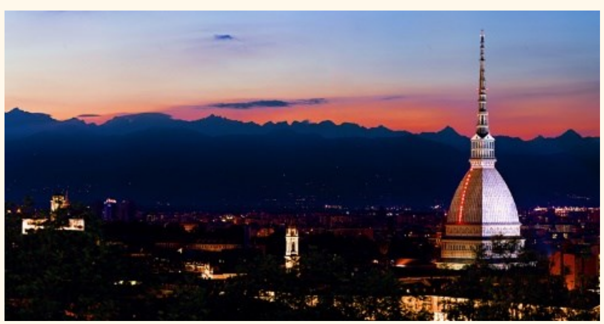
GRAPHENE TUNABILITY AT MICROWAVE FREQUENCY

Patrizia Savi
Department of Electronics and Telecommunications
Politecnico di Torino, Italy

TORINO, ITALY ⟹ COCHIN, INDIA

Piedmont region



Mole antonelliana (1863-1889)
height 168m

torino 2006

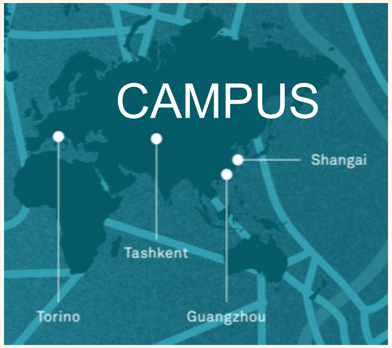
FIAT

Politecnico di Torino from 1859

Engineering and Architecture

POLITECNICO DI TORINO

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



International 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%

POLITECNICO DI TORINO

DET

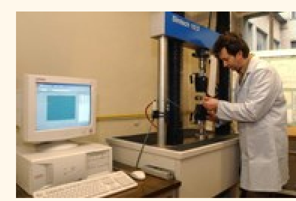
Elettronics and Telecommunications Department

11 departments

- DAD - Department of Architecture and Design
- 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
- DISEG - Department of Structural, Geotechnical and Building Engineering
- DISMA - Department of Mathematical Sciences
- DIST - Interuniversity Department of Regional and Urban Studies and Planning

