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Original

Dynamically tunable phase shifter with commercial graphene nanoplatelets / Yasir, M.; Savi, Patrizia. - In: MICROMACHINES. - ISSN 2072-666X. - ELETTRONICO. - (2020), pp. 1-11. [10.3390/mi11060600]

Availability:

This version is available at: 11583/2836763 since: 2020-06-21T18:35:52Z

Publisher:

MDPI

Published

DOI:10.3390/mi11060600

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1 Article

2 Dynamically tunable phase shifter with commercial 3 graphene nanoplatelets

4 Muhammad Yasir ¹, Patrizia Savi ^{2*}

5 ¹ Department of Electronics and Telecommunications; Politecnico di Torino; muhammad.yasir@polito.it

6 ² Department of Electronics and Telecommunication; Politecnico di Torino; patrizia.savi@polito.it

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8 * Correspondence: patrizia.savi@polito.it

9 Received: date; Accepted: date; Published: date

10 **Abstract:** In the microwave frequency band the conductivity of graphene can be varied to design a
11 number of tunable components. A tunable phase shifter based on commercial graphene
12 nanoplatelets is introduced. The proposed configuration consists of a microstrip line with two stubs
13 connected with a taper. On each side of the stubs there is a gap, short circuited through a via, where
14 the commercial graphene nanoplatelets are drop casted. By applying a DC bias voltage that alters
15 the graphene resistance the phase of the transmitted signal through the microstrip line can be varied.
16 In order to maximize the phase shift of the transmitted signal and minimize the insertion loss, the
17 length of the taper and the stubs are optimized by the help of circuit model and full-wave
18 simulations. A prototype working at 4GHz is fabricated and measured. A phase variation of 33
19 degrees is acquired with an amplitude variation of less than 0.4dB.

20 **Keywords:** commercial graphene nanoplatelets; tunable microwave devices; phase shifter; voltage
21 controlled microwave components.
22

23 1. Introduction

24 Among the various carbon based materials, graphene is the most notable [1-3]. Due to its
25 interesting properties graphene has caught significant attention [4]. Not only has graphene been
26 studied in its original form but also for functionalization and patterning [5,6]. One of the most
27 popular deposition methods of carbon based materials is their deposition as films [7,8]. The
28 advantage of using graphene is that a lot of research work has been performed on its fabrication
29 techniques that has facilitated its production and reduced its cost over the years. This has incentivized
30 its widespread use in a number of different applications.

31 Graphene has remarkable electrical, mechanical and thermal properties. Due to the remarkable
32 properties of graphene, it has found inwards into several applications including electrochemical
33 sensors [8-9], biosensors [10-11], gas sensors [12-14], humidity and temperature monitoring [15-17],
34 absorbing materials [18], passive [19-21] and active devices [22-23]. The electrical properties of
35 graphene vary with frequency. Due to the occurrence of plasmonic effect in graphene at the terahertz
36 frequency range, it has been deeply analyzed [24-25]. In the microwave frequency band, graphene
37 has emerged only recently in components as tunable phase shifter [26], attenuators [27-29] and
38 antennas [30-31]. It has been noted that graphene varies its electron mobility with the application of
39 a DC voltage. The variation of electron mobility results in taking the Fermi energy level from
40 conduction to valence band. This makes graphene from a highly insulative material to a considerably
41 conductive material. This variation of conductivity with the application of a DC voltage is valid
42 through a wide frequency band covering the entire microwave frequency spectrum.

43 Communication systems involve a number of components working at different frequencies. For
44 efficient working, there needs to be an interconnection between components that form an entire

45 communication system. This interconnection can be facilitated if the components are able to tune
46 their working frequency. Therefore, the tuning of microwave components that form a communication
47 system is vital to efficient functionality. Graphene being tunable with the application of a DC bias, is
48 a good contender for being deployed in microwave communication systems. The acquisition of
49 monolayer graphene is technologically demanding and not very cost effective. Multilayer graphene
50 on the other hand bears tunable conductive behavior similar to monolayer graphene albeit with
51 reduced cost and very low technological complexity. Until recently, multilayer graphene has been
52 grown in laboratory. The availability of commercial graphene nanoplatelets on a large scale takes the
53 ease of fabrication and commercialization of tunable components based on graphene one step further.
54 Recently, a tunable attenuator [29] and antenna [30] have been realized exploiting the tunable
55 conductivity of commercial graphene nanoplatelets.

