Experimental Demonstration of Transparent Microwave Absorber Based on Graphene

Da Yi[1], Xingchang Wei[1], Yili Xu[1]

[1]College of Information Science and Electronic Engineering, Zhejiang University, Hangzhou 310027, China
Email: weixc@zju.edu.cn

***Abstract* — A novel transparent microwave absorber is proposed in this paper. Fluorine-doped tin oxide glass, glass and monolayer graphene are applied as the reflector layer, substrate and absorbing layer respectively to form a Salisbury absorber. The performance of the absorber is measured by the rectangular waveguide. An improved equivalent circuit model is proposed to analyze the transparent absorber. There is a good correlation between absorption coefficients obtained from the equivalent circuit model, 3-D full wave simulation and measurement. As high as 95% incident power can be absorbed by using the proposed absorber.**

***Index Terms* — Transparent microwave absorber, monolayer graphene, waveguide.**

I. Introduction

With the rapid increasing integration of active devices, electromagnetic radiation pollution has been one of the most serious global problems. Materials for shielding/absorbing electromagnetic wave attract much more attention than before. In some special occasions, such as in the military vehicles and office building, in order to keep an optical window for observation, transparent and compact shielding/absorbing materials are of great demand. Traditional absorber is usually backed by a metal layer to reflect microwave efficiently. The absorption is provided by the lossy substrate or the absorbing film placed on the substrate. To compose a transparent absorber, the transparent conductive layer and bulk lossy materials are needed. In [1], a transparent absorber applying Indium Tin Oxide (ITO) glass with multi-layered substrate was manufactured. In [2], a wide band transparent absorber with metal grid served as the reflector and metal tie array served as the absorbing film was proposed. But both absorbers have complex process and their optical transmittivities are below 80%. In this paper, we propose a Salisbury type absorber composed of monolayer graphene, glass and FTO glass.

Fluorine-doped Tin Oxide (FTO) glass is an alternative for the reflector in absorber. It was firstly developed to replace ITO due to its low cost. Now it is widely applied as display screen, substrate of solar cell and photocatalysis film, etc. As a kind of conducting glass, its surface impedance can be easily below 15 Ohm, which can reflect most of the incident microwave when it serves as the reflector in an absorber. Also, its optical transmittivity can reach 85% or above.

As a novel 2-D material, graphene finds many applications in THz band due to its frequency-sensitive surface impedance and tunable conductivity in that region [3]. In microwave band, graphene remains the impedance tunable property, but shows a frequency independent resistance over the whole microwave band, which limits its application in antennas or filters designs where a larger imaginary part of the impedance is required for the tuning of resonance frequencies [4]. However, for the absorbing film in transparent absorber, graphene film can provide a good solution [5]. The advantages of graphene film are that its optical transmittivity is above 95%, which is greater than those available absorbing films; graphene has high thermal conductivity (5000 W/mK) which is required for absorbing high-power microwave; and it is very thin (only one atom thickness), which is beneficial for the compact design.

II. Proposed Absorber

The proposed absorber is composed of monolayer graphene, glass and FTO glass with the thickness of one atom, 2.2 mm and 300 nm respectively. FTO glass together with the 2.2 mm glass is fabricated first. The monolayer graphene is grown by chemical vapor deposition (CVD) method, and it is then transferred onto the glass to form a Salisbury absorber. Two samples are

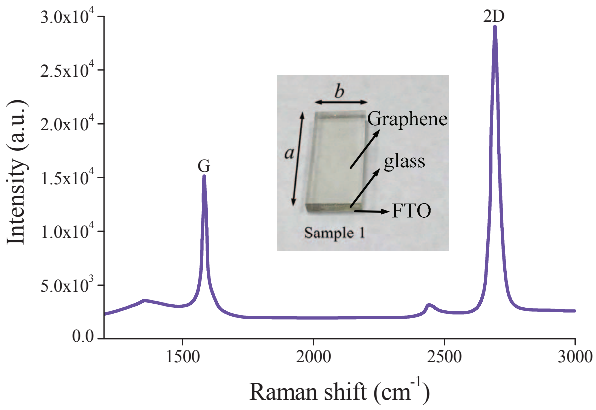


Fig. 1. Raman spectra of graphene film on sample 1. Sample 1 is shown as the inset figure.