DET

DiSAT chimica fisica materiali scienza e ingegneria



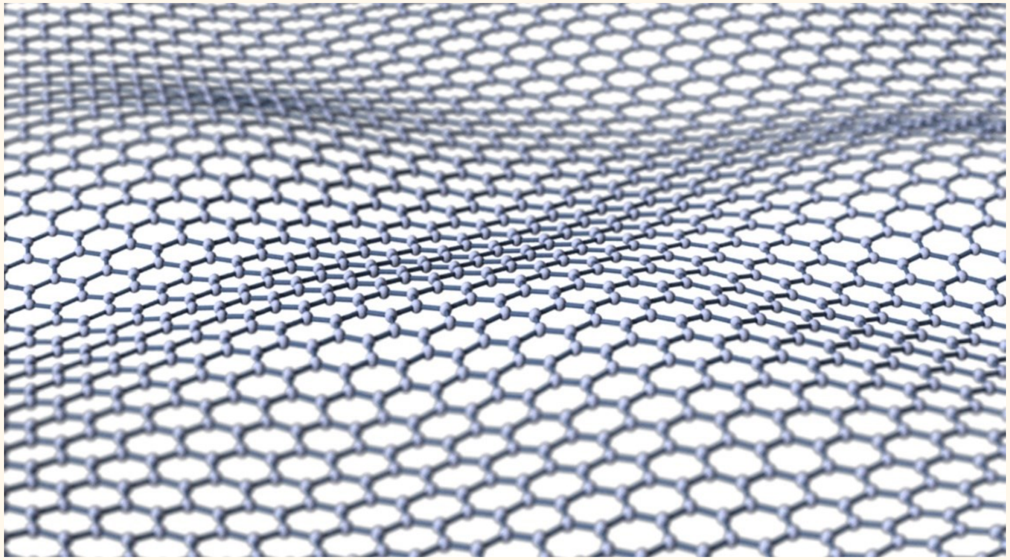
OUTLINE

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

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

Theoretically studied for many years

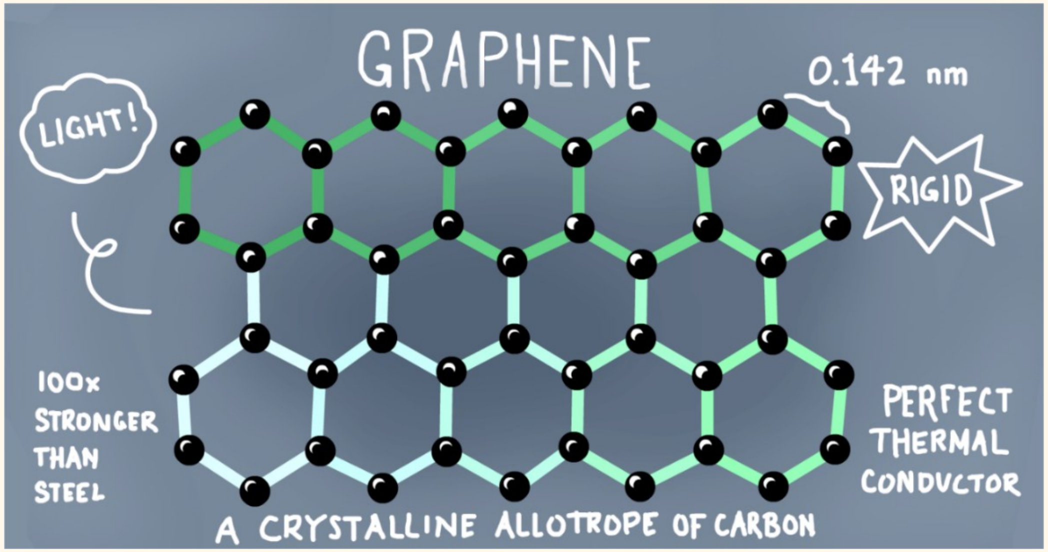


https://www.tradefinanceglobal.com/posts/graphene-the-next-big-thing/

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 → high resistance

DC voltage applied → resistance is reduced

↓

MICROWAVE TUNABLE DEVICES

phase shifters

TUNABLE ATTENUATOR

Patch Antennas with stubs

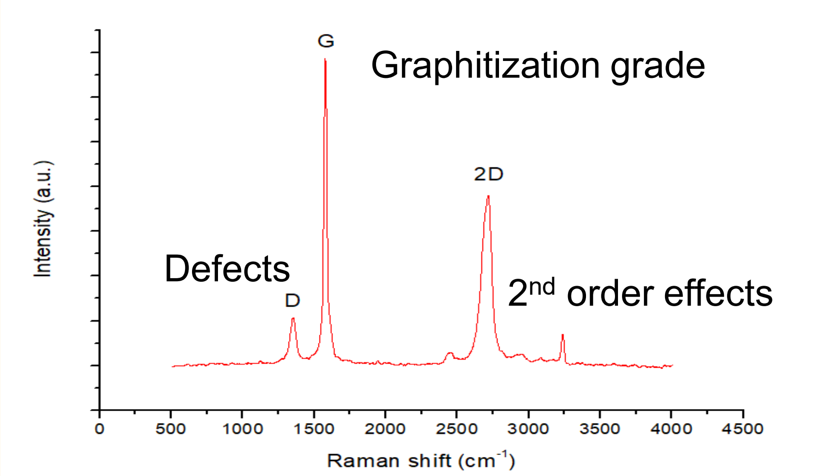
↓

COMMERCIAL GRAPHENE

Muhammad Yasir

COMMERCIAL GRAPHENE: RAMAN

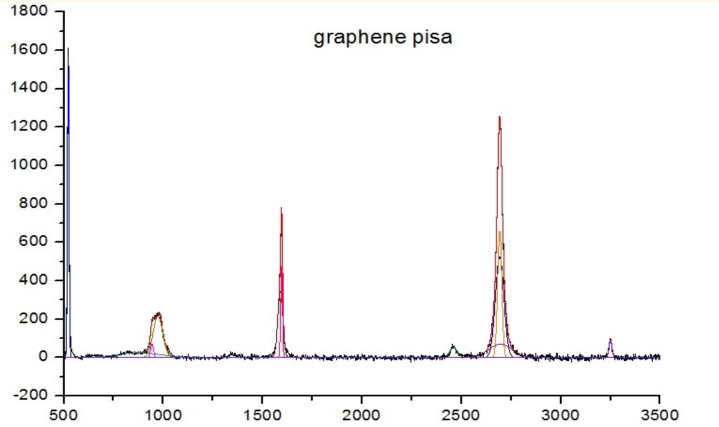
- Nanoinnova graphene flakes

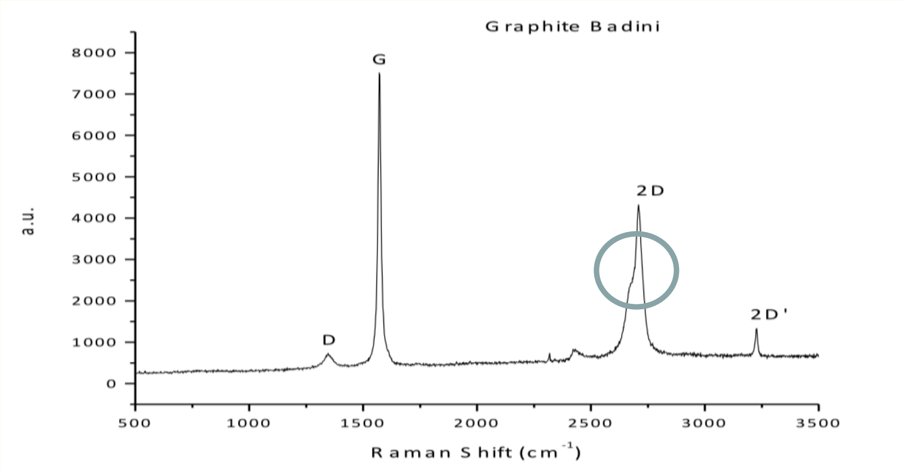


I_D/I_G=0.15, I_D/I_{2D}=0.27 and I_{2D}/I_G=0.56

→ few layer graphene

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

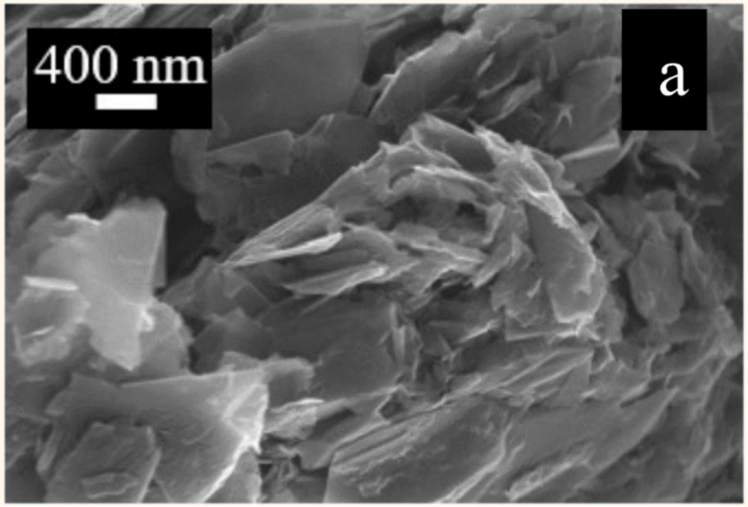


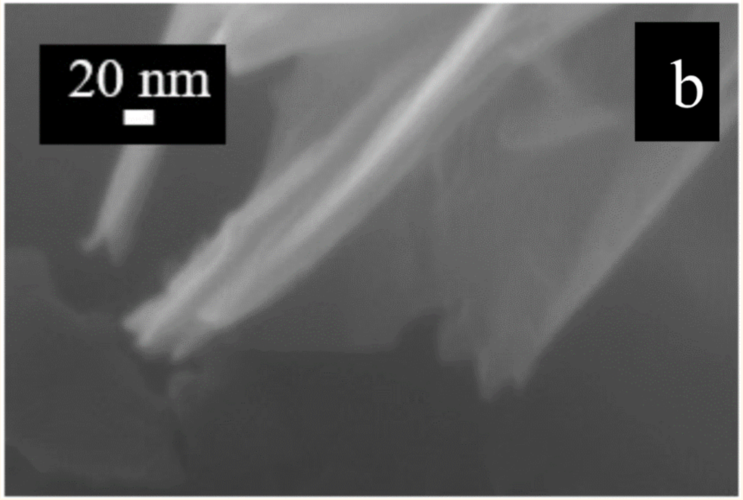


Massimo Rovere, DISAT

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





Massimo Rovere, DISAT

TUNABLE ATTENUATOR

Rogers 4350B

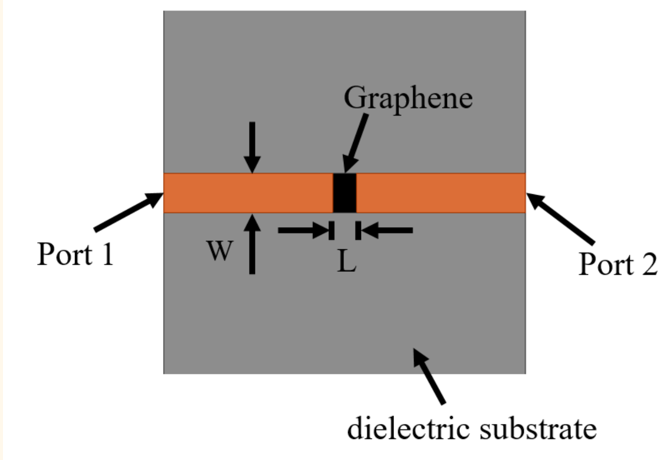
Thichness 0.786mm

Epsilon_r=3.66, tan delta=0.004

W=1.66mm Z0=50Ohm

Aspect Ratio: AR=L/W

Commercial Graphene



When DC bias voltage applied

⇓

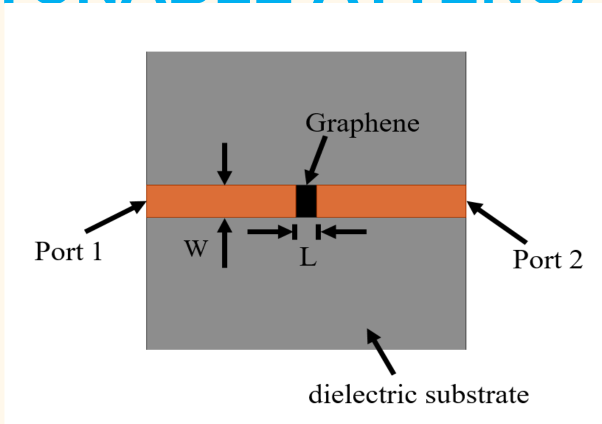
Graphene resistance ↓

⇓

attenuation ↓

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

TUNABLE ATTENUATOR

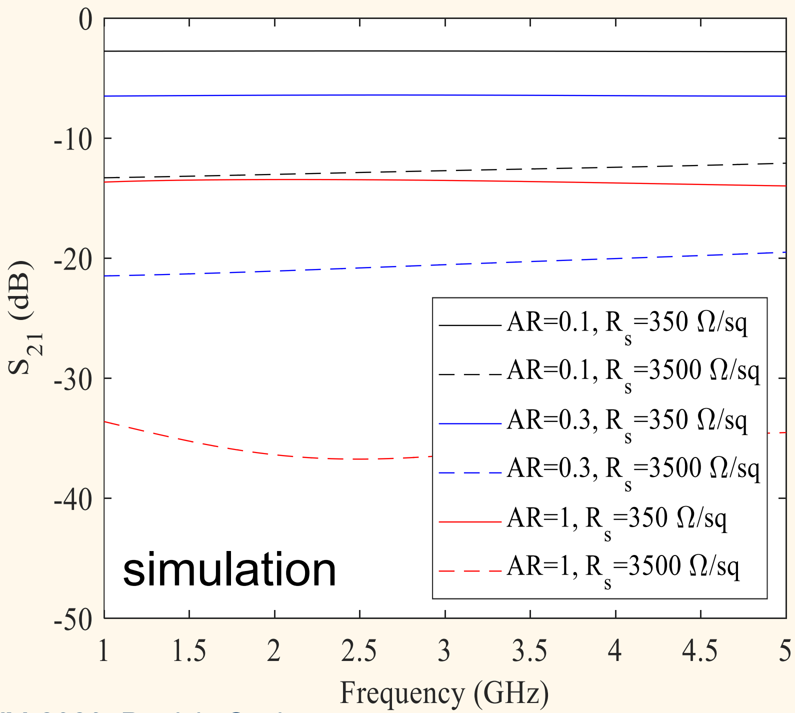


Influence of Aspect Ratio: AR=L/W

Ansys HFSS simulations

Graphene -> thin resistive sheet, Rs=350-3500 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

