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Application of graphene in passive micro- and millimetre wave components

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INTRODUCTION

Graphene was first isolated in 2004 and since numerous application concepts based on graphene have been demonstrated [1]. Graphene has been recognized from the very beginning as a promising candidate for future radio electronics because graphene shows high carrier mobility, excellent mechanical and thermal stability, superior thermal conductivity and exceptional resistance to electro migration [2]. Experimental results from transport measurements show that graphene has a remarkably high mobility at room temperature, with reported values in excess of 10^6 $cm^2{\cdot}V^{-1}{\cdot}s^{-1}$ [3]. The carriers in graphene are confined to a layer that is only one atom thick. This allows unprecedented electrostatic confinement, and also makes graphene extremely flexible and transparent. However up to now most of the radio related research focuses very much on development of high frequency graphene transistors. In just a few years, high frequency graphene transistors have reached a performance level rivalling the best semiconductor devices that have over sixty years research effort behind them [2,4]. However no analog radio circuitry can be built without passive components. In this paper we evaluate opportunities of usage of graphene in passive micro- and millimetre wave components.

GRAPHENE PROPERTIES IN TERMS OF ITS APPLICATION IN PASSIVE AND MILLIMETER WAVE COMPONENTS

Graphene is a one-atom-thick layer of carbon atoms arranged in a honeycomb lattice. Graphene is a zero-band gap material where the conduction and valence bands touch each other at a point called the Dirac point. Due to zero-band gap graphene can be considered as a semi-metal or zero-gape semiconductor. The density of states in graphene is zero at the Dirac point and increases linearly for energies above and below it, which allows for carrier modulation.

Conductivity is the key graphene properties defining it's applicability in passive radio components. Graphene conductivity depends on graphene unique band structure and on a number of parameters including Fermi energy, electron velocity, temperature, doping, and amount of defects as well as electrical and magnetic bias fields. The conductivity of graphene is very frequency-dependent, and can have completed different behaviour e.g. at microwave and THz.

Fig. 1 shows behaviour of graphene conductivity as a function of chemical potential (bias electric field) [5].

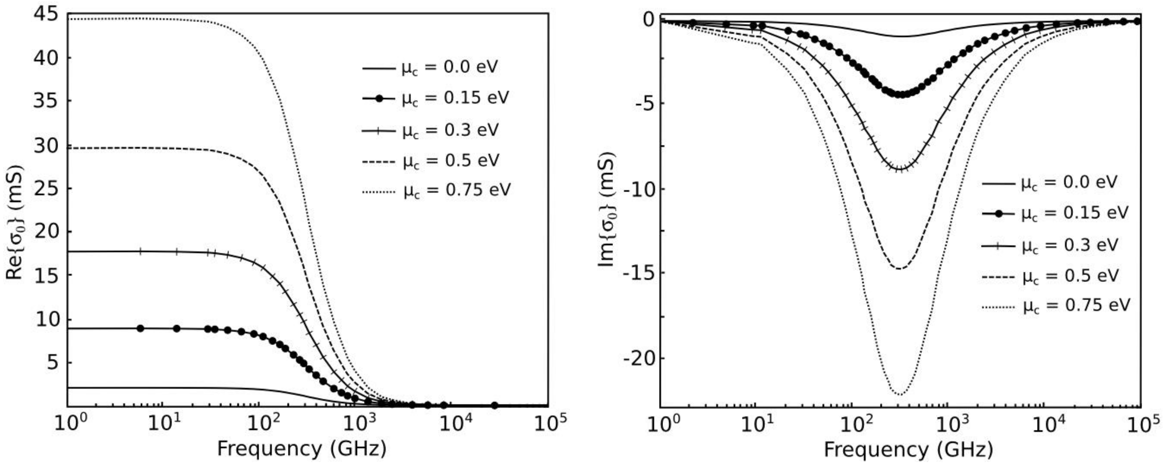


Fig. 1. Real (a) and imaginary (b) parts of graphene conductivity versus chemical potential (bias electric field).

It can be seen from Fig. 1 that conductivity of graphene can be changed by applying electric field. An applied electric field bias injects more electron or hole carriers in graphene and thereby allows the dynamic control of both real and imaginary part of the conductivity.

