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Graphene based Reflect Standard for VNA Calibration

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Abstract

This paper presents a preliminary analysis on usage of graphene as reflect standard for vector network analyzer (VNA) calibration operating at millimeter-wave frequencies. As an example, WR03 waveguide flange is used for investigation. It is found that multilayer graphene exhibits reflection properties that makes it a suitable candidate for reflect standard to calibrate the VNA test setups operating at millimeter-wave frequencies. A parametric analysis to study the effects of graphene thickness, chemical potential and relaxation time on reflection coefficient has also been presented and discussed.

1 Introduction

In RF & microwave engineering, the Vector network analyzer (VNA) is commonly used for characterization of active and passive microwave & millimeter-wave devices. Before performing the measurements, it is necessary to calibrate the VNA using mechanical/electronic calibration standards. The purpose of calibration is to reduce the measurement errors. These errors are classified into three types, which include systematic, random and drift errors. The systematic errors are repeatable & time invariant and include the VNA test setup imperfections such as signal reflections & leakage and frequency response of test setup. The calibration procedure minimizes the systematic errors. The other two classes of errors i.e. random and drift errors can't be eliminated, however, they can be minimized through different procedures such as increasing the source power, VNA recalibration, narrower IF bandwidth or stable ambient temperature. The uncorrected measurement errors become the source of uncertainty associated with the measurements of the devices under test (DUTs) [1], [2].

The VNA test setups are available for coaxial, waveguide and on-wafer measurement environments. With technological advancements, the VNA test setups are available to perform measurements at millimeter-wave frequencies as high as up to 1.1 THz. The calibration procedure, required for each measurement environment, uses a particular combination of 1-port and 2-port standards to perform the calibration. The one-port standards may include short, open, load while the two-port standards include the Line and thru standards. Common calibration techniques include the TRL (Thru-Reflect-Line), LRM (Line-Reflect-Match) and SOLT (Short-Open-Load-Thru) [3] - [13].

The traditional one-port waveguide calibration standards include conductive metal plate (i.e. short standard), adding an offset to a short standard makes it an open standard (i.e. to avoid unwanted radiations at the open end of waveguide flange) and a load or match standard that consists of ferrite based cone or pyramid structure designed to act as a absorber for electromagnetic (EM) energy [2].

This paper presents analysis of graphene as potential candidate for reflect standard to perform VNA calibration. The aim is to introduce the new form of VNA calibration standards. Another aspect of this analysis is to link the VNA calibration to the quantum realization of base units of International System of units (SI) [14], [15] by developing graphene based calibration standards. Here, a 10 nm multilayer graphene section is analyzed along with WR03 waveguide flange section with frequency range of 220-325 GHz. A parametric analysis on material properties of the graphene section is also carried out to study the effect on reflection coefficient.

The organization of this paper is as follows: Section 2 presents the graphene based reflect standard model and the details of simulation environment. The results are discussed in Section 3 followed by conclusion in Section 4. The acknowledgement and references followed afterwards.

2 Electromagnetic (EM) Simulations

In order to investigate the subject matter, the electromagnetic (EM) simulations have been performed. The reflection characteristics of the multilayer graphene, both magnitude and phase, are numerically computed using time-domain solver available in CST Microwave Studio® [16], which is a 3D EM simulation software package. The simulation model, highlighting the connection strategy of graphene section with WR03 waveguide flange, is depicted in Figure 1. The excitation port is placed on one end of the waveguide flange, while the other end is terminated with graphene section. The exact dimensions of different components in simulation model are presented in Table I.

Table 1. Dimensions for Waveguide Flange and Multilayer Graphene Section (where "a" denotes width, "b" denotes height and "*l*" denotes length/thickness)

Parameter/mm	**Waveguide Flange**	**Graphene Section**
a	0.8636	0.8636
b	0.4318	0.4318
l	2	1e-5

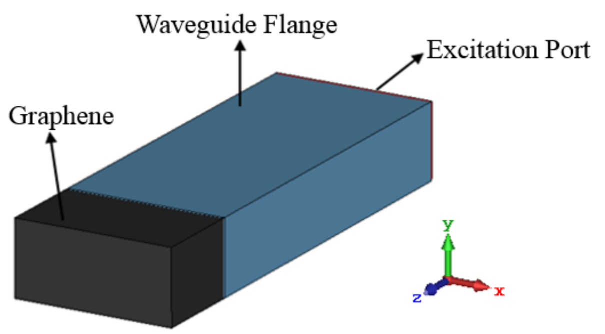

Fig. 1. The proposed simulation model depicting the graphene based reflect standard connection strategy. (The actual dimensions for above model are mentioned in Table 1.)