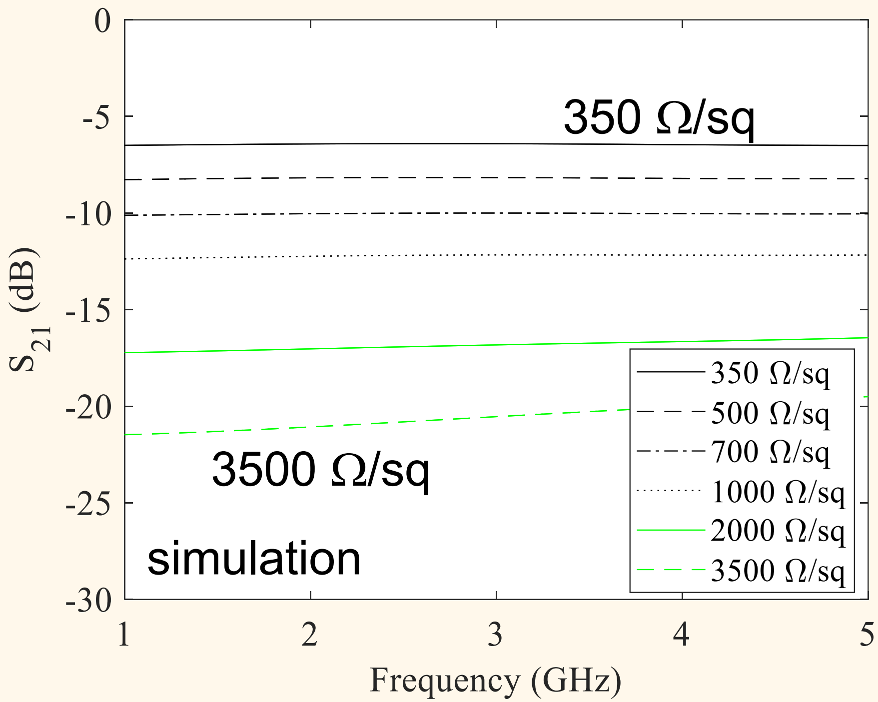
⇩

AR=0.5	**S21**	**Range**
	-6dB	>15dB

TUNABLE ATTENUATOR

A/R=0.5

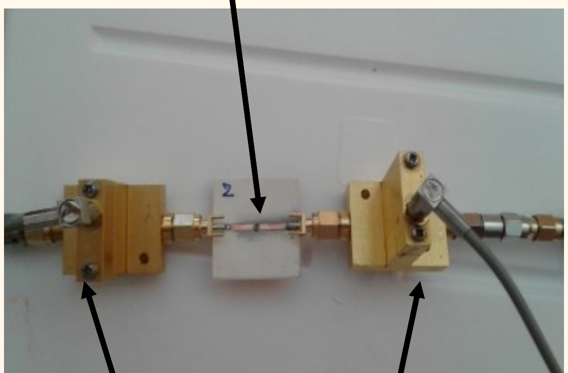
Influence of graphene sheet resistance



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

TUNABLE ATTENUATOR: MEASUREMENTS

Graphene deposition

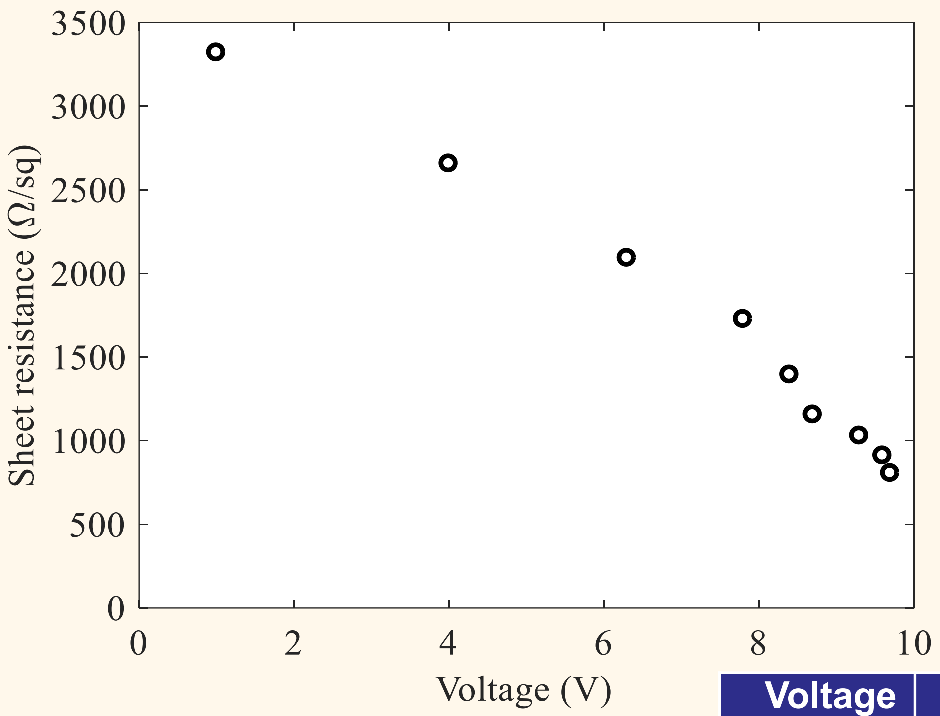


Broadband bias-tee

Vector Network analyzer (300MHz-67GHz)

TUNABLE ATTENUATOR

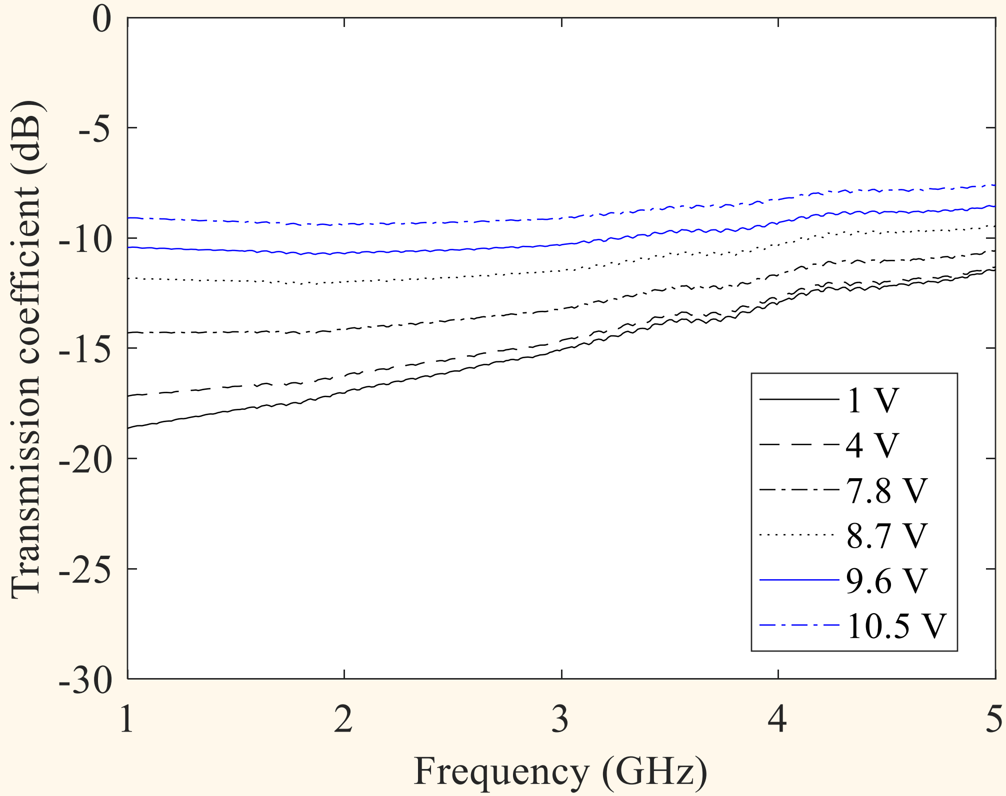
Measured sheet resistance of the tunable graphene attenuator



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.

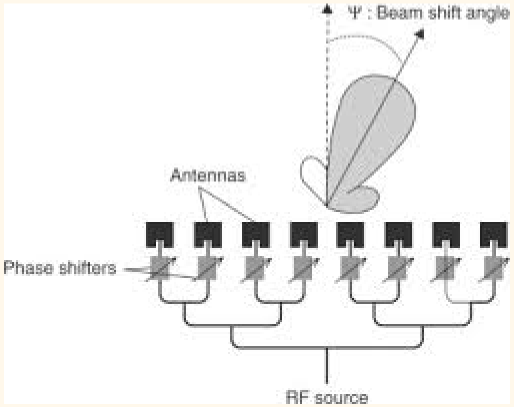


PHASE SHIFTER

Applications

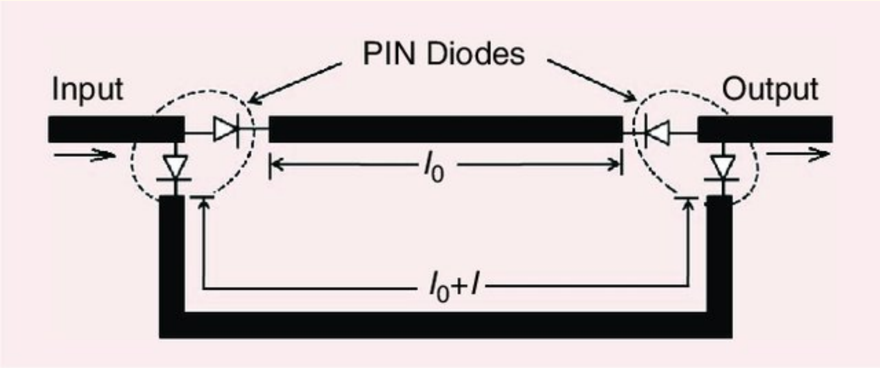
Electronically stearable antennas:

- 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

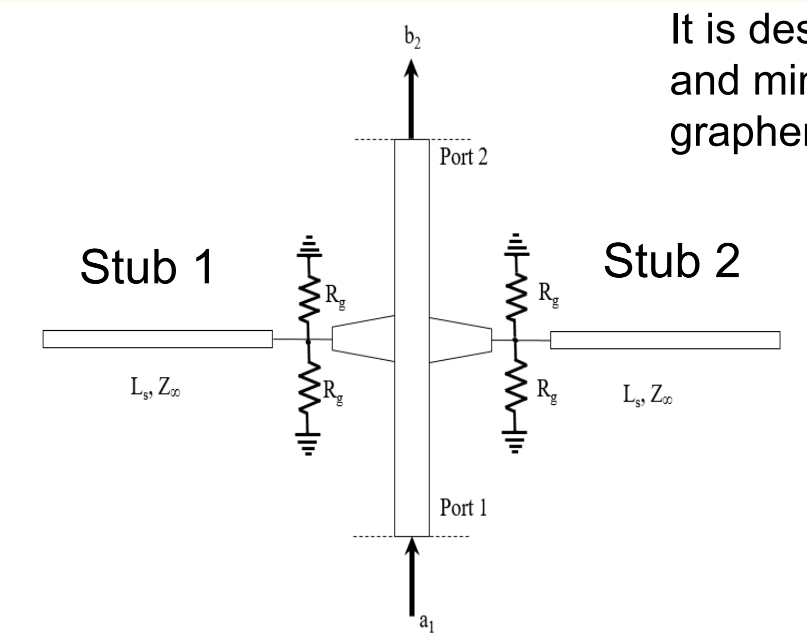
Principle



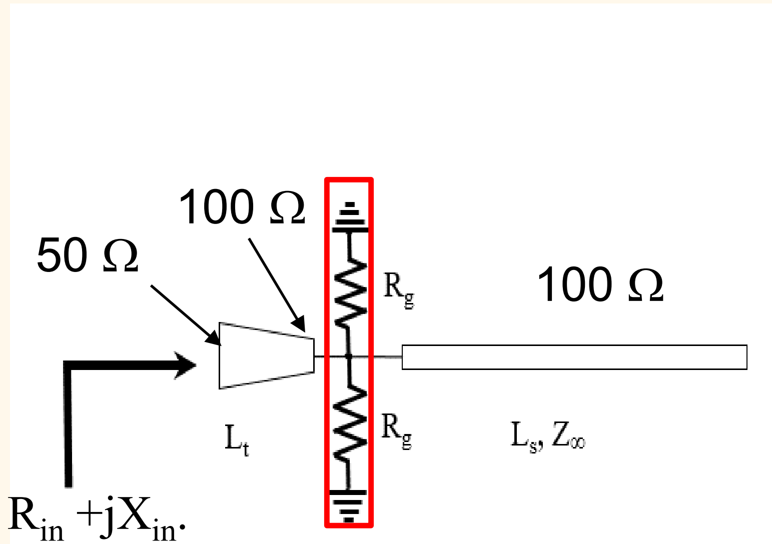
A. Chakraborty, B. Gupta, Paradigm Phase Shift: RF MEMS Phase Shifters: An Overview, January 2017
IEEE Microwave Magazine 18(1):22-41

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.



Microstrip line



$Z_{in} = R_{in} + jX_{in}.$

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.

