5-2020

Voltage Controlled Laser Scribed Graphene (LSG) Microstrip Attenuator

Nathaniel Michael D’Agati

Voltage Controlled Laser Scribed Graphene (LSG) Microstrip Attenuator

by

Nathaniel Michael D'Agati

A thesis submitted to the College of Engineering and Science of
Florida Institute of Technology
in partial fulfillment of the requirements
for the degree of

Master of Science
in
Electrical Engineering

Melbourne, Florida
May, 2020

We the undersigned committee hereby approve the attached thesis,
"Voltage Controlled Laser Scribed Graphene (LSG) Microstrip Attenuator."
by
Nathaniel Michael D'Agati

Josko Zec, Ph.D,
Associate Professor
Computer Engineering and Sciences
Major Advisor

Brian Lail, Ph.D.
Professor
Computer Engineering and Sciences

Daniel Kirk, Ph.D.
Professor
Aerospace, Physics and Space Sciences

Philip Bernhard, Ph.D.
Associate Professor and Department Head
Computer Engineering and Sciences

Abstract

Title: Voltage Controlled Laser Scribed Graphene (LSG) Microstrip Attenuator

Author: Nathaniel Michael D'Agati

Advisor: Josko Zec, Ph. D.

In this paper, a preliminary design of a voltage-tunable microstrip attenuator using Laser Scribed graphene (LSG) is proposed. The paper will demonstrate that the fabrication of LSG from graphene oxide on standard doubled-sided FR-4 Copper-clad Substrate can be used as a voltage-controlled resistor that results in a tunable microstrip attenuator across the microwave frequencies from 50MHz to 5.5GHz. The measured attenuation ranges from 2.6 dB to 11.5dB at 4 GHz with a DC bias voltage ranging from 0V (minimum attenuation) to 6.0V (maximum attenuation).

Graphene is a unique material with interesting electromagnetic and mechanical properties. Graphene conducts electricity better than copper and rapidly dissipates heat, making it useful for many applications. Large-scale production of graphene has been made possible for applications such as printable electronics and electrodes for Supercapacitors and has started to gain interest for use in microwave circuits; however, traditional methods of creating graphene involve many chemical steps and are costly for microwave circuits.

Removing oxygen from graphene oxide to obtain high-quality graphene has been a major challenge over the past two decades for the scientific community due to how oxygen distorts the pristine atomic structure of graphene and degrades its properties. A study some time ago, done by researchers at UCLA, introduced a novel way of making graphene [1]. The research used direct laser writing of graphene electronics with a consumer grade

LightScribe DVD burner for the synthesis, patterning, and writing of graphene electronics from a graphite oxide source to create electrodes for supercapacitors [2]. The laser will resonate with the natural frequency of the graphene and oxygen bond, and thus the graphene oxide will be reduced to graphene on the substrate. Laser scribing the graphene oxide into graphene allows for very accurate fabrication of graphene designs. An important feature of graphene is the omnidirectional resistance and tunable resistivity [3]. This allows graphene to be considered for applications such as tunable resonators, sensors, tunable absorbers and tunable attenuators.

Graphene used in microwave circuits such as tunable attenuators usually focuses on using exfoliated graphene, deposited graphene nanoplatelets, or graphene produced by microwave irradiation. This paper focus on the process of using a laser scribing method to reduce graphene oxide into laser scribed graphene (LSG) used as a voltage variable component to design a prototype tunable LSG microstrip transmission line attenuator over microwave frequencies.

Table of Contents

List of Figures

Acknowledgement

I would like to thank my family and friends for always supporting me and helping me to continuously achieve my goals and dreams.

Chapter 1
Research Background Introduction

1.1 Graphene

Graphene is a single layer of one atom thick material made from graphite. It was first discovered when Professors Sir Andre Geim and sir Kostya Novoselov used tape to repeatedly remove layers away from a bulk of graphite, allowing them to create graphene. This "Scotch Tape Method", also known as the micromechanical cleavage technique, was a very simple way to achieve what is known as 2-dimentional graphene material.

Graphene is chemically made up of only carbon atoms arranged in a single layer hexagonal honeycomb lattice due to sp2 hybridization, with an atomic thickness of 0.345 nm. The bonds created by the sp2 hybridization causes a mixing between one s and two p atomic orbitals. One electron in the s orbital is promoted to one of the 2 p atomic orbitals [4]. The combination of s and p atomic orbitals creates three new hybrid orbitals that are equal in energy-level. The hybrid orbitals are higher in energy than the s orbital but slightly lower in energy than the p orbitals. This causes graphene to have no band gap due to the one electron left over in every carbon atom, which is oriented perpendicular to the graphene sheet, and thus, delocalized. This means that there very little to no energy required for an electron to move from one valance band to another, meaning it can be treated like a semi-metal material [3].

Another special property of graphene is that its Fermi level can be controlled by applying energy. As more energy is applied the Fermi level shifts more and more into the conduction band, lowering the surface resistivity. The energy applied can be in the form of an external electric field (potential) [3]. The focus of this paper will be to use this material property to control the surface resistivity of graphene nanoflakes using a DC bias voltage.

1.2 Graphene Oxide

Graphene oxide (GO) is described as a single atom thick layer of graphene with various oxygen-containing compounds, such as epoxide, carbonyl, carboxyl, and hydroxyl groups. These combinations of oxygen and graphene create a material that is a very good insulator and has a strong elastic modulus. It is created from graphite oxide submerged into a solution and sonicated, allowing for the graphene oxide to exfoliate and separate into sheet layers on top of one another. With respect to electrical conductivity, GO is an electrical insulator and not a good conductor of electric current. For example, when the resistance of a graphene oxide pad was measured with standard multi-meter equipment, the resistance of a graphene oxide pad was observed to be an open circuit, high impedance. GO could, however, work as an intermediary in the production of conductive graphene as shown in Figure 1[5].

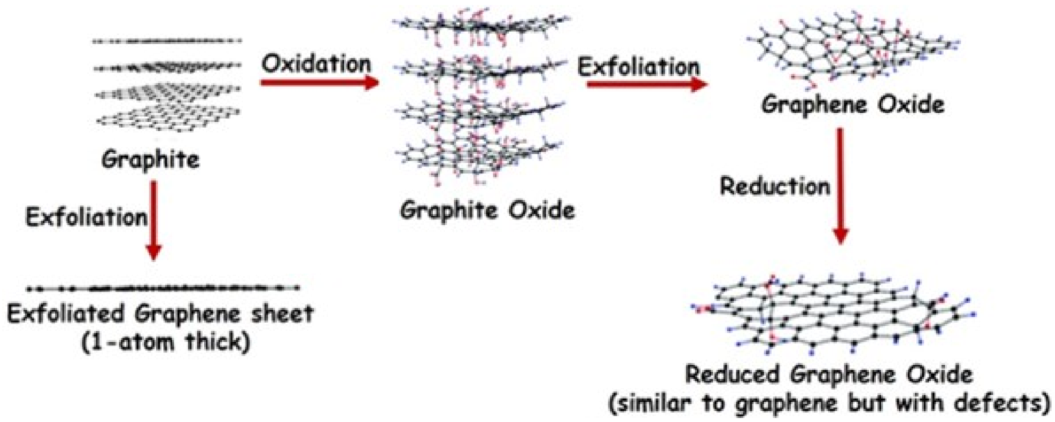

Figure 1: Atomic level model of LSG fabrication process [5]

1.3 Electromagnetic Properties of Graphene

To better understand the applications of graphene in the microwave systems it is critical to understand its electromagnetic properties. The study of graphene's response within the EM spectrum can provide reference for graphene modeling in simulations, so that further graphene related designs can be conducted. The characterization of graphene is mainly done using two methods, transmission line method and free space method. This paper will focus on the transmission line method.

