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Article

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High Frequency Transmission Properties of Printed Graphene

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The microwave transmission properties of printed graphene are studied by measuring different length graphene coplanar wave guides up to 10 GHz and by modelling this behaviour with simple transmission line models. The graphene coplanar wave guide is printed on a PET ST 506 flexible substrates by screen printing method. Vorbeck inks S301 were used in the printing process. 10 and 30 mm long graphene transmission line samples were attached on FR4 test boards and measured. These two graphene lines were modelled with lumped equivalent circuits with scalable parameters. Two equivalent circuit approaches were compared and the high frequency fits suggest that a simple model for graphene conductivity is not sufficient. High frequency behaviour is not possible to model with a bulk conductor but a capacitive path has to be added lowering the high frequency conductivity. This is probably a result of the flake structure of printed graphene.

Keywords:

The microwave properties of graphene are of interest because of potential graphene applications in microwave components and devices.[1,2] The high frequency transmission properties of monolayer graphene have been studied recently.[3,4] Printing techniques are competitive alternatives to conventional photolithography for the production of electronic devices with advantages of low cost, ease of mass production, and flexibility.[5] It is important to know the microwave properties of printed graphene in terms of its usage in printed radio components, antennas and interconnections.[6,7] This letter presents the first experimental work on study of high frequency transmission properties of printed graphene from DC to 10 GHz.

Graphene samples were mounted on test boards fabricated of a FR4. The test board included three copper coplanar waveguides (CPWs): two with slots for graphene samples and one full length copper CPW for reference. Central parts of two CPWs (30 mm and 10 mm long) were replaced by graphene CPW with the same geometries but made of graphene printed on PET ST 506 flexible substrates by screen printing method. Vorbeck inks S301 were used in the printing process.[8] The CPW line center conductor width was 300 μm and the gap was 850 μm. These dimensions were chosen from the resolution of utilized printed process. Silver paste was used for making electrical contact between copper and graphene parts of the CPW-lines. The test structure with inserted graphene parts is shown in Figure 1.

The S-parameters of CPWs were measured over the frequency range DC-10 GHz using an Agilent E8362B network analyser.

A representative example of measured S_{21} scattering parameters magnitude, for CPW with 10 mm long graphene part is shown in Figure 2. Above 6 GHz the curve shows ripples although a very careful calibration and measurement was performed. A microscope picture of the graphene CPW in Figure 3 shows the manufacturing inaccuracy in the edges of CPW graphene electrodes. These inaccuracies could be the reason for the observed ripples. It is known that asymmetrical ground paths can cause resonance loops in conductive structures[9] causing the ripple effect in tested graphene lines.

A two stage CPW lumped element model shown in Figure 4 was utilized for modelling the CPW with a 10 mm long inserted graphene line. The model includes CPW circuit models of copper parts (CPW-line in figure),

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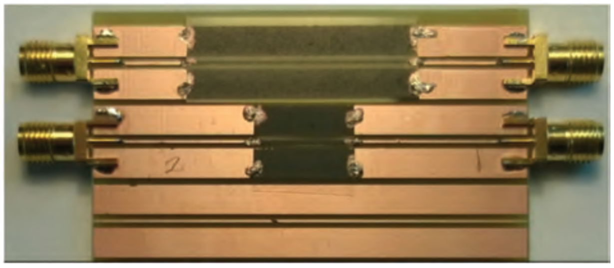

Figure 1. Test structure: copper coplanar waveguides with printed graphene parts inserted. Board and device lengths are 60 mm.

CLC-π-equivalent circuits of graphene CPW and the contact resistance RC between them. One CLC-π-subsection describes a 5 mm graphene CPW section.

The values of graphene DC sheet resistance and estimate of graphene CPW inductance were used as initial parameters of a fitting procedure and extraction of parameters of the model. Measured graphene DC sheet resistance was 43 $\Omega/\square$. The inductance value 0.7 nH/mm was estimated from electromagnetic (EM) simulations with AWR AXIEM EM simulator. The parameters of the copper part of CPW were extracted from the 60 mm long reference CPW. Capacitance C_p and R_C were purely fitting parameters.