978-1-5090-0696-0/16/$31.00 ©2016 IEEE

fabricated. Sample 1 is shown as the inset in Fig.1. For both samples, the optical transmittivities are above 80% under a light of 550 nm wavelength.

The Raman spectra of the graphene film transferred onto the glass is measured using 488nm laser Raman spectroscopy. The Raman spectra of the graphene film in sample 1 is shown in Fig. 1. Clear characteristic peaks (G band at 1585 cm^{-1}, 2D band at 2695 cm^{-1}) demonstrate that the high quality graphene film is successfully transferred onto the glass. The similar measurement result is obtained for sample 2.

In our previously work [6], a transmission line mode is proposed to analyze the absorber placed in the *free space*.

In this paper, the absorber samples are inserted into the waveguide to measure their absorption coefficients, where the samples are cut to match the cross section of the waveguide (WR-62, for Ku band) for the measurement. Since the characteristic impedance and propagation constant of the TE_{10} mode of the waveguide are different from those of the TEM mode in free space, an equivalent circuit based on the TE_{10} mode is proposed in Fig. 2 (b). In Fig. 2 (b), the equivalent circuit is composed of three segments of transmission line and two resistors. From top to bottom, the three segments of transmission line represent the air-filled waveguide above the sample, glass-filled waveguide and the air-filled waveguide below the sample, respectively. For the TE_{10} mode in rectangular waveguide, the longitudinal propagation constant k_{zi} and the characteristic impedance Z_{ci} (i=0 for the air parts, i=1 for the glass substrate) can be written as

$$k_{zi} = \sqrt{k_0^2 \varepsilon_{ri} - k_x^2}\,, \qquad (1)$$

$$Z_{ci} = \frac{\omega \mu_0}{k_{zi}} \times \frac{b}{a}\,, \qquad (2)$$

in which a and b are the length and width of the cross section of the waveguide respectively, $k_0=2\pi f/c$ is the propagation constant in free space, $k_x=\pi/a$ is the transverse propagation constant, ε_{ri} is the relative permittivity of air or glass substrate, μ_0 is the permeability in free space.

In the equivalent model, R_g and R_{FTO} represent the equivalent resistance of graphene layer and FTO glass. Under TE_{10} mode incidence, R_g and R_{FTO} are expressed as

$$R_g = R_{gs} \times \frac{b}{a}\,, \qquad (3)$$

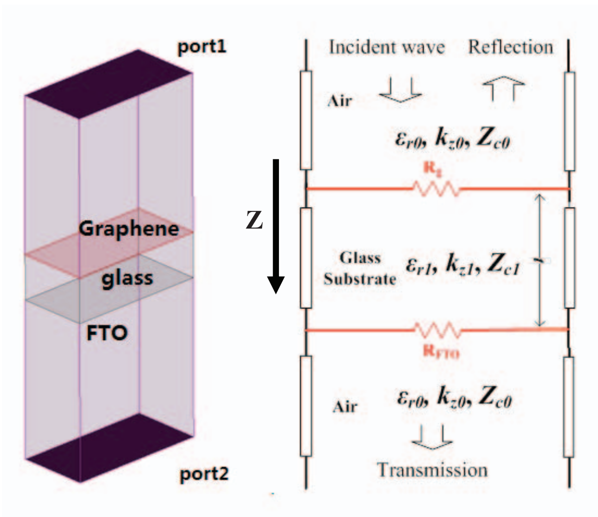
$$R_{FTO} = R_{FTOs} \times \frac{b}{a}\,, \qquad (4)$$

in which R_{gs} and R_{FTOs} are the surface resistance of graphene film and FTO, respectively.

The principle of such an absorber can be illustrated as below. The conductive FTO layer guarantees little microwave transmits through the absorber, and once the input impedance seen from the graphene layer matches with the characteristic impedance of the above air-filled waveguide, the microwave energy can totally goes into the absorber without the reflection. Since the energy does not transmit through or is reflected by the absorber, it will be absorbed by the graphene film and FTO glass.