56 In this paper, a tunable phase-shifter based on commercial graphene nanoplatelets is designed.
57 The proposed configuration consists of a microstrip line with two stubs connected with a taper. On
58 each side of the stubs there is a gap, short circuited through a via, where the commercial graphene
59 nanoplatelets are drop casted. By applying a DC bias voltage that alters the graphene resistance the
60 phase of the transmitted signal through the microstrip line can be varied. The lengths of the tapered
61 line and open line section are optimized by the help of a circuit model. The phase shifter is further
62 optimized with a full-wave simulator. A prototype of the tunable phase shifter is fabricated and
63 measured. A variable phase shift of 33 degree is obtained with a degradation of the insertion loss of
64 less than 0.4 dB.
65

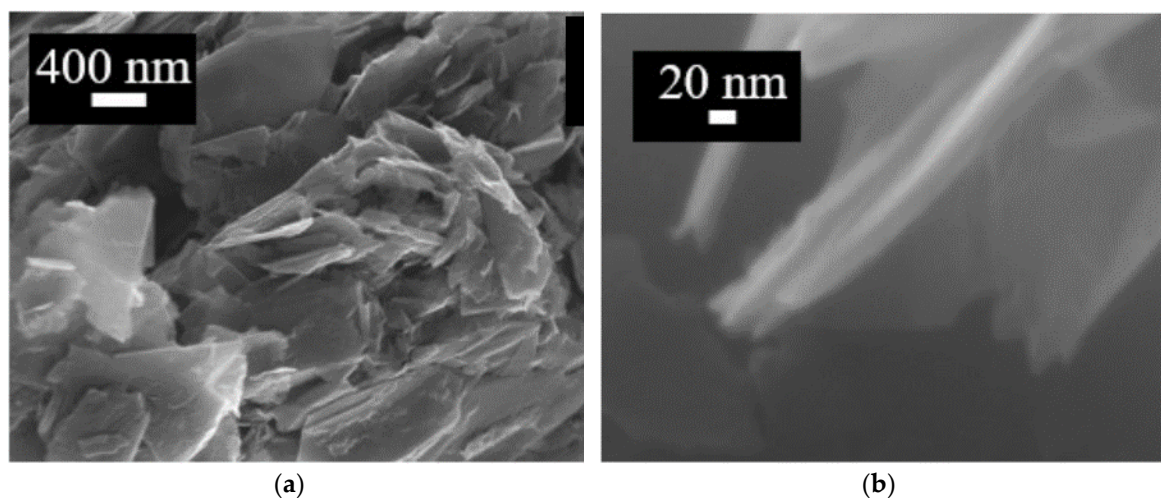
66 2. Materials and Methods

67 2.1 Graphene characterization

68

69 The type of graphene used in this work is graphene nanoplatelets based on multiple graphene
70 layers. The graphene nanoplatelets are produced by NanoInnova. Raman and FESEM (Field Emission
71 Scanning Probe Microscope) are used for the morphological characterization of the graphene
72 nanoplatelets.

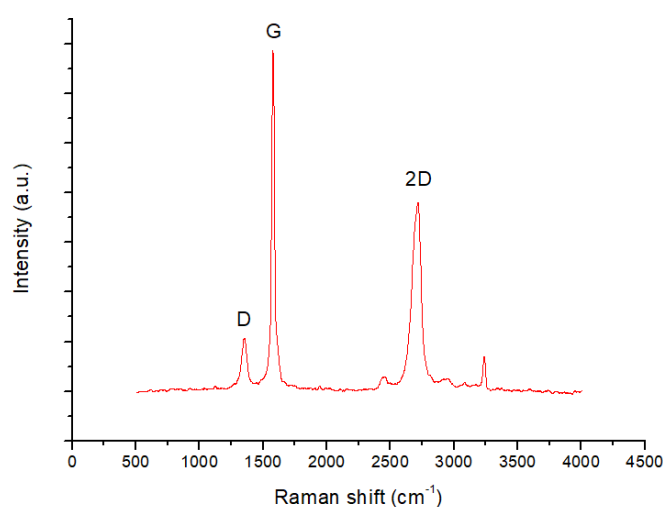
73 For the FESEM analysis of the commercial graphene nanoplatelets, a ZEISS SUPRA™ 40
74 microscope was used. The FESEM images are shown in Figure 1. In the Figure 1a, a zoomed out
75 image of the graphene nanoplatelets can be seen. A zoomed in image of a single graphene
76 nanoplatelet is shown in Figure 1b. The transparency of flake at such a scale shows that the thickness
77 of the individual flake is a few nanometers and hence is composed of only a few graphene layers.
78



79

Figure 1. FESEM images of the commercial graphene nanoplatelets.

80 Raman spectroscopy performed on the graphene nanoplatelets is shown in Figure 2. There are
 81 two different spectral ranges for characterizing the Raman spectrum of graphene. The first one in the
 82 range of 1000-1700 cm^{-1} contains the D (defects) and G (graphitization grade). The second spectral
 83 range from 2200-3500 cm^{-1} is the second order Raman spectral range containing overtones. The ratios
 84 of the peaks are $I_D/I_G=0.15$, $I_D/I_{2D}=0.27$ and $I_G/I_{2D}=1.81$. According to guidelines described in [32], the
 85 Raman spectroscopy shows a similar behavior to that of few layer graphene. A detailed analysis of
 86 the relation between the intensities and shape of the peaks G and 2D to the number of graphene layers
 87 can be found in [4]. In the case of monolayer graphene $I_{2D}/I_G \geq 1$ and there is no broadening in the
 88 feature of the 2D band. For the commercial graphene used here, the shape of the 2D is slightly
 89 broadened and $I_{2D}/I_G=0.55$. This shows that the graphene nanoplatelets used comprise of a number
 90 of graphene layers.



