Establishing a new form of primary impedance standard at millimeter-wave frequencies

Yasameen Azeez, Richard J. Collier, Nick M. Ridler, *Fellow, IEEE*, Paul R. Young

***Abstract*—This paper investigates the possibility of using layers of graphene to form primary impedance standards for millimeter-wave rectangular metallic waveguide. It is shown that standards with values of Y_0, $2Y_0$ and $3Y_0$ can be produced by a mono-, bi- or tri-layer of graphene, respectively, where Y_0 is the characteristic admittance of the waveguide. These standards could then be used in the calibration of vector network analysers (VNA).**

***Index Terms*—Graphene, impedance standards, millimeter-waves, rectangular waveguide.**

I. INTRODUCTION

Nearly all guided-wave measurements are defined with respect to a nominal characteristic impedance. For example, in coaxial lines, it is common to refer measurements of scattering parameters (i.e. reflection and transmission coefficients) to a 50 Ω characteristic impedance. It is therefore very important to be able to achieve accurate realizations of characteristic impedance to ensure the reliability of all subsequent, related, measurements.

For more than 50 years, the realization of characteristic impedance at microwave frequencies has been achieved using either precision air-spaced coaxial lines [1, 2], or, precision near-matched terminations [3]. During this period, these standards have been used successfully at all microwave frequencies and extended into the millimeter-wave region (to 110 GHz), using coaxial lines with outer conductor diameters as small as 1 mm [4]. However, for high millimeter-wave frequencies and above (i.e. above 110 GHz) the preferred transmission medium is rectangular metallic waveguide, which is nowadays being used for measurements at frequencies to at least 1.1 THz [5]. Although sections of precision air-filled waveguide can be used as impedance standards at these frequencies, the achievable tolerances on the critical dimensions of the waveguide (i.e. the height, width and overall shape of the waveguide) [6] along with the difficulty in accurately aligning the waveguides during connection [7] cause these waveguides to become poorly-defined standards of impedance at these frequencies [8].

This is driving the need for new forms of impedance standard at high millimeter-wave and terahertz frequencies. This paper investigates one candidate for a new form of standard, based on using layers of graphene suspended across the waveguide aperture. Sheets of mono-, bi- and tri-layer graphene have been investigated in order to provide different values of impedance for the electromagnetic wave in the waveguide. Since the physical properties of graphene can be linked to fundamental laws of nature (defined by quantum mechanics) [9], the long term goal for this research is to link measurements at millimeter-wave frequencies and above to these fundamental laws, providing a primary standard of impedance.

This paper describes some initial investigations into using layers of graphene as impedance standards in waveguide operating at millimeter-wave frequencies (50 to 75 GHz). At these frequencies, the size of the waveguide is relatively large and so is ideal for testing initial designs of impedance standards. The size-scalability of waveguide is such that any designs found to work at low millimeter-wave frequencies should be able to be scaled to operate at high millimeter-wave frequencies, and ultimately at terahertz frequencies.

II. MEASUREMENT SETUP AND DE-EMBEDDING

The graphene mono-, bi- and tri-layer samples were supplied by Graphenea and produced by chemical vapor deposition (CVD) and transferred to quartz substrates by a wet transfer process. Each of the quartz substrates were 500 μm thick and 5 mm by 5 mm wide with a 0.6 nm surface roughness. To measure the surface impedance of the graphene the samples were placed directly at the end of an open-ended WR-15 waveguide (which operates from 50 to 75 GHz) with the graphene side touching the waveguide aperture. This setup is shown in the Fig. 1.

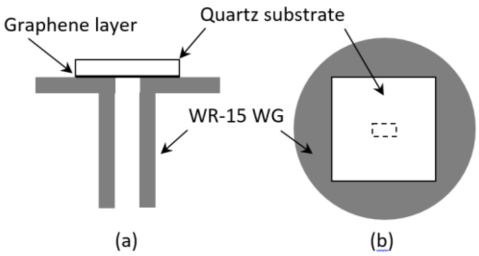

Fig. 1. Measurement setup, showing quartz substrate with graphene layer placed onto an open-ended WR-15 waveguide. (a) side-view. (b) top-view.

