

Graphene tunability at microwave frequency

Original

Graphene tunability at microwave frequency / Savi, Patrizia. - ELETTRONICO. - (2020), pp. 1-38. ((Intervento presentato al convegno International Symposium on Antennas and Propagation (APSYM-2020) tenutosi a Cochin, India nel December 14-16, 2020.

Availability:

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Publisher:

IEEE

Published

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APSYM-2020, December 14-16, 2020



GRAPHENE TUNABILITY AT MICROWAVE FREQUENCY

Patrizia Savi

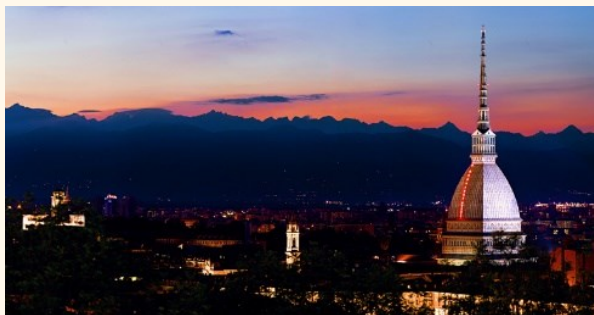
Department of Electronics and
Telecommunications
Politecnico di Torino, Italy



TORINO, ITALY → COCHIN, INDIA



Piedmont region



Mole antonelliana (1863-1889)
height 168m



POLITECNICO DI TORINO FROM 1859



Engineering and Architecture





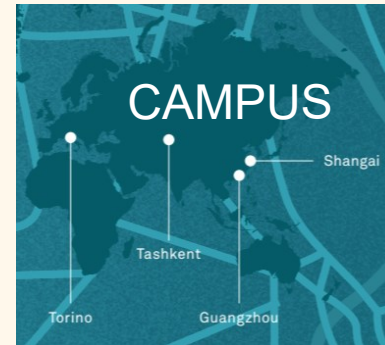
International Students

MEET US WORLDWIDE



INTERNATIONAL STUDENTS VIDEO

- 33,461 students
- 16% international students
- 700 PhD students



CINA	23,67%
IRAN	7,61%
PAKISTAN	6,84%
ROMANIA	5,33%
SPAGNA	3,76%
ALBANIA	3,66%
CAMERUN	3,52%
FRANCIA	3,52%
UZBEKISTAN	3,34%
COLOMBIA	3,00%
MAROCCO	2,44%
TURCHIA	2,38%
INDIA	2,19%
LIBANO	2,13%
PERÙ	2,03%
Altri paesi	24,6%

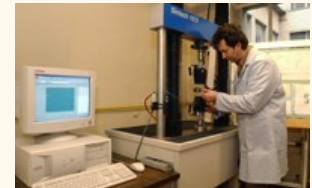


DET

Electronics and Telecommunications Department

11 departments

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- ▶ DAUIN - Department of Control and Computer Engineering
- ▶ DENERG - Department of Energy
- ▶ **DET - Department of Electronics and Telecommunications**
- ▶ DIATI - Department of Environment, Land and Infrastructure Engineering
- ▶ DIGEP - Department of Management and Production Engineering
- ▶ DIMEAS - Department of Mechanical and Aerospace Engineering
- ▶ **DISAT - Department of Applied Science and Technology**
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- ▶ DISMA - Department of Mathematical Sciences
- ▶ DIST - Interuniversity Department of Regional and Urban Studies and Planning



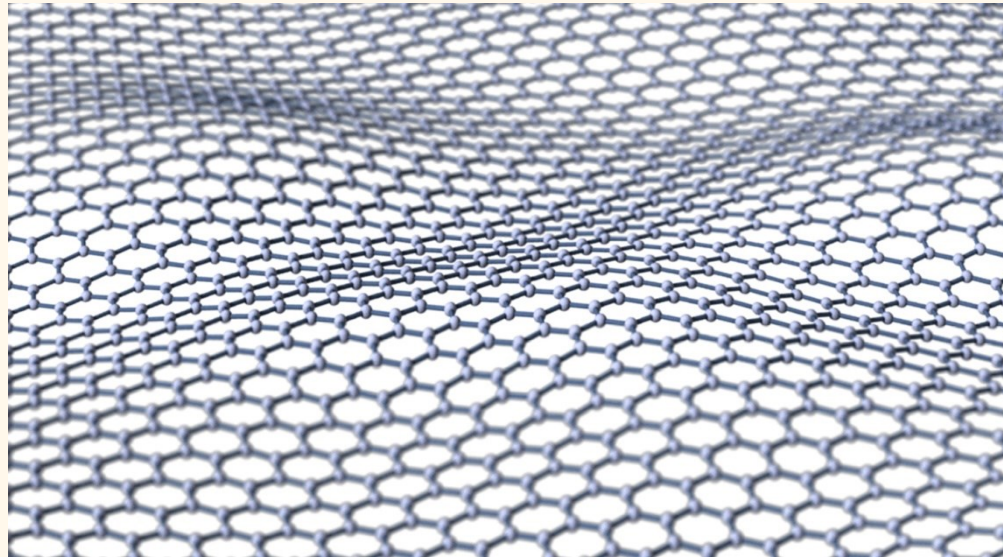
OUTLINE



1. Graphene **Properties** at Microwave Frequencies
2. Commercial Graphene flakes **characterization**
3. Tunable devices:
 - Graphene-based Tunable attenuator
 - Graphene-based Tunable phase shifter
 - Graphene-based Tunable Antenna: one, two and three stubs
4. Conclusions and Future Perspectives

Graphene, a **two-dimensional array of carbon atoms in honeycomb lattice**

Theoretically studied for many years



<https://www.tradefinanceglobal.com/posts/graphene-the-next-big-thing/>

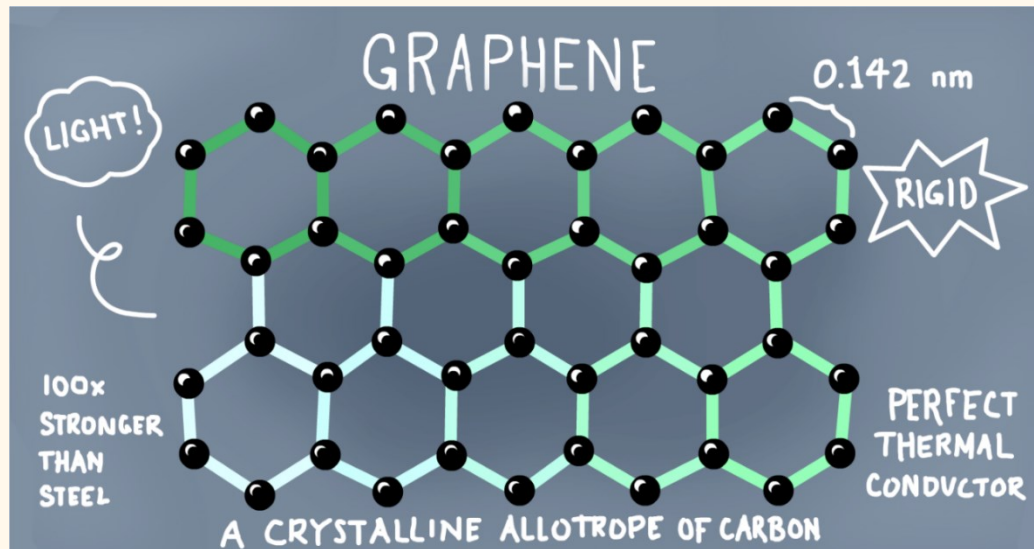
GRAPHENE



Graphene exhibits a variety of properties (including **high values of conductance, mobility, and mechanical strength**)



a promising material for a wide variety of applications



<https://de.slideshare.net/Uj17/graphene-properties-and-uses/22>

At microwave frequency, **graphene behaves as a tunable resistor**

GRAPHENE TUNABILITY AT MICROWAVE FREQUENCY

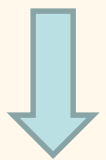


graphene \longrightarrow high resistance

DC voltage applied \longrightarrow resistance is reduced



MICROWAVE TUNABLE DEVICES



TUNABLE ATTENUATOR

phase shifters

Patch Antennas with stubs

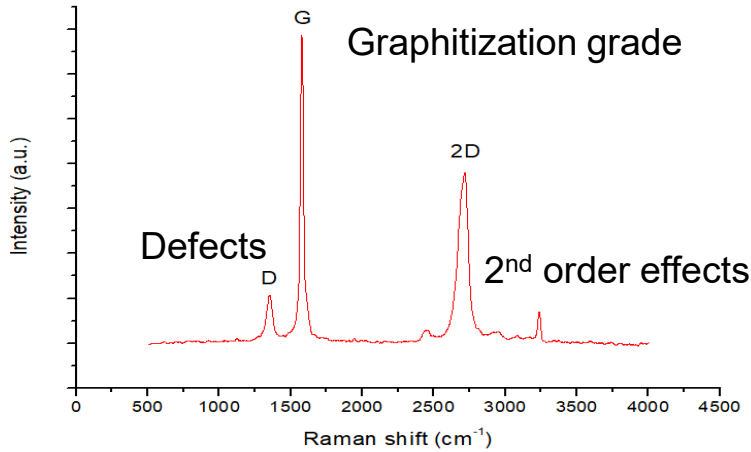
COMMERCIAL GRAPHENE

Muhammad Yasir

COMMERCIAL GRAPHENE: RAMAN



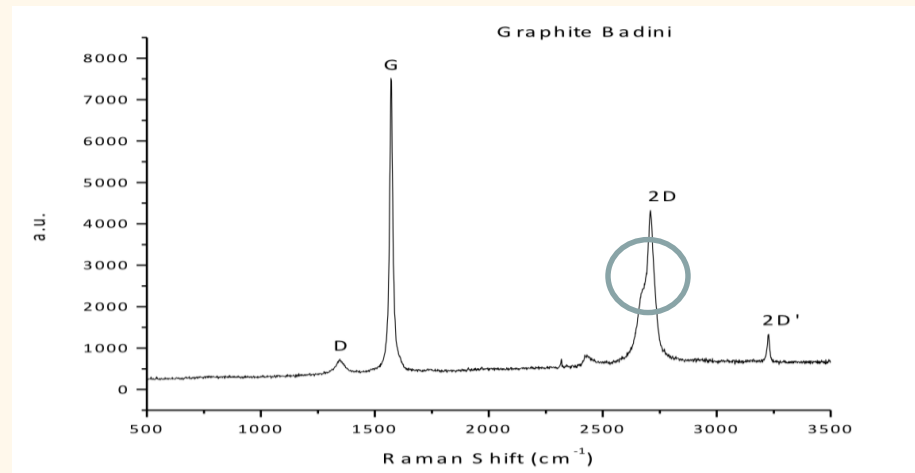
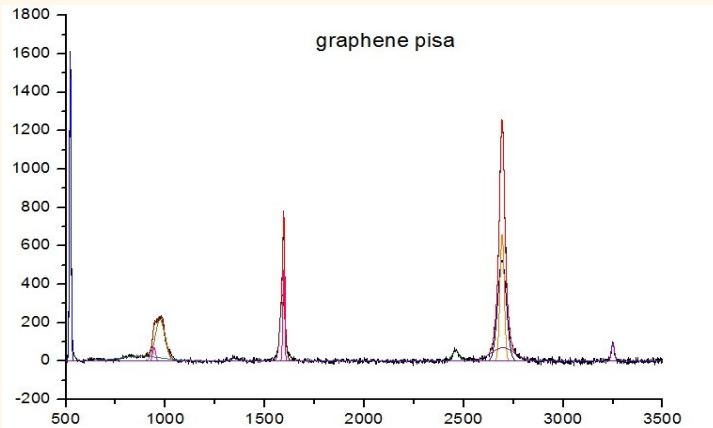
- Nanoinnova graphene flakes



