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# Study On Microwave Devices Farcated By Graphene-Layers

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***Abstract:*** This study presents a review of Graphene-layered microwave devices. Because of its very frequency-dependent characteristics, exceptional graphene exhibits distinct behavior in the THz and microwave bands. The article discusses graphene's characteristics and uses in the microwave band, including cutting-edge uses in Internet of Things gadgets like biosensors and graphene ink printing. There is a discussion of current research on graphene-layered devices such as antennas, waveguides, and microwave filters. Graphene is still regarded as a promising material in Internet of Things and biosensor communication devices that operate in the microwave range because it can offer tunability, flexibility, and transparency, even though its carrier mobility and conductivity in the microwave band do not enable better results when compared to traditional materials.

***Index Terms* -** Graphene-layered, Microwave devices, Microwave filters, Biosensors

## I. Introduction

There are still some debates about the potential uses of graphene in microwave technology since it was separated in 2004 by mechanical exfoliation [1] and its characteristics were made public. Since the THz frequency region is predicted to reveal the finest of graphene's exceptional physical features, research worldwide is concentrated on a variety of applications within this range. Since devices don't produce the desired effects, the microwave frequency band moves to the second plan. Nevertheless, other studies indicate that greater outcomes can be achieved by improving graphene quality or by utilizing novel manufacturing techniques (such as printing graphene ink). Mechanical exfoliation, chemical vapor deposition, epitaxial growth, graphene oxide dispersion in hydrozine [2], and production methods based on microwave plasma are the four primary ways for producing graphene. These methods are constantly changing. The majority of graphene is still produced via mechanical exfoliation, despite the introduction of new, promising techniques like graphene ink printing [3]. The study that follows demonstrates how advancements in manufacturing techniques contribute to the production of graphene samples of higher quality. This makes it possible to use graphene at microwave frequencies and obtain the most efficiency possible from it.

In the spectrum of microwave frequencies, graphene is regarded as an extremely lossy material. However, some recent studies (which are examined in more detail in the paper) demonstrate that the radiation efficiency of graphene antennas may be increased by utilizing new fabrication processes. According to promising study, multilayer graphene behaves differently from monolayer graphene in the microwave spectrum. This makes it worthwhile to examine potential uses of graphene at microwave frequencies. The characteristics of graphene in the microwave region are discussed in the paper, along with current issues and newly established methods. One excellent example is the current approach to graphene devices from the standpoint of wearable technology and the Internet of Things. In contrast to efficiency and optimal performance, IoT technologies, wearables, and biosensing devices prioritize flexibility, transparency, and a simple production process.

This paper's primary goal is to evaluate the difficulties in employing graphene at microwave frequencies and talk about potential fixes. To demonstrate the most recent advancements made in the field, a comprehensive survey of devices incorporating graphene layers is given.

## II. PROPERTIES OF GRAPHENE IN MICROWAVE APPLICATIONS

### A. *Graphene's properties*

Graphene is a 2D carbon structure with a honeycomb lattice that is very thin (0.34 nm) and usually consists of one or a few atom layers. Due to its exceptional qualities, graphene is the subject of several studies for use in the microwave, THz, and optical ranges [4]. Because graphene's characteristics are frequency sensitive, they change over several frequency ranges. Due to its ability to direct surface plasmon polaritons, graphene has been the subject of much study examining applications in the THz and optical fields. Since the majority of graphene's capabilities manifest themselves most effectively at THz frequencies, there is a limited amount of study on graphene in the microwave field. This raises the primary query of whether graphene can be effectively employed at microwave frequencies. The remarkable carrier mobility of graphene, which surpasses 200000 $cm^2$ /Vs at normal temperature, is one of its exceptional qualities [4]. Graphene samples should be in the order of tens or hundreds of millimeters as structures for microwave range applications (such as antennas) must adhere to wave specifications. Additionally, it is shown that at room temperature, the carrier mobility decreases. Carrier mobility is thought to be less than 100,000 $cm^2$/Vs for radio frequency range. Graphene's ambipolarity and tunability are other exploitable characteristics. Because graphene is tuneable, its characteristics may be altered by an electric or magnetic field, usually according to Microwave Theory and Techniques in Wireless Communications. Additionally, graphene exhibits zero bandgap semiconductor or semimetal behavior.