A. Mathematical Model for Graphene:

The graphene can be modelled as an infinitely thin layer [17]-[19]. It can described via its surface conductivity which is defined as follows:

$$\sigma^g = \sigma^g_{intra} + \sigma^g_{inter} \tag{1}$$

where, σ^g_{intra} is the intraband contribution towards surface conductivity (σ^g). It can be expressed as:

$$\sigma^g_{intra}(\omega) = \frac{2q_e^2 T}{\pi\hbar} ln\left[2\cosh\left(\frac{\mu_c}{2T}\right)\right]\frac{i}{\omega+i\tau^{-1}} \tag{2}$$

while, σ^g_{inter} is the interband contribution to σ^g which can be expressed as:

$$\sigma^g_{inter} = \frac{q_e^2}{4\hbar}\left[G\left(\frac{\omega}{2}\right) - \frac{4\omega}{i\pi}\int_0^\infty d\varepsilon \frac{G(\varepsilon)-G(\omega/2)}{\omega^2-4\varepsilon^2}\right] \tag{3}$$

with

$$G(\varepsilon) = \frac{sinh\left(\frac{\varepsilon}{T}\right)}{cosh\left(\frac{\mu_c}{T}\right) + cosh\left(\frac{\varepsilon}{T}\right)},$$

where, $\hbar$ represents reduced Planck's constant, τ represents relaxation time, μ_c represents chemical potential, T represents temperature and q_e represents electron charge.

B. Simulation Environment:

The 3D EM simulations have been performed using the graphene simulation model which is based on Eqs. (1)-(3). The integral in Eq. (3) is computed numerically in CST Microwave Studio®. The 10 nm multilayer graphene section is modelled as a three dimensional object.

The reflection magnitude and phase characteristics are computed using the multilayer graphene and waveguide sections of dimensions shown in Table 1. The WR03 waveguide flange section (operating in frequency range of 220-325 GHz) is used. However, similar analysis may be performed for other waveguide flanges e.g. WR-02, WR-1.5 and WR-01. For initial analysis, the graphene material parameters i.e., μ_c=1.25 eV, τ=0.5 ps, and T= 300 K are used. Afterwards, a parametric analysis of graphene section connected with WR-03 waveguide flange is carried out. The parameters under observation include the graphene thickness (l), the chemical potential (μ_c) and the relaxation time (τ) for the graphene material.

To develop the simulation model, the two waveguide flanges are defined via vacuum bricks. The perfect electrical conductor (PEC) is used as background material. The wave port is used for excitation at one end of the waveguide flange while the other end is terminated with 3D graphene section. The time-domain solver is used for simulation purposes, whereas hexahedral mesh type is employed for discretization purposes.

3 Results and Discussion

The reflection coefficient (S_{11}) results are shown in Figs. 2 and 3.

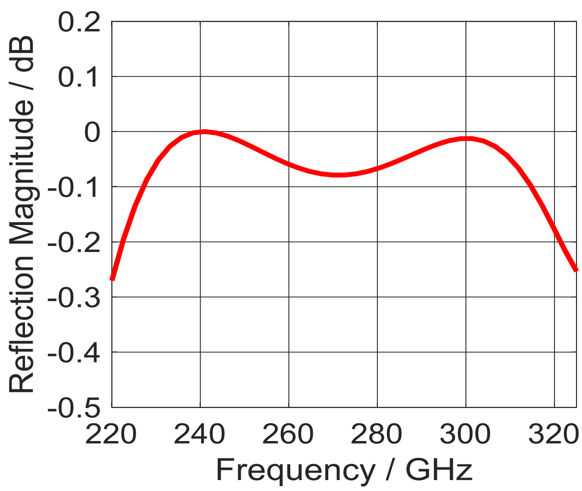

Fig. 2. The $|S_{11}|$ values of graphene based reflect standard

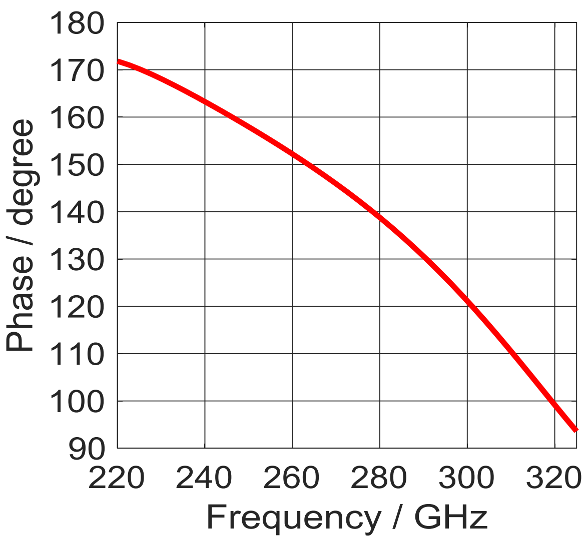

Fig. 3. The $\angle S_{11}$ values of graphene based reflect standard

It can be seen from Fig. 2 that the multilayer graphene, when used as a reflect standard, has provided a reasonable reflection coefficient magnitude i.e. < -0.3 dB over the whole frequency band of 220-325 GHz. Therefore, it can be inferred that the graphene can be considered as a potential candidate for reflect standard to perform VNA calibration. Similarly, the reflection coefficient phase values for graphene based reflect standard are shown in Fig. 3.

The parametric analysis to study the effects of graphene thickness, chemical potential and relaxation time on reflection coefficient has also been carried out. It can be observed from Fig. 4 that by varying the graphene thickness from 10 nm to 50 nm with a step of 10 nm, the reflection coefficient magnitude varied as low as <-0.1 dB over frequency band of 220-325 GHz. It can be inferred that different reflection coefficient values can be achieved by varying graphene thickness.

