Compatible Carbon Nanotube Array Transfer Method", *Micromachines*, vol. 12, p. 95, Jan. 2021.
- [11] J. M. de Saxcé et al., "E-band vertically aligned carbon nanotubes based air-filled waveguide," in *IEEE Microwave and Wireless Technology Letters*, vol. 33, 2023.



(a)



(b)

Fig. 6. S-parameters of (a) Cavity (b) 2-pole Filter; at 80 GHz

of designed cavity and filter is carried out and a feedback upon fabrication challenges is analysed.

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