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Because of the way graphene is modeled, its behavior differs from that of other metallic formations. A extremely thin conductivity surface is used to simulate graphene. The Kubo formula describes the intraband and interband conductivity modes [5]:

$$\sigma_g = -j\frac{e^2 k_B T}{\pi\hbar^2(\omega - j2\Gamma)}\left(\frac{\mu_c}{k_B T} + 2\ln\left(e^{-\frac{\mu_c}{k_B T}} + 1\right)\right) - \frac{je^2}{4\pi\hbar}\left(\frac{2|\mu_c| - \hbar(\omega - j2\Gamma)}{2|\mu_c| + \hbar(\omega - j2\Gamma)}\right),$$

where e is the charge of an electron, ħ is the reduced Planck's constant, $k_B$ is the Boltzmann's constant.

The Kubo formula shows that the angular frequency (ω), chemical potential (μc), scattering rate (Γ), and temperature (T) all affect graphene's surface conductivity. Doping and applying an external field are the two ways to alter the graphene's electrochemical potential. On a graphene sheet, magnetic bias may be used to dynamically regulate Faraday's rotation. By altering the bias voltage applied, the conductivity of graphene may be dynamically regulated since applying electric bias to its sheet results in the injection of more carriers into the system.

The interband portion of (1) may be ignored at microwave frequencies, and the conductivity of graphene is solely dependent on intraband conductivity. The electrochemical potential of graphene's sheet can be enhanced by introducing an external electric field. The surface conductivity of graphene is impacted by the application of the DC voltage (V́'). This occurs as a result of the Fermi level shift μc = eαV' = eV, where V́' is the applied voltage and α is a geometry-dependent parameter [8]. According to the formula, graphene is a very frequency-dependent material, which explains why it behaves differently at THz and microwave frequencies [9]. Graphene has a relatively high surface resistance and is a modest conductivity at microwave frequencies when compared to metals. As a result, it is still regarded as a material that may be used in passive devices (like antennas). When compared to common metals, graphene may exist as an extremely thin conductive layer, which can be a major benefit. For instance, copper is unable to exist at the same thinness as graphene. It should be noted that the conductivity of copper may deteriorate far more quickly than that of graphene when the in-plane dimensions of the copper lattice decrease [8].

### *B. Graphene's application*

Graphene is frequently referred to as the ideal material for a variety of applications due to certain properties, including standard electronic devices (such as transistors), microwave devices (such as electrically tunable or reconfigurable filters, waveguides), tunable antennas, attenuators, and many more. By applying an electric field, graphene applications in passive components can result in miniaturization, mechanical flexibility, and effective tunability [10]. Numerous modulators, polarizers, diodes, and other device types and topologies are given and studied extensively in optoelectronics. Standard methods and structures may be used to produce graphene-layered replicas of microwave devices. The majority of popular structures fall into one of three categories: devices or structures made of graphene on a dielectric substrate, graphene layers sandwiched between dielectric layers, or conventional structures that may be enhanced with graphene flakes to allow for tunability. It is necessary to employ innovative structures, non-standard implementations, and methodologies since the conventional structures and methods employed in silicon technologies are not always the best option, particularly in the microwave field.

Another field of study is biosensing devices that enable the identification of a person's bodily status. It is growing quickly in tandem with IoT technology. Due to the many drawbacks of conventional biosensors, novel techniques such as electrical transduction, photoelectrochemical transduction, and current and potential changes are being used. These new techniques call for other kinds of equipment, and graphene is thought to be a promising material for innovative light detectors or other biosensing devices [14]. It is anticipated that the technology used to build wearable biosensing devices and microsystems would be able to offer wireless communication in the radio frequency spectrum in order to receive and transmit data as required. One viewpoint technique in biosensing technologies is harmonic sensing technology. Due to its great performance and lack of clutter echoes and backscattering noise, this technique is highly popular in RFID and wireless sensor applications [15]. By integrating a sensor, frequency multiplier, and graphene antenna into a single circuit, it is possible to utilize harmonic sensor technology. Because of its exceptional flexibility and transparency, graphene makes it possible to include harmonic sensors into eye wearing technology.