$$I_D/I_G=0.15, I_D/I_{2D}=0.27 \text{ and } I_{2D}/I_G=0.56$$

➔ few layer graphene

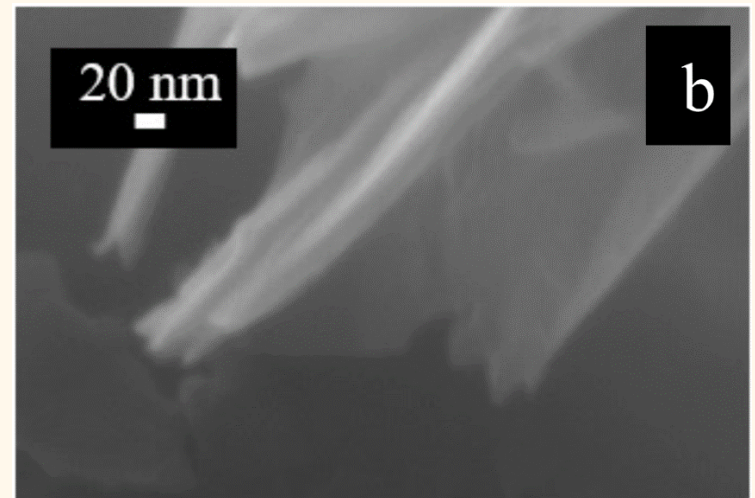
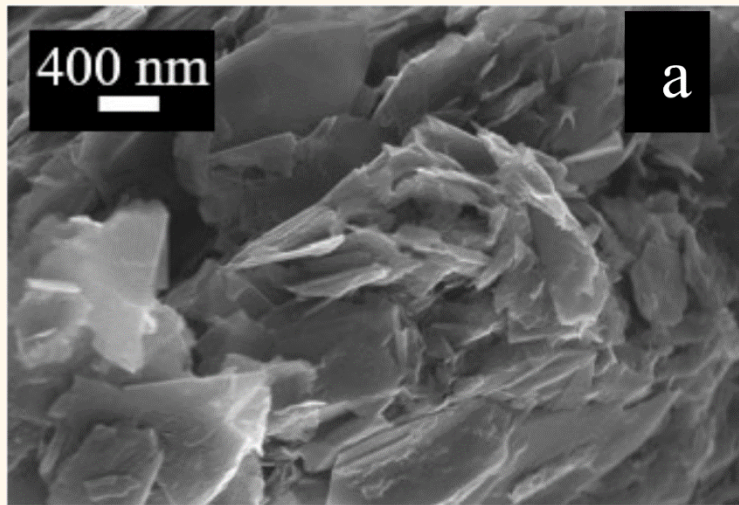
Monolayer: - $I_{2D}/I_G > 1$
- no broadening D



COMMERCIAL GRAPHENE: FESEM ANALYSIS



- Individual flake's transparency shows that it is composed of a few graphene layers
- Dimensions in nanometers show small size of flake



TUNABLE ATTENUATOR



Rogers 4350B

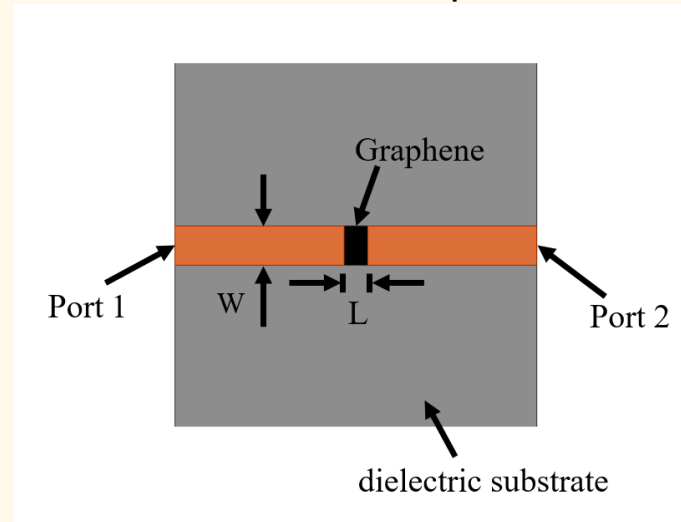
Thickness 0.786mm

Epsilon_r=3.66, tan delta=0.004

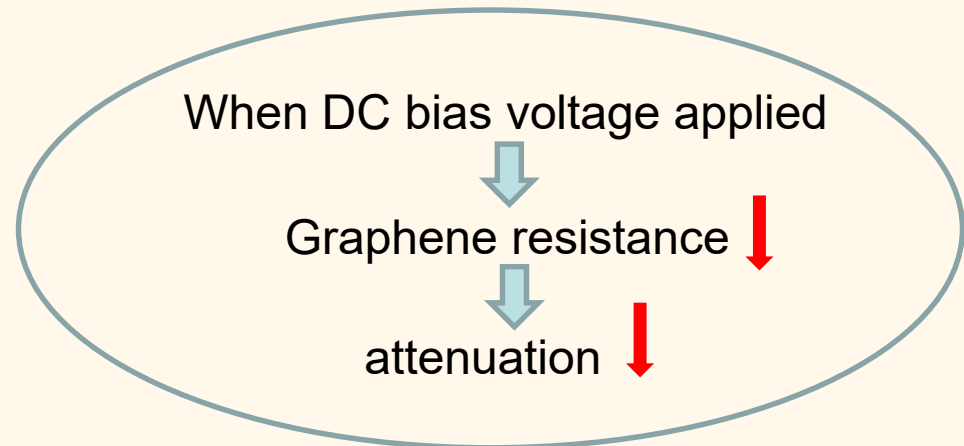
W=1.66mm

Z₀=50Ω

Commercial Graphene

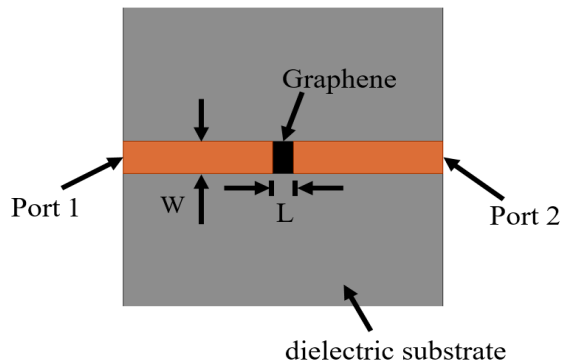


Aspect Ratio: $AR=L/W$



Yasir, M., Savi, P., ``Commercial graphene nanoplatelets-based tunable attenuator', *IET Electronics Letters*, Vol. 56, Issue 4, pp. 184-187, Feb. 2020.

TUNABLE ATTENUATOR

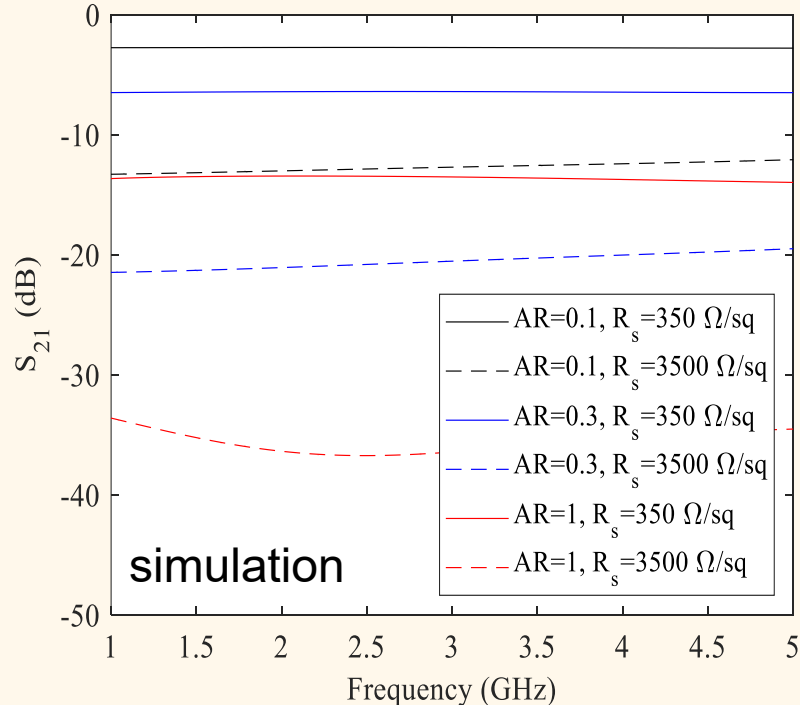



Influence of Aspect Ratio: $AR=L/W$


Ansys HFSS simulations

Graphene -> thin resistive sheet, $R_s=350-3500 \text{ Ohm/sq}$

Transmission (S_{21}) for minimum and maximum sheet resistance with different aspect ratio.