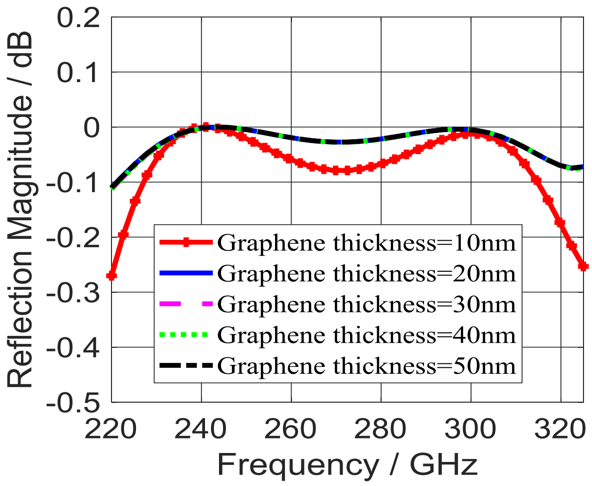

Fig. 4. The $|S_{11}|$ values of graphene based reflect standard for different thickness values of graphene

The effects on reflection coefficient magnitude due to the chemical potential (μ_c) variation from 0 eV to 1.25 eV are presented in Fig. 5. It can be observed that by varying μ_c, the reflection magnitude varied as low as <-0.1 dB over frequency band of 220-325 GHz. This trend is similar to the one shown in Fig 4. In practice, the μ_c can be varied via application of electric field and chemical doping [17].

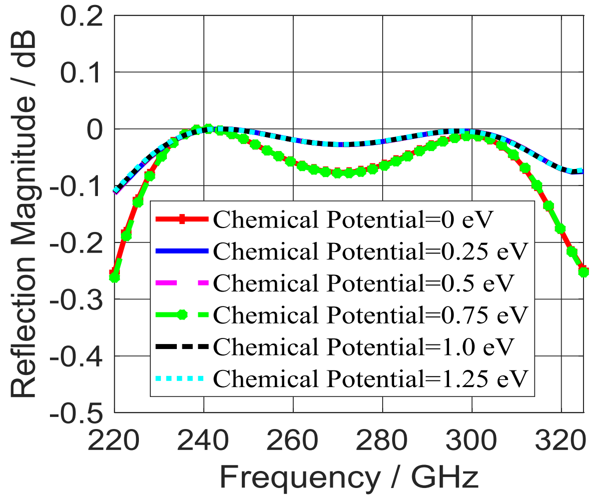

Fig. 5. The $|S_{11}|$ values of graphene based reflect standard for different chemical potential (μ_c) values.

It can be seen from Fig. 6 that the relaxation time (τ) also has a significant effect on reflection coefficient magnitude. As τ is varied from 0.1 to 0.5 ps, the reflection coefficient magnitude approached as low as <-0.025 dB, especially for lower values of τ.

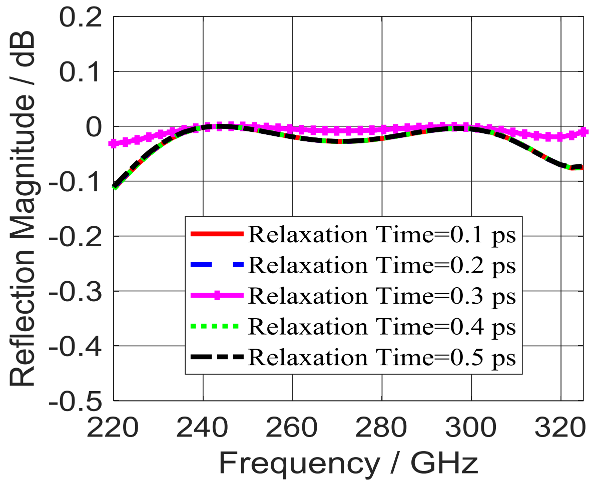

Fig. 6. The $|S_{11}|$ values of graphene based reflect standard for different relaxation time (τ) values.

From parametric analysis, it can be concluded that different reflect standard including short and open calibration standards can be developed by varying the different properties of graphene material.

4 Conclusion

This paper has presented the analysis of graphene based reflect standards that may be used to calibrate millimeter-wave VNA test setups. As an example, WR03 waveguide flange is used in this analysis, operating at 220-325 GHz. However, it can be extended to other waveguide flange standards as well. It is inferred that the graphene section can provide reasonable reflection coefficient values which makes it a potential material to be used for development of for future VNA calibration standards. It is also observed that the reflection coefficient magnitude varies by varying the graphene thickness, relaxation time and chemical potential of the graphene section. By developing such graphene based standards, it could be possible to link the VNA calibration procedure to the quantum realization of base units of SI [14], [15].

The future work may include the development and validation of the graphene based reflect standards followed by a comparison of performance with traditional calibration standards [20]-[23]. The repeatability of such standards and environmental effects may be studied to validate their practical demonstration.

5 Acknowledgements

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