Though graphene is the best electrical conductor known, it is mono-atomic and thus the surface resistance is very high compared to metals at micro and mm-wave frequencies (which have much higher thickness in radio applications), even with the possibility of doping and electric field biasing of graphene. In radio frequency (RF) range graphene is thus mostly a moderate to bad conductive surface.

However graphene conductivity has a totally different behaviour at THz range. It can be seen in Fig. 1 that real resistivity of graphene drops in THz. Graphene plasma frequency is lower than for noble metals in the THz. Plasmonic propagation can thus be supported by graphene at THz.

The conductivity of graphene has been measured at RF in [6-8]. Measured sheet resistance of single layer graphene was as high as 1.25 kΩ/square. Values of graphene resistivity measured at RF were close to measured values of graphene resistivity at DC. Recently fast progress has been done with fabrication of high quality single layer graphene. Graphene with resistivity below 300 Ω/square are available on market [15]. Resistance of graphene can be decreased by usage of multilayer graphene. Usage in transmission lines with up to 5 graphene layers is demonstrated in [8].

The low density of states in graphene makes it possible for the quantum capacitance to be the same order of magnitude as the oxide capacitance for experimentally achievable gate dielectric thicknesses. This property, combined with the fact that the density of states varies as a function of energy, means that the capacitance in a metal-oxide-graphene capacitor can be tuned by varying the carrier concentration [9].

The quantum capacitance has a minimum value that is close to zero at the Dirac point, and as shown in Fig. 2, the capacitance increases linearly with potential with a slope of about 23 μF cm^{-1} V^{-1} on each side of the Dirac point.

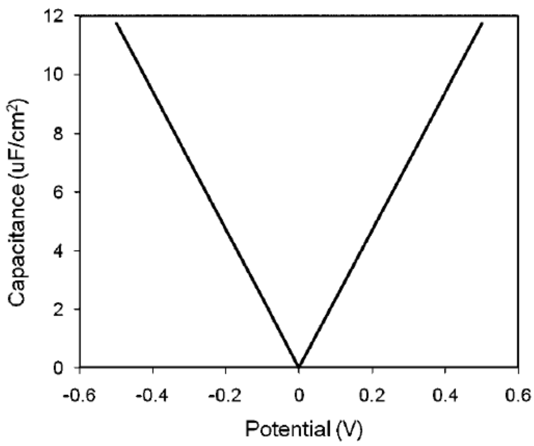


Fig. 2. Quantum capacitance for single layer graphene.

The very high mobility and zero band gap in graphene also allow it to remain conductive throughout the entire tuning range, making graphene a promising material to realize varactors.

METHODS OF GRAPHENE FABRICATION

There are several methods to produce mono layer graphene. The first method used for fabrication of monolayer graphene is known as mechanical exfoliation that is taking layers off multi-layered graphite by scotch tape or depositing one layer of carbon onto another material [10]. This amazingly simple method has been effective at producing graphene flakes 20–1000 um in length, and has been the primary source material for most papers reporting graphene's extraordinary physical and electronic properties. Exfoliation is still popular for laboratory use but it is not suited to the electronics industry.

Extensive researches have focused on developing methods for large area synthesis of graphene. The two most common methods are silicon carbide (SiC) sublimation and chemical vapour deposition (CVD).

Heating silicon carbide (SiC) to high temperatures (>1100 °C) under low pressures (~10^{-6} torr) reduces it to graphene [11]. This process produces epitaxial graphene with dimensions dependent upon the size of the wafer. The face of the SiC used for graphene formation, silicon- or carbon-terminated, highly influences the thickness, mobility and carrier density of the resulting graphene. Unfortunately, the high cost and relatively small size of available SiC wafers (up to 4" in diameter) does not make this process amenable to large wafer scale processing.

CVD graphene can be grown on arbitrary sized wafers coated with thin film catalysts. These metal catalysts serve to help decompose hydrocarbon gases into elemental carbon and hydrogen, and provide a substrate for carbon deposition. The two most common metal catalysts used today are nickel and copper, each of which can be deposited as a thin film or rolled into thin foils. Carbon deposited on the surface of the catalyst diffuses into the bulk, creating a solid solution of metal and carbon. Due to the change in solubility with respect to temperature, carbon begins to precipitate out of solution as the sample is cooled down. Through careful control of the cooling rates, the surface coverage of single and bilayer graphene can be controlled. Recently it has been shown that due to the lower bulk solubility of carbon in copper, the reaction of graphene on copper is surface limited, producing almost complete coverage of single-layer graphene [12].