AR=1 	S21	Range
	-12dB	good

AR=0.1 	S21	Range
	-3dB	<10dB



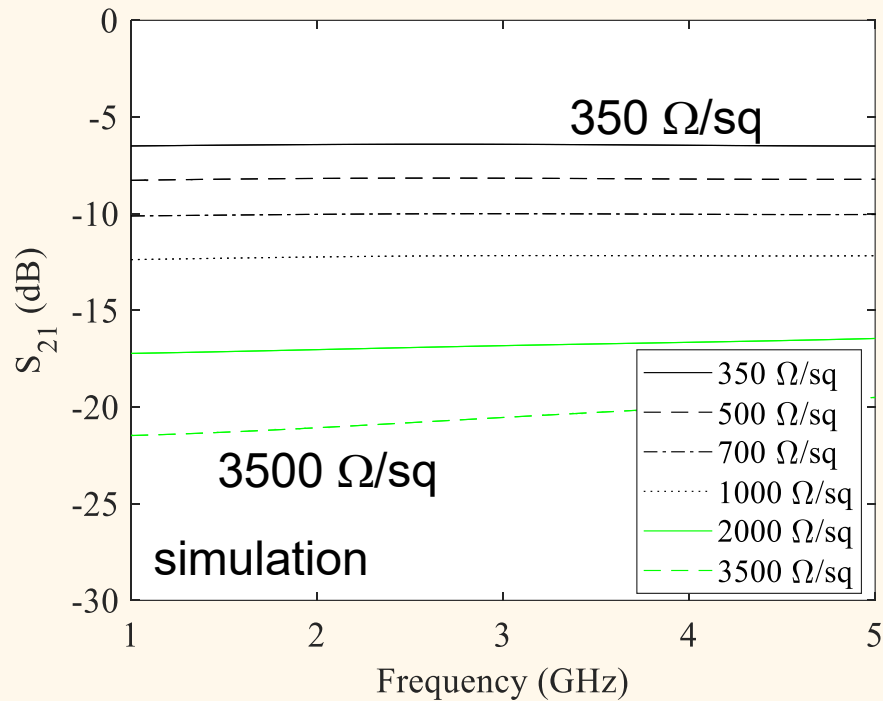
AR=0.5 	S21	Range
	-6dB	>15dB

TUNABLE ATTENUATOR



A/R=0.5

Influence of graphene sheet resistance



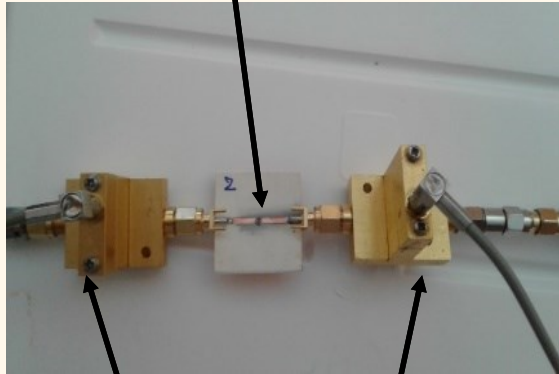
Transmission (S_{21}) for different values of graphene sheet resistance.

TUNABLE ATTENUATOR: MEASUREMENTS



Vector Network analyzer (300MHz-67GHz)

Graphene deposition



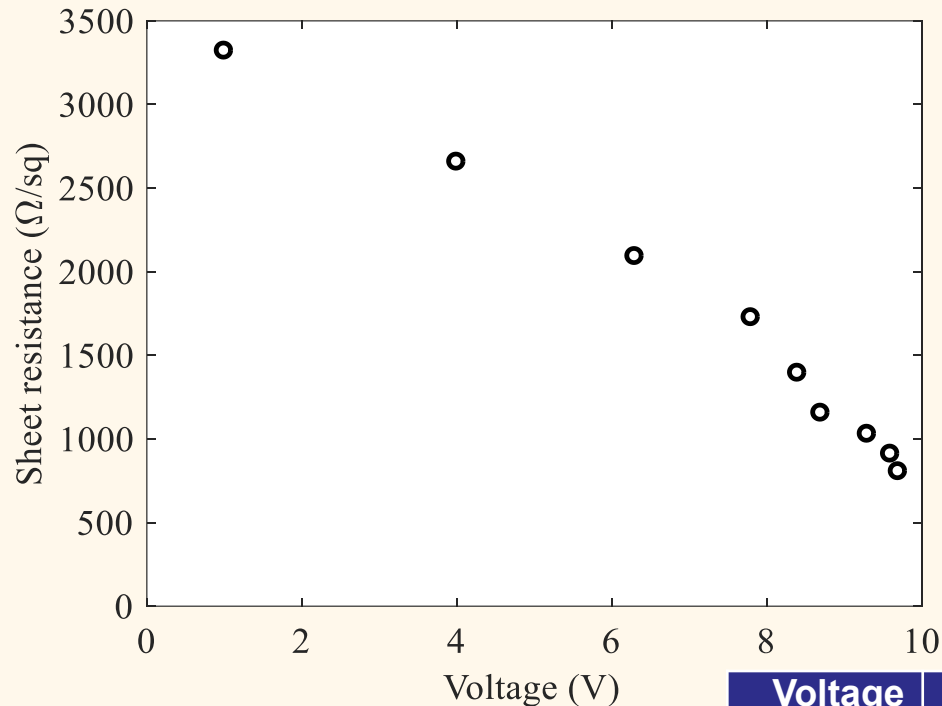
Broadband bias-tee



TUNABLE ATTENUATOR



Measured sheet resistance of the tunable graphene attenuator

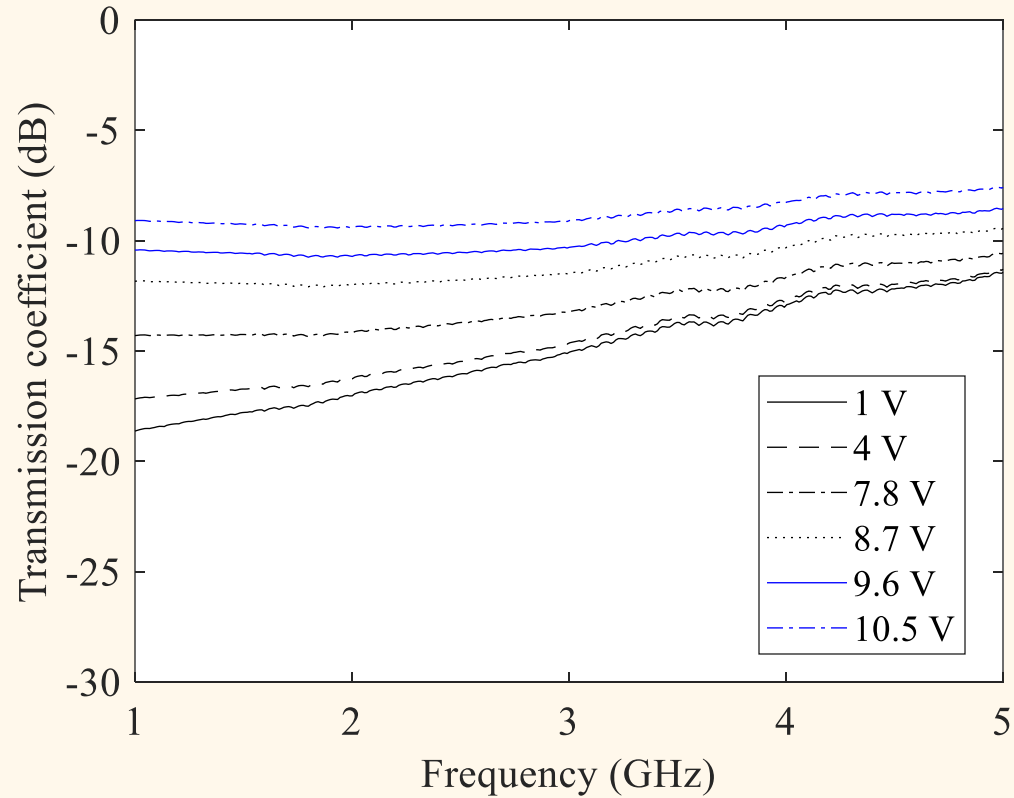


Voltage (V)	Current (mA)	Resistance (Ω)	Sheet Resistance (Ω/sq.)
1	1	1000	3320
4	5	800	2656
7.8	15	520	1726
8.4	20	420	1394
8.7	25	348	1155
9.3	30	310	1029
9.6	35	274	910

TUNABLE ATTENUATOR



Measured transmission coefficient at different applied bias voltages.



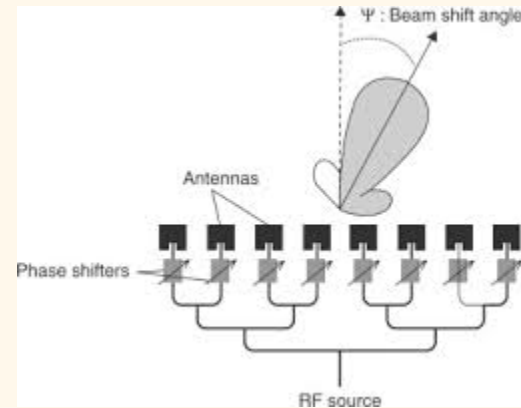
PHASE SHIFTER



Applications

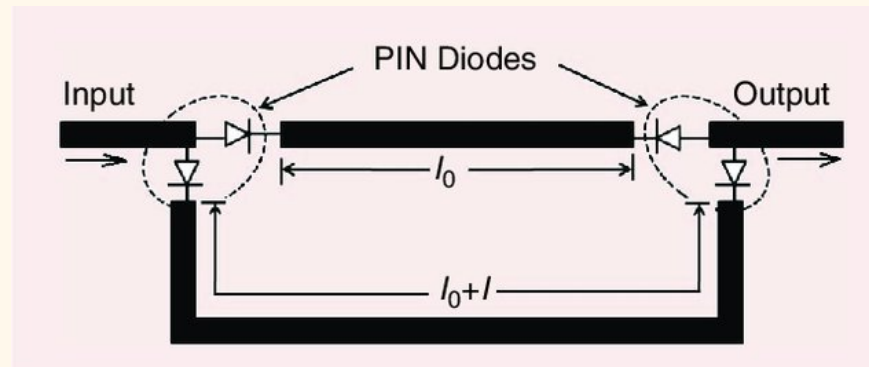
Electronically steerable antennas:

- cellular communication
- WLAN
- Automotive radar
- Navigation and landing aids
- Space system



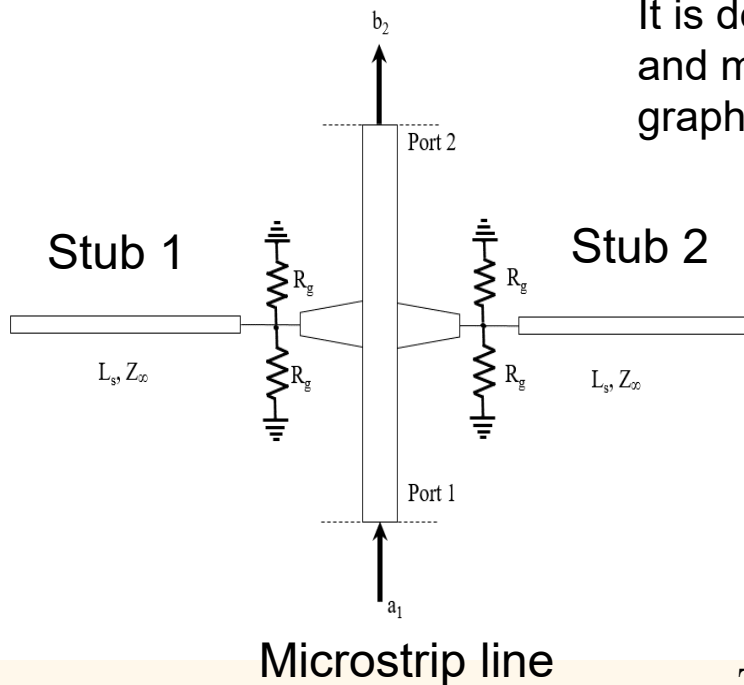
V. Puyal, Cea Leti, Laas Cnrs, D. Titz,
5 - RF MEMS phase shifters for wireless applications, Editor(s): Deepak Uttamchandani,
Handbook of MemS for Wireless and Mobile Applications, Woodhead Publishing, 2013