When modeling graphene pads in the microwave spectrum, the size of the pad does not need to be considered due to its very consistent surface resistivity vs frequency, and consistent insertion loss vs conductivity [6], shown in Figure 2.

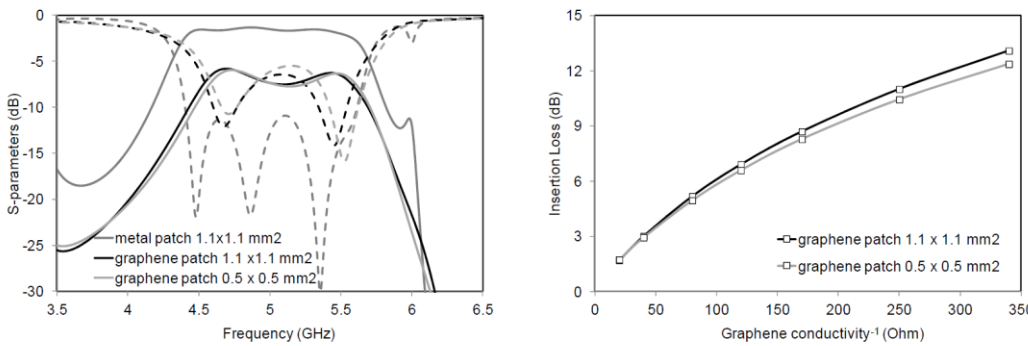

Figure 2: Graphene S-parameters vs frequency (left) and graphene insertion loss vs conductivity (right) comparing a metal patch to different sized graphene patches [6]

The tunability of a graphene pad relative to its size does need to be considered. Research has shown that larger the area of the graphene pad that is in contact with the microstrip line, the greater the tunability of the resistance [7]. As a result of this information the graphene pads in the prototype design will be 1 mm by 1 mm to maximize the tunability and minimize the physical size of the graphene pad.

1.4 Graphene Fabrication

Several different fabrication methods have been proposed and used in order to create graphene for use in research and commercial applications. The main fabrication methods are exfoliation, hydrothermal self-assembly, epitaxy or chemical vapor deposition, nanotube slicing, microwave assisted oxidation, and laser scribing.

Exfoliation uses purely mechanical techniques in order to create graphene from graphite. The first discovery of graphene used the “Scotch Tape Method” where used adhesive tape to split graphene into graphene. Other exfoliation techniques include using a sharp single-crystal diamond wedge to penetrate under the graphite source to exfoliate layers as well as shearing using mixers inside a solution containing graphite.

Chemical Vapor Deposition, a type of epitaxy, can be used to create graphene layers [8]. The graphene is exposed to a catalyst, which causes a reaction and decomposes graphene films onto the desired surface. Frequently, volatile by-products are also produced, which are removed by gas flow through a reaction chamber.

Nanotube slicing involves cutting a single wall carbon nanotube open to create one layer of graphene. A rolled-up carbon nanotube can be cut lengthwise using a solution-based oxidative process [9] and opened, causing the tube to become a sheet that is one atom thick.

The microwave exfoliation method takes advantage of solvent-free microwaves directly and violently exfoliates pristine graphite into graphene sheets by using ammonium bicarbonate (NH4HCO3) as a peeling media. As the microwave heats the material, the decomposition of NH4HCO3 into H2O steam, CO2, and NH3 generates strong pressures that exceeds the van der Waals force between the sheet layers of graphite. This causes a peeling-off of the sheets to create the graphene [10].

Laser scribed graphene (LSG) is created by shooting a 780nm laser at graphene oxide to separate the oxygen compounds connected to the graphene. When hit with the laser, the graphene oxygen bond resonates due to the lasers small wavelength and provides enough energy to separate the oxygen from the graphene to create reduced graphene oxide or laser scribed graphene (LSG) [1].

1.5 Microwave Microstrip Transmission Line

Microstrip microwave transmission lines are used in RF applications in order to reduce the amount of attenuation, noise, and delay on a signal through the line. As frequencies increase, the amount of attenuation increases. Also, the medium that a signal travels through, such as wires, cables, and PCB substrates, can cause parasitic elements. Using microstrip transmission lines, the frequency of the signal and the frequency band being used can be considered to reduce the attenuation, parasitics, and delay on the RF signal. A 50 Ohm characteristic impedance is the standard impedance used for RF microstrip transmission line applications in order to maximize power transfer.

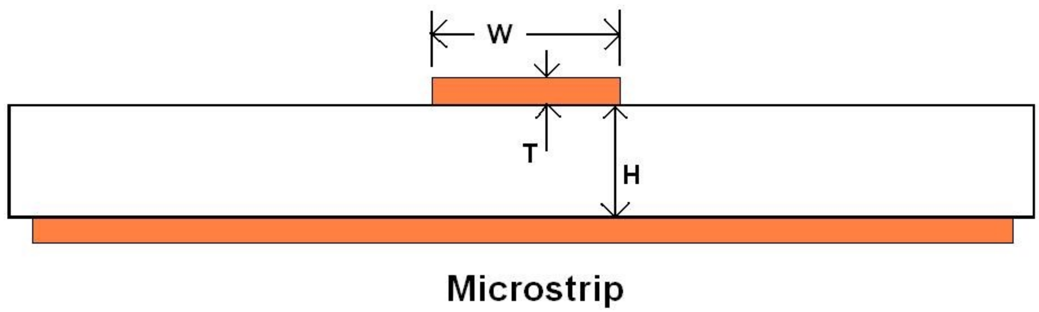

Figure 3:Conventional microstrip transmission line PCB stack-up

To calculate the 50 Ohm characteristic impedance of the microstrip transmission line, the following formula is used, shown in equation (1.5.1), where w = width of the copper microstrip line, h = the dielectric thickness, Z_0 = the desired characteristic impedance (50 Ohms), ε_r = the relative dielectric constant of the substrate, and t = the trace thickness.

$$w = \frac{7.48 \times h}{e^{\left(Z_0 \frac{\sqrt{\varepsilon_r + 1.41}}{87}\right)}} - 1.25 \times t \tag{1.5.1}$$

Chapter 2
Equivalent Circuit Model Analysis and Simulation

2.1 Introduction

To show LSG can be used in microwave applications in this paper it is applied to a tunable attenuator design. The equivalent circuit model to describe graphene and to analyze how it will behave as an attenuator is described in this chapter. The results of these simulations are displayed and will be compared to experimental measured results later in the paper to verify that the LSG fabricated can be applied to microwave applications as modeled in the simulations.

