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Magnetically Biased Graphene Based Switches for Microwave Applications

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Abstract: This paper presents a magnetically biased graphene based switch for CPW resonator applications. Graphene patches are set in the gap between signal and ground lines, thus obtaining the whole structures act as switchable elements. Graphene was modeled as a general material with appropriate surface conductivity. The presented CPW resonator structure acts like a switch in ON state even for magnetic bias field of around 0.5 T. The simulated S parameters of the CPW resonator structure with different magnetic field biasing are presented.

Index Term—magnetically biased graphene; microwave switch; CPW resonator.

I. INTRODUCTION

Next generation of wireless communication networks based on the Cognitive Radio [1], is already in use and will be further engaged and developed in order to increase communication network capacity. Great demands in hardware specifications require the use of advance and complex microwave circuits. These circuits must be able to operate at several frequency bands and for several types of signal modulations. They also, must be able to reconfigure themself in real time depending on users' demands, and/or the physical change in the channels, and many other, time variable criteria. To achieve some this, a variety of tunable and reconfigurable elements are employed such as varactor diodes, RF MEMS, optical switches, PIN diodes and others.

Graphene is recently discovered material which has shown many outstanding features in comparison with previously known materials [2]. These features include graphene mechanical, optical, thermal and electrical properties. Advantages of graphene can be explained by its surprising, two dimensional (2D) structure. It is a pure carbon material where atoms are located in the nodes of a plane hexagonal network. Till recently, this 2D configuration of atoms was assumed as something impossible to be found in nature due to its thermal instability. Nevertheless, graphene electrical characteristics are very promising and it can be regarded as future material which will be used in reconfigurable and tunable circuits. So far, many structures based on graphene are reported. However, most of these applications are designed for THz bands and are not suitable for GHz frequencies. Some of potential applications of graphene for GHz bands can be found in the changing polarization angle of passing wave using magnetically biased graphene sheet [3], in coplanar waveguides (CPW) [4], switches [5], and etc.

This paper presents a graphene based CPW resonator structure. Here graphene is used as reconfigurable element which incorporated in circuits cause switchable effect. The state of the switch is controlled by magnetic bias field. Magnetic biasing is not utilized so far in a great number as it was situation with electric biasing and this paper explains basic theory about magnetic biasing. The structure was designed, through simulation, to be operational at microwave frequencies. This is very promising for further development of the current wireless communication systems which work at low GHz frequencies. Also, the simplicity of proposed structure qualifies the same design methodology and structure configurations to be applied at higher frequencies. In that way, this will gain benefit in the future wireless communication systems.

The paper is organized as follows. In the section II, the theoretical background is given concerning electric properties of a single 2D graphene sheet. This section explains the basic ideas around magnetic biases. The section III presents a graphene based structures with switching properties, and CPW resonator. All simulation results are given in the same section as well. Finally, conclusion is given in the section IV.

II. THE GRAPHENE SURFACE CONDUCTIVITY

In the most general case electrical properties of graphene, conductivity, can be modeled by property tensor. Due to the fact that graphene is 2D material, this property tensor $\bar{\bar{\sigma}}$, will represent graphene electrical surface conductivity. The tensor will be expressed as 2 by 2 matrix, totally 4 scalar elements, among there are two different σ_d and σ_o.

$$\bar{\bar{\sigma}} = \sigma_d \hat{x}\hat{x} + \sigma_o \hat{x}\hat{y} - \sigma_o \hat{y}\hat{x} + \sigma_d \hat{y}\hat{y} \qquad (1)$$

Here, $\hat{x}$ and $\hat{y}$ represent unit vectors. All formulas are already given in [6] but here all of them will be repeated once again because of completeness and clearance.