Principle

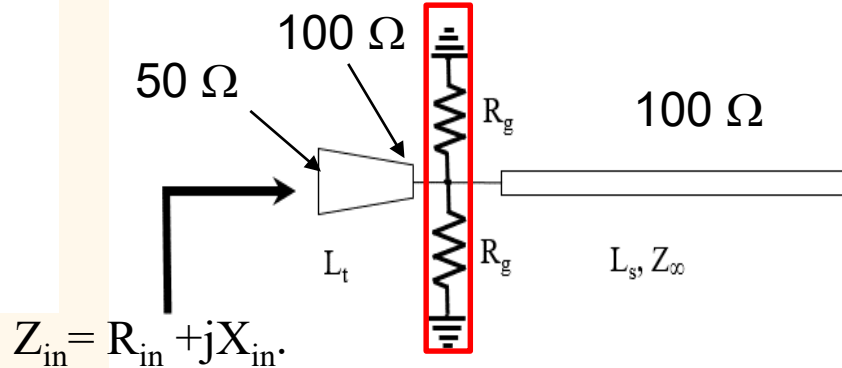


A. Chakraborty, B. Gupta, Paradigm Phase Shift: RF MEMS Phase Shifters: An Overview, January 2017
IEEE Microwave Magazine 18(1):22-41

PHASE SHIFTER: ADS SIMULATIONS



It is desirable to maximize the variation of X_{in} and minimize the variation of R_{in} when the graphene resistance, R_g is varied.



Graphene modeled as lumped resistor

The lengths of the tapered line, L_t and the open line section, L_s is therefore optimized for a maximum X_{in} and minimum R_{in} variation when graphene's resistance R_g is varied.

PHASE SHIFTER

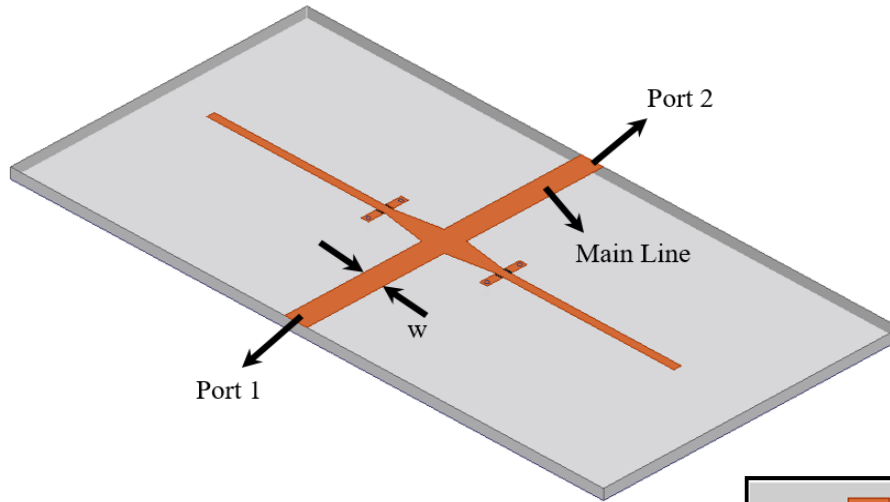


The variation of real and imaginary input impedance with graphene resistance variation with different values of L_s and L_t . All ΔR_{in} and ΔX_{in} are in (Ω).

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

M. Yasir, P. Savi, ``Dynamically Tunable Phase Shifter with Commercial Graphene Nanoplatelets'', *Micromachines*, Vol. 11, n. 6, pp. 1-12, 20 June 2020.

PHASE SHIFTER: FULL-WAVE ANALYSIS



metallic pads: length, $L_p=1$ mm
width, $w_p=2$ mm

Deposition: $W_g = 0.2$ mm
length $L_g=1$ mm

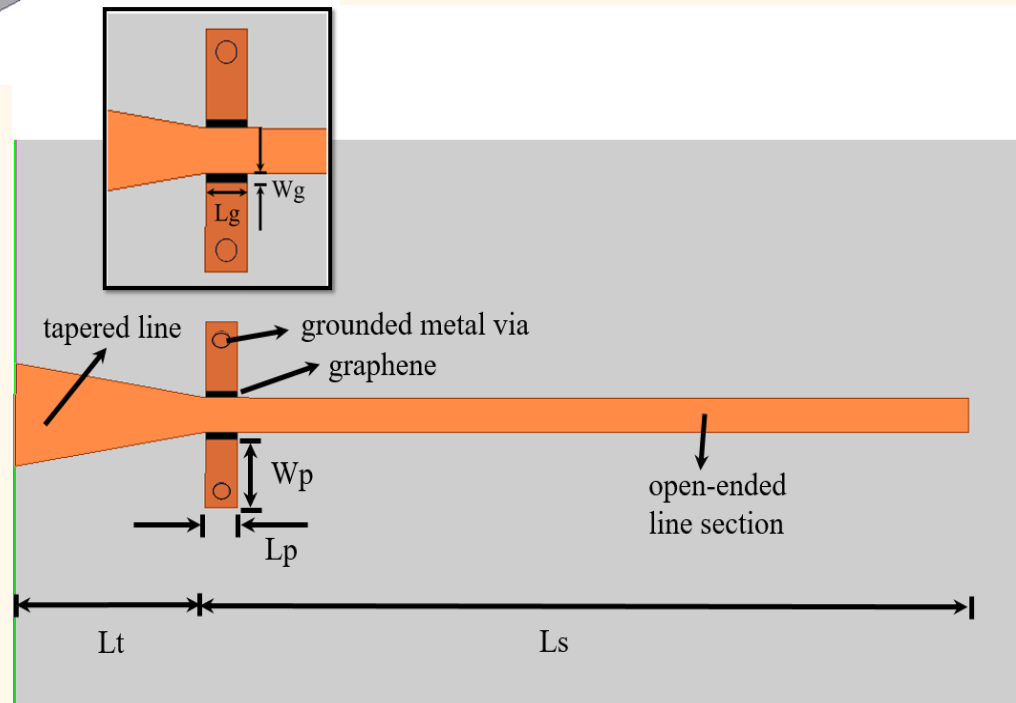
Rogers 3035

Thickness $t=1.52$ mm

$\epsilon_r=3.5$, $\tan\delta=0.0015$

copper 35 mm

$w = 3.2$ mm $Z_0=50 \Omega$

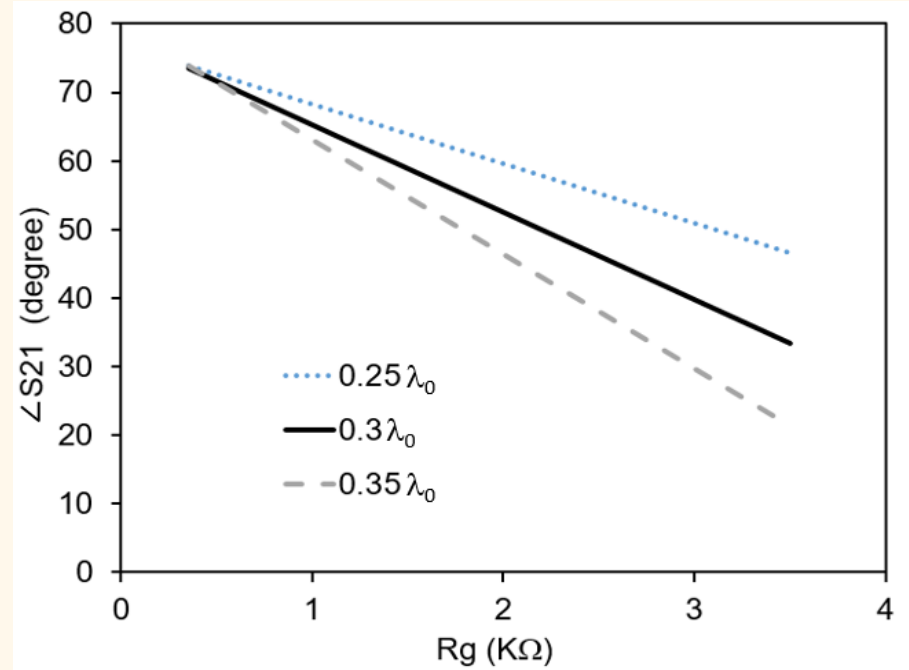
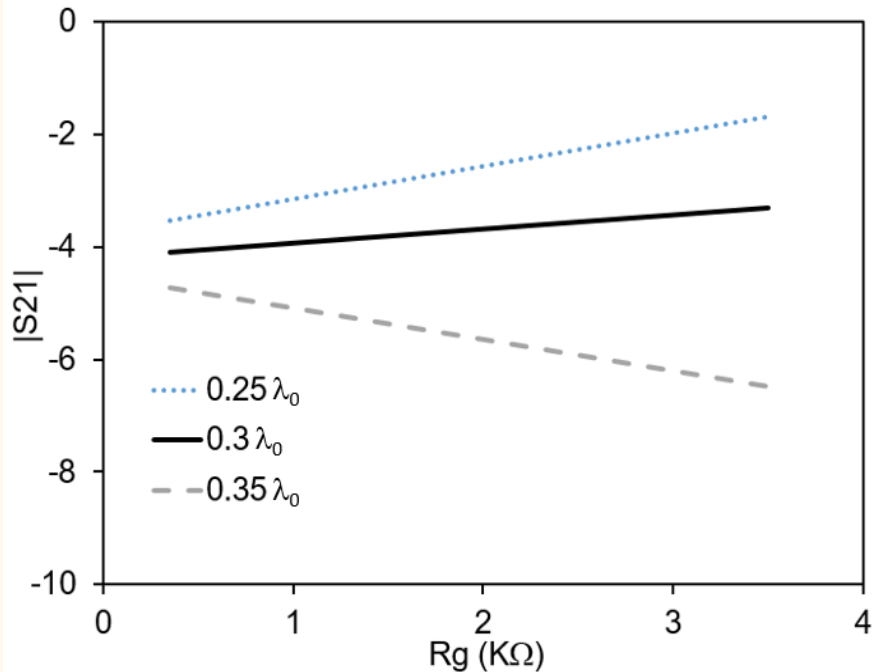