## III. MICROWAVE DEVICES WITH GRAPHENE LAYERS

### *A. Microwave filters with graphene layers*

Advancement in communication technologies increase requirements for filtering modules. The main requirements that can be identified are tunability and dimensions. Communication systems are expected to work broad range of frequency bands and should be as compact as possible on their dimensions [16]. There are various approaches proposed to ensure tunability such as MEMS switches, magnetic tuning, electronic tuning using diodes or ferroelectrics, that can be implemented in standard microwave devices. The graphene is considered as perspective material in similar applications, but most designs are created for THz frequency as monolayer graphene does not show effective results in microwave frequency. Different strategies are needed for the microwave frequency range, such as the use of graphene-based switches that may be used for a reconfigurable waveguide resonator. The switch is represented as a graphene sheet of a certain size positioned on a substrate at the metallic fin's end. Graphene stretches the metallic fin and core frequency of resonator varies when an electrical field is applied. A similar strategy may be applied to tunable filters to provide effective microwave frequency results [17] presents a microstrip graphene filter that operates at 5.8 GHz. The filter is entirely transparent and is constructed on quartz glass. The typical copper filter concept, in which graphene is used in place of copper, was selected for this design. These kinds of structures can be produced effectively, according to practical experiments, and their parameters agree with those of simulations. Reconfigurability is made possible by the use of graphene-based switching components in filter architectures. In [18], a mid-band frequency filter operating at 6.85 GHz with a programmable notch at 5.8

GHz is introduced. Controlling the filter's notch is made possible using graphene switching components. In the whole frequency range of 3.1 to 10.6 GHz, graphene switches function as insulators and filters when no bias is applied. The conductivity of a graphene switch is altered by applying bias. In this instance, the material functions as a conductor, and the filter exhibits a notch at 5.8 GHz, which may be used for WLAN applications.

***B.Waveguides with graphene layers***

Coplanar waveguides up to 50 GHz were introduced in [15].Studies have shown that the insertion loss is dependent on waveguide dimensions. Additionally, a few layers were displayed. End contact structure and graphene can be utilized to reduce loss of insertion. Graphene loaded waveguides can be employed as polarization rotators because magnetically biased graphene has excellent gyrotropic characteristics at microwave frequencies [10, 11]. In [11], a circular waveguide polarization rotator working in the microwave region was introduced. Its cut-off frequencies were 2.29 GHz for the $E_{01}$ (high order) mode and 1.1 GHz for the $H_{11}$ (dominant) mode. Waveguides have a cylinder-like shape. Its axis is perpendicular to the graphene sheet that has been inserted. Since graphene is nearly frequency independent at microwave frequencies, the waveguide's bandwidth is determined by its dimensions and other characteristics.

This may be seen as this construction's primary benefit. Rectangular waveguides filled with graphene are being studied in [10] as they are a more common design in communication and transmission systems. In contrast to a cylindrical construction, a rectangular waveguide's polarization cannot be rotated in the same manner, and graphene features are revealed through significant mode coupling and conversion between various waveguide-guided modes.In [15], a theoretical study of a rectangular waveguide loaded with two graphene sheets with a quartz substrate inside the cross section and biased with a static magnetic field in the +z direction revealed that self-reflection and self-transmission are increased while forward and backward conversion between various modes is decreased.

***C.Antennas and other Microwave devices***

The potential of graphene antennas at microwave frequencies is severely constrained, as demonstrated in [18], since actual graphene is very lossy and causes input power dissipation.The scientists also demonstrated how actual graphene's low tunability in the microwave frequency has hampered the potential for developing reconfigurable antennas that might rival other technologies. Having high-quality graphene that is produced with strong conductivity is essential for microwave applications, such as wireless connection and similar ones. The study of research findings begs the question of whether graphene is a material that can be used for microwave-range antenna applications. In [8], a graphene-based patch antenna with a 12 GHz resonating frequency and radiation properties akin to those of metallic antennas was demonstrated. The surface impedance of graphene must be minimal (less than 10 Ω) in order to guarantee metallic antenna behavior. This implies the usage of high-quality graphene. Additionally, by varying the external voltage from 0.36 V to 7.5 V, the tunability characteristics were shown. Surface impedance may be adjusted from 42 **Ω** to 2 **Ω** thanks to these voltage adjustments.