2.2 Modeling of Graphene

In the absence of applied magnetic fields, graphene's conductivity can be computed using the Kubo formula [11] shown in equation (2.2.1),

$$\sigma(\omega, \mu_c, \Gamma, T) = \frac{jq_e^2(\omega - j2T)}{\pi\hbar^2}\left[\frac{1}{(\omega - j2\Gamma)^2}\int_0^\infty \epsilon\left(\frac{\partial f_d(\epsilon)}{\partial\epsilon} - \frac{\partial f_d(-\epsilon)}{\partial\epsilon}\right)\partial\epsilon - \int_0^\infty \frac{f_d(-\epsilon) - f_d(\epsilon)}{(\omega - j2\Gamma)^2 - 4(\epsilon/\hbar)^2}\right]\partial\epsilon \tag{2.2.1}$$

where ω is the radian frequency, Γ is the phenomenological scattering rate, ε is the energy, T is temperature, $-q_e$ is the charge of an electron, $\hbar$ and h are the reduced and normal Planck's constants, μ_c is the Fermi level of graphene, and k_B is Boltzmann's constant. Using this formula, a plot for typical graphene behavior is shown in Figure 4 from baseband to the visible EM spectrum.

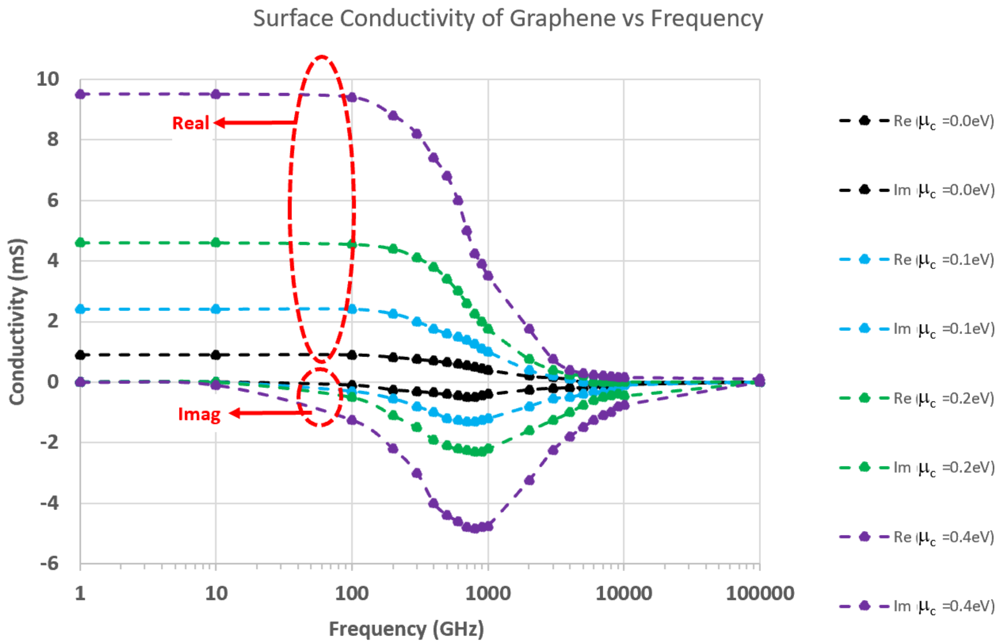

Figure 4: Graphene complex conductivity for different values of μ_c. Plotted from baseband to visible light frequencies

As shown in the plot the surface conductivity of graphene stays relatively constant and almost completely real in the microwave to millimeter wave region (10 GHz) even when a DC bias voltage potential is applied, changing the Fermi level. This means that graphene can be modeled as an almost frequency-independent resistance.

2.3 Equivalent Circuit Model

Due to the constant conductivity in the microwave to millimeter wave region the equivalent circuit model can be established using tunable graphene pads to attenuate a signal through a microstrip line, shown in Figure 5.

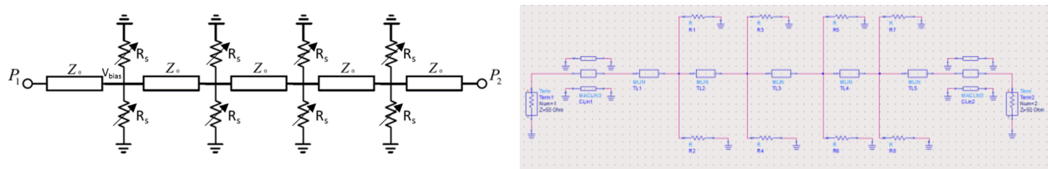

Figure 5: Equivalent circuit model for the Tunable Graphene Microstrip Attenuator (left) and equivalent circuit model schematic in Keysight ADS (right)

The 50 Ohm microstrip line has 8 graphene pads that connect directly from the microstrip line to ground vias. When there is no DC bias voltage across the graphene, the resistance is high, and the signal flows undisturbed through the 50 Ohm microstrip line. When a DC bias voltage is applied, the resistance of the graphene decreases, causing the signal to flow partially through the graphene pads to ground, attenuating the signal.

2.4 Keysight ADS Simulation of a Tunable Graphene Microstrip Attenuator

To simulate the tunable graphene microstrip attenuator the equivalent circuit model created was created in Keysight ADS. The DC model for the graphene pads were input as the values for the resistors in order to simulate how the graphene would react to a DC bias voltage. The tunable graphene microstrip attenuator is then simulated to obtain the Insertion Loss (S21) curves for each attenuation across all frequencies with varying externally applied voltage. This plot was done from 0 V to 6 V stepping 1 V for each plot.

Chapter 3
Laser Scribed Graphene (LSG) Prototype

3.1 Prototype Design

A prototype tunable microstrip attenuator was then developed to obtain experimental results using the LSG pads as a voltage-controlled resistor to verify the simulated results.

A PCB was cut out using a CNC milling machine using the exact dimensions calculated in the simulation for a 50 Ohm characteristic impedance microstrip transmission line. LSG graphene pads were then fabricated and tested to verify its tunability. After fabrication and testing, the graphene pads were placed onto the PCB connecting the microstrip line to the ground vias using conductive silver epoxy.

3.1.1 CNC Milling 50 Ohm Characteristic Impedance Microstrip Line on FR-4 Substrate

The lengths and widths of the microstrip line, via pads, and SMA connector pads were all simulated in ADS to obtain a 50 Ohm characteristic impedance. For FR-4 substrate, using formula 1.5.1, the width of the microstrip line was calculated to be 55.5 mils. The length was kept at 1 inch to keep enough spacing for all 4 pairs of graphene pads. Using the calculated dimensions, a CNC mill path was created in Fusion 360. A Tormach 1100M CNC milling machine was used to fabricate the PCB using the FR-4 substrate, shown in Figure 6.

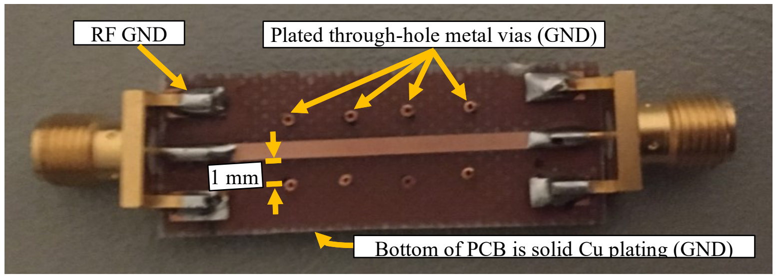

Figure 6: FR-4 PCB fabricated using a Tormach 1100M CNC milling machine

The 8 plated through-hole metal vias, that connect the top Cu metal pad to the Cu plated bottom of the PCB, are 1mm away from the 50 Ohm microstrip transmission line to allow for the LSG pads to connect to ground (both DC and RF GND on the PCB).