PHASE SHIFTER: FULL WAVE SIMULATIONS



$f = 4 \text{ GHz}$

open-ended line section L_s ($0.25 \lambda_0$, $0.3 \lambda_0$ and $0.35 \lambda_0$)
graphene resistance values $350 \Omega/\text{sq.}$ to $3500 \Omega/\text{sq.}$



Amplitude variation of the transmission decreases from $L_s = 0.25 \lambda_0$ to $L_s = 0.3 \lambda_0$.

variation of $\angle S_{21}$ increases with increasing L_s

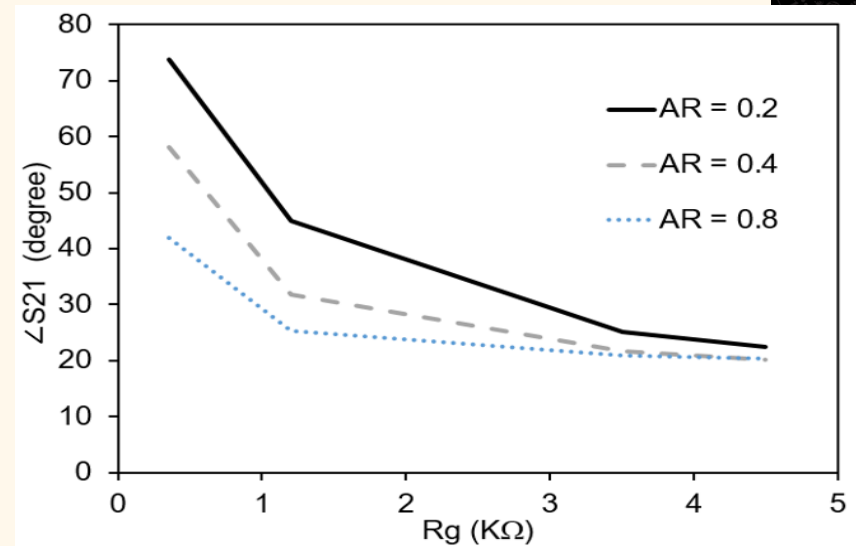
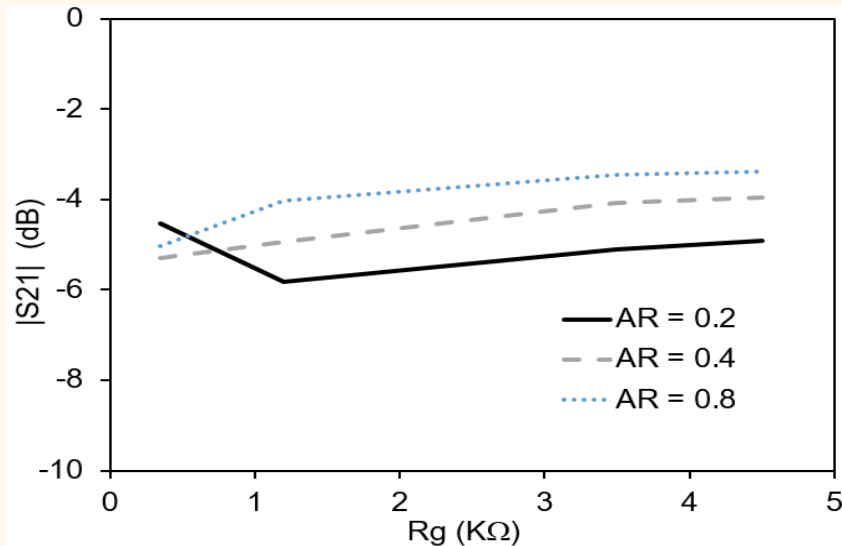


Optimum length $L_s = 0.3 \lambda_0$

it provides minimum amplitude variation with reasonable phase variation.

PHASE SHIFTER: SIMULATIONS

AR=Wg/Lg analysis

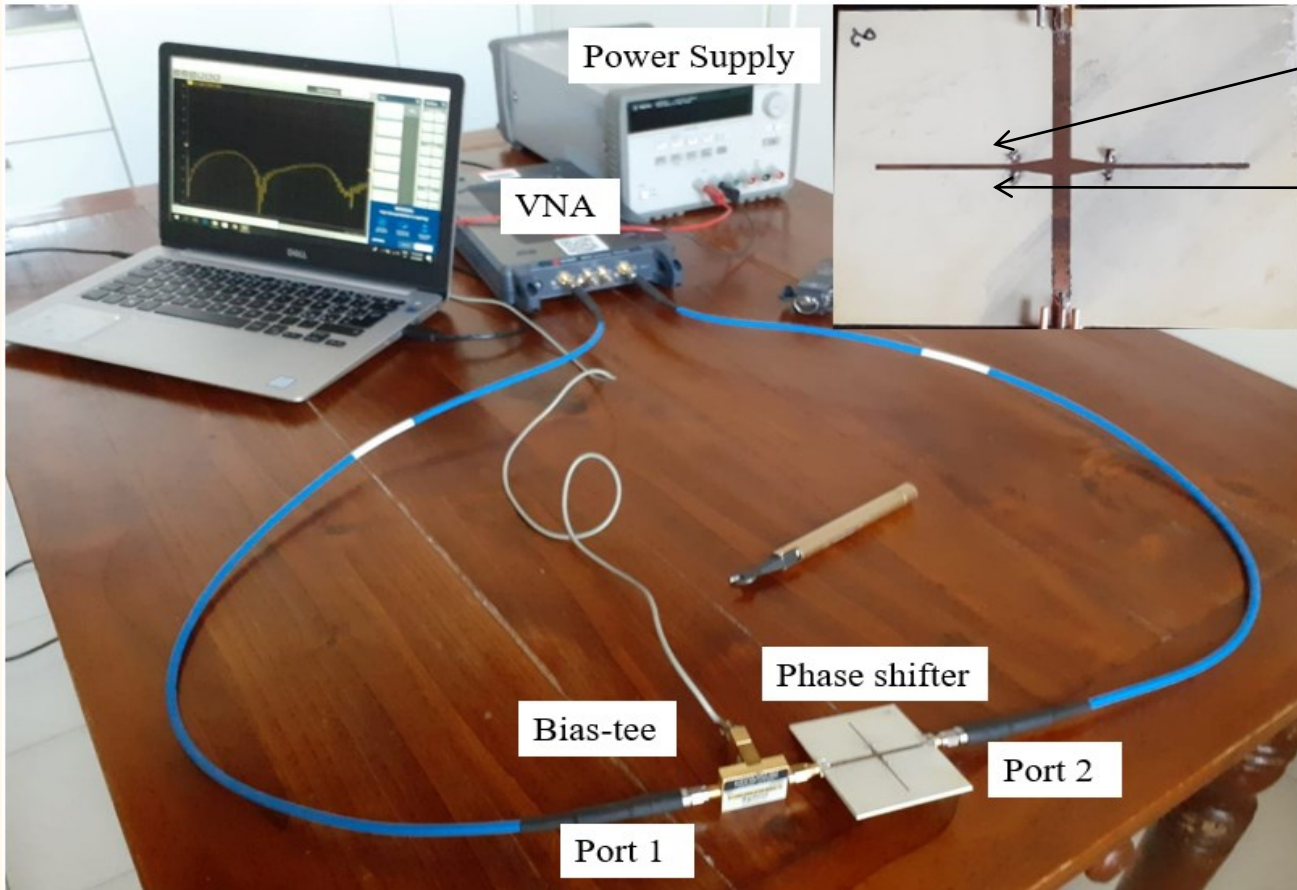


AR	Max $ S_{21} $	Min $ S_{21} $	Max $\angle S_{21}$	Min $\angle S_{21}$
0.2	-4.5dB	-5.8dB	73°	
0.8	-3.3dB	-5dB		22°

a reduction of the AR reduces the variation of the amplitude of the transmission coefficient and increases the variation of the phase of the transmission coefficient

a highly desirable trait of tunable phase shifters

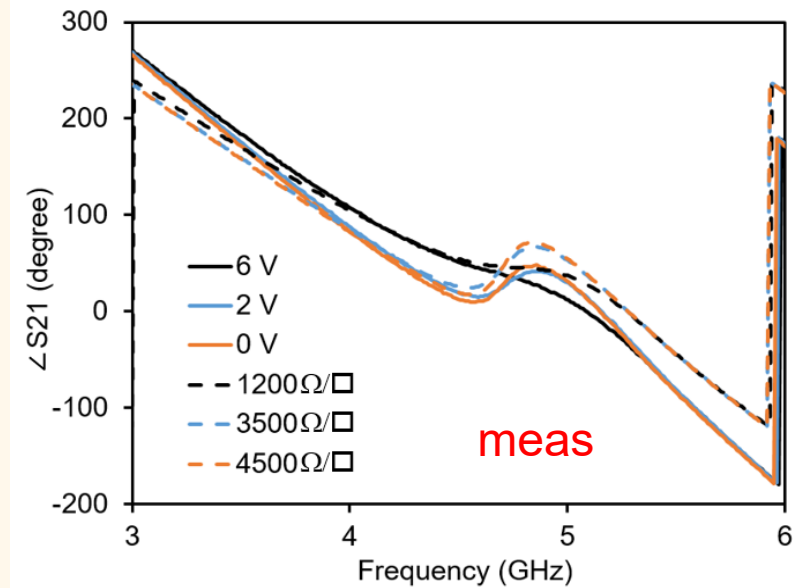
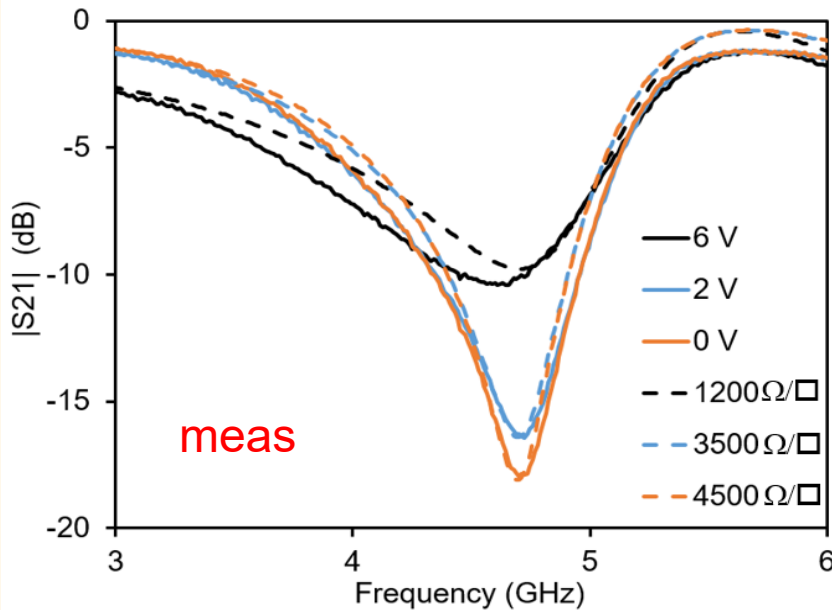
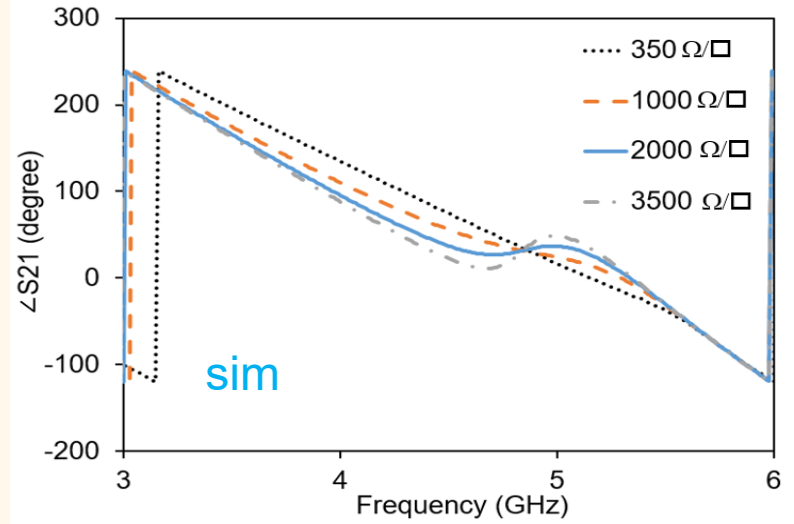
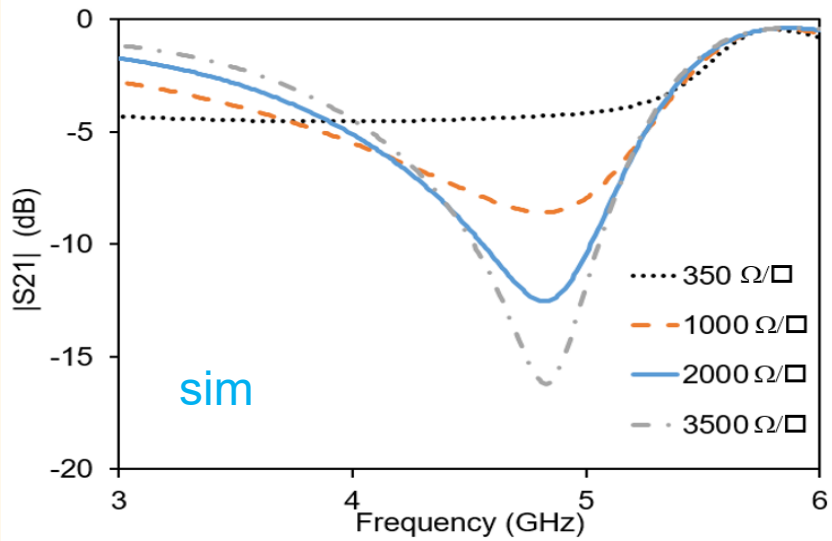
PHASE SHIFTER MEASUREMENTS