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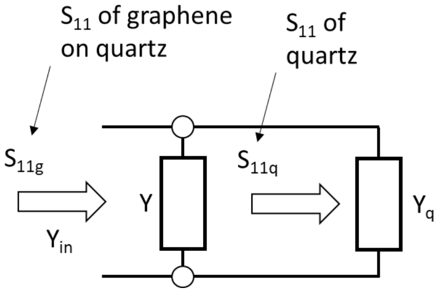

Fig. 2. De-embedding circuit.

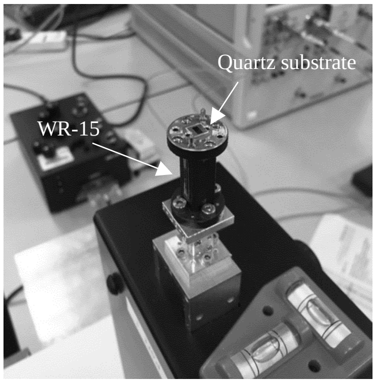

Fig. 3. Photograph of measurement setup with quartz substrate placed on open-ended WR-15 waveguide.

To de-embed the effect of the quartz sample and determine the admittance of the graphene surface the following procedure was followed. First, a quartz sample with no graphene layer was placed at the end of the waveguide and measured, resulting in an S-parameter measurement S_{11q}. Secondly, a quartz sample with a graphene layer was placed on the waveguide resulting in a measured S-parameter S_{11g}. Finally, by assuming that the graphene layer can be modelled as a simple shunt admittance, Y (Fig. 2), the value of this admittance is calculated by

$$\frac{Y}{Y_0} = \frac{Y_{in}}{Y_0} - \frac{Y_q}{Y_0} = \frac{1-S_{11g}}{1+S_{11g}} - \frac{1-S_{11q}}{1+S_{11q}} \quad (1)$$

This is similar to the method applied in [10]. The characteristic admittance of the waveguide, Y_0, is given by [11]

$$Y_0 = \frac{1}{\eta_0 k_0}\sqrt{k_0^2 - \left(\frac{\pi}{a}\right)^2} \quad (2)$$

Where η_0 and k_0 are the free-space wave impedance and phase constant, respectively, and a is the broadwall dimension of the waveguide; a = 3.8 mm for WR-15.

The above method for determining the admittance was preferred over transmission methods such as in [12, 13] because of the relatively large thickness of the quartz substrate.

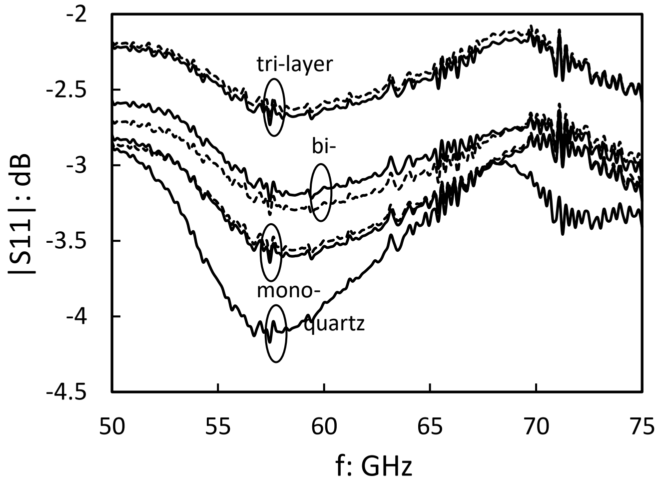

Fig. 4. Measured S-parameters. Dotted lines show repeat measurements.

III. MEASURED RESULTS

The measurements where performed using a Keysight Technologies PNA-X vector network analyzer (VNA) using VDI waveguide extender heads covering the frequency range 50 to 75 GHz. The system was calibrated using the TRL calibration technique [12] using WR-15 waveguide standards. The samples were placed on the end of the waveguide aperture and were therefore measured at the reference plane established by the calibration. A photograph of the measurement setup together with a quartz sample is shown in Fig. 3.

Fig. 4 shows the measured S_{11} of the mono-, bi- and tri-layer samples as well as the quartz sample. In each case the samples were measured twice to assess any repeatability issues with the attachment of the samples to the measurement system.