91

92

Figure 2. Raman spectroscopy of the commercial graphene nanoplatelets.

93 2.2 Circuit model optimization

94 The phase shifter is composed of a microstrip line connected to two stubs (see Fig 3a). For a two-
 95 port device the transmission properties are defined by the scattering parameter $S_{21}=b_2/a_1$, where b_2 is
 96 the signal transmitted at port 2 with a_1 incident at port 1. S_{21} is a complex number and can be
 97 represented as either real and imaginary part, or amplitude and phase.

98 The stubs are composed of a linear tapered line and an open line section connected to each other
 99 through grounded resistors, representing graphene as shown in Figure 3. The tapered line has length,
 100 L_t and thickness corresponding to a characteristic impedance of 50Ω at one end. The other end of the
 101 tapered line, which is connected to the stub, has a thickness corresponding to 100Ω . The tapered line
 102 reduces reflection from the open line section that has a characteristic impedance of 100Ω and length
 103 L_s . Graphene is modelled as a lumped resistor with resistance R_g .

104 The current passing into the stub is controlled through the graphene's resistance. A higher
 105 resistance of graphene means that the impact of the stub is maximized and so is the total reactance as
 106 seen at the input. A lower graphene's resistance means a maximum current passing through
 107 graphene into the ground minimizing the impact of the stub. The input impedance of the stub
 108 structure is given by $Z_{in}=R_{in}+jX_{in}$. This is composed of a real part, R_{in} , and an imaginary part, X_{in} .
 109 When the graphene's resistance varies both the values of R_{in} and X_{in} varies. It is desirable to maximize
 110 the variation of X_{in} and minimize the variation of R_{in} when the graphene resistance, R_g is varied. The
 111 lengths of the tapered line, L_t and the open line section, L_s is therefore optimized for a maximum X_{in}
 112 and minimum R_{in} variation when graphene's resistance R_g is varied.

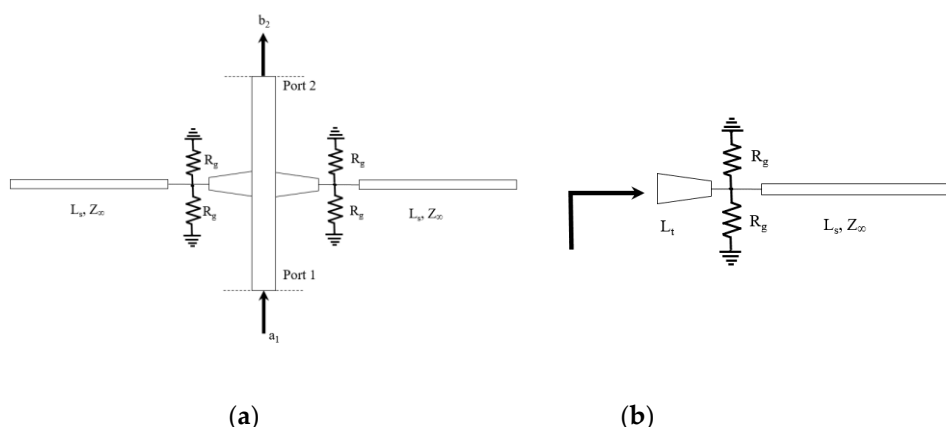


Figure 3. (a) Two-port phase shifter circuitual representation (b) Circuitual representation of the stub.

Simulation are performed based on the circuit model shown in Figure 3 at a frequency of 4 GHz. The length L_t is varied from $0.04 \lambda_0$ to $0.08 \lambda_0$ and the length L_s is varied from $0.05 \lambda_0$ to $0.35 \lambda_0$ where $\lambda_0 = c/f$, c is the speed of light and f is the frequency used in the design (4 GHz).

For each set of values of L_t and L_s , the input impedance is simulated for values of R_g ranging from 70Ω to 700Ω . The values $\Delta R_{in} = R_{in} [R_g = 700 \Omega] - R_{in} [R_g = 70 \Omega]$ and $\Delta X_{in} = X_{in} [R_g = 700 \Omega] - X_{in} [R_g = 70 \Omega]$ are found as shown in Table 1. It can be observed that by increasing the length, L_s the value of ΔX_{in} is increased while increasing the value of L_t , the value of ΔR_{in} is reduced up to length $L_s = 0.3 \lambda_0$. Increasing the length, L_s further reduces the value of both ΔR_{in} and ΔX_{in} . For the case of $L_s = 0.15 \lambda_0$, in which there is no impact of the variation of R_g on Z_{in} . The best case from this analysis is thus: $L_s = 0.3 \lambda_0$ and $L_t = 0.08 \lambda_0$.