Commercial graphene nanoplatforms mixed in isopropyl alcohol are drop casted

Voltage	Resistance	
0V	4500 W/sq	
6V	1200 W/sq	

PHASE SHIFTER: SIMULATIONS AND MEASUREMENTS



PHASE SHIFTER: FIGURE OF MERIT



Figure of Merit (FoM) \Rightarrow
$$\frac{\text{phase shift variation (degree)}}{\text{insertion loss variation (dB)}}$$

f=4.5GHz

82.5 degree/dB

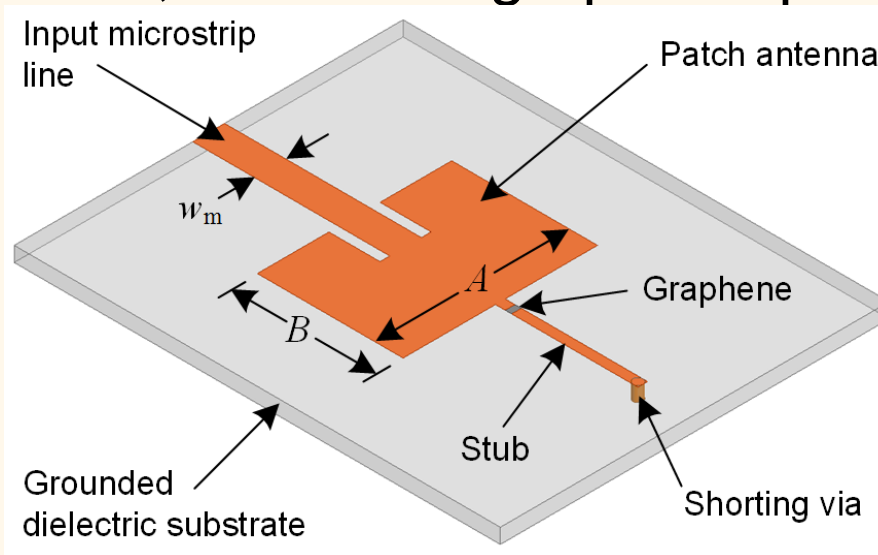
Ref.	$\Delta\phi$ (°)	Δ IL(dB)	FOM(°/dB)
[1]	40	3	13.3
[2]	53.76	2	26.88
This work	33	0.4	82.5

1. Yasir, M.; Bistarelli, S.; Cataldo, A.; Bozzi, M.; Perregrini, L.; Bellucci, S. Tunable Phase Shifter Based on Few-Layer Graphene Flakes. *IEEE Microwave and Wireless Components Letters* **2019**, 29 (1), 47-49.
2. Dragoman, M.; Aldrigo, M.; Iordanescu, S.; Modreanu, M.; Povey, I.; Vasilache, D.; Dinescu, A.; Romanitan, C. Low-Voltage Phase Shifters Based on HfxZr1-xO2 Ferroelectrics Integrated with Phased Antenna Arrays, in *Proceedings of 2018 48th European Microwave Conference (EuMC)*, Madrid, Spain, 2018.



ONE-STUB DESIGN

- The antenna consists of a **patch with a shorted microstrip stub**, where the graphene pad is inserted.



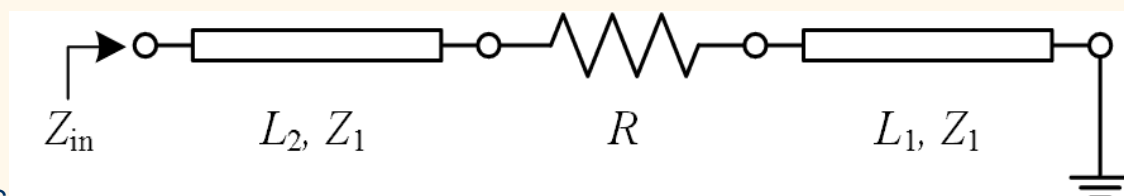
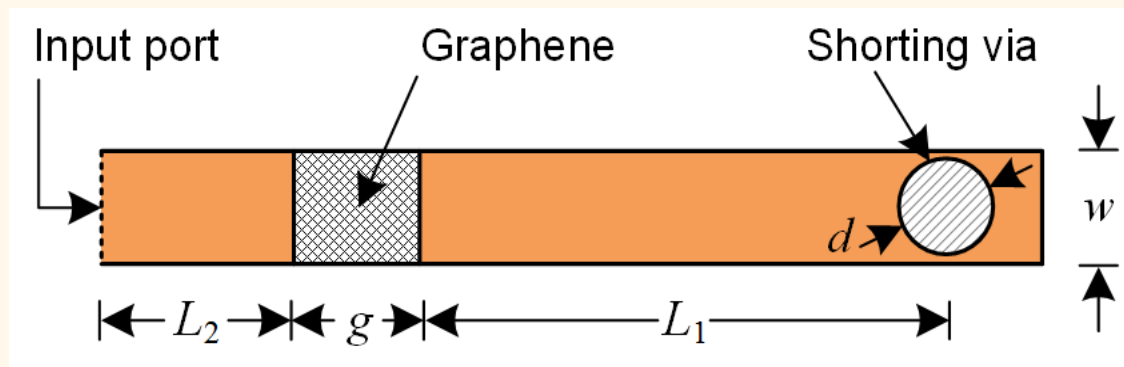
K. Naishadham, "An investigation on the tuning of a microstrip patch antenna using carbon nanotube thin films," IEEE Antennas Propagat., Symp., Memphis, USA, July 2014

TUNABLE GRAPHENE ANTENNA



OPERATING PRINCIPLE

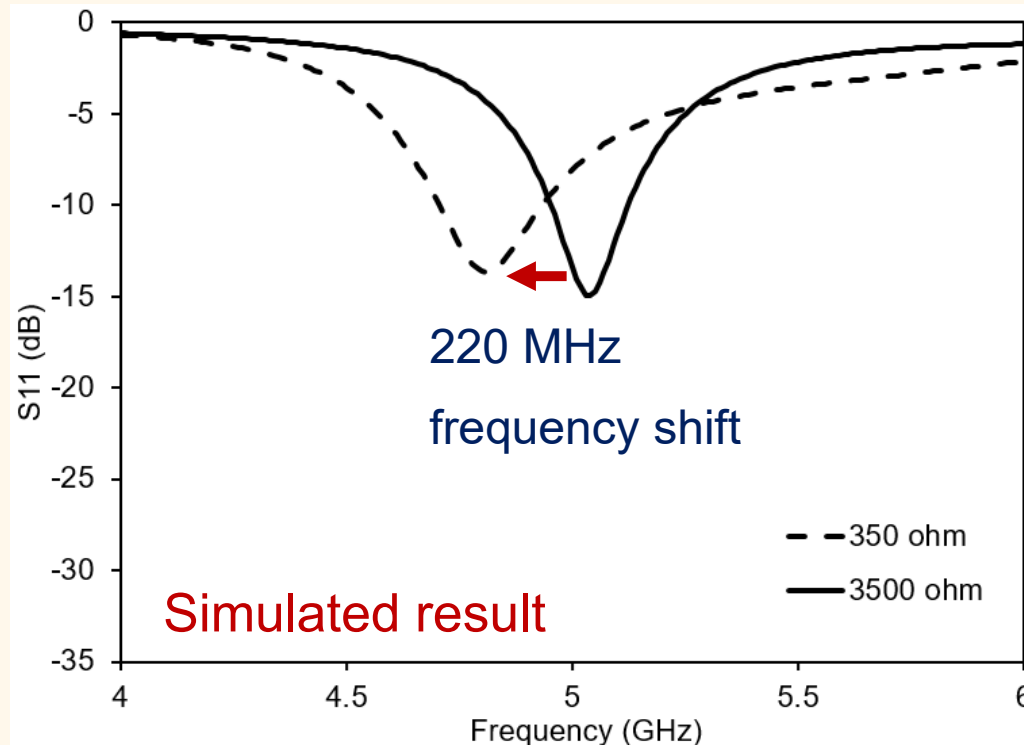
- **Aim:** Maximum variation of the imaginary part of the input impedance (versus the range of graphene resistance)
- to mimic **tunable Capacitor (varactor)**.