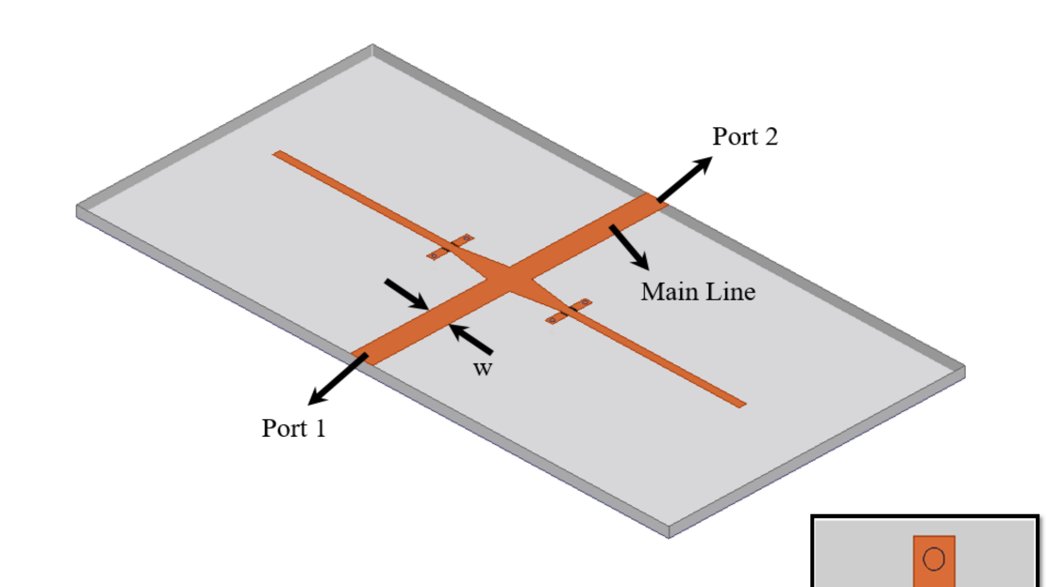
PHASE SHIFTER

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

Ls	L_t=3mm (0.04 λ_0)		L_t=4mm (0.053 λ_0)		L_t=5mm (0.067 λ_0)		L_t=6mm (0.08 λ_0)	
	ΔR_{in}	ΔX_{in}	ΔR_{in}	ΔX_{in}	ΔR_{in}	ΔX_{in}	ΔR_{in}	ΔX_{in}
0.05 λ_0	41.5	46.9	37.6	40	34.5	34.7	31.75	30.8
0.15 λ_0	0.3	0.02	0.3	0.02	0.3	0.02	0.3	0.03
0.3 λ_0	48	67	45	58	41	50	38	44
0.35 λ_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 Lg=1 mm

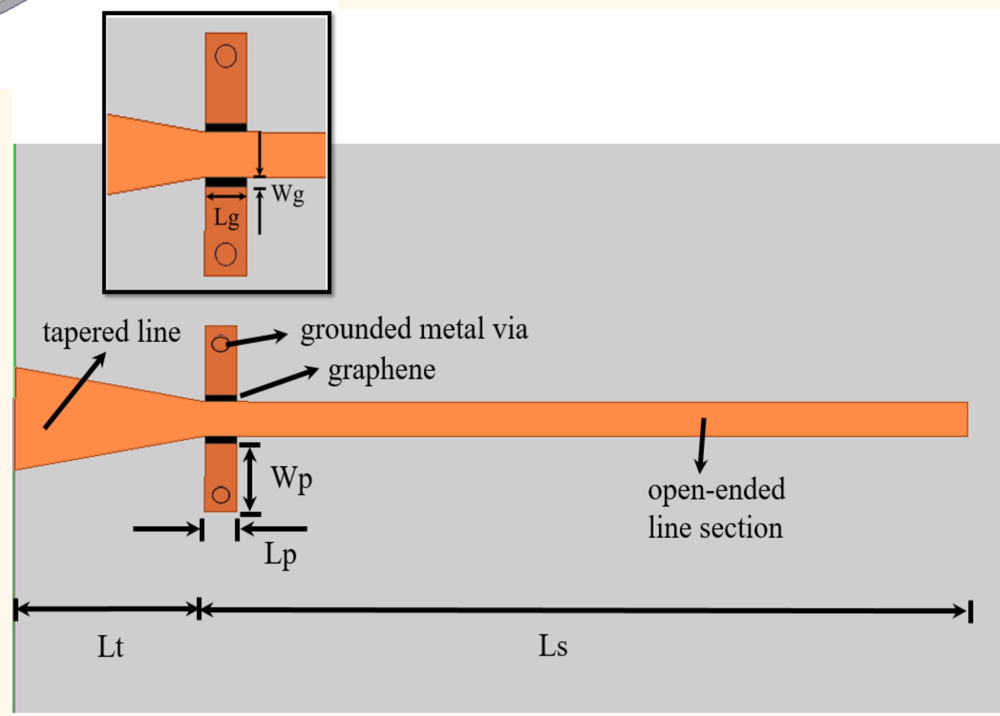
Rogers 3035

Thickness t=1.52 mm

e_r=3.5, tand=0.0015

copper 35 mm

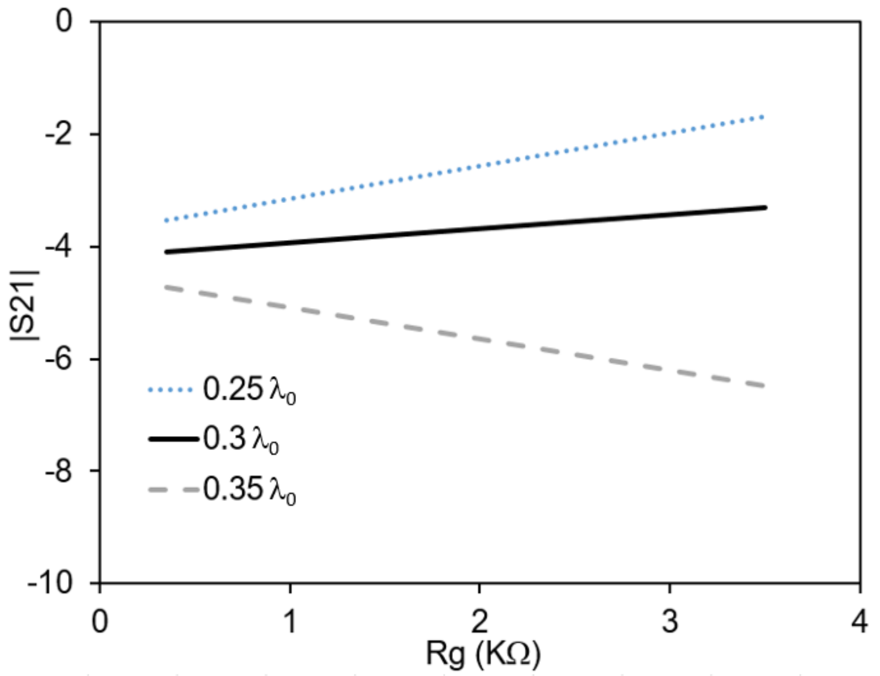
w= 3.2 mm Z_0=50 Ω

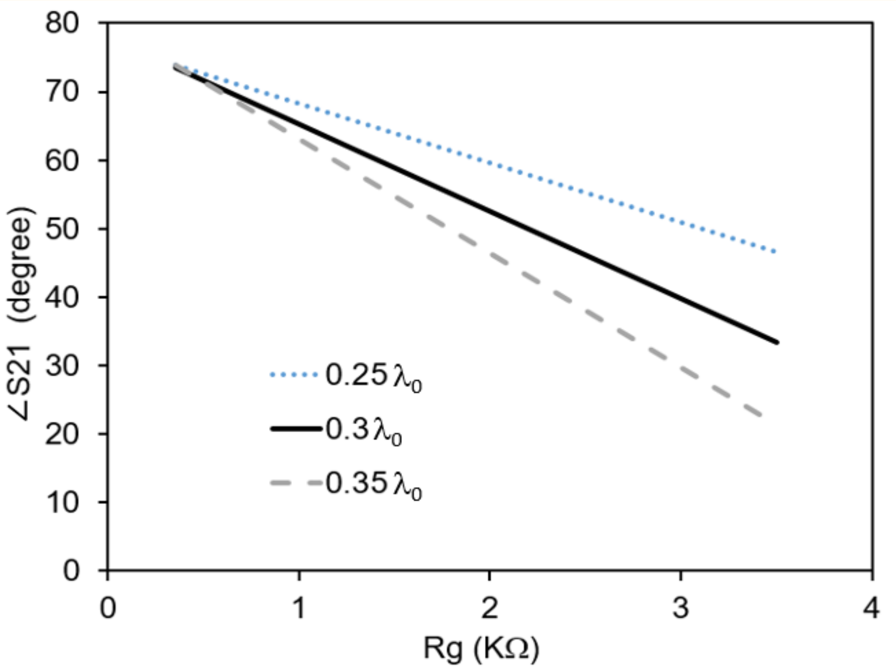


PHASE SHIFTER: FULL WAVE SIMULATIONS

f= 4 GHz

open-ended line section L_s (0.25 λ_0, 0.3 λ_0 and 0.35 λ_0)
graphene resistance values 350 Ω/sq. to 3500 Ω/sq.





Amplitude variation of the transmission decreases from L_s=0.25 λ_0 to L_s= 0.3 λ_0.