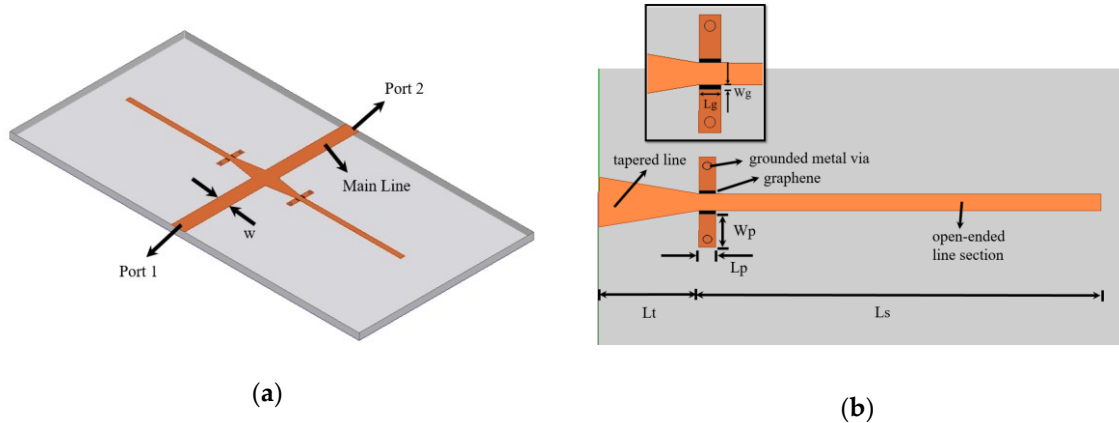
Table 1. The variation of real and imaginary input impedance with graphene resistance variation with different values of L_s and L_t . All ΔR_{in} and ΔX_{in} are in (Ω).

L_s	$L_t = 3\text{mm } (0.04 \lambda_0)$		$L_t = 4\text{mm } (0.053 \lambda_0)$		$L_t = 5\text{mm } (0.067 \lambda_0)$		$L_t = 6\text{mm } (0.08 \lambda_0)$	
	ΔR_{in}	ΔX_{in}	ΔR_{in}	ΔX_{in}	ΔR_{in}	ΔX_{in}	ΔR_{in}	ΔX_{in}
$0.05 \lambda_0$	41.5	46.9	37.6	40	34.5	34.7	31.75	30.8
$0.15 \lambda_0$	0.3	0.02	0.3	0.02	0.3	0.02	0.3	0.03
$0.3 \lambda_0$	48	67	45	58	41	50	38	44
$0.35 \lambda_0$	43	52.6	39	45	36.6	38	33.4	34.5

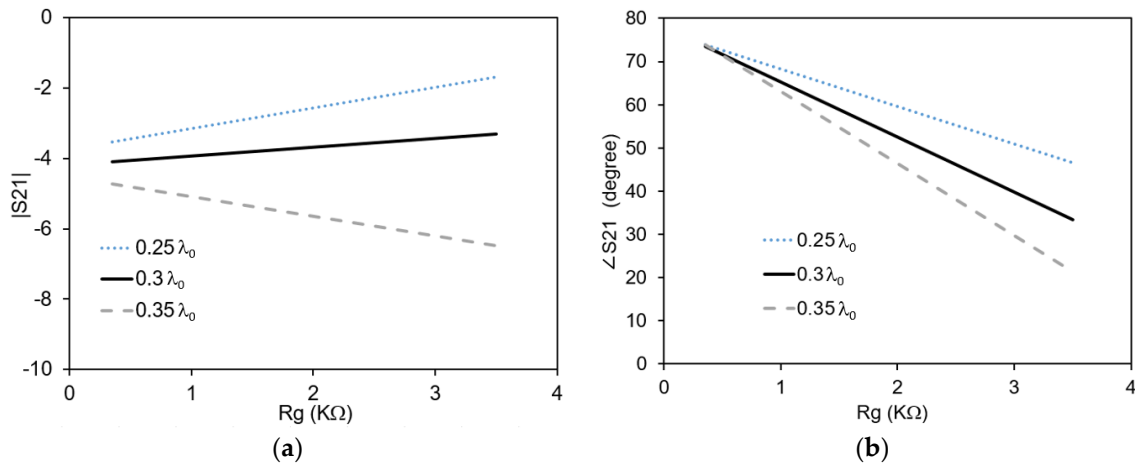
2.3 Full-wave design

The operating principle of the phase shifter is to have a variable reactance on a transmission line caused by the optimized stubs of the Section 2.2. In order to achieve considerable phase variation, two stubs are connected to a 50Ω transmission line forming a two-port structure. A geometrical representation of the phase shifter is shown in Figure 4. The phase shifter is designed on a Rogers 3035 dielectric substrate of thickness $t = 1.52$ mm. The dielectric permittivity of the substrate is $\epsilon_r = 3.5$ and loss tangent is $\tan \delta = 0.0015$. The thickness of copper is $35 \mu\text{m}$. The width of the main line is $w = 3.2$ mm, corresponding to a characteristic impedance of 50Ω . The stub is shown in detail in Figure 4b. The stub is composed of a tapered line section of length, L_t and an open ended line section of length, L_s . In order to realize the grounds, two grounded metallic vias are symmetrically placed on each side of the line section in the middle of a metallic pad. The metallic pad has length, $L_p = 1$ mm and width, $w_p = 2$ mm. In between the metallic pad and the line section, graphene is deposited. The length of graphene deposition is equal to the length of the metallic pad, $L_p = 1$ mm. The graphene