However it should be pointed out that graphene fabricated by large wafer scale processing has polycrystalline structure that makes impact on its properties.

After the graphene has been prepared, common semiconductor processing techniques (such as lithography, metallization and etching) can be applied to fabricate graphene devices.

APPLICATION OF GRAPHENE IN PASSIVE COMPONENTS

Antennas

A graphene-based patch antenna at microwaves was studied in [5]. The antenna was designed to resonate at 2.3GHz and fed by a matched microstrip line. Although the patch is well-matched to the feeding line; the antenna radiation efficiency was low due to the intrinsic dissipation losses of graphene. A second important observation is that applying an electric field bias to the antenna modifies the resonant frequency of the patch only slightly. This behaviour is perfectly explained by Fig. 1, where it is seen that at microwave frequencies only the real part of the conductivity is significant and affected by the bias field. Therefore bias here allows controlling of the antenna efficiency but not its frequency.

Based on these results it can be concluded that for microwave antennas graphene is not useful: it does not provide efficient tunability or miniaturization. However graphene has a totally different behaviour at THz range (see Fig. 1). Plasmon propagation can be supported by graphene at THz, providing much better conductivity. An antenna based on plasmon modes of graphene can be obtained connecting the THz source to two graphene patches or two stacked graphene sheets separated by an insulating layer [5]. The second setup allows antenna tuning by applying DC voltage between the stacked sheets. This antenna exhibits several very interesting features. First, the real part of the input impedance at resonance is very high, providing good matching to THz photomixers. Secondly, the resonant frequency can be tuned in a wide band of 0.5 - 2 THz. Finally the antenna is highly miniaturized which relates the small size of the resonating structure to the low phase velocity of plasmon modes. It was demonstrated that the total efficiency of the antenna when operating with a source having an internal impedance of 10 kΩ exceeds 6% [5]. Typical metal resonant antennas can reach 20% of total efficiency, but metal antennas are larger and cannot be frequency tuned. However it is extremely unlikely that the efficiency of graphene antenna will supersede that of their metal counterparts. Thus tunability in wide range can be considered as the main advantage of graphene antenna in THz frequency range.

Inductors

Graphene has very high surface resistance compared to metals at micro and mm-wave frequencies. Thus high Q inductors made of graphene is a challenge. So far we know only one publication where graphene inductor is studied [13]. The structure is just a spiral inductor in which a spiral is made of single layer graphene. The performance of the inductor is quit predictable. Measurements show that the inductor has a very high series resistance. Thus Q-factor of the inductor is very low. Additionally to intrinsic resistance of graphene itself, the contact resistance between metal electrodes and graphene coil have an effect on the series resistance of the inductor. Usage of graphene in inductors doesn't bring any benefits at micro and mm-waves frequency range due to high resistivity of single graphene layer. Probably some solutions can be found at terahertz range where propagation of plasmon modes is possible.

Graphene based RF-NEMS

Concept of graphene RF-NEMS similar to RF-MEMS: a multilayer graphene membrane can be suspended over an air gap and mechanically actuated using an electrostatic force to create a RF switch or variable capacitor. Electromechanical switch devices employing suspended graphene as movable elements have been demonstrated [14]. Suspended graphene over SiO_2 trenches was employed as a movable element. The substrate used was a heavily p-doped Si substrate with a 300-nm thermal oxide layer on top. The silicon substrate can serve as the gate electrode to control the movement of suspended graphene to form physical contact with a static electrode nearby. The devices exhibit on–off ratios of up to 10^4 and lifetimes of over 500 cycles. The prototype device demonstrates the feasibility of using multilayer graphene in electromechanical systems. However graphene based RF NEMS is still an infancy phase. The use of graphene could be mainly to benefit from the exceptional mechanical properties of graphene, achieving among other a very low actuation voltage.