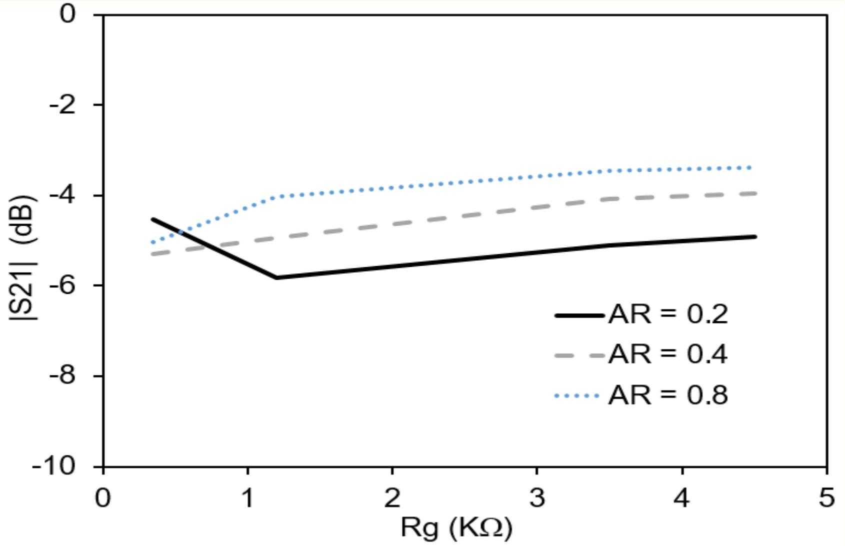
variation of $\angle S_{21}$ increases with increasing L_s

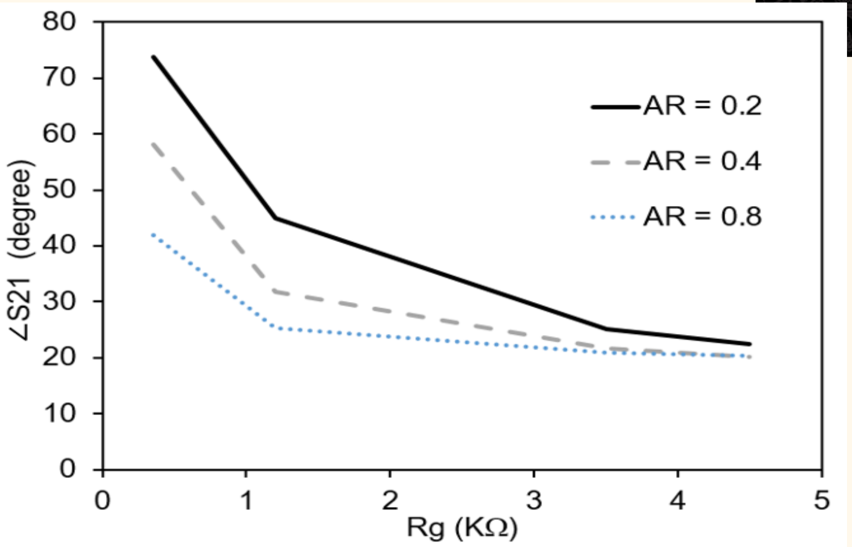
Optimum length L_s=0.3 λ_0

it provides minimum amplitude variation with reasonable phase variation.

PHASE SHIFTER: SIMULATIONS

AR=Wg/Lg analysis



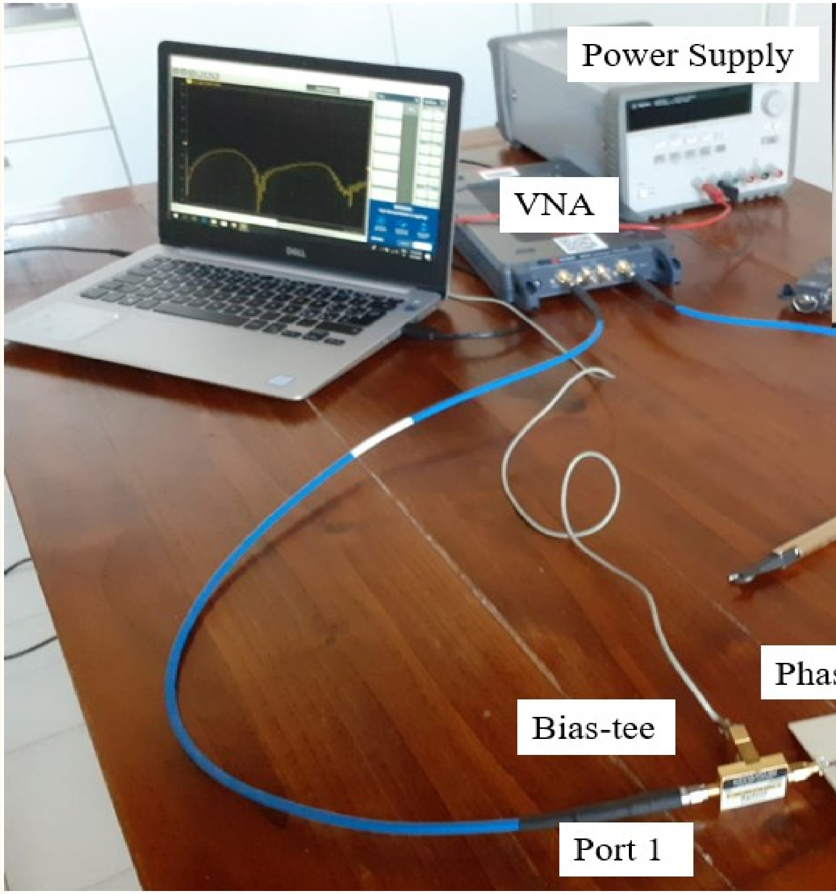


AR	Max $\|S_{21}\|$	Min $\|S_{21}\|$	Max $\angle S_{21}$	Min $\angle S_{21}$
0.2	-4.5dB	-5.8dB	73°	
0.8	-3.3dB	-5dB		22°

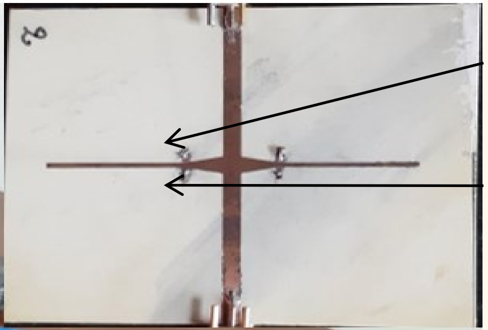
a reduction of the AR reduces the variation of the amplitude of the transmission coefficient and increases the variation of the phase of the transmission coefficient

a highly desirable trait of tunable phase shifters

PHASE SHIFTER MEASUREMENTS



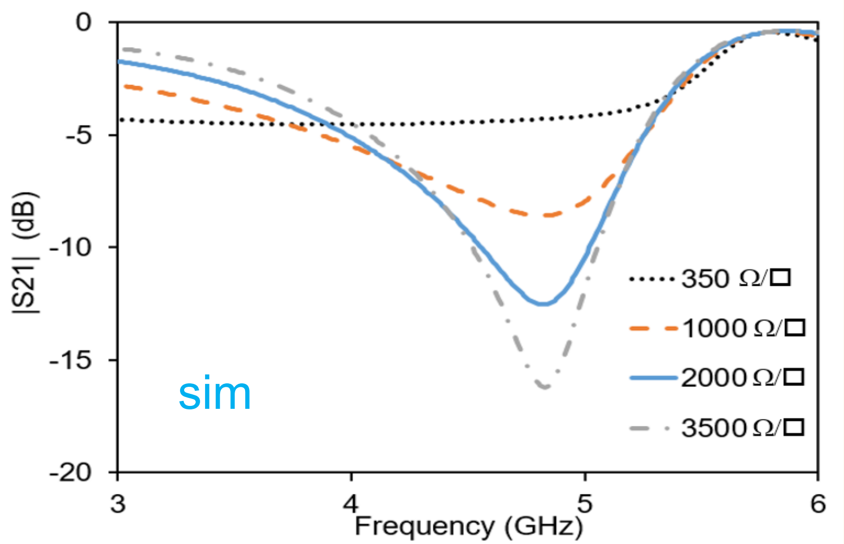
prototype

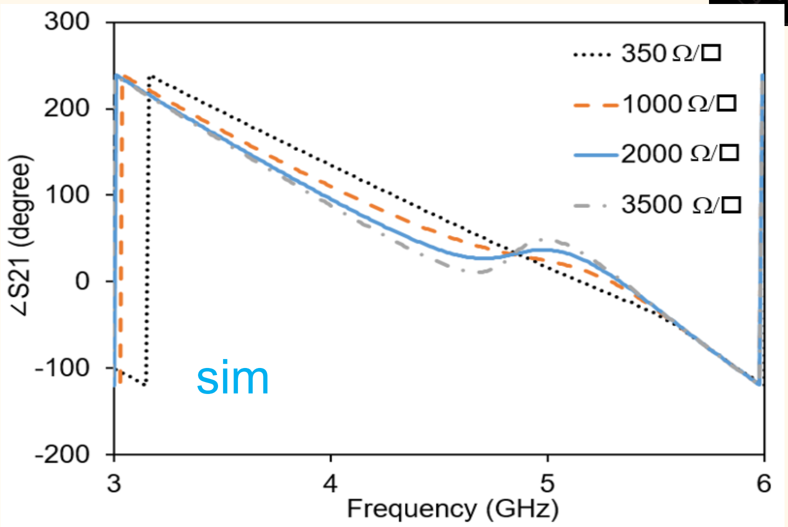


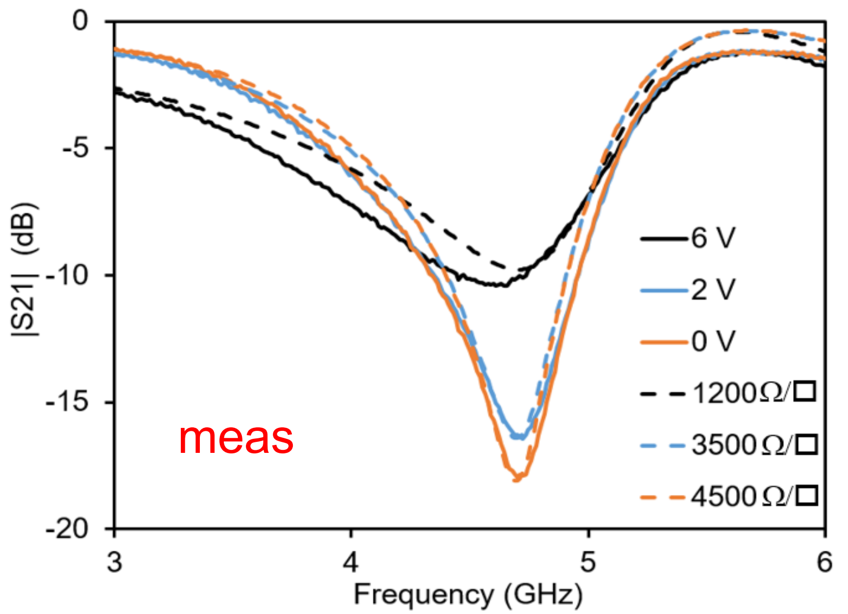
Commercial graphene nanoplatelets mixed in isopropyl alcohol are drop casted