The main diagonal elements of the tensor matrix are

$$\sigma_d(\mu_c(E_0),B_0)=\frac{e^2v_F^2|eB_0|(\omega-j2\Gamma)\hbar}{-j\pi}\times\sum_{n=0}^{\infty}\left\{\frac{f_d(M_n)-f_d(M_{n+1})+f_d(-M_{n+1})-f_d(-M_n)}{(M_{n+1}-M_n)^2-(\omega-j2\Gamma)^2\hbar^2}\times\left(1-\frac{\Delta^2}{M_nM_{n+1}}\right)\frac{1}{M_{n+1}-M_n}+\frac{f_d(-M_n)-f_d(M_{n+1})+f_d(-M_{n+1})-f_d(M_n)}{(M_{n+1}+M_n)^2-(\omega-j2\Gamma)^2\hbar^2}\times\left(1+\frac{\Delta^2}{M_nM_{n+1}}\right)\frac{1}{M_{n+1}+M_n}\right\} \tag{2}$$

The side diagonal elements of tensor matrix are defined as

$$\sigma_o(\mu_c(E_0),B_0)=-\frac{e^2v_F^2eB_0}{\pi}\times\sum_{n=0}^{\infty}\{f_d(M_n)-f_d(M_{n+1})+f_d(-M_{n+1})-f_d(-M_n)\}\times\left\{\left(1-\frac{\Delta^2}{M_nM_{n+1}}\right)\frac{1}{(M_{n+1}-M_n)^2-(\omega-j2\Gamma)^2\hbar^2}+\left(1+\frac{\Delta^2}{M_nM_{n+1}}\right)\frac{1}{(M_{n+1}+M_n)^2-(\omega-j2\Gamma)^2\hbar^2}\right\} \tag{3}$$

And where is

$$M_n=\sqrt{\Delta^2+2nv_f{}^2|eB_0|\hbar} \tag{4}$$

All above j is the imaginary unit, E_0 and B_0 are electric and magnetic bias fields, respectively. The physical value Δ represents excitonic energy gap, ω is angular frequency, Γ signifies phenomenological scattering rate, μ_c is chemical potential, e is the elementary electron charge, f_d is Fermi-Dirac distribution function, v_f is velocity of electrons and $\hbar$ designates reduced Planck's constant, $\hbar=h/2\pi$. Scattering rate is defined as $\Gamma = 1/2\tau$, where τ being average relaxation rate. The value of v_f is close to 10^6 m/s. Additionally, through all simulations temperature T was set on the value close to room temperature, 300 K. For range of temperatures around 300 K, the value of Δ can be approximated to 0. For special cases, including only one either electric or magnetic bias filed, some further simplifications can be done.

When only magnetic bias field is presented the value of σ_o is 0. So, the surface conductivity tensor $\bar{\bar{\sigma}}$ can be reduced to the scalar with the value equal to σ_d. Figure 1 shows real and imaginary parts of the surface resistivity when only magnetic field B_0 is applied.

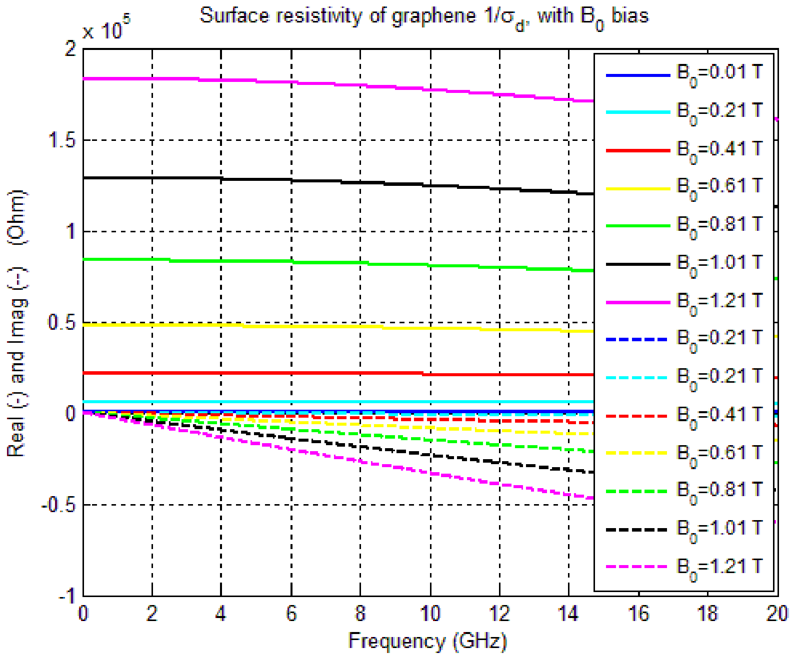


Figure 1 Real and imaginary parts of surface resistivity of graphene sheet for different magnetic field biases B_0, where relaxation time is $\tau = 0.025$ ps and temperature is T = 300 K

For frequencies of interest the imaginary part of surface resistivity is few times lower in comparison to its real part. Furthermore, contrary to electric biasing, it is interesting to be mentioned that by increasing magnetic bias field the surface conductivity drops down. This is the property which will be used in switch design. Basically, by different magnetic bias filed applied, the graphene switch changes its resistivity and thus can conduct or block electric current thought it.