3.1.2 LSG Fabrication

Using a Lightscribe optical DVD-ROM drive and a compatible Lightscribe DVD disc, LSG was fabricated. Graphene oxide (GO) was placed onto the DVD disc covered with PET (Polyethylene terephthalate) substrate and allowed to settle and dry. Using the Lightscribe DVD software, a pattern was created for a 1 mm by 1 mm square pad and printed into the GO using the 780 nm laser within the DVD-ROM drive. Figure 7 shows a diagram of the process [1], Figure 8 shows the purchased graphene oxide, and a sample of the graphene oxide and the resulting light scribed graphene fabricated for the prototype is shown in Figure 9.

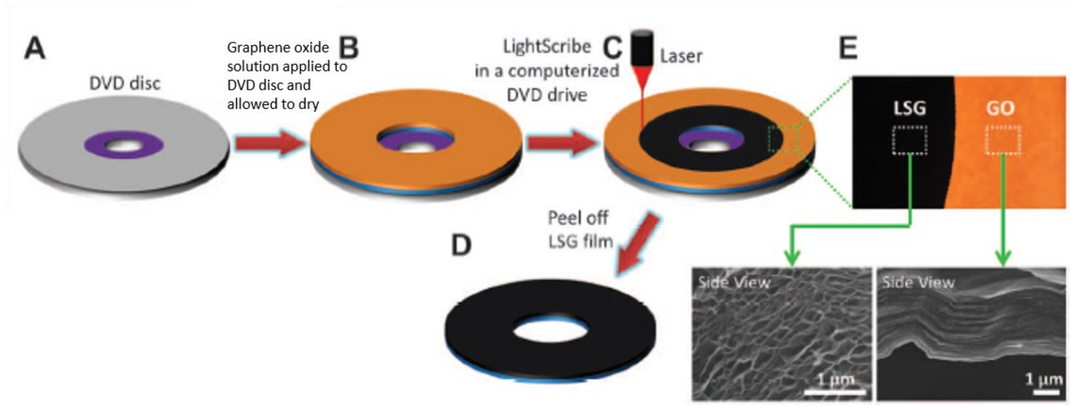

Figure 7: Laser scribe graphene (LSG) fabrication process using a Lightscribe DVD optical drive [1]

Figure 8: Highly Concentrated Graphene Oxide Dispersion in Water [60 ml] (Concentration: 5g/L, 0.33g per bottle, Composition: C (≥46%), O (≤46%), Flake size: 0.5-5 microns, Thickness: 1 atomic layer)

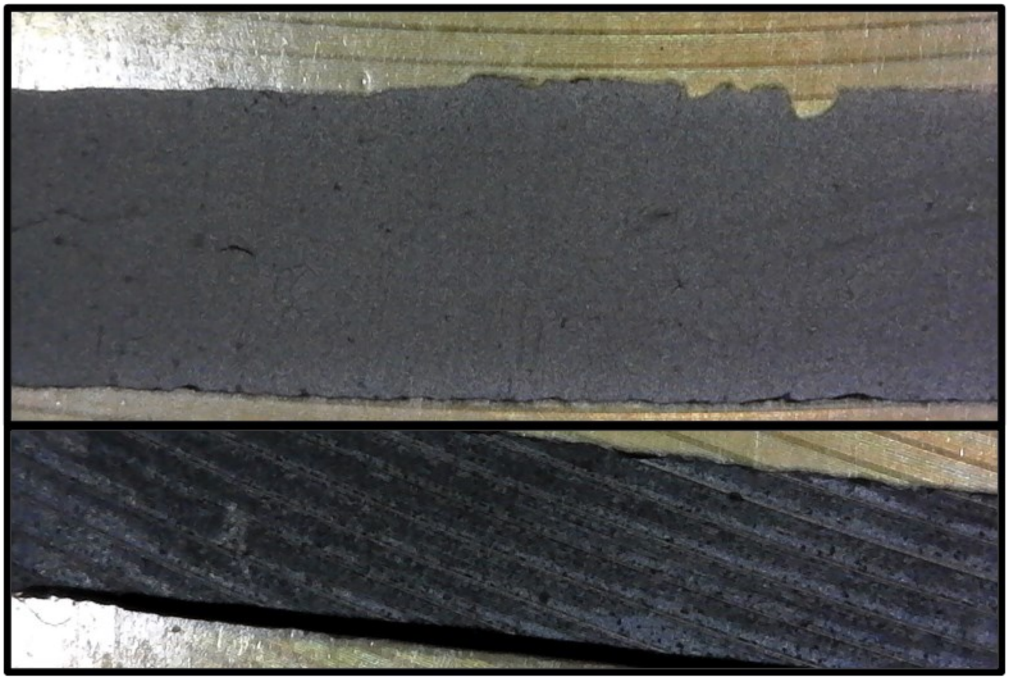

Figure 9: Sample of the dried solution of Graphene oxide on the DVD disc (Top) and resulting laser scribed graphene (LSG) sample (Bottom)

Due to the Lightscribe optical drive laser having no overlap between passes as it spirals around the DVD disc, there are lines of LSG divided with lines of GO. This means that in the direction perpendicular to the laser scribed lines there will be no current flow, whereas in parallel to the laser scribed lines current can flow through the LSG.

3.1.3 LSG Measurement

The resulting fabricated LSG was tested to determine the change in resistance based on an externally applied varying voltage input. Figure 10 shows the measured results of the LSG pad which was used to model the graphene “resistor”. The LSG pad was measured with standard multi-meter equipment and ranged from 1311 Ohms to 150 Ohms with 0 to 6 volts, respectively. More than 7 volts causes a breakdown of the graphene pad.

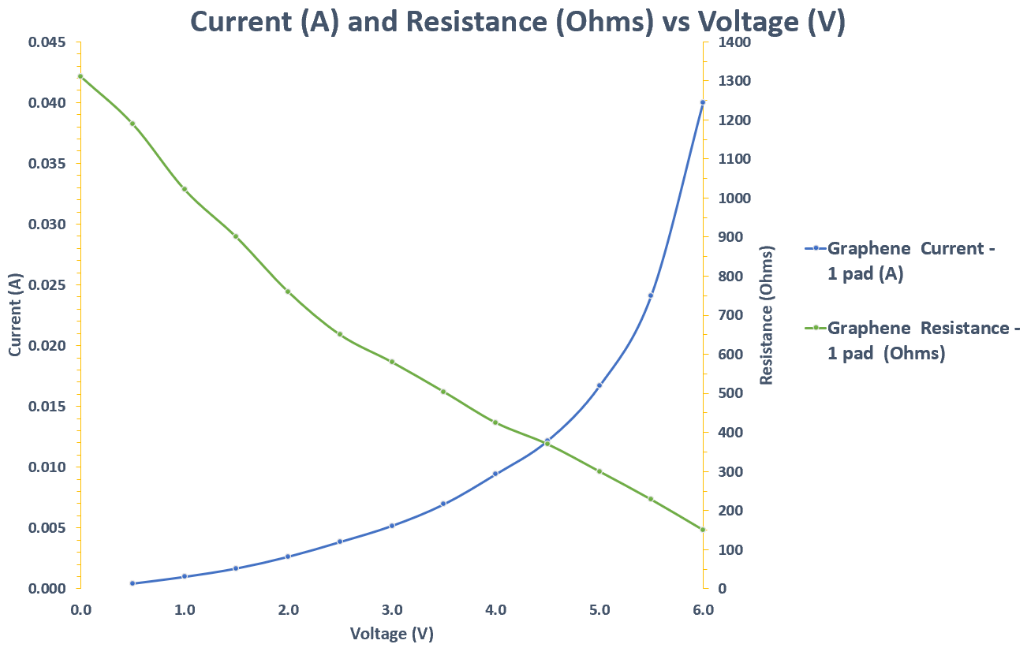

Figure 10: LSG Pad current (Amps) [blue line] and resistance (Ohms) [green line] vs voltage (Volts)