Fig. 5 shows the measurement results after de-embedding using equation (1). It is seen that the mono-, bi- and tri-layers of graphene have a real part of admittance very close to Y_0, $2Y_0$ and $3Y_0$, respectively. Since Y_0 converges to $1/\eta_0$ over the 50-75 GHz waveguide band (equation 2), the sheet impedance of the graphene is approximately equal to 377 Ω/sq for a single layer, and 189 Ω/sq and 126 Ω/sq for the bi- and tri-layers, respectively. This suggests that these samples could be used as calibration standards; providing a matched load standard, and reflection standards with linear magnitude 0.33 and 0.5.

The rapid reduction in the real part of the admittance above 65 GHz is attributed to resonances in the quartz substrate and is not indicative of the graphene. The wavelength in quartz at 75 GHz is approximately 2 mm and therefore there are a number of resonances that can occur in the 0.5 × 5 × 5 mm quartz sample over the 50-75 GHz band. Since the de-embedding process required two measurements (one of a quartz substrate and one of a quartz substrate with graphene layer) any small differences in alignment and the geometry of the two substrates would have a much more significant effect on the de-embedded admittance near a resonance. It is believed that this same effect is resulting in the rather inconsistent imaginary component of admittance seen in Fig 5.

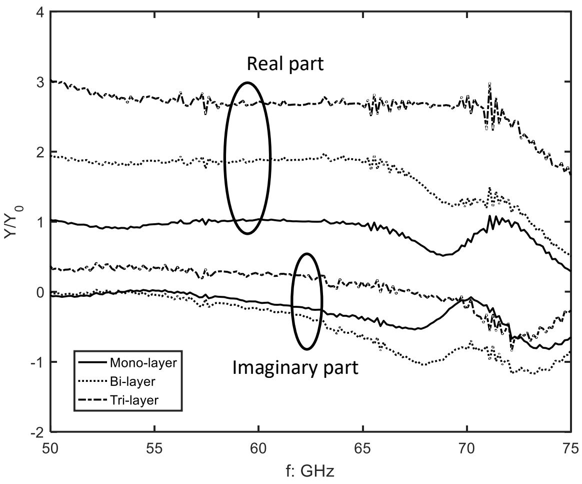

Fig. 5. The de-embedded value of normalized admittance for mono-, bi- and tri-layer graphene samples.

There are likely to be a number of practical difficulties that would need to be overcome to form reliable, repeatable, impedance standards using layers of graphene. As seen in Fig. 4, the quartz substrate has a very significant effect on the S-parameters of the structure and consequently the graphene would ideally be suspended at the end of the waveguide without the use of a quartz substrate. In practice, this would be very challenging since a mono-layer of graphene is only one atom thick. However, it would be possible to use a much thinner dielectric supporting layer than the 500 μm quartz used in this investigation. If this layer could be reduced to tens of micrometers, it would have a very small effect on the impedance of the graphene layer.

Another issue that would need to be addressed is the environmental stability of the graphene layer and the effects of repeated use. This could probably be overcome by using a thin dielectric protective layer to ensure the graphene is not exposed to the environment and 'wear-and-tear'.

IV. CONCLUSION

This paper has shown that it is feasible to realize standards of impedance (or equivalently, admittance) at millimeter-wave frequencies using layers of graphene suspended across waveguide test ports. Such standards could be used to calibrate a waveguide VNA. For example, the paper has shown that standards with values Y_0, $2Y_0$ and $3Y_0$ can be realized using samples of mono-, bi- and tri-layer graphene, respectively. This is something that would be very difficult to achieve, consistently, using other thin-film conductors. These three standards could be used for three-known-loads calibrations employing a 12-term error model [15, 16]. This also suggests that further standards could be realised by adding additional layers of graphene so that over-determined calibration schemes could be deployed to further increase the accuracy of a calibrated VNA [17, 18].

By understanding the fundamental physical properties of the graphene, and relating these properties to the observations made by the VNA during calibration, it will be possible to link the calibration of the VNA to quantum realizations of the base units of the International System of units (SI). This suggests that it may be possible to establish metrological traceability at microwave and millimetre-wave frequencies to quantum phenomena, thus potentially enabling these measurements to be harmonized within the upcoming redefinition of the SI [19, 20].

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