In [16], the potential use of hybrid metal-graphene frequency reconfigurable antennas in the microwave spectrum is examined for the LTE (1.8 GHz, 2.5 GHz, 2.6 GHz, and 3.6 GHz) and WiFi (2.4 GHz, 3.6 GHz, and 5 GHz) frequency bands. The antenna's metal construction (copper) incorporates reconfigurable graphene strips. Bias voltage regulates graphene's surface impedance value, and it is possible to mimic the states of switches (MEMS, transistors, diodes, or varactors). The authors talk about the possibility of low efficiency and limited reconfigurability at microwave frequencies. There are two antenna forms are presented. The results confirm the prediction that graphene has poorer antenna efficiency than other technologies. WiFi frequency band efficiency ranged from 9.4% to 68%, but other switching technologies may attain efficiency as high as 90%. However, the construction permitted frequency tunability up to 1.2 GHz. The question of whether graphene's losses can be decreased and its efficiency increased while maintaining tunability—a crucial prerequisite for today's RF frequency devices—comes up.

Two primary causes of the low graphene antenna efficiency (around 50%) were covered in [17].The first ex planation is the nature of the graphene sheet, which results in large ohmic losses at microwave frequencies d ue to high surface resistance.The second explanation is the geometrical constraints and sheet size of graphen e.Multilayer graphene sheets are being researched as a solution to these issues.A UWB antenna with a radiation efficiency of over 80% in the frequency range of 3.1 to 10. 6 GHz was created as a consequence of the aforementioned study.

In order to create the necessary antenna structure, graphene ink technology was used.
gadgets that use radio frequency. When compared to an identical copper antenna, the graphene antenna's radiation pattern was almost comparable, but with a somewhat smaller amplitude.

In [18], microstrip antennas with Sband and C-band switching are made using graphene ink on textile printing technique. Peak gain of 2.09 dBi and radiation efficiency of 74% were attained at 3.03 GHz (dominant mode). Graphene may be employed in the same way that metals are used to make antenna structures thanks to high-quality graphene ink, which enables surface conductivity of $0.37 \times 10^5$ $Sm^{-1}$ and strong surface structural features. The multilayered substrate technique is the means by which structures printed with graphene ink can overcome their poor surface conductivity. Such a substrate makes it possible to enhance the antenna's radiating properties. The fact that graphene does not sustain primary radiating currents makes it a potentially beneficial material for developing components free of parasitic radiation when considering its potential uses in microwave antennas. Radiation characteristics are crucial for antenna applications. The effectiveness of graphene antennas in the microwave spectrum is quite poor when compared to normal systems, according to estimations and comparisons. Additionally, the tunability of such antennas is rather restricted. More intricate arrangements or many graphene layers may be used to display the views.
One major drawback of using multilayer graphene is that it can be difficult to manufacture, which essentially means that standard systems won't be enhanced. The way that could work integrating graphene in microwave antennas is to start exploiting its other qualities like exceptional flexibility, that could give printable designs for IoT or wearable electronics.

In addition to antennas, communication or data transmission lines also need a variety of additional devices, such attenuators, which may lower signal strength without altering the signal. An array of resistors is used to create the passive attenuator. In [19], a 5 GHz graphene-based attenuator concept is introduced, illustrating viewpoints on passive device tunability in the microwave spectrum. A biased graphene patch is placed between the input and output microstrip lines to create a graphene-based attenuator structure. This allows for the electrical tuning of the attenuator's insertion loss in the range of 1.7 dB to 13 dB by altering the surface conductivity of graphene according to applied voltage values. In [20], a novel adjustable attenuator structure that enables insertion loss adjustment by varying applied voltage was reported. This attenuator construction uses a microstrip line with graphene flakes in a few layers. The device provides for 25 dB tunability and operates at frequencies up to 10 GHz. In [21], a voltage-controlled attenuator running at 5 GHz was shown, demonstrating yet another effective attenuator construction. Additionally, the construction is built on a microstrip line with graphene patches attached to both the line's input and output. It is theoretical.