3.1.4 Tunable Microstrip Attenuator Assembly

To manufacture the prototype, graphene first needed to be fabricated. Graphene oxide was placed, and allowed to dry, on top of a Lightscribe compatible DVD. The DVD with graphene oxide was then put into a Lightscribe optical DVD-ROM drive and light scribed. The 780nm laser in the DVD-ROM drive laser scribes the graphene oxide and reduces the graphene oxide to LSG. The 1 mm by 1 mm LSG pad is then cut away from the DVD disc and placed onto the PCB connecting the 50 Ohm line to the grounded vias using conductive silver epoxy. The completed assembly is shown in Figure 11.

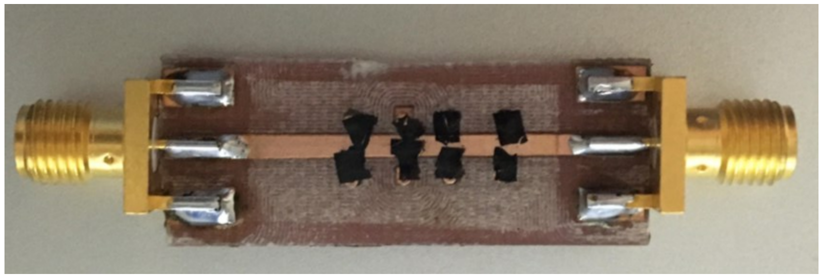

Figure 11: Final 8 LSG Pad prototype tunable microstrip attenuator

3.2 Experimental Results

Once assembled and fabricated the completed PCB was then connected in between two, off-the-shelf, bias-tee components (Figure 12). This allowed for a DC bias voltage to be put across the graphene pads as well as isolating the DC bias voltage from the HP8720D Vector Network Analyzer RF ports (Figure 13). When connected to a (VNA), the insertion loss (S21) was measured while increasing the voltage from 0 to 6 volts. The test setup is shown in Figure 14.

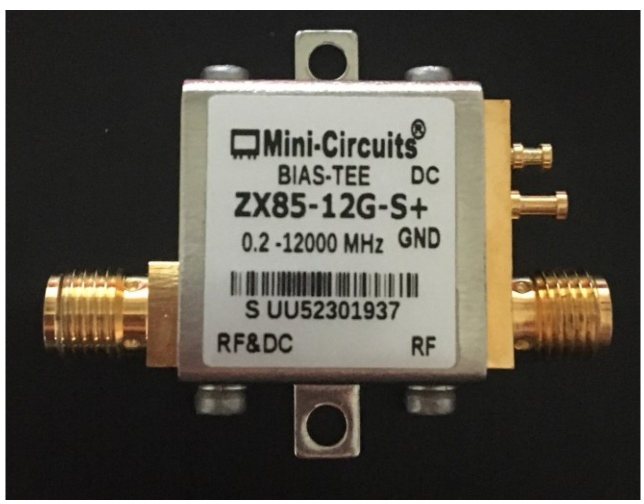

Figure 12: Bias Tee used to input both RF signal and DC bias voltage as well as isolate DC bias voltage from the VNA

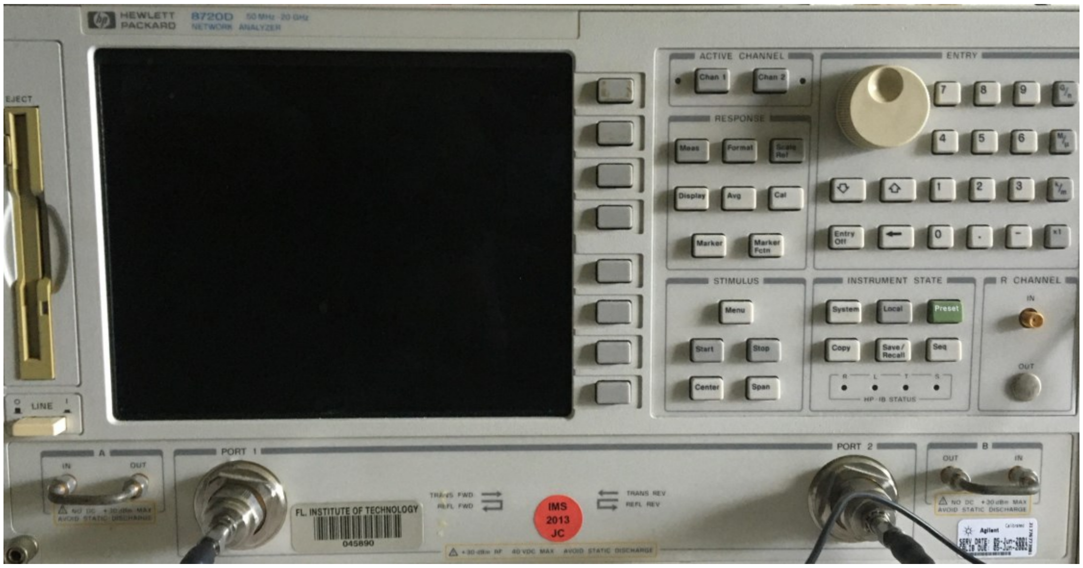

Figure 13: HP8720D Vector Network Analyzer

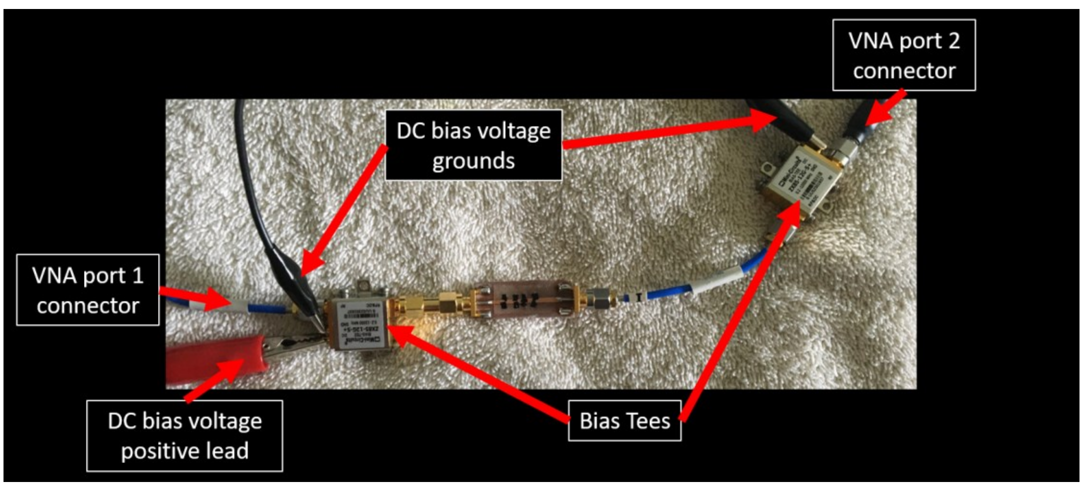

Figure 14: LSG tunable microstrip attenuator test setup

3.2.1 LSG Voltage vs Resistance Measurement

Prior to testing for RF attenuation on the prototype FR-4 PCB, the LSG was tested to see its resistive tuning range performance under a varying voltage potential. The prototype LSG tunable microstrip attenuator was connected to bias tees on either side. The bias tee allows for an RF signal and a DC bias voltage to be introduced to a device under test (DUT), but does not allow the DC bias voltage to return to the RF signal transmission or RF signal return ports, only allowing the dc current to flow to ground. This setup was used to test the equivalent graphene resistance of the 8 pads of LSG fabricated and adhered on the prototype over the 0 Volts to 6 Volts DC bias range used and is displayed in Figure 15.