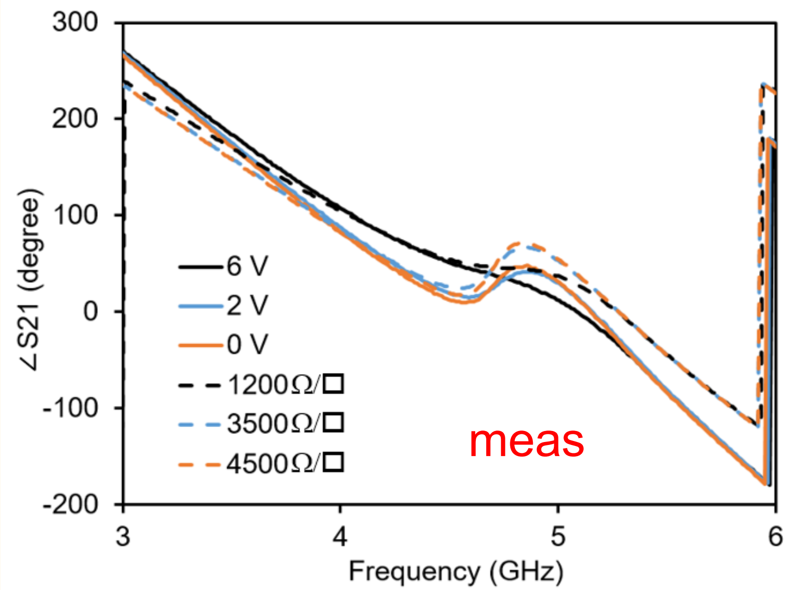
Voltage	Resistance	
0V	4500 W/sq	
6V	1200 W/sq	

PHASE SHIFTER: SIMULATIONS AND MEASUREMENTS









PHASE SHIFTER: FIGURE OF MERIT

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

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

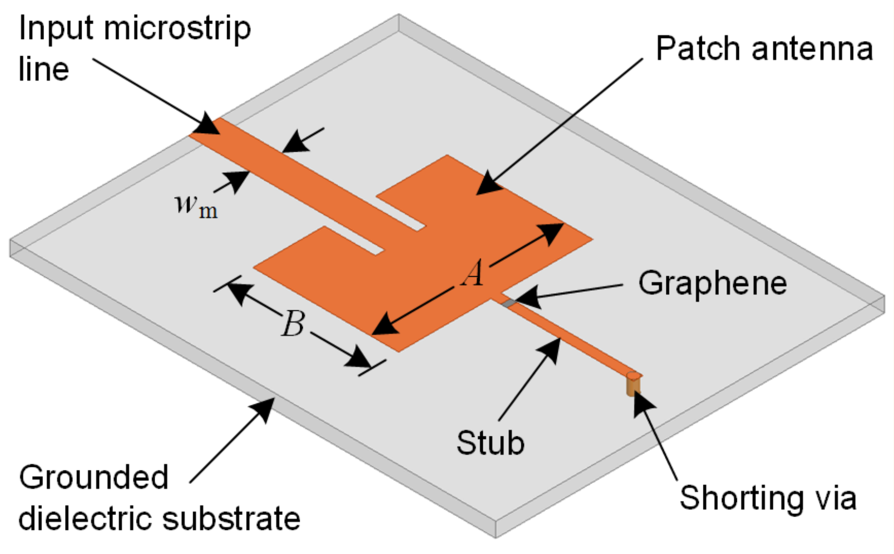
1. *Yasir, M.; Bistarelli, S.; Cataldo, A.; Bozzi, M.; Perregrini, L.; Bellucci, S. Tunable Phase Shifter Based on Few-Layer Graphene Flakes. IEEE Microwave and Wireless Components Letters* ***2019,*** *29 (1), 47-49.*

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.*

TUNABLE GRAPHENE ANTENNA

ONE-STUB DESIGN

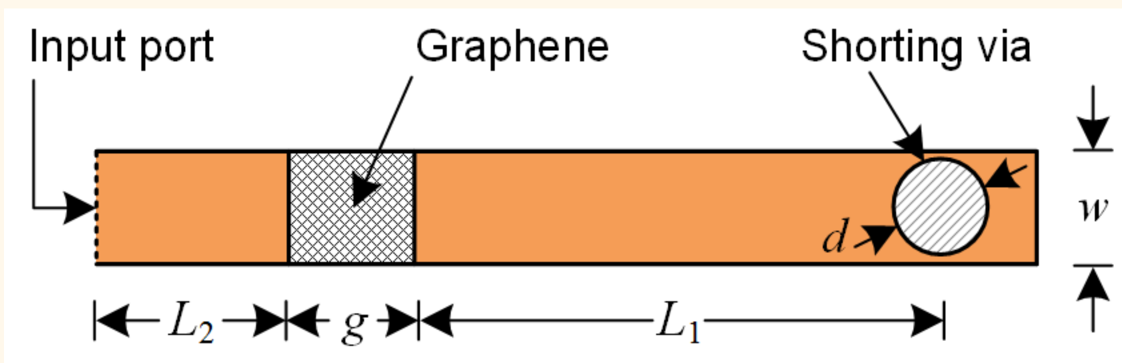
- The antenna consists of a **patch with a shorted microstrip stub**, where the graphene pad is inserted.

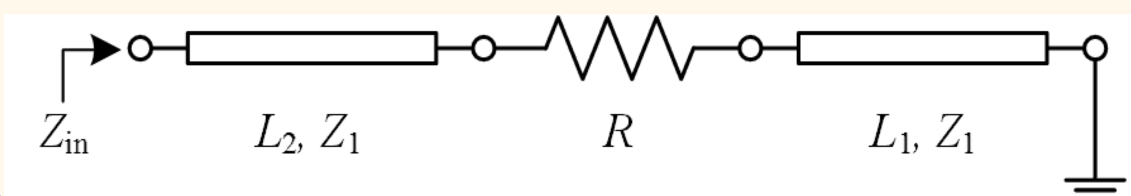


K. Naishadham, "An investigation on the tunning of a microstrip patch antenna using carbon nanotube thin films," IEEE Antennas Propagat., Symp., Memphis, USA, July 2014

OPERATING PRINCIPLE

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

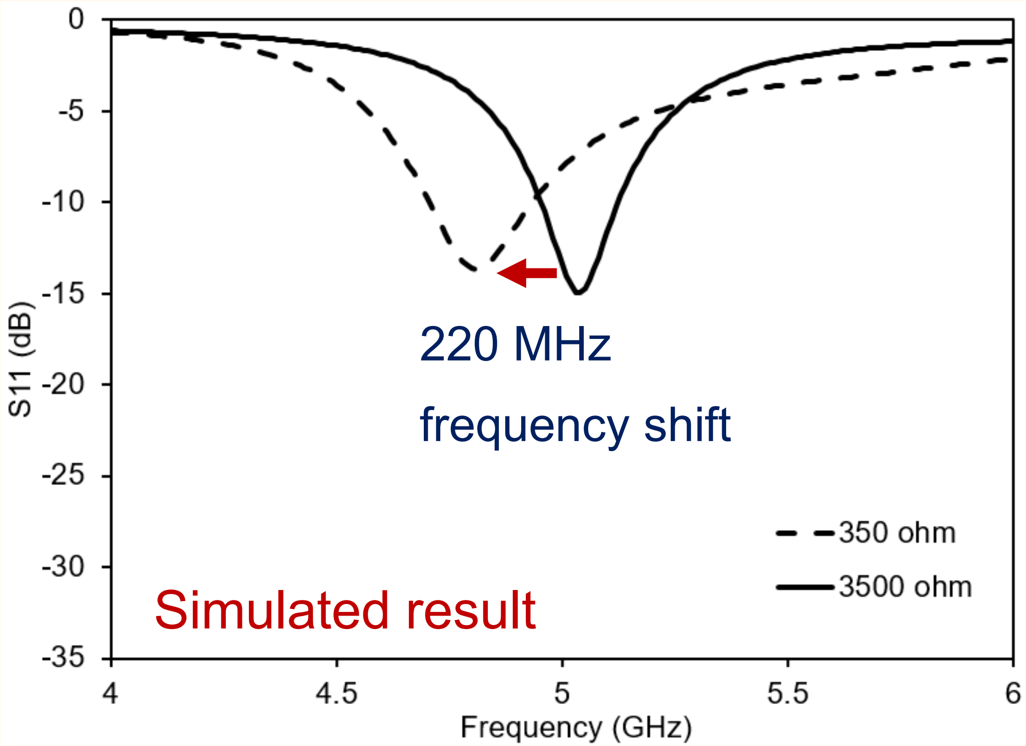




TUNABLE GRAPHENE ANTENNA

ONE STUB DESIGN

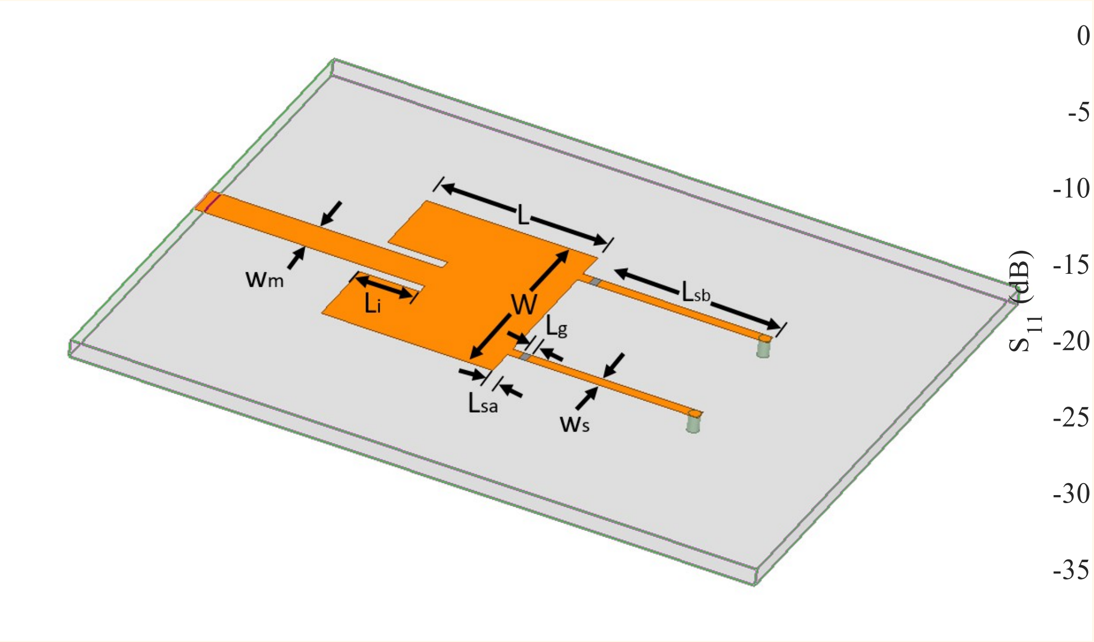
- Shift in resonant frequency from 5.04 GHz to 4.8 GHz with varying graphene resistance.