To verify the accuracy of the proposed equivalent circuit in Fig. 2 (b), the results from the 3-D full wave simulation of the absorber is compared with the results from the equivalent circuit. The model used in 3-D full wave simulation is shown in Fig. 2 (a). The surface impedance of FTO is 14 Ohm/□ measured using Four-point probe method. For the monolayer graphene, three typical values of surface resistance (300 Ohm/□, 450 Ohm/□, 600 Ohm/□) are set to get a series of results of scattering parameters, which are shown in Fig. 3. The results of equivalent circuit show very good agreement with those of 3-D full wave simulation. Once the scatting parameters are obtained, the absorption coefficient can be calculated as

$$Absorption = 1 - |S(1,1)|^2 - |S(2,1)|^2\,. \qquad (5)$$



(a) (b)

Fig. 2. (a) The model of 3-D full wave simulation and (b) its equivalent circuit.

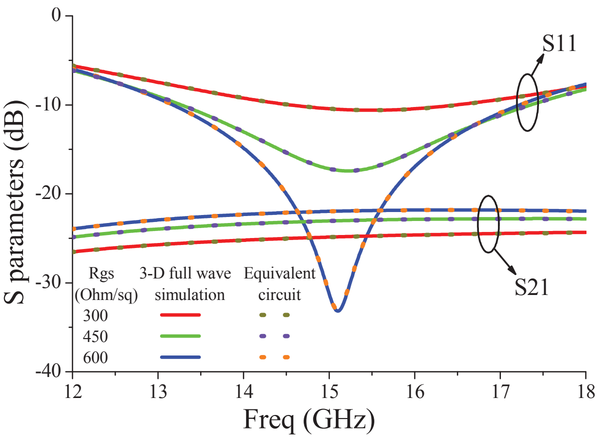


Fig. 3. The scattering parameters calculated by using 3-D full wave simulation and equivalent circuit.

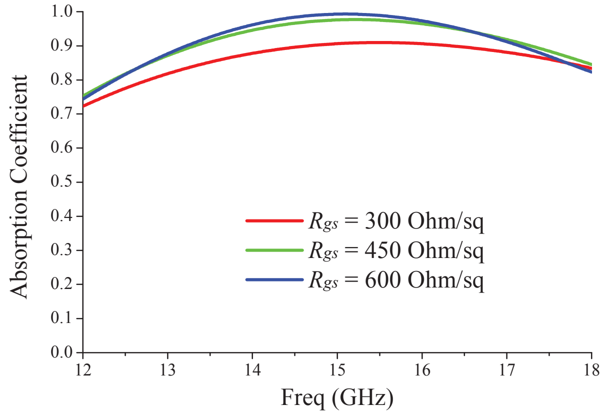


Fig. 4. The absorption coefficients under different value of R_{gs}.

The absorption coefficients are shown in Fig. 4, in which we can find the peak absorption can exceeds 95% at around 15.1GHz.

III. Measurement Results and Improved Equivalent Circuit

The performance of two samples is demonstrated by waveguide measurement. A rectangular waveguide with the working frequency ranging from 11.9 GHz to 18 GHz is employed. A piece of smooth foam, which has almost the same permittivity as the air, is stuffed into the waveguide to support the sample. After the waveguide is calibrated together with the supporting foam, the sample is placed on the foam, as shown in Fig. 5. The surface impedances of the graphene films are measured using Four-point probe method, which are 540 Ohm/□ for sample 1 and 534 Ohm/□ for sample 2 respectively.

Results of scattering parameters and absorption coefficients of two samples are shown in Fig. 7 and Fig. 8 respectively. Both samples show peak absorption coefficients of 0.95, and the peaks occur at about 14.5 GHz. In comparing with the simulation results in Fig. 3 and Fig. 4, we can see a frequency shift (about 500 MHz) of the peak absorbing. At the same time, the absorption

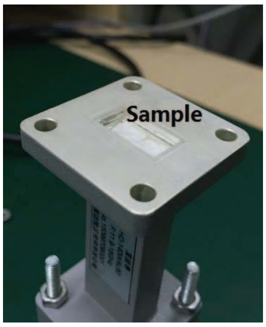


Fig. 5. The placement of the sample in the waveguide.