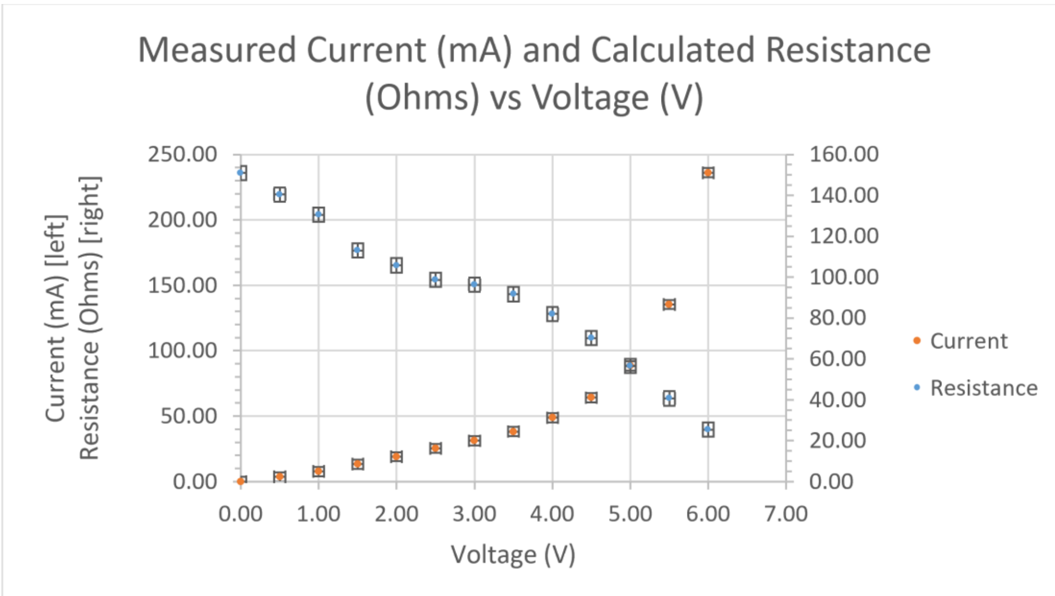

Figure 15: Fabricated 8 Pad LSG prototype PCB current (mA) vs voltage (Volts) measurement (0V – 6V) volts and resulting resistance (Ohms)

With four-pairs of graphene pads on the FR-4 PCB substrate, when the voltage is varied from 0 to 6 volts, the resistance of the prototype decreases from 151 Ohms to 25.41 Ohms respectively, inclusive of the 50 Ohm Source and Load impedance from the VNA.

3.2.2 VNA PCB Characteristic Impedance Measurement

A VNA was used to verify that a 50 Ohm characteristic impedance was achieved in the fabricated PCB boards across the selected spectrum. When connected to the VNA, the S21 parameter was measured across a frequency range from 50 MHz to 5.5 GHz and showed a good match with a slight attenuation at higher frequencies. This matches with simulated results and makes sense intuitively considering that FR-4 is a lossy substrate at microwave frequencies.

3.2.3 Experimental Results vs Simulated Results

When measured on the VNA the attenuator performed very similar to the simulation results. At 0 volts there was minimal attenuation and at a maximum of 6 volts, there was -11.5 dB of attenuation. Figure 16 shows the measured attenuation at 4GHz and Figure 17 shows the simulated values for a voltage range of 0 to 6 volts versus the measured value at 6 volts. Figure 18 shows the measured attenuation curves on the VNA. The simulated results compared to the measured results only varied by a maximum of about 8%, showing a good initial approximation for the LSG when modeled as a resistor.

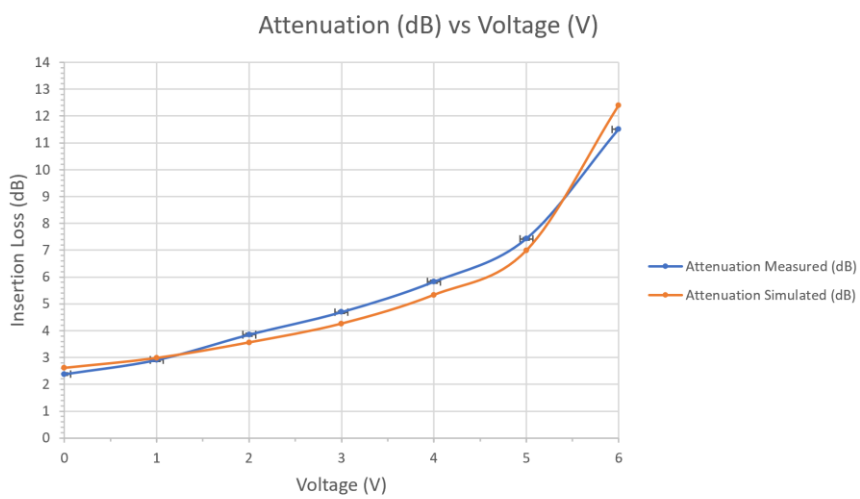

Figure 16: Measured and simulated attenuation at 4 GHz due to dissipation vs voltage