The simulation result of the simple lumped element model is shown in Figure 2. The proposed model describes behaviour of graphene CPW very precisely for frequencies up to 3 GHz. The parameters of the graphene section CPW extracted from the fitting procedure were $R_{\text{SH}} = 36\ \Omega/\square$, $C_l = 50$ fF/mm and $L_l = 0.8$ nH/mm. R_S, L_S and C_p component values were calculated from these geometry dependent values. These fitted parameters are in good agreement with the measured graphene DC values and the estimated value of inductance. The fitted contact graphene-copper contact resistance R_C was 81 Ω. However for frequencies above 3 GHz the experimentally measured insertion losses are much lower than predicted by the model.

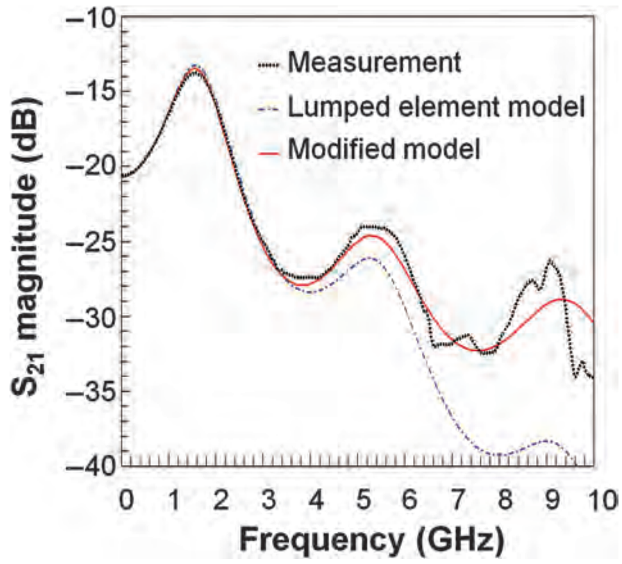

Figure 2. Measured and simulated S_{21} magnitude of CPW with 10 mm long graphene section.

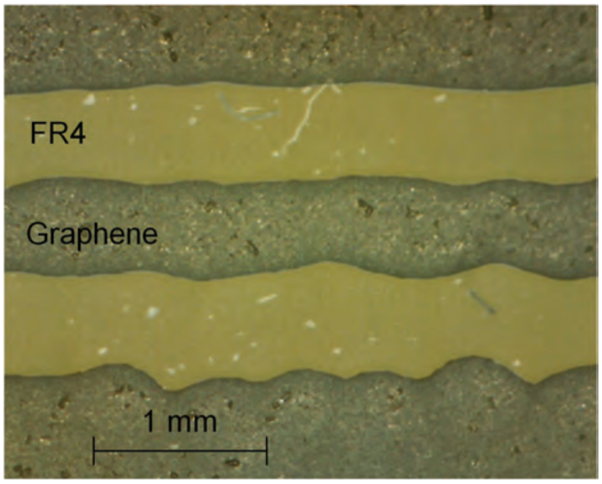

Figure 3. A microscope image of the graphene CPW. Tolerance of the CPW electrodes can be seen. Graphene is grey and the FR4 surface is in between.

Our hypothesis is that the reason for the observed effect is the enhancing of high frequency conductivity between graphene flakes due to capacitive coupling between them. It is known that contact resistance between graphene flakes is a key contributor of the resistivity of printed graphene films.[10] Printed graphene films have a porous and irregular structure (see Fig. 5) which results in high ohmic contact resistance between flakes.

However there is considerable overlap between graphene flakes in multilayer flake structure. Due to this overlap there is high capacitance between separate flakes. This capacitance should considerably decrease the effective conductivity between graphene flakes at high frequencies as it is shown in Figure 6.

An extra "capacitive" branch was added to the lumped element model as shown in Figure 7 to take into consideration the effect of "capacitive" conductivity in printed graphene. This modified model describes graphene's high frequency transmission properties well for frequencies up to 10 GHz. The extracted values for added elements in the model were $C_{x0} = 8.3$ fF/mm and $R_{\text{SHC}} = 4.3\ \Omega/\square$. C_x and R_{s2} component values were calculated from these geometry dependent parameters.

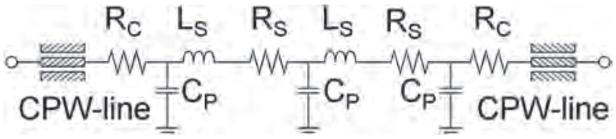

Figure 4. A transmission line lumped element model of a 10 mm long graphene CPW.