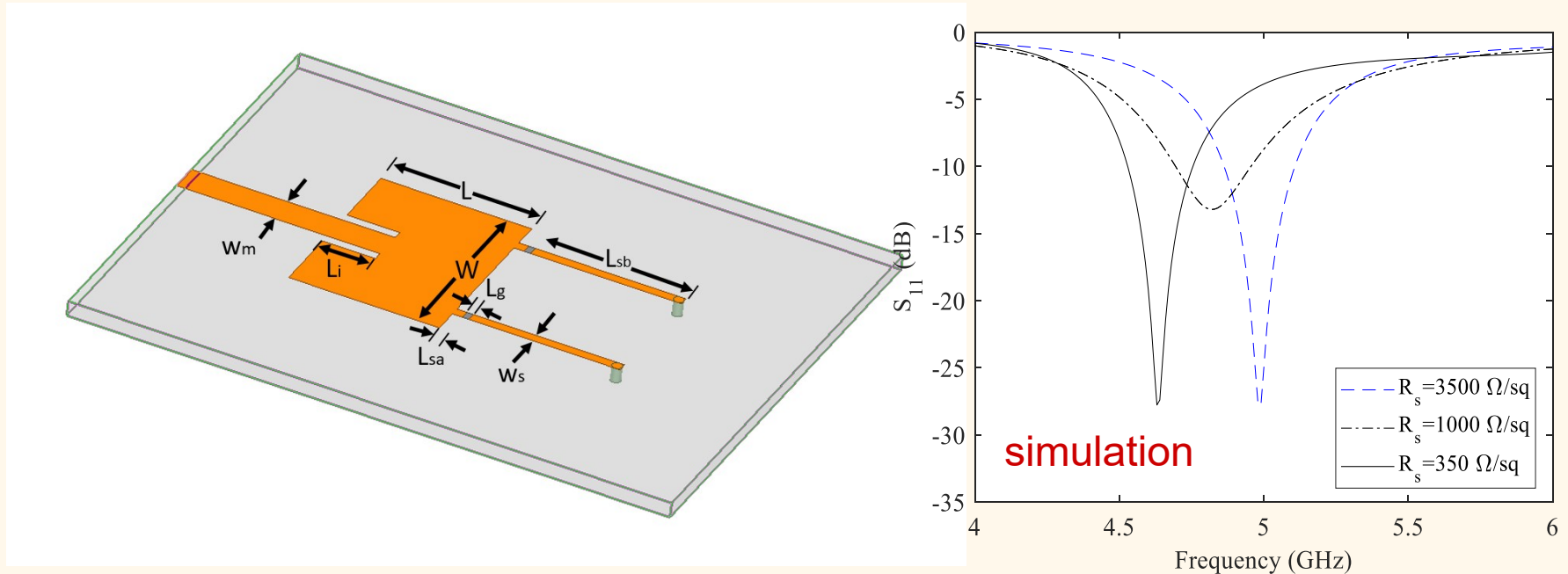
ONE STUB DESIGN

- Shift in resonant frequency from 5.04 GHz to 4.8 GHz with varying graphene resistance.



TWO STUB DESIGN

- The antenna consists of a **patch with two shorted microstrip stubs**, where the graphene pad is inserted.



Very low reflection coefficient of < -27 dB

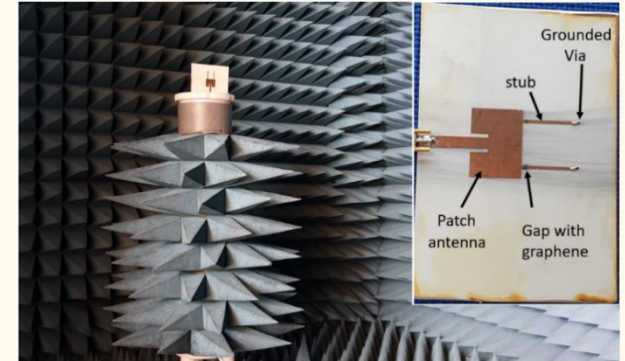
TUNABLE GRAPHENE ANTENNA



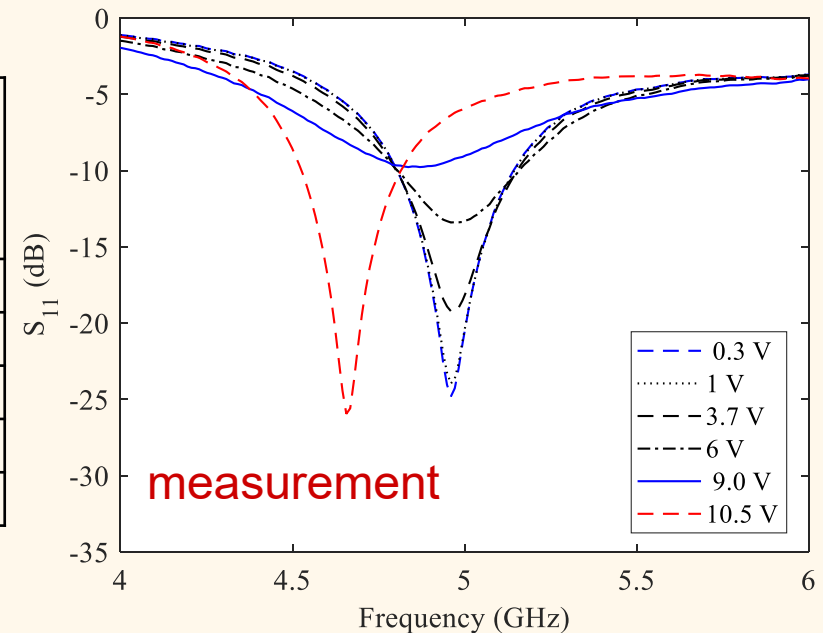
Prototype

TWO STUB DESIGN

- Measured frequency shift of 350 MHz (from 4.98 GHz at a bias voltage of 0.36 V to 4.63 GHz at a bias voltage of 10.5 V).



Voltage (V)	Current (mA)	Resistance (Ω)	Sheet Resistance ($\Omega/\text{sq.}$)
0.36	1	720	4800
3.7	25	298	1989
6.1	60	202	1355
9	140	120	800
10.5	300	70	466

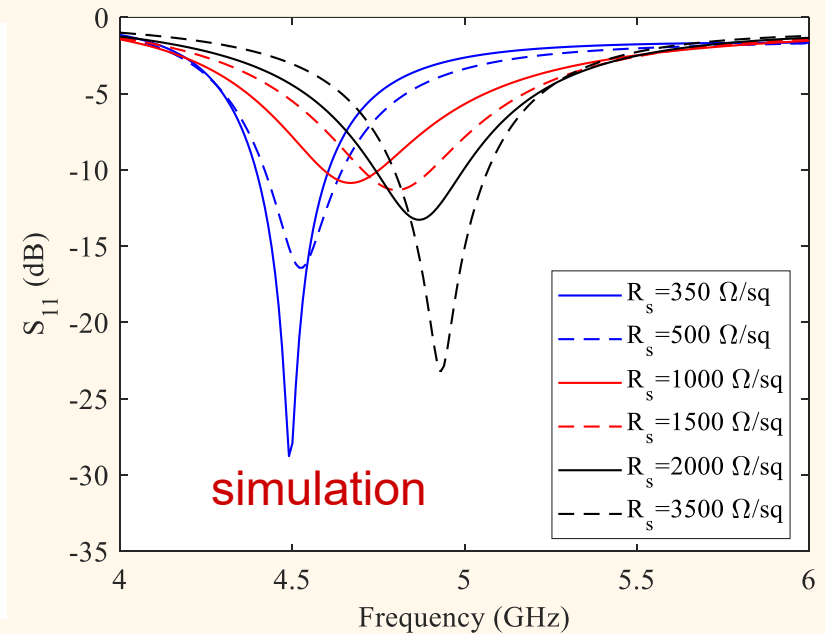
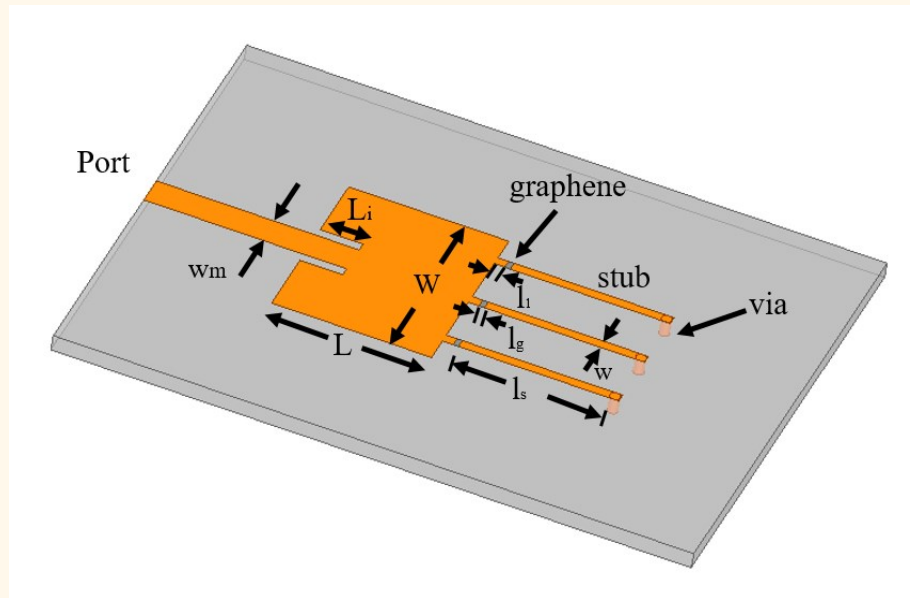