III. PROPOSED STRUCTURE AND RESULTS

A CPW resonator structure shown in Figure 2 is presented here. Green coloured parts represent copper metallization, with 2 µm thickness. Graphene has been shown in pink colour. Transparent grey colour designates substrate with GaAs, $\varepsilon_r = 12.9$, $\tan\delta = 0.006$ and thickness of 150 µm. Resonator is designed as standard CPW circuit without graphene patches. After it, simply, two graphene patches were inserted in the gaps between ground lines and signal line. In absence of magnetic bias field, graphene patches act like bad conductor. Besides that, graphene patches are wide enough to obtain low resistance between signal line and ground lines and thus connect them electrically. In that way, the whole signal propagation through the structure is blocked. This is equivalent to the open switch, OFF state. In the present of strong magnetic bias field, graphene patches perform like dielectrics and the whole structure behaves like the same structure but without graphene patches. This is related to the ON state of the switch. Dimensions of the resonator are given in Table 1. The simulated S parameters of the proposed CPW grapheme based resonator are presented in Figure 3.

Table 1.

Dimensions of the CPW resonator

Length and width of the box	30 mm, 40 mm
Length and width of signal line	25.1 mm, 3.2 mm
Length and width of graphene patch	25 mm, 3.2 mm
Length and width of ground line	30 mm, 11.8 mm
Width of the gap between signal line and ground line	0.8 mm
Width of the gap between signal line and feeding port line	0.05 mm

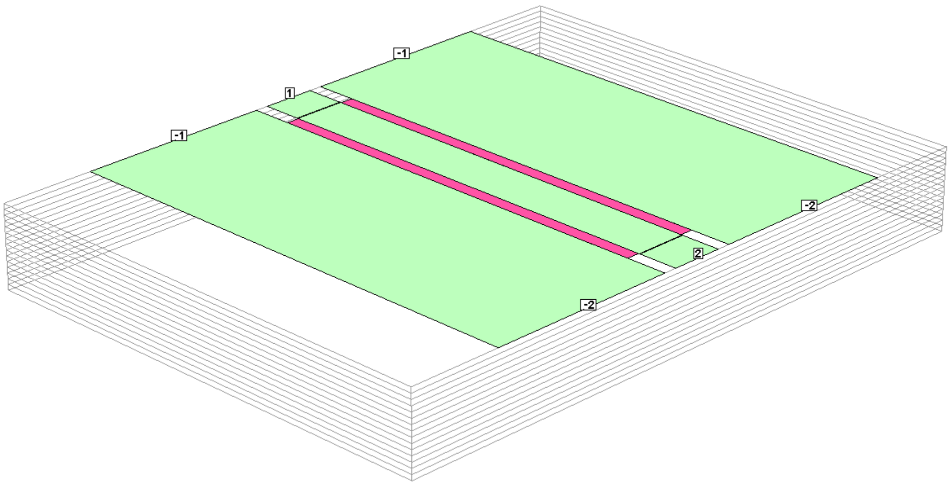
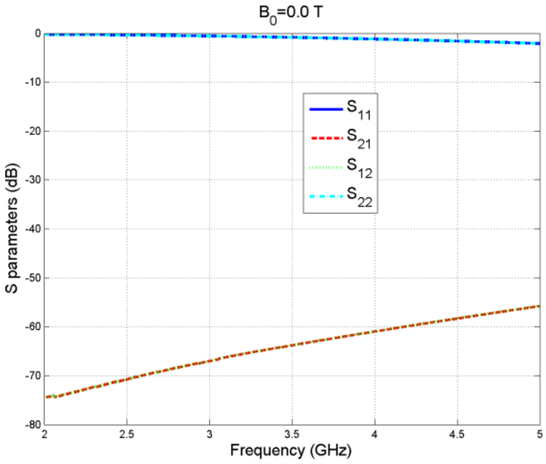
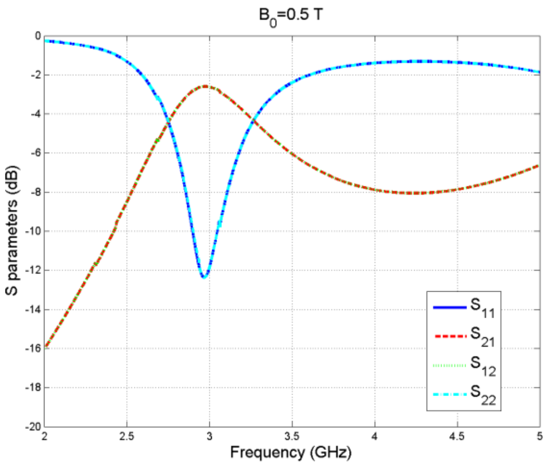