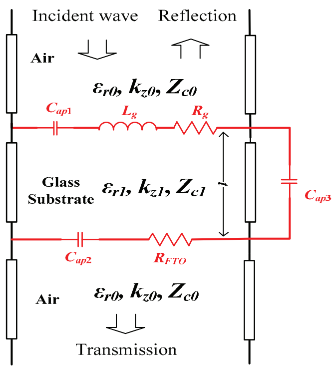


Fig. 6. The improved equivalent circuit model.

bandwidth of measurement results is smaller than the simulation result. We attribute the difference to the non-ideal samples.

1) There are gaps between the samples and the waveguide walls. These gaps introduce series capacitance especially for the graphene layer and FTO layer. When the graphene layer is transferred onto the glass substrate, to avoid wrinkle, the graphene size is a little smaller than the cross section of the sample. In addition, from the electric field distribution (not shown here for space limitation), we find longitudinal component of electric field between graphene layer and FTO layer, which indicates that there exists fringing capacitance between graphene layer and FTO layer, and this fringe capacitor is in parallel with the equivalent transmission line of glass substrate.

2) Due to the gap between glass substrate and the waveguide walls, the relative permittivity in calculating the longitudinal propagation constant k_{z1} and the characteristic impedance Z_{c1} of the equivalent transmission line of the glass substrate should be modified as [7]

$$\varepsilon_{r1eff} = \frac{\varepsilon_{air}\varepsilon_{glass}}{\varepsilon_{air} + (\varepsilon_{glass} - \varepsilon_{air})x_{air}}, \tag{6}$$

in which ε_{air} and ε_{glass} are the relative permittivity of the air gap and glass substrate respectively, x_{air} is the gap distance along the short edge of the waveguide between the glass substrate and the waveguide walls.

3) Though graphene is mainly resistive in microwave region, its inductive part, which can be calculated using formulas below [8], should be taken into account for the accurate modeling.

$$L_{gs} = \frac{\pi\hbar^2}{q_e k_B T 2\ln 2}, \tag{7}$$

in which L_{gs} is the surface inductance of graphene, $\hbar$ is the reduced Planck's constants, $-q_e$ is the charge of an electron, k_B is Boltzmann's constant, and T is temperature.

The equivalent circuit in Fig. 2 (b) is improved based on above discussion, as shown in Fig. 6, where C_{ap1} and C_{ap2} are the series capacitance in graphene layer and FTO layer respectively, C_{ap3} is the fringing capacitance between graphene layer and FTO layer, L_g is the equivalent inductance of graphene layer.

The values of R_g, R_{FTO}, L_g and ε_{r1eff} are obtained by measurement results or above formulas. For the values of C_{ap1} to C_{ap3}, by tuning their values, the scattering parameters results of the improved equivalent circuit can agree very well with those of 3-D full wave simulation under different gap distance, and the capacitance-gap curves can be obtained. The measured gap of sample 1 and 2 are 0.44 mm and 0.4 mm respectively. From the

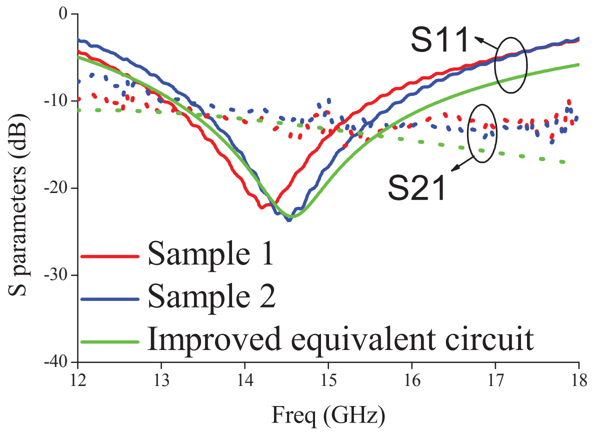


Fig. 7. The scattering parameters of measurement and improved equivalent model.