TUNABLE GRAPHENE ANTENNA



THREE STUB DESIGN

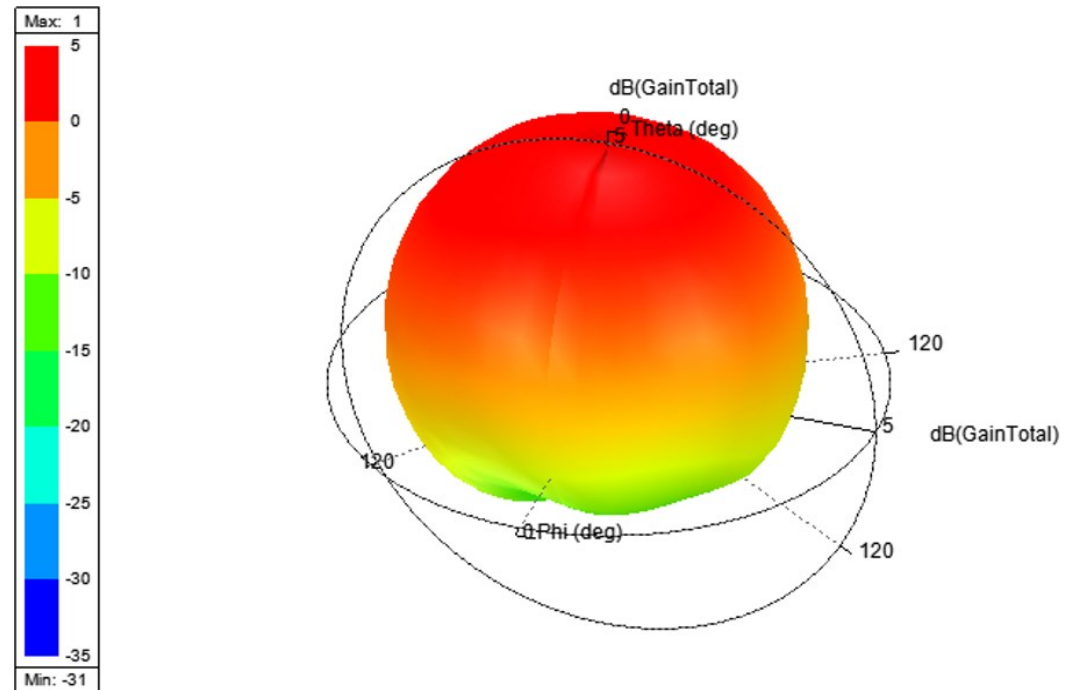
- The antenna consists of a **patch with three shorted microstrip stubs**, where the graphene pad is inserted.



Shift of resonant frequency of **440 MHz**
(4.98 GHz to 4.63 GHz)

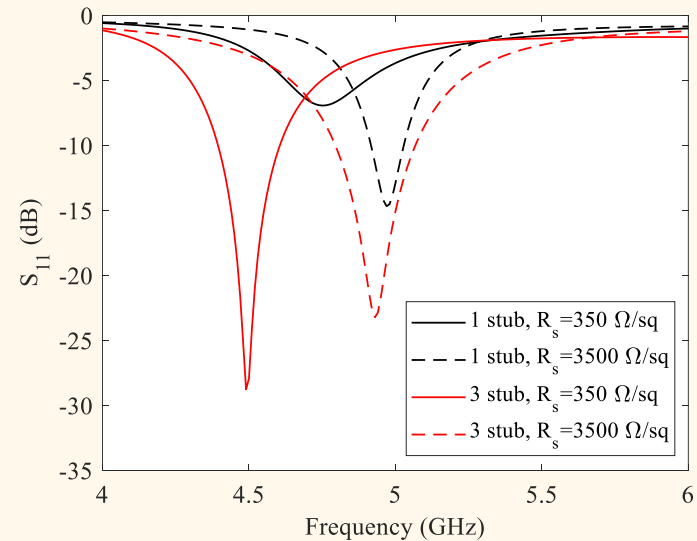
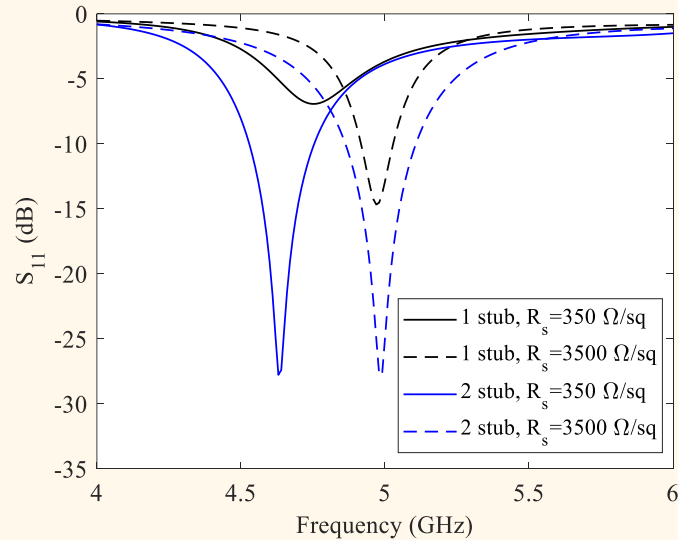
THREE STUB DESIGN- GAIN

- No significant radiation from the three stubs. Main radiating element is still the patch antenna.
- Gain value is not effected.





COMPARISON OF ONE, TWO AND THREE STUBS



Significant improvement in reflection coefficient value and shift of resonant frequency

CONCLUSIONS



- Cheap fabrication of tunable microwave components based on graphene with a commercial graphene product
- Graphene's tunable properties at microwave frequency have been exploited
- Attenuator and phase shifter with good performance
- Patch antennas with graphene:
 - Significant improvement in antenna reflection coefficient has been realized.
 - No particular impact on antenna gain ensured

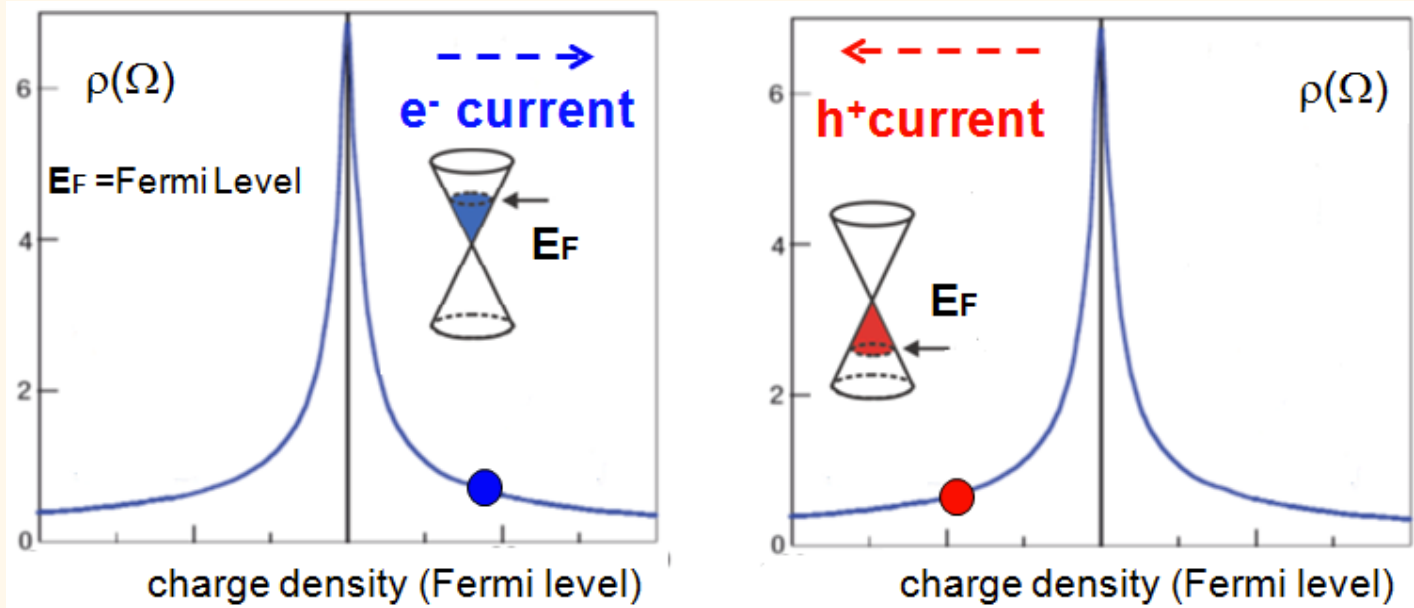


The End

GRAPHENE



- By applying energy to the graphene, one can shift its Fermi level and modify/control its electrical properties.

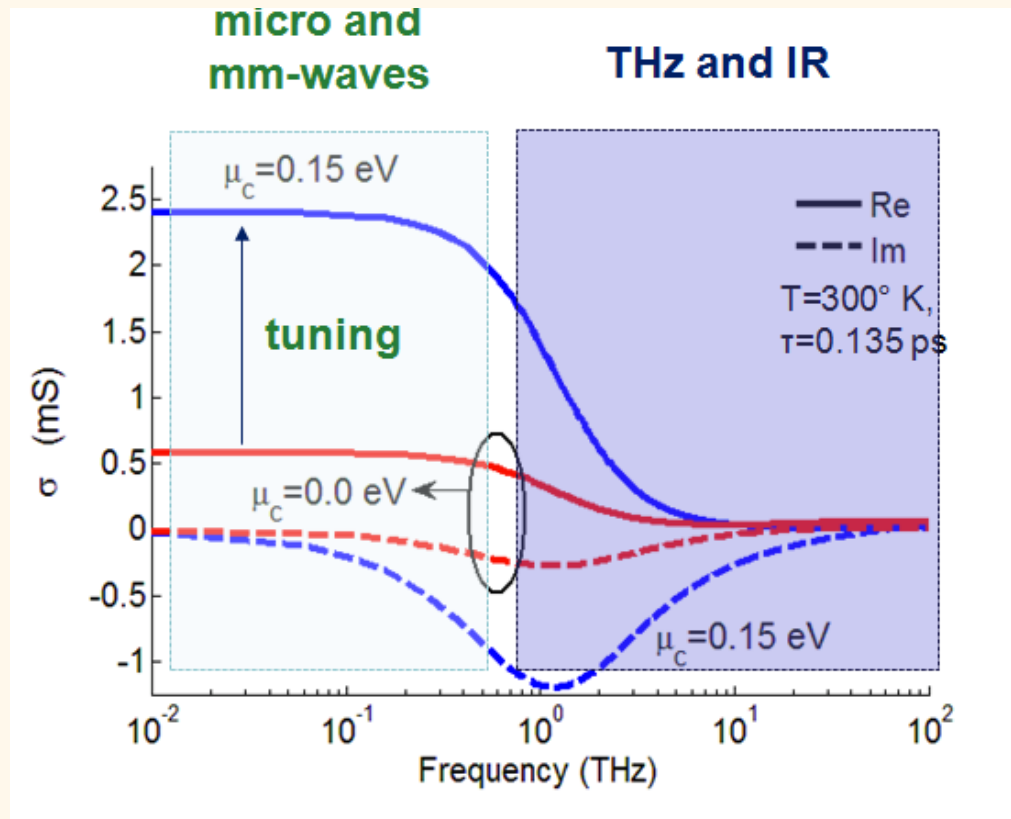


- When the Fermi level (electrochemical potential) moves into the valence or conduction band, the hole/electron conduction begins to dominate the current transport and the resistance becomes low.



GRAPHENE AT MICROWAVE FREQUENCY

- Surface conductivity at different frequency bands.



- At microwave frequency, **graphene behaves as a tunable resistor.**