Resistors

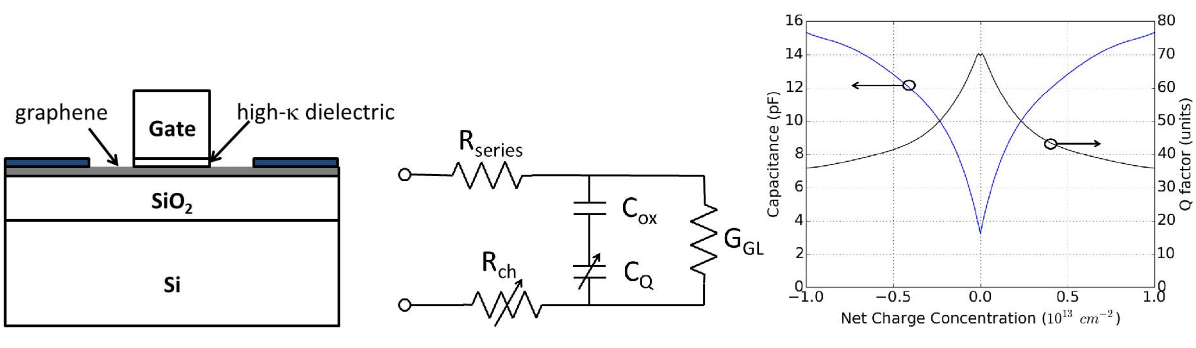
Resistors are categorized based on the material used for their fabrication: metal resistors, polysilicon resistors, diffusion resistors and well resistors. All known RF resistors are 3D structures. The electric current flows mainly at the "skin" of the conductor, between the outer surface and a level called the skin depth. The skin effect causes the effective resistance of the conductor to increase at higher frequencies where the skin depth is smaller, thus reducing the effective cross-section of the conductor. Graphene is unique 2D structure thus we can assume that there is no skin effect in graphene. Thus we can fabricate very wideband resistor. Value of resistors can be defined simply by the geometry of a graphene sheet. The possibility of modulation of graphene resistance by applied voltage allows the design of tunable resistors. According to our knowledge the usage of graphene as a material of RF resistors hasn't been studied so far.

Transmission lines

To study the usability of graphene in transmission lines a coplanar wave guide (CPW) with metallization replaced with graphene was simulated. The CPW has a center conductor with the width of 40 µm and length of 200 µm, the gap spacing is 4 µm. The CPW was simulated with AWR Microwave office EM simulator AXIEM. Graphene was modelled with the thinnest practical layer in AWR of 2 nm and the conductivity was 300 Ohm/square (conductivity of commercially available graphene [15]). The simulated losses in CPW were as high as 27 dB due to the high series resistance of the graphene.

Varactors

Graphene varactor utilizes property of quantum capacitance of graphene to be tuned by varying voltage applied. The physical structure of the graphene varactor cell is shown in Fig. 3 a) [16].



a) b) c)

Fig. 3. Graphene varactor geometries (a), equivalent circuit model of graphene varactor (b), graphene varactor capacitance and quality factor plotted vs. net charge concentration at a fixed frequency of 1 GHz (c).

A multi-finger varactor structure is needed in practice to enable the capacitance to be increased while minimizing series resistance. A simple equivalent circuit model (Fig. 3 b)) has been proposed to analyze the potential performance of varactor [16]. The equivalent circuit includes: C_{ox} is gate capacitance due to oxide; C_Q is quantum capacitance of graphene; R_{ch} is channel resistance; R_{series} includes a fixed contact resistance between the metal and the graphene and resistance associated with all metallization in the structure; G_{GL} is associated with gate leakage.

The simulated capacitance and Q-factor of the varactor as a function of net charge concentration n_{net} is plotted in Fig. 3 c) at f = 1 GHz. The simulation done for the following parameters: equivalent oxide thickness is 0.5 nm, gate length is 0.2 um, extension length is 0.1 um, number of fingers 200. Capacitance tuning ratios > 4 can be achieved while Q remains > 30 over the entire tuning range. Modulation of varactor Q-factor is due to dependence of graphene resistivity on applied voltage.

Experimental study of graphene varactors are presented in [17]. Samples with 2 different thickness of $Hf0_2$ were fabricated: 20 nm and 10 nm. The results show that the capacitance tuning range increases with decreasing $Hf0_2$ thicknesses, as expected. The capacitance tuning ranges were 1.17: 1 and 1.38: 1 , respectively.

Compared to MEMS-based varactors the extremely-large capacitance per unit area of graphene varactors should allow orders-of-magnitude improvement in scalability. However, high resistivity of graphene is a challenge again. To reach a reasonable Q factor in the varactors high resolution lithography is needed.