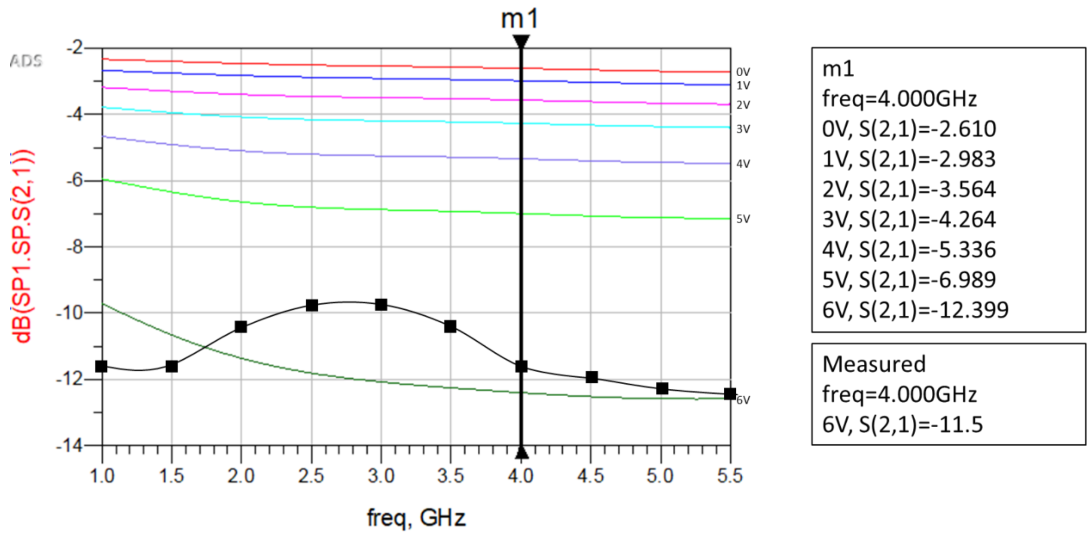

Figure 17: Voltage variable (0V - 6V) LSG attenuation vs frequency

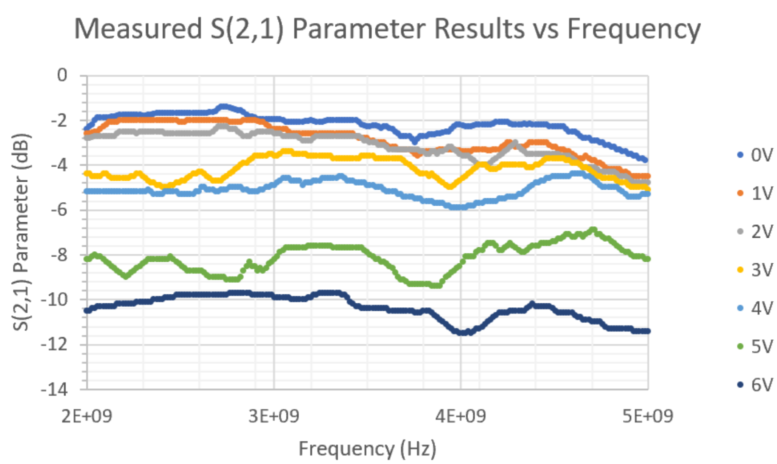

Figure 18: LSG tunable attenuator prototype measured S (2,1) parameter results for DC bias voltages ranging from 0 volts to 6 volts

After achieving these measured results, modifications were done within the simulation in order to more closely model the attenuator. Various other papers have also modeled the use of graphene for their application [12]. Figure 19 shows the modified equivalent circuit model for the tunable LSG microstrip transmission line attenuator. As shown, a series inductor and series capacitor form an R-L-C network with the LSG pad. A capacitor (Cp) was also added in parallel to the inductor (Ls). This network forms a bandpass resonance consistent with the measured results over the frequency band from 2.0 GHz to 3.5 GHz.

The R-L-C network is mostly wideband with a low Q factor (Q<<1). The transfer function for the series R-L-C network is given as:

$$T(s) = Vo(s)/(Vs(s) = (s^2 +(1/LC))/(s^2 + (R/L)s+ (1/LC)) \quad (3.2.1)$$

Plug in s = jw to get the frequency response T(jw):

$$T(jw) = (R/L)*[(jw)/[((1/LC) - w^2) +((R/L)*jw)]] \quad (3.2.2)$$

The T(jw) reaches a maximum when the denominator is a minimum, which occurs when the real part in the denominator equals 0. This results in w0 and is the center frequency of the maximum:

$$(1/LC)-w^2 = 0 \rightarrow w_0 = 1/((LC)^{1/2}) \quad (3.2.3)$$

The cutoff frequencies are at the -3dB half-power points. The -3 dB point occurs when the real part in the denominator is equal to Rw/L

This results in the two appropriate roots of the equation that provides the cutoff frequencies at w_{c1} and w_{c2}:

$$w_{c1} = - (R/2L) + [(R/2L)^2 + (1/LC)]^{1/2} \quad (3.2.4)$$

$$w_{c2} = + (R/2L) + [(R/2L)^2 + (1/LC)]^{1/2} \quad (3.2.5)$$

The bandwidth (BW) can be calculated by using the following equation:

$$BW = w_{c2} - w_{c1} = (R/L) \quad (3.2.6)$$

The quality factor (Q) of the resonant network is defined as the ration of the center frequency to the bandwidth:

$$Q = (w_0/BW) = [(1/(LC)^{1/2})/(R/L)] = (1/R) * [(L/C)^{1/2}] \qquad (3.2.7)$$

The resulting Q of the resonant network at 6 volts dc bias is:

$$Q = (2.75\ \text{GHz})/(3.5\ \text{GHz} - 2.0\ \text{GHz}) = 1.83$$

A Q of 1.8 shows that the resonant circuit has a low Q factor is relatively wideband.

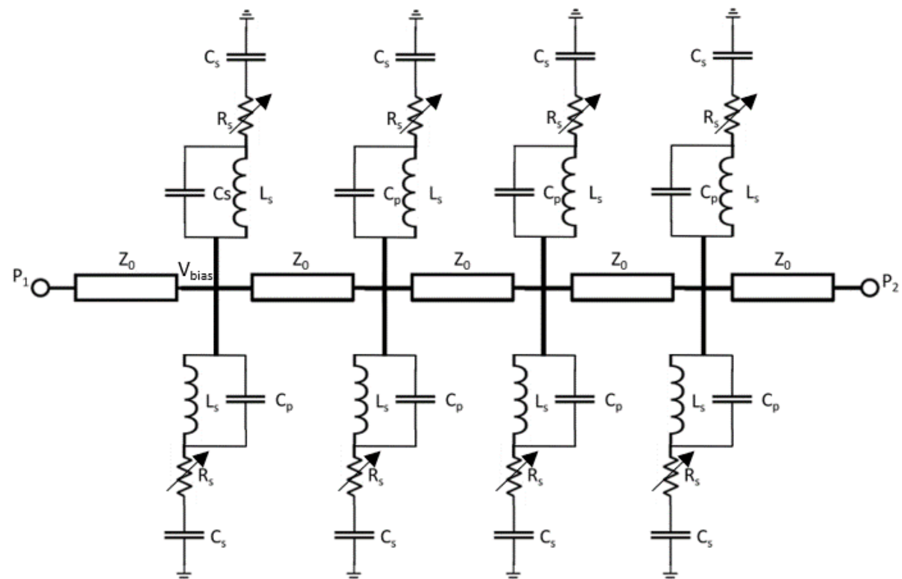

Figure 19: Updated equivalent circuit model for the tunable LSG microstrip attenuator

While very tiny, these extra values allowed the simulation model to represent the measured graphene more closely. The small amount of added capacitance is created by the gaps between the graphene patches and Cs represents the series capacitance introduced by the gaps. The inductance Ls is most likely caused by the length of the ground pad metal vias to the RF GND on the bottom of the PCB as well as the connection of the graphene to the microstrip line itself using FR-4 PCB substrate material. Also, due to LSG fabrication creating multiple nanoflakes of graphene instead of one continuous strip, there is most likely some capacitance between the nanoflakes themselves. Using the updated equivalent circuit model for the tunable graphene microstrip attenuator the following plots are obtained, shown in Figure 20, closely modeling the measured results for the graphene.

Further simulations could be performed to find the resonant network that would more closely match the measured results.