Devices with frequency multipliers are utilized in wireless communication. The most appealing material for these models is graphene as they need to operate across a wide bandwidth and with little power consumption. A frequency multiplier circuit using graphene diodes was built in [22]. With an output frequency of 9.2 GHz, the circuit can reach –25.3 dB of conversion gain and –15.3 dBm of output power while operating in the 7–13 GHz broadband band. This circuit is one of the uses of graphene in microwave frequencies as it may be implemented on a variety of inexpensive substrates. Microwave frequency may be used to develop a variety of devices. The radio frequency nanoelectromechanical system (NEMS) is one such example. Shunt switches with a microwave working range were introduced for uses requiring low voltage and quick switching [23]. A graphene membrane draped above the center conductor makes up the switch. The switch uses voltage to function. The graphene membrane buckles down on the dielectric when an electrical field is present.

Numerous FET transistor solutions have been offered in recent years, and they show good cut-off frequency results. A transistor with a current cut-off at 2.2 GHz and a cut-off at 550 MHz was created on an organic substrate in 2013 [24]. The FET for a zero-bias linear resistive mixer was introduced in the same year [25]. It was shown that a graphene FET with a 0.25 µm gate length could produce a cut-off frequency of 20 GHz. Laser technology might be an intriguing area for multilayer graphene applications. Because of its low saturation fluences, rapid recovery times, and diameter distributions, graphene can be used as saturable absorbers in laser technology applications. In [26], a 2-µm monolithic waveguide laser with 7.8 GHz pulses was introduced.

Several graphene layers were employed to get the best results. The structure is thought to consist of about 40 graphene layers with a 40 nm film thickness. Nonlinear frequency conversion and surgery are two possible applications for this technology. Graphene technology can be used to develop sensors and other technologies. In [14], a glucose waveguide sensor based on graphene was introduced. Graphene is deposited onto a FET in the design, and a PDMS overlay serves as a waveguide. This innovative method makes it possible to develop graphene-based photodetectors for application in a variety of biochemical sensor types. This gadget works on the basis of the idea that photocurrent varies according to the material's refractive index. A novel method to FET transistors with graphene applications was shown in [27], where a graphene FET transistor with an ion-gel dielectric layer atop a graphene channel was used to create an artificial synaptic emulating the learning and forgetting processes of the human brain. Graphene and Ion-Gel are both new materials. It is an ionic liquid that has been immobilized by being submerged in another liquid.In [15], a transparent harmonic sensor with a built-in graphene antenna for eye wearing technology was introduced. Graphene antennas are used on flexible, biocompatible substrates to create the sensor. Similar graphene antennas are less effective than metal-based ones due to surface conductivity, as was previously mentioned. This aspect does not limit the use of graphene in wearable electronics and sensor technologies, where flexibility and transparency are more crucial characteristics. It was previously claimed that certain conductivity issues can be resolved by putting a few layers of graphene. Higher conductivity values can be attained by applying multi-layer heavily doped graphene.5.8 GHz and 11.6 GHz (second harmonic) are the resonance frequencies of the suggested antenna. Reduction of return loss is possible by increasing the number of graphene layers.

## IV. CONCLUSIONS

The characteristic of graphene that permits device designs is its tunability with respect to electric or magnetic fields. Applying bias voltage to electrical tunability is a highly practical method in the THz frequency band, but regrettably, it does not produce effective results at microwave frequencies. The extremely high surface resistance and surface conductivity of graphene at microwave frequencies are the basis for this phenomenon. This results in increased interest in and research into multi-layer graphene as well as the pursuit of novel nonstandard methods—such as graphene switches, NEMS devices, and nonstandard structures—to achieve tunability. The rapid advancement of IoT and sensor technologies prompts research into graphene as a potential material for biosensors or wearable technology. It is possible to make flexible and transparent graphene devices using innovative techniques like graphene ink. Graphene is regarded as a useful material for devices like eye wearing sensors, glucose or other biosensors, Internet of Things devices, and others since it offers a significant advantage over conventional silicon technology.

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