Phase shifters

An idea of a microstrip phase shifter based on quantum capacitance properties of graphene was studied. The phase shifter consists of a microstrip line overlapping the ground electrode and dielectric layer between them. The ground electrode and/or microstrip conductor is made of graphene. See Fig. 4 a). The lumped-element model of a small section of the microstrip is shown in Fig. 4 b).

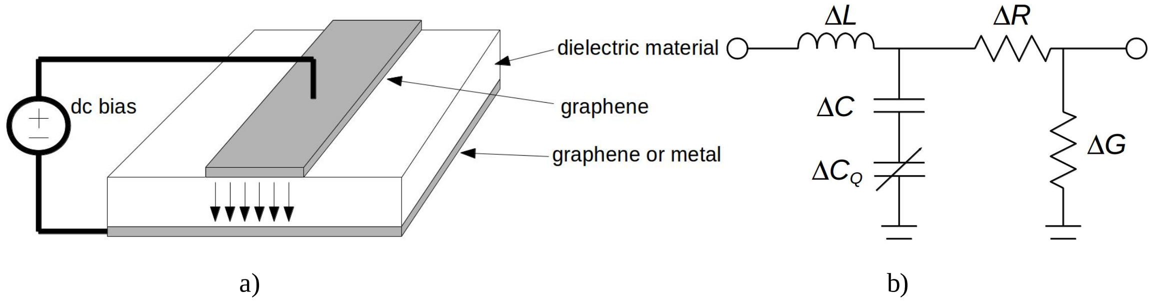
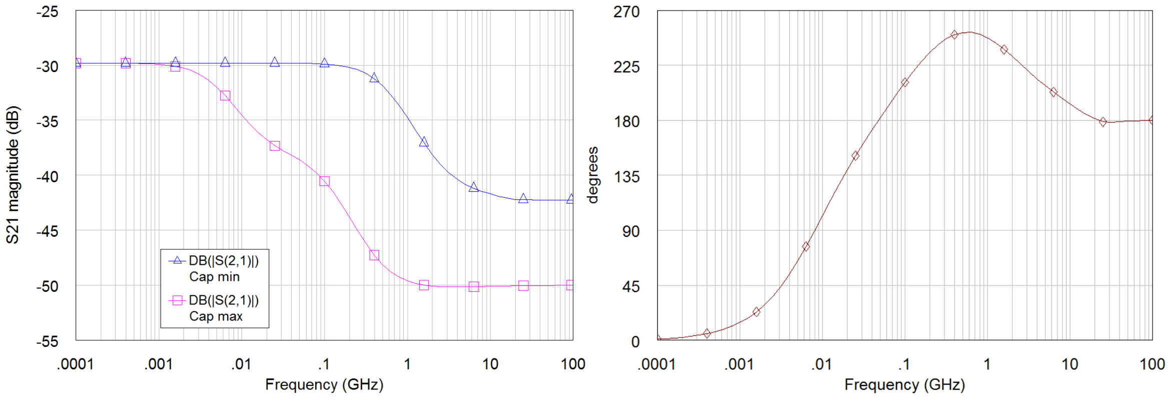


Fig. 4. Graphene microstrip phase shifter a) and its b) lumped element model for one subsection.

As it can be seen that quantum capacitance due to graphene center conductor C_Q is connected in series with geometrical capacitance of dielectric layer C. The quantum capacitance can be modulated by applying a DC voltage between the microstrip line and the ground electrode. Thus the propagation constant $\beta = 2\pi\sqrt{\Delta L \Delta C_T}$ of the RF signal will depend upon the bias field. ΔC_T is the series connection of ΔC and ΔC_Q. The time delay will become a function of the bias voltage, and, therefore, will produce a phase shift.

Performance of such phase shifter is studied for the case where the microstrip conductor is made of graphene and ground electrodes made of metal. The microstrip substrate in this study is just a 10 nm HfO_2 layer in order to enable the quantum capacitance effect of the graphene layer. The microstrip was simulated with AWR Microwave office EM simulator AXIEM. Graphene was modelled with the thinnest practical layer in AWR of 2 nm and the conductivity was calculated for that thickness from experimental sheet resistance value of 300 Ω/square.