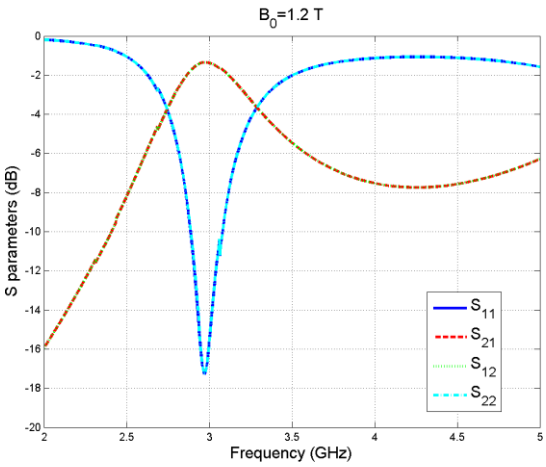
Figure 2 Proposed graphene based CPW resonator with magnetic field biasing, B_0



a



b



c

Figure 3 Simulated S parameters of the CPW resonator structure with magnetic field biasing, (a) B_0 = 0.01 T, (b) B_0 = 0.5 T, (c) B_0 = 1.2 T

As can be seen, the presented structure above acts like a switch in ON state even for magnetic bias field of around 0.5 T. So, in most common circumstances there is no need for further increase of magnetic bias field.

All simulated results were obtained by full wave electromagnetic simulation in Sonnet em [8]. The Graphene was modeled as a general material with appropriate surface conductivity, calculated by formulas described in Section II. It is also very important to stress the fact that theoretical and measured results of graphene conductivity differ. This difference is sometimes even larger than 100, comparison between [6] and [7]. There are some researches which suggest that this is due to the fact that graphene patch reacts with substrate material, something similar to ohmic junction, and that effect causes dramatic drop in conductivity. Still, this drop in conductivity can be described by (2) and (3) as a change of scattering rate Γ. Moreover, some metal materials are also more inappropriate than others, probably because of similar reason. Nevertheless, proposed method with adjusting length and width of the graphene patches is very flexible and in most cases can compensate first phenomenon. For example, if scattering rate Γ is higher, the length of the graphene patch should be decreased and/or width of the graphene patch should be increased. The second phenomenon can be overcome by use of suitable metals which will cause less intense effect. Anyway, thicknesses of metallization used in this simulation can be varied in wider range in order to decrease losses and get better results. One more, to increase the range of values of the surface conductivity of graphene, both biasing can be used, but separately. For lower values of the surface conductivity the magnetic bias filed should be applied, whereas electric biasing should be applied in order to achieve higher values of the surface conductivity of the patch. For example, to force graphene patch to act as dielectric magnetic bias field should be applied, where the same patch in the same circuit can act as conductor by using electric biasing.

IV. CONCLUSION

A magnetically biased graphene based switch for CPW resonator applications has been presented. The presented CPW structure where biasing of graphene was achieved using magnetic field has been designed. The state of equivalent switch is controlled by the strength of applied bias field. Described design method is very simple and flexible and can be applied in the wide range of conditions, and thus overcome problems related to electrical characteristic of graphene placed on dielectric materials. The structures barely have any loss in power due to biasing. It can be biased with static magnets which do not use any additional energy. More important, shown results indicate very flat response over wide microwave frequency range. This is a very interesting property for current and future wireless communication systems due to demands for larger frequency bandwidth.

V. ACKNOWLEDGEMENT

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