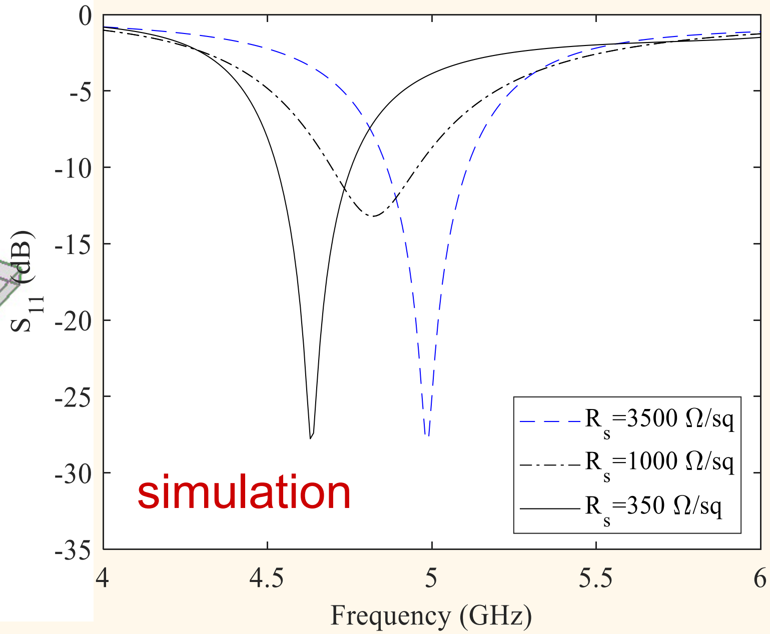


TUNABLE GRAPHENE ANTENNA

TWO STUB DESIGN

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

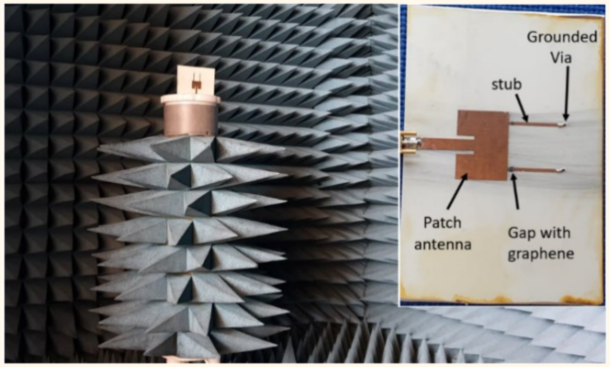




Very low reflection coefficient of <-27 dB

Tunable Graphene Antenna

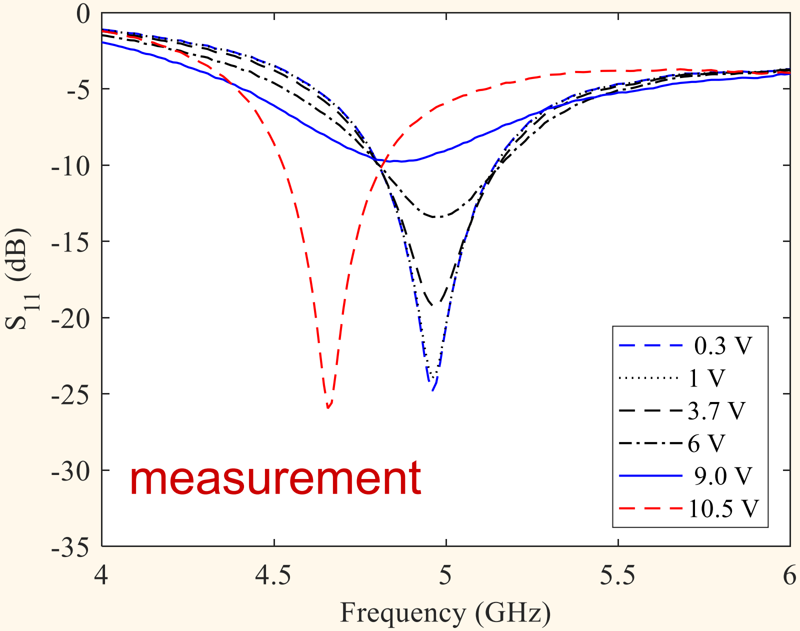
Prototype



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).

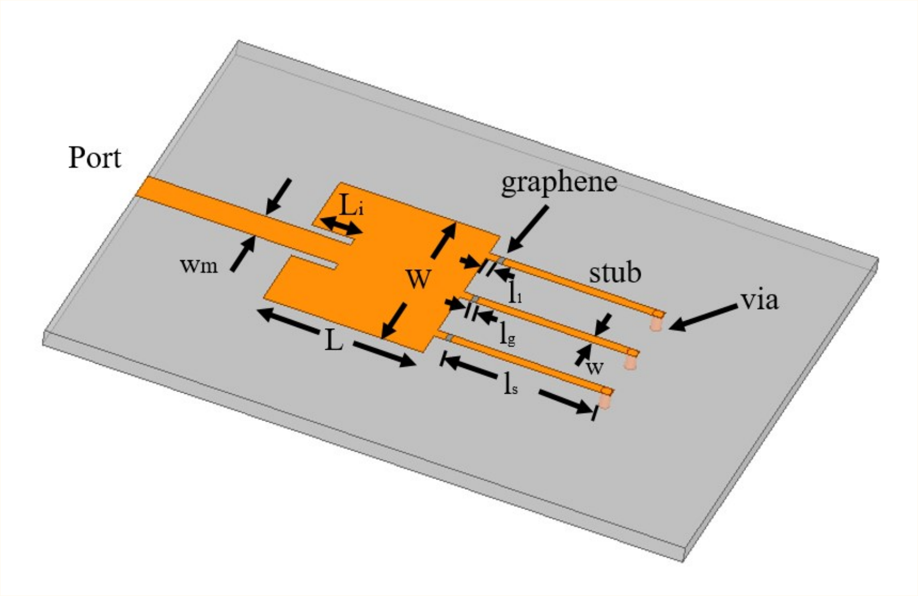
Voltage (V)	Current (mA)	Resistance (Ω)	Sheet Resistance (Ω/sq.)
0.36	1	720	4800
3.7	25	298	1989
6.1	60	202	1355
9	140	120	800
10.5	300	70	466