Microstrip was 200 µm long and 20 µm wide. To simulate the quantum capacitance effect in graphene the HfO_2 relative permittivity was varied from 12.5 to 25. Fig. 5 b) shows the simulated S_{21} phase difference between the maximum and minimum quantum capacitance load of the microstrip. Variation of phase up to 270° was observed. However losses in the device are high being about 30 dB at very low frequencies.



a) b)

Fig. 5. a) S_{21} magnitude and b) phase difference of the graphene microstrip EM simulation between the maximum and minimum capacitive loading of the transmission line.

Simulation of a phase shifter based on graphene microstrip line shows that the device works. But it has high losses in 50Ω system as the series resistance caused by graphene resistivity is large.

RF passive circuits utilizing graphene varactors as “lumped” elements

Graphene varactors could be used as “lumped” elements in transmission line realizations of phase shifters, matching circuits and narrow band switches. Lumped approach could decrease the losses caused by the graphene resistivity.

Distributed transmission line phase shifter

A phase shifter based on “lumped” graphene varactors is shown in Fig. 6. The phase shifter is a distributed CPW transmission line loaded every 640 μm with graphene varactors where a 80-100 Ω coplanar wave guide impedance is lowered with distributed varactors close to the 50 Ω region.

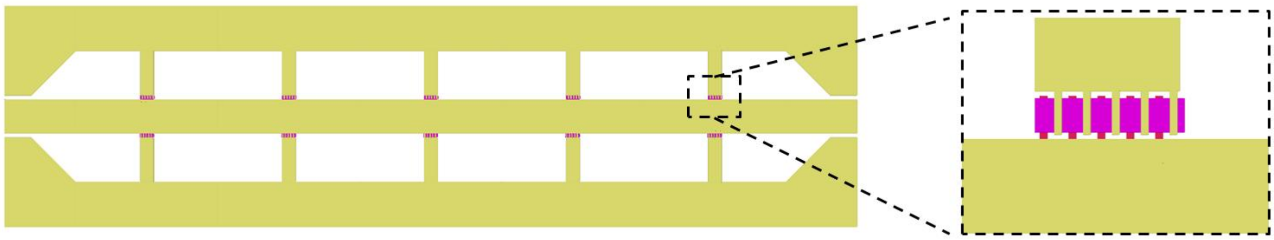
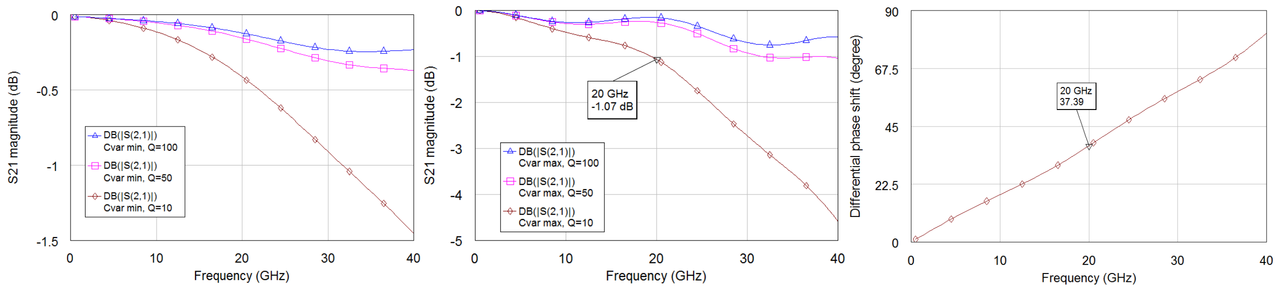


Fig. 6. Distributed transmission line phase shifter with graphene varactors loading CPW center conductor.

According to [13] the available graphene varactor capacitance is approximately 1 – 2 fF for every μm of finger edge. An example simulation for the above circuit is made with coplanar wave guide fabricated out of gold having a width of 150 μm, spacing of 220 μm and thickness of 2 μm. The varactor pitch along the CPW is 640 μm and total length is 3.8 mm with the GSG measuring pads. The total varactor capacitance was simulated to vary between 45 fF to 90 fF for every element (or varactor pair). Simulated S_{21}, magnitudes and phase shift in both states are shown in Fig. 7. The loss at 20 GHz is less than 0.2 dB for a Q value of 100 and largest for the Q value of 10 being 1.1 dB. If a full 360 degree phase shifter is designed 47 stages would be needed and the resulting length would be about 3 cm and maximum losses are about 2 – 10 dB depending on varactor Q factor. Probably the larger loss values are more realistic as characterization of graphene varactors have shown Q factors between 10 and 70 [16].