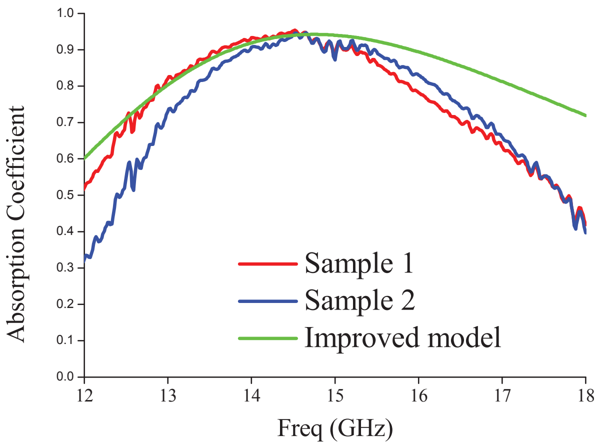


Fig. 8. The scattering parameters of measurement and improved equivalent model.

TABLE I

VALUES OF PARAMETERS IN IMPROVED EQUIVALENT CIRCUIT

R_g (Ohm)	R_{FTO} (Ohm)	L_g (pH)	C_{ap1} (fF)	C_{ap2} (fF)	C_{ap3} (fF)	ε_{r1eff}
233	6	102	255	293	41	4.4

simulated capacitance-gap curves, their C_{ap1} to C_{ap3} can be obtained. The values of all parameters for sample 1 are listed in TABLE I. The scattering parameters results and absorption results of the improved equivalent circuit after applying the values in TABLE I are shown in Fig. 7 and Fig. 8, where we can see the frequency of the peak absorption is corrected. This further indicates that this improved model is accurate for the absorber under measurement. This experiment demonstrates that the proposed transparent absorber has a remarkable absorption under the TE_{10} mode incidence. Based on the improved equivalent circuit, its performance can be well illustrated.

IV. CONCLUSION

In this paper, an absorber with above 80% optical transmittivity based on graphene film is proposed and analyzed using 3-D full wave simulation and improved equivalent circuit. Two samples are fabricated and measured using the waveguide. The performance of the absorber is accurately illustrated by the improved equivalent circuit model. Such an experiment demonstrates that this design is an admirable solution for transparent absorber. Due to its easy design method and fabrication process, it can find much potential applications in electromagnetic compatibility area.

ACKNOWLEDGEMENT

This work was jointly supported by the National Science Foundation of China under Grant (61274110), Zhejiang Provincial Natural Science Foundation of China (LZ12F04001), and National Science and Technology Major Project of the Ministry of Science and Technology of China (2014ZX02501).

REFERENCES

[1] Takizawa, Koji, and Osamu Hashimoto. "Transparent wave absorber using resistive thin film at V-band frequency." *Microwave Theory and Techniques, IEEE Transactions on* 47.7 (1999): 1137-1141.

[2] Jang, Taehee, et al. "Transparent and flexible polarization-independent microwave broadband absorber." *ACS Photonics* 1.3 (2014): 279-284.

[3] Gomez-Diaz, Juan Sebastian, and Julien Perruisseau-Carrier. "Microwave to THz properties of graphene and potential antenna applications." *Antennas and Propagation (ISAP), 2012 International Symposium on*. IEEE, 2012.

[4] Wei, Xing-Chang, et al. "A non-contact graphene surface scattering rate characterization method at microwave frequency by combining Raman spectroscopy and coaxial connectors measurement." *Carbon* 77 (2014): 53-58.

[5] Wu, Bian, et al. "Experimental demonstration of a transparent graphene millimetre wave absorber with 28% fractional bandwidth at 140 GHz."*Scientific reports* 4 (2014).

[6] D.Yi, Xing-Chang Wei, et al. "Transparent Microwave Absorber based on Single Layer Graphene Film." *APMC 2015. 2015 Asia-Pacific Microwave Conference.* 2001.

[7] Papapolymerou, Ioannis, Rhonda Franklin Drayton, and Linda PB Katehi. "Micromachined patch antennas." *Antennas and Propagation, IEEE Transactions on* 46.2 (1998): 275-283.

[8] Gomez-Diaz, Juan Sebastian, et al. "Non-contact characterization of graphene surface impedance at micro and millimeter waves." *Journal of Applied Physics* 111.11 (2012): 114908.