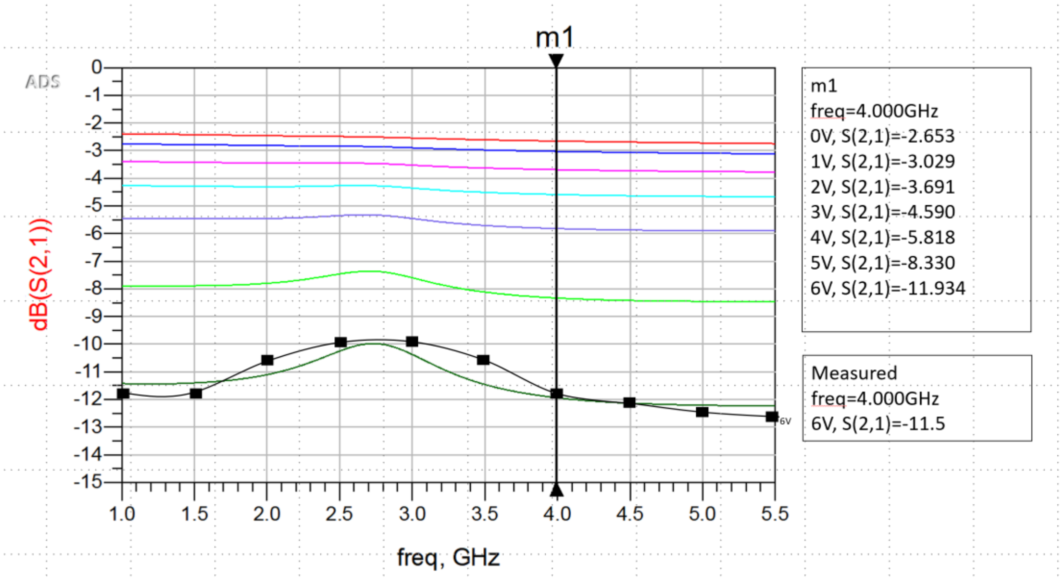

Figure 20: Updated simulated equivalent circuit model results compared with measured results

Chapter 4
Conclusion and Future Work

4.1 Conclusion

A new way to produce graphene for microwave components is provided in this paper using a laser scribing method with off-the-shelf commercially available optical DVD ROM Drive. It has been demonstrated that LSG can be created in the prototype of a voltage controlled LSG tunable microstrip transmission line attenuator. This method can also be used in other microwave applications such as tunable phase shifter, absorbers, and microwave filters, that require high conductivity and tunability. In this application, the LSG fabricated was used to create an attenuator that could provide attenuation from 2.6 dB to 11.5dB using an externally applied DC bias voltage from 0V to 6V across a frequency range from 50 MHz to 5.5 GHz.

4.2 Future Work

The work done in this paper provided a model for an LSG tunable microstrip attenuator. In future work, this model would be used to design systems using graphene in different applications and fabricate them. LSG has many future applications due to its high conductivity, tunability, fast and easy fabrication process, and EM properties. Diodes, transistors, antennas, and other electronic devices would benefit from the use of graphene and could help to make them smaller with better performance. Future work could involve manufacturing these components and comparing them back to the model created in this paper to show similarities in performance and tune the model even further.

Improved manufacturing techniques could help improve the method of fabrication and assembly of components and systems using graphene. By removing the 780 nm laser from the Lightscribe optical drive and placing it onto a CNC bed, more precise and smaller designs could be created using the laser scribing method. Also, by applying a thinner layer of graphene oxide, the laser scribing could reduce all the graphene oxide layers into graphene. This means the laser scribing can be done directly on the substrate that graphene pads needed to be adhered to, eliminating the need to cut off and move the produced graphene from the temporary PET (Polyethylene terephthalate) substrate to the FR-4 PCB substrate. The power of the laser could be increased for laser scribing as well. This would allow for faster fabrication times as well as the use of thicker layers of graphene oxide due to the higher penetration of the laser. The type of PCB substrate is another fabrication design parameter that could be taken into consideration. Using substrates such as Rogers 4003C and Rogers Duroid 5880 drastically improves the loss tangent as well as decreases the amount of parasitics at higher frequencies, allowing for a cleaner signal and more linear response, reducing the resonant network, of the controlled attenuation. Lastly, the attenuator architecture could be revised to consider the 50 Ohm characteristic impedance. When the dc bias voltage was increased to increase the attenuation, the Return Loss S (1,1) of the circuit also increased, thereby degrading the matched impedance that would potentially distort the incoming RF signal. By changing the attenuator into a T-shaped attenuator design, both the attenuation and reflection coefficient could be tuned, while maintaining a 50 Ohm impedance match throughout the voltage-controlled range of attenuation.

References

[1] M. F. El---Kady et al., Laser Scribing of High-Performance and Flexible Graphene-Based Electrochemical Capacitors. Science. 335, 1326 (2012). doi:10.1126/science.1216744

[2] Maher F. El-Kady and Richard B. Kaner, Direct Laser Writing of Graphene Electronics. ACS Nano 2014, 8, 9, 8725-8729 (September 12, 2014). doi.org/10.1021/nn504946k

[3] Bozzi, Maurizio & Pierantoni, Luca & Bellucci, Stefano. (2015). Applications of Graphene at Microwave Frequencies. Radio engineering. 24. 661-669. 10.13164/re.2015.0661.

[4] Hu, Meng & Dong, Xu & Yang, Bingchao & Xu, Bo & Yu, Dongli & He, Julong. (2015). Three-dimensional sp2-hybridized carbons consisting of orthogonal nanoribbons of graphene and net C. Phys. Chem. Chem. Phys.. 17. 10.1039/C5CP01621E.

[5] Jhaa, Gaurav. (2018). Re: What is difference between graphene oxide and exfoliated graphite?. Retrieved from: https://www.researchgate.net/post/What_is_difference_between_graphene_oxide_and_exfoliated_graphite/5bebc19e3d48b71dc54c7939/citation/download.

[6] L. Pierantoni, D. Mencarelli, M. Bozzi, R. Moro and S. Bellucci, "Graphene- based electronically tunable microstrip attenuator," 2014 IEEE MTT-S International Microwave Symposium (IMS2014), Tampa, FL, 2014, pp. 1-3.

[7] Wang, Rong & Raju, Salahuddin & Chan, Mansun & Jiang, Li. (2017). Low frequency behavior of CVD graphene from DC to 40 GHz. Progress In Electromagnetics Research C. 71. 1-7. 10.2528/PIERC16111901.

[8] L. Pierantoni et al., "Broadband Microwave Attenuator Based on Few Layer Graphene Flakes," in IEEE Transactions on Microwave Theory and Techniques, vol. 63, no. 8, pp. 2491-2497, Aug. 2015.

[9] Kosynkin, D., Higginbotham, A., Sinitskii, A. et al. Longitudinal unzipping of carbon nanotubes to form graphene nanoribbons. Nature 458, 872–876 (2009). https://doi.org/10.1038/nature07872

[10] Juxiang Lin, Yajing Huang, Shi Wang, and Guohua Chen." Microwave-Assisted Rapid Exfoliation of Graphite into Graphene by Using Ammonium Bicarbonate as the Intercalation Agent" in Industrial & Engineering Chemistry Research 2017 56 (33), 9341-9346 DOI: 10.1021/acs.iecr.7b01302

[11] J. S. Gomez-Diaz and J. Perruisseau-Carrier, "Microwave to THz properties of graphene and potential antenna applications," 2012 International Symposium on Antennas and Propagation (ISAP), Nagoys, 2012, pp. 239-242.

[12] O. Sanusi, P. Savi, S. Quaranta, A. Bayat, and L. Roy, "Equivalent Circuit Microwave Modeling of Graphene-Loaded Thick Films Using S-Parameters," Progress In Electromagnetics Research Letters, Vol. 76, 33-38, 2018. doi:10.2528/PIERL18040903