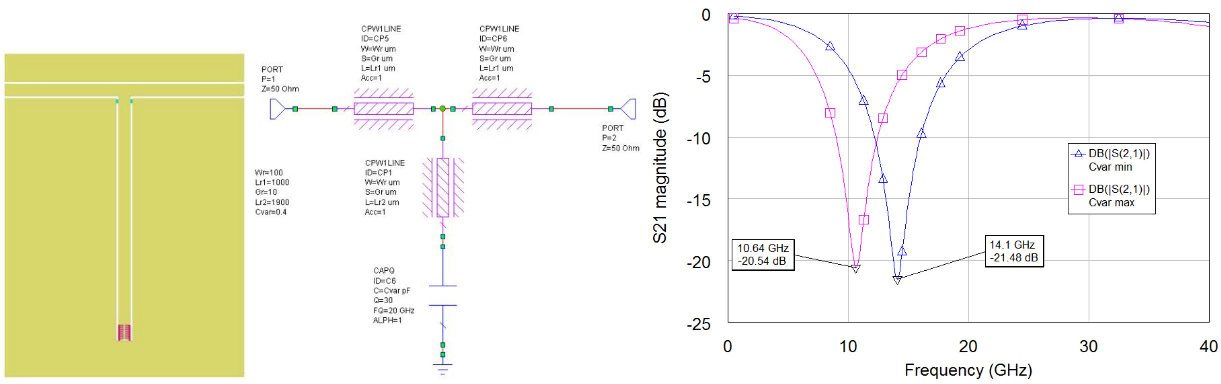
a) b) c)

Fig. 7 Simulated S_{21} magnitude of the five element distributed CPW phase shifter as a function of varactor Q factor in a) varactor minimum and b) maximum capacitance state and c) differential phase shift between the two states.

Designing the phase shifter for higher frequencies can be easier as the required device length is reduced.

RF stub loaded with a varactor

Another useful RF component is the stub which can be used for matching, filters and narrow band switch applications. An example layout of a 1.9 mm long stub loading a 2 mm CPW line is shown in Fig. 8 a) and its simplified equivalent circuit in Fig. 8 b).



a) b) c)

Fig. 8. RF CPW line stub loaded with a graphene varactor. a) top view of layout and b) simplified equivalent circuit for simulation. c) Simulated S_{21} magnitude with two capacitance values of the graphene varactor.

The RF stub is a $\lambda/4$ resonator loading the CPW line. Thus it short circuits the RF signal to ground at stub resonance as shown in Fig. 8 c). Tuning the varactor changes the resonance frequency as in this example the varactor capacitance is changed from 0.2 to 0.4 pF resulting in a 3.5 GHz frequency difference. The simulated Q factor of the graphene varactor was assumed to be 30. This circuit can be used as a simple band-stop-filter or even phase shifting is possible with different design parameters. In this example there is a phase shift difference of 20 degrees at 9 GHz.

Results of simulations show that graphene varactors can be used as “lumped” elements in transmission line realizations of phase shifters, matching circuits and narrow band switches. Lumped approach could decrease the losses caused by the graphene resistivity.

CONCLUSIONS

The review and analyses done in the paper shows that usage of graphene in passive micro- and millimetre wave components is a challenge. High resistance of single layer graphene is the main reason for that. Though graphene is the best electrical conductor known, it is mono-atomic and thus the surface resistance is very high compared to metals at micro and mm-waves frequencies, even with the possibility of doping and electric field biasing of graphene. In these frequency ranges graphene is thus mostly a moderate to bad conductive surface. Surface resistance of graphene is very high in comparison to metals at micro and mm-waves frequency. At these frequencies, graphene conductivity is essentially real and the electric field bias allows controlling this resistivity but it doesn't bring advantages because components have low performance.

The picture is quite different at terahertz frequency range above 500 GHz, as a result of the plasmonic nature of the imaginary conductivity allowing plasmonic modes. At terahertz electric field affects strongly the imaginary part of the graphene conductivity. This mode can be used in tunable terahertz devices, for example terahertz antennas.

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