143 deposition has width, $W_g = 0.2$ mm and length, $L_g = 1$ mm. The aspect ratio is kept low to ensure lower
 144 resistance since commercial graphene nanoplatelets possess higher sheet resistance value.
 145
 146



147 **Figure 4.** Geometrical representation of the phase shifter with dimensions: (a) phase shifter; (b) individual stub.



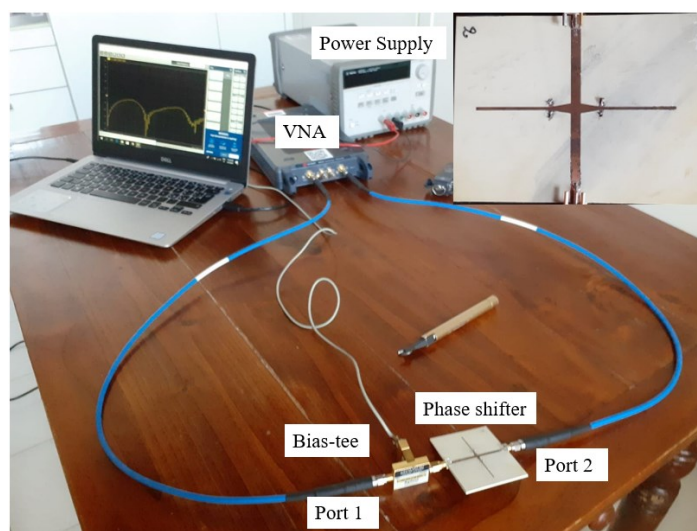
148 **Figure 5.** S_{21} versus R_g for different L_s : (a) amplitude variation; (b) phase variation.

149 The phase shifter is simulated with a full-wave simulator Ansys HFSS. In order to further
 150 optimize the structure, the phase shifter has been simulated at a frequency of 4 GHz with three
 151 different lengths of the open-ended line section, L_s ($0.25\lambda_0$, $0.3\lambda_0$ and $0.35\lambda_0$) for graphene resistance
 152 values ranging between $350 \Omega/\text{sq.}$ and $3500 \Omega/\text{sq.}$ (the graphene sheet resistance is measured in
 153 Ohm/square). The amplitude and phase variation of the phase shifter versus graphene sheet
 154 resistance are shown in Figure 5. The amplitude variation of the transmission (see Figure 5a) as seen
 155 from the slope of the curves, decreases from $L_s = 0.25\lambda_0$ to $L_s = 0.3\lambda_0$. Increasing the value of L_s
 156 further to $0.35\lambda_0$ results in increased variation of $|S_{21}|$. The phase variation is shown in Figure 5b. It can be
 157 seen that the variation of $\angle S_{21}$ increases with increasing L_s . The maximum phase variation is attained
 158 in the case of $L_s = 0.35\lambda_0$. The optimum length is $L_s = 0.3\lambda_0$ because it provides minimum amplitude
 159 variation with reasonable phase variation.

160 161 2.4 Prototype realization

162 The structure of the phase shifter with optimized dimensions resulting from Section 2.2 and
 163 Section 2.3 is realized by using a standard etching process. Lithographic film is used to pattern the
 164 structure of the phase shifter on a dielectric substrate with both sides covered with copper. The
 165 substrate with the pattern is then immersed in acid to etch away excess copper. The metal vias are
 166 realized by drilling holes and soldering metal wires to the top and bottom. Commercial graphene
 167 nanoplatelets mixed in isopropyl alcohol are then drop casted on the designated spots of the phase

168 shifter. The excess alcohol evaporates leaving behind the commercial graphene nanoplatelets. The
 169 fabricated prototype is as shown in Figure 6.
 170