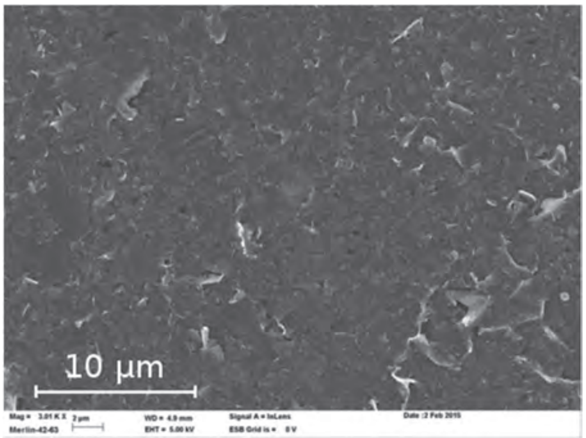

Figure 5. Scanning electron microscope image of printed graphene film.

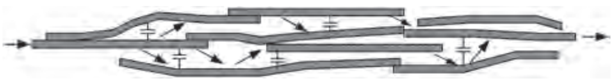

Figure 6. RF signal propagation through printed graphene flakes.

A similar procedure was done for the CPW with the 30 mm graphene part. The model of 30 mm graphene line was divided into six sections. Each of the sections represents a 5 mm length of the graphene CPW-line similar to the 10 mm line case. The same initial fitting values were used for sheet resistance and series inductance for both of the 10 mm and 30 mm graphene lines.

The measured and modelled scattering parameters S_{21} for the CPW with the 30 mm graphene part are shown in Figure 8. It can be seen that model taking into account capacitive component of resistance describes experimental results more accurately in this case also. Due to the longer device with more irregularities as in Figure 3 the fit was generally more inaccurate than for CPW with 10 mm graphene part. There was larger capacitance per unit length in the longer device but we decided to use the same parameters for both sizes to have a better insight to model scalability.

The capacitive coupling between flakes of printed graphene can be used for enhancing conductivity of printed graphene structures at microwaves frequencies.

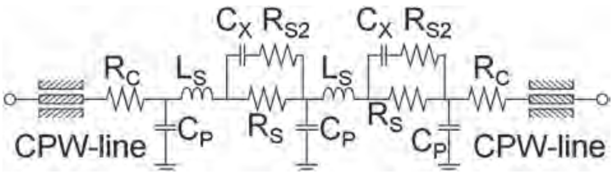

Figure 7. A modified version of the transmission line lumped element model of a 10 mm long graphene CPW taking into account the capacitive coupling between graphene flakes.

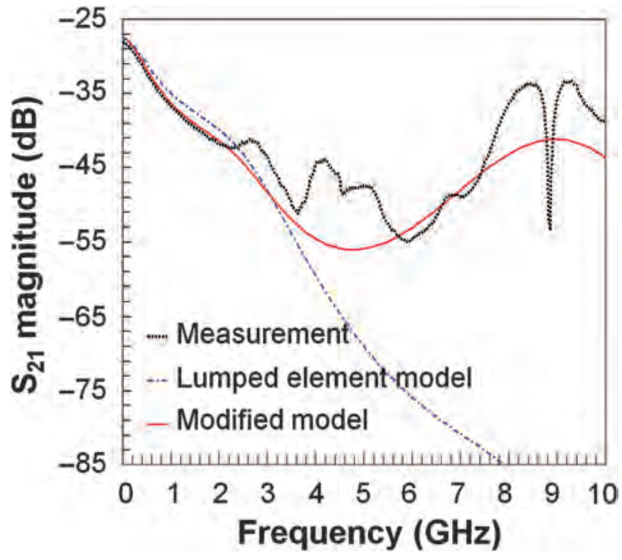

Figure 8. Measured and simulated S_{21} magnitude of CPW with 30 mm long graphene part.

Capacitive coupling could be increased by decreasing gaps between graphene flakes or using binders with high dielectric constant. As an example improvement of conductivity achieved by rolling compression of binder free graphene laminate could be partly related to decreasing gaps between flakes.[7] The obtained results are applicable to other materials with flake structure also.

High frequency transmission properties of printed graphene were studied in frequency range DC-10 GHz. A strong frequency dependence of printed graphene conductivity was observed. Capacitive coupling between graphene flakes could be the reason for the observed effect.

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