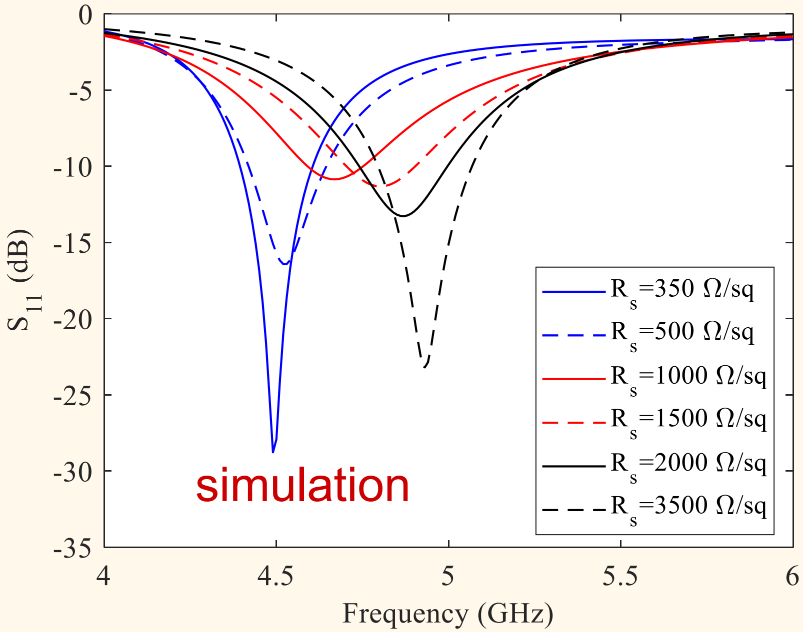


TUNABLE GRAPHENE ANTENNA

THREE STUB DESIGN

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





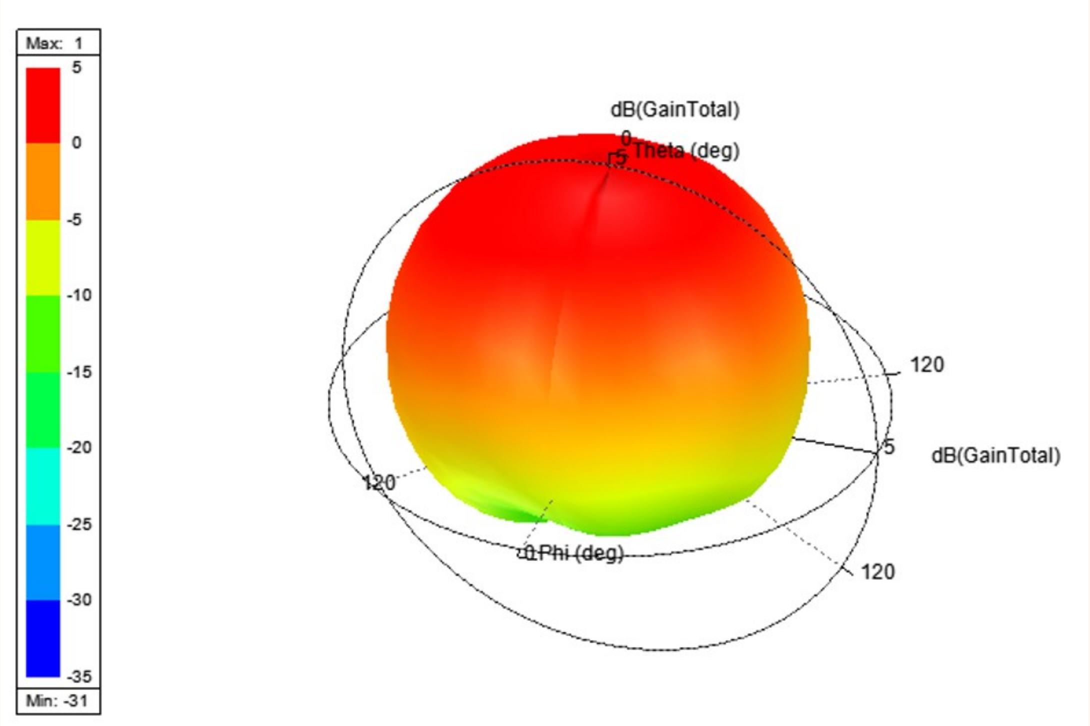
Shift of resonant frequency of 440 MHz

(4.98 GHz to 4. 63 GHz)

TUNABLE GRAPHENE ANTENNA

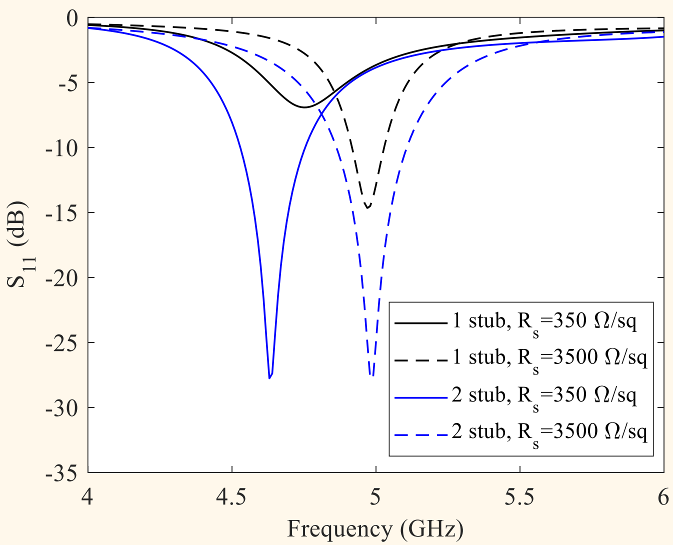
THREE STUB DESIGN- GAIN

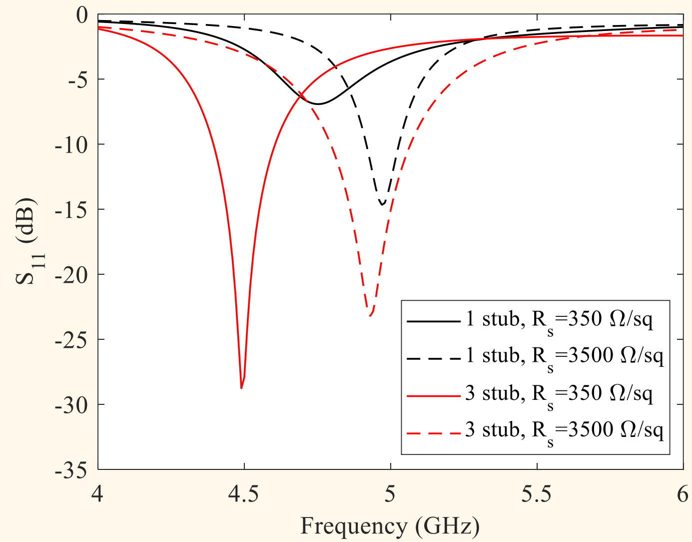
- No significant radiation from the three stubs. Main radiating element is still the patch antenna.
- Gain value is not effected.



TUNABLE GRAPHENE ANTENNA

COMPARISON OF ONE, TWO AND THREE STUBS





Significant improvement in reflection coefficient value and shift of resonant frequency

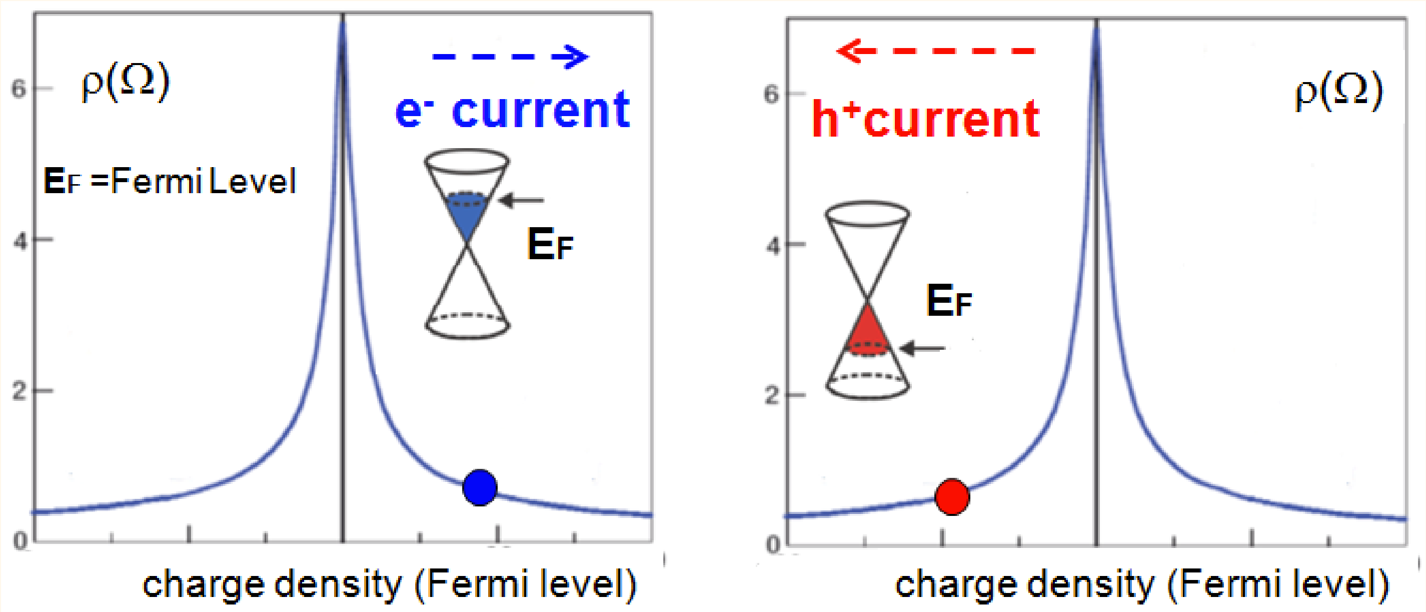
CONCLUSIONS

- 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

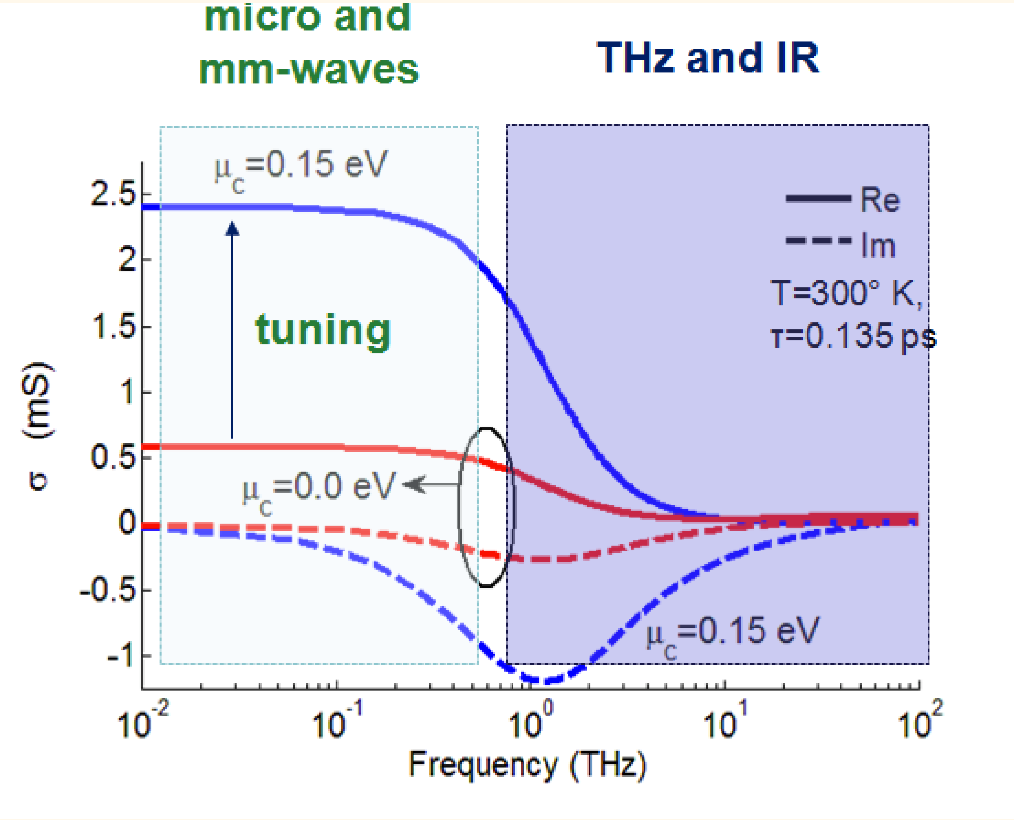
- By applying energy to the graphene, one can shift its Fermi level and modify/control its electrical properties.



- 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.**