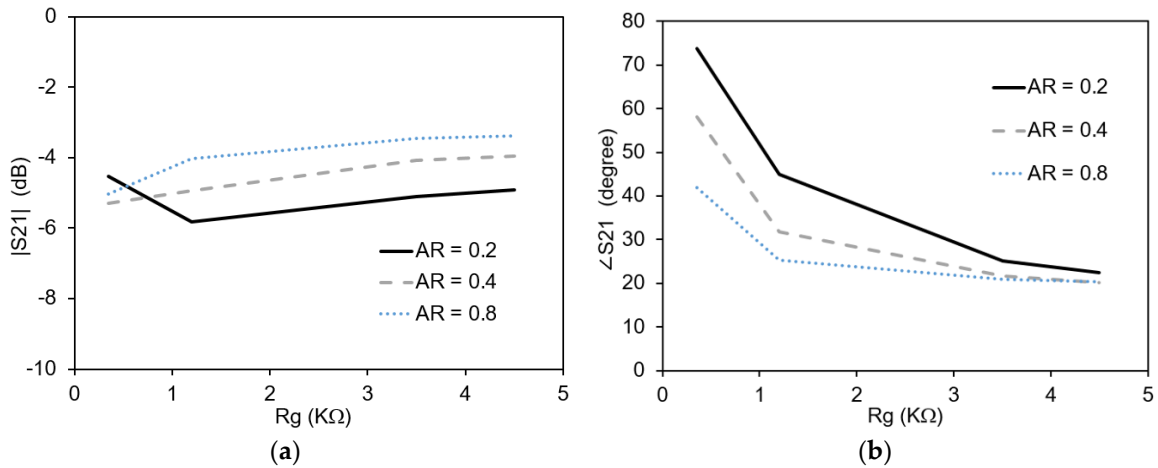


171
 172 **Figure 6.** Measurement setup of the commercial graphene based tunable phase shifter. In the inset a photograph
 173 of the prototype is shown.

174 3. Results

175 3.1 Full-wave simulations

176 The aspect ratio of the gap with graphene can be defined as: $AR = Wg/Lg$ (see Figure 4b inset).
 177 This is an important parameter in the determination of the resistance $R = Rg \cdot AR$. The value of the
 178 resistance, R can also be calculated from the ratio of the applied bias voltage and the current drawn
 179 by graphene [19]. In order to evaluate the impact of the aspect ratio on the transmission properties of
 180 the phase shifter, full-wave simulations are performed with different values of the aspect ratio
 181 ranging from 0.2 to 0.8 at a frequency of 4 GHz. The resultant amplitude and phase variation versus
 182 graphene sheet resistance, Rg , is shown in Figure 7. The reduction of AR causes a reduction in the
 183 variation of $|S_{21}|$. For an AR of 0.2, the maximum and minimum $|S_{21}|$ is -4.5 dB and -5.8 dB
 184 respectively. For the maximum AR value of 0.8, the maximum and minimum $|S_{21}|$ is -3.3 dB and -5.0
 185 dB respectively. The value of the phase of the transmission coefficient increases with a reduction in
 186 the aspect ratio. The maximum value of $\angle S_{21}$ for an AR of 0.2 is 73° while the minimum value is 22° .
 187 This shows that a reduction of the AR reduces the variation of the amplitude of the transmission
 188 coefficient and increases the variation of the phase of the transmission coefficient, a highly desirable
 189 trait of tunable phase shifters.



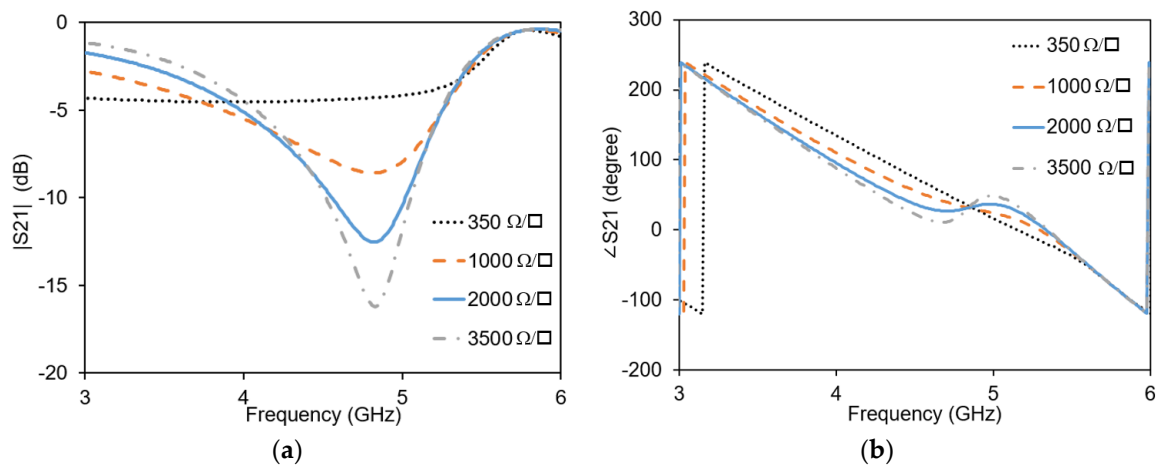
190 **Figure 7.** Impact of the aspect ratio on the transmission: (a) Amplitude variation; (b) Phase variation.

191 The optimized phase shifter is simulated with full-wave simulator in the frequency range of 3-6
 192 GHz. Graphene nanoplatelets are modelled as infinitely thin resistive sheets with assigned resistance
 193 values ranging from 350 $\Omega/sq.$ to 3500 $\Omega/sq.$ The resulting simulated values of the transmission
 194 coefficient are shown in Figure 7. The amplitude of S_{21} (Figure 8a.) reduces from 4GHz to 5GHz for
 195 higher resistance values. At the frequency of 4.3 GHz, the amplitude variation is minimum. The phase
 196 variation (Figure 8b) increases slightly from 3 GHz to 5 GHz.

197 **3.2 Measurements**

198 The measured results of the transmission are shown in Figure 9. Measurements of the prototype
 199 are carried out by the help of a vector network analyzer. A commercial broadband bias-tee is used to
 200 bias the commercial graphene nanoplatelets. The bias is applied between the ground plane and the
 201 main line. By varying the bias voltage applied to the commercial graphene nanoplatelets, their
 202 resistance is varied. This causes a variation of the phase of the signal transmitted between the two
 203 ports. At a minimum applied bias voltage of 0 V, the graphene resistance is 4500 $\Omega/sq.$ Increasing the
 204 bias voltage to 6 V results in reducing the graphene resistance to 1200 $\Omega/sq.$ The corresponding sheet
 205 resistance values as derived from the aspect ratio are 4500 $\Omega/sq.$, 3500 $\Omega/sq.$ and 1200 $\Omega/sq.$
 206 respectively.

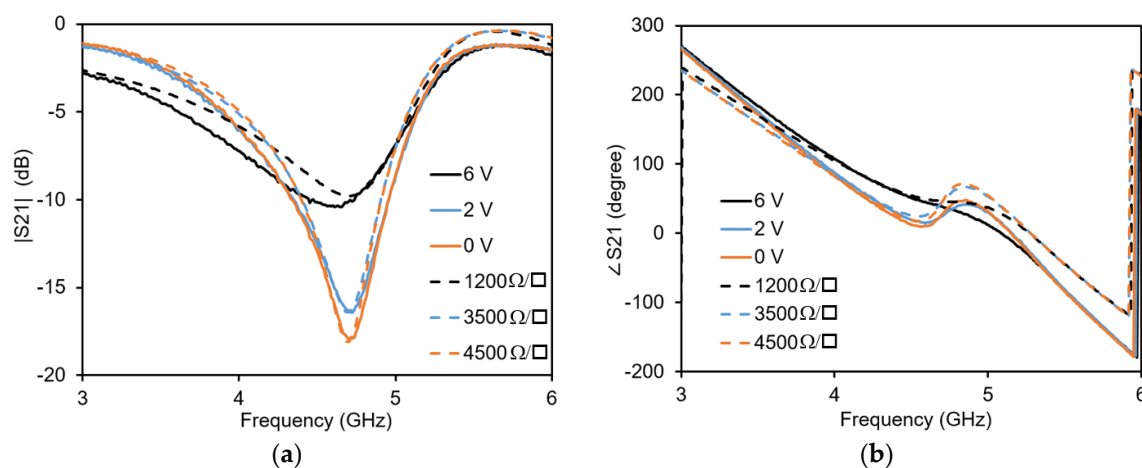
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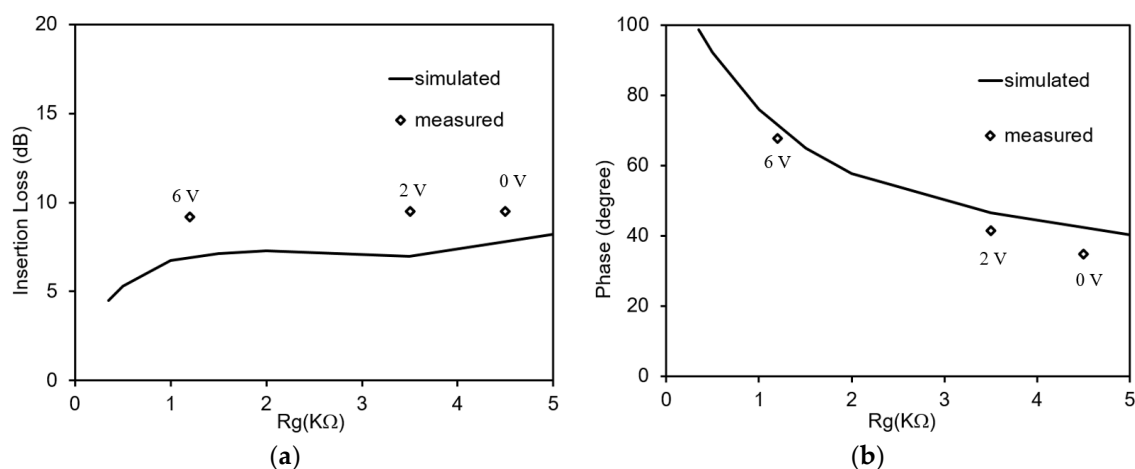
208 **Figure 8.** Simulated transmission with different graphene resistance: (a) amplitude shift; (b) Phase shift.

209 In order to compare measured and simulated values, simulations are performed with graphene
 210 sheet resistance values corresponding to the measured graphene resistance values. The simulated

211 amplitude (dashed lines) of the S_{21} is shown in Figure 9a and the simulated phase (dashed lines) of
 212 S_{21} is shown in Figure 9b. It can be seen that the simulated and measured S_{21} are in good agreement
 213 with each other. For similar measured and simulated values of graphene, similar amount of phase
 214 and amplitude variation is observed. The maximum Figure of Merit (FoM=phase shift variation
 215 (degree)/ insertion loss variation (dB)) is observed at a frequency of 4.3 GHz. The measured phase
 216 shift at the frequency of 4.3 GHz is almost 33 degrees with a measured amplitude variation less than
 217 0.4 dB. Hence the maximum figure of merit is 82.5 degree/dB.
 218
 219



220 **Figure 9.** Transmission coefficient with measured (solid lines) and simulated values (dashed lines): (a)
 221 Amplitude; (b) Phase.
 222
 223



224 **Figure 10.** Measured and simulated results at 4.3 GHz: (a) Insertion loss versus R_g ; (b) Phase versus R_g .
 225
 226

227 At this frequency the insertion loss and phase variation are simulated for different R_g values as
 228 shown in Figure 10. The measured insertion loss and phase are indicated as diamonds and marked
 229 by the voltage applied to the graphene deposition. The phase of the simulated and measured
 230 transmission coefficient are in good agreement with each other. Due to losses that are not totally
 231 taken into account in the simulated results, there is a slight difference between the simulated and
 232 measured insertion loss.

233 4. Discussion

234 The phase shifter presented is a dynamically tunable phase shifter that varies its phase upon an
 235 application of a voltage bias. The phase shifter deploys commercial graphene nanoplatelets and is

236 thus a step towards mass-production of tunable microwave components based on graphene. The
 237 phase shifter provides almost 34 degrees of phase shift with negligible variation of the insertion loss.
 238 A comparison of the phase shifter with other similar phase shifters based on novel materials is shown
 239 in Table 2. In comparison to other phase shifters, the phase shift is slightly lower but the variation of
 240 the insertion loss is negligible. This results in a higher figure of merit as compared to similar phase
 241 shifters. The phase shifter works really well at the designed frequency with minimal variation of the
 242 insertion loss and is thus suitable for deployment in steerable antennas. For an array comprising of 2
 243 patch antennas spaced half a wavelength, this phase shift can produce a beam steering of almost 10
 244 degrees.

245 **Table 2.** Comparison of the commercial graphene based phase shifter with others in the literature.

Ref.	$\Delta\phi$ (°)	ΔIL (dB)	FOM(°/dB)
[26]	40	3	13.3
[33]	53.76	2	26.88
This work	33	0.4	82.5

246
 247 As shown in Section 3.2 the simulated results compared to the measured results show a slightly
 248 smaller phase and amplitude variation. This is due to a higher graphene sheet resistance value. The
 249 fabrication process of the phase shifter is of preliminary nature and needs to be improved for a more
 250 gradual variation of the phase with more voltage points. In addition, the commercial graphene
 251 nanoplatelets can be sonicated in order to reduce the number of graphene sheets per nanoplatelet
 252 and an increased variation of the graphene resistance and to obtain a smaller value. This would result
 253 in the possibility of depositing graphene in a gap with a higher aspect ratio and further ease the
 254 fabrication process. If a higher phase shift is desired, the number of the stubs can be further increased
 255 to 3 or 4. This can result in further increasing the beam steering value.

256 The effects of a negative bias applied to the graphene nanoplatelets are predicted to change the
 257 carrier charge, the Fermi level and the electron mobility [4] resulting in an increase in the
 258 conductivity. This is a behavior similar to the one noted when applying a positive bias voltage.

259 5. Conclusions

260 A voltage controlled dynamically tunable phase shifter based on commercial graphene
 261 nanoplatelets is presented. The phase shifter is composed of a microstrip transmission line connected
 262 to a tapered line and an open stub. Graphene connected to grounded metallic vias are symmetrically
 263 placed at the interconnection between the tapered line and the stub. The electrical conductivity of
 264 graphene is tuned by a voltage bias, which results in the variation of the insertion loss and phase of
 265 the signal transmitting through the microstrip line. In order to maximize the phase shift and minimize
 266 the insertion loss, optimization of the lengths of the open stub, tapered lines and the dimensions of
 267 the graphene's depositions are performed by the help of circuit models and full wave simulations. A
 268 prototype is fabricated and measured. The measured phase shift of the phase shifter is almost 34
 269 degrees with a variation of the insertion loss of less than 0.5 dB at the frequency of 4.3 GHz.

270
 271 **Author Contributions:** The authors contributed equally to this article. All authors have read and agreed to the
 272 published version of the manuscript.

273 **Funding:** This research received no external funding

274 **Acknowledgments:** Authors wish to acknowledge Salvatore Guastella for FESEM characterization and Massimo
 275 Rovere for Raman analysis.

276 **Conflicts of Interest:** The authors declare no conflict of interest.

277

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279

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