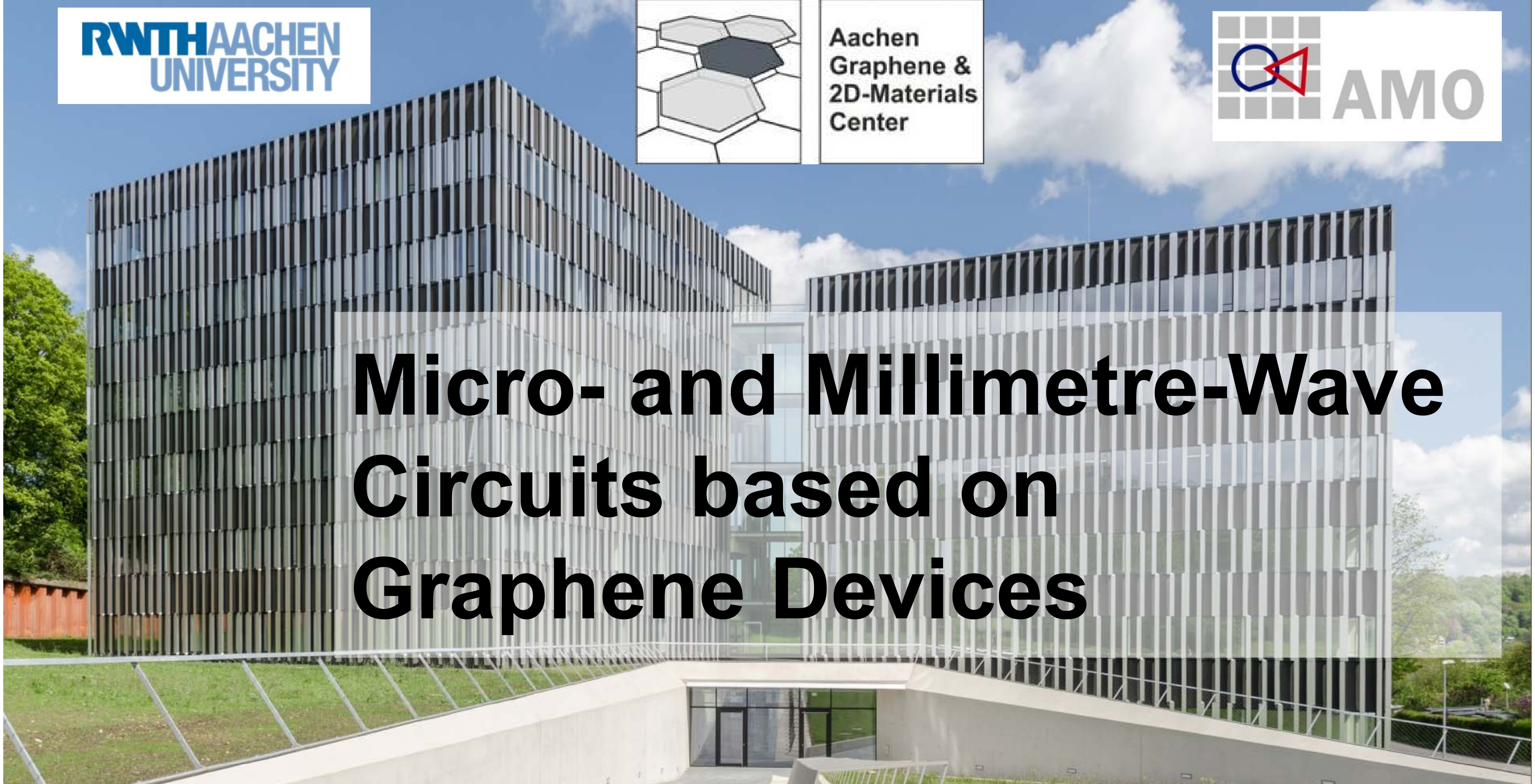


Micro- and Millimetre-Wave Circuits based on Graphene Devices

Aachen Graphene & 2D-Materials Center

RWTH AACHEN UNIVERSITY

AMO

Univ.-Prof. Dr. sc. techn. Renato Negra

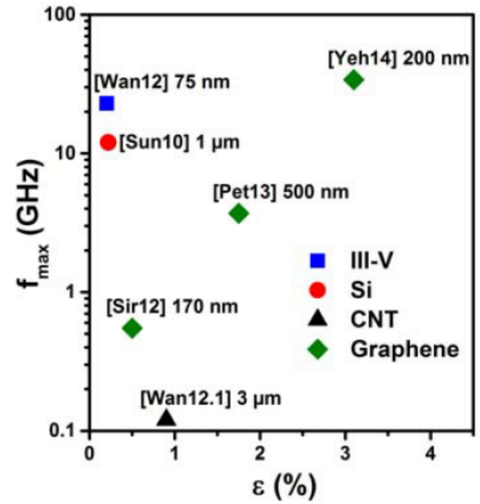
Chair of High Frequency Electronics

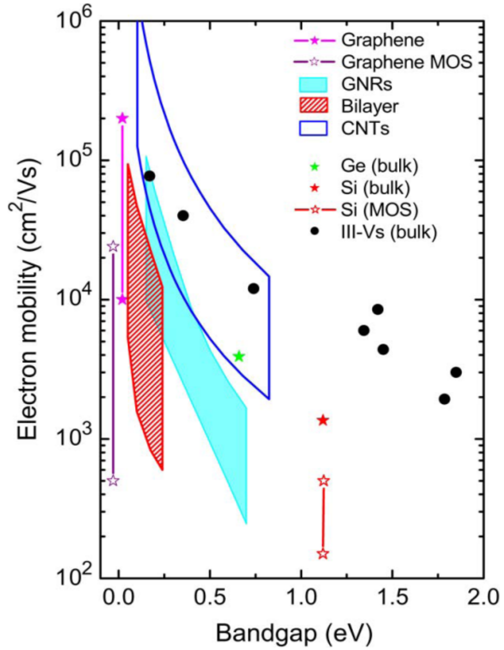
www.hfe.rwth-aachen.de

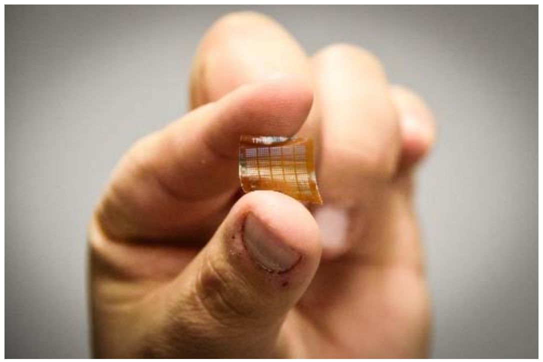
HFE

Graphene …… Why?

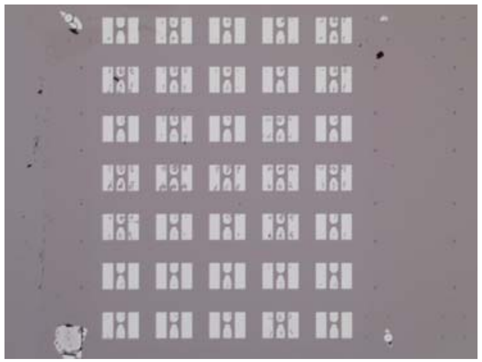
- Excellent electrical characteristics
  - High potential for micro- and millimetre-wave applications
  - Electron mobility up to 15000 cm^2/Vs
- 2D material with outstanding mechanical properties
  - Suitable for flexible electronics, smart wearable devices, …
  - Substrate independent device characteristics
  - Integration in wide range of applications as NFC, IoT, …







Graphene-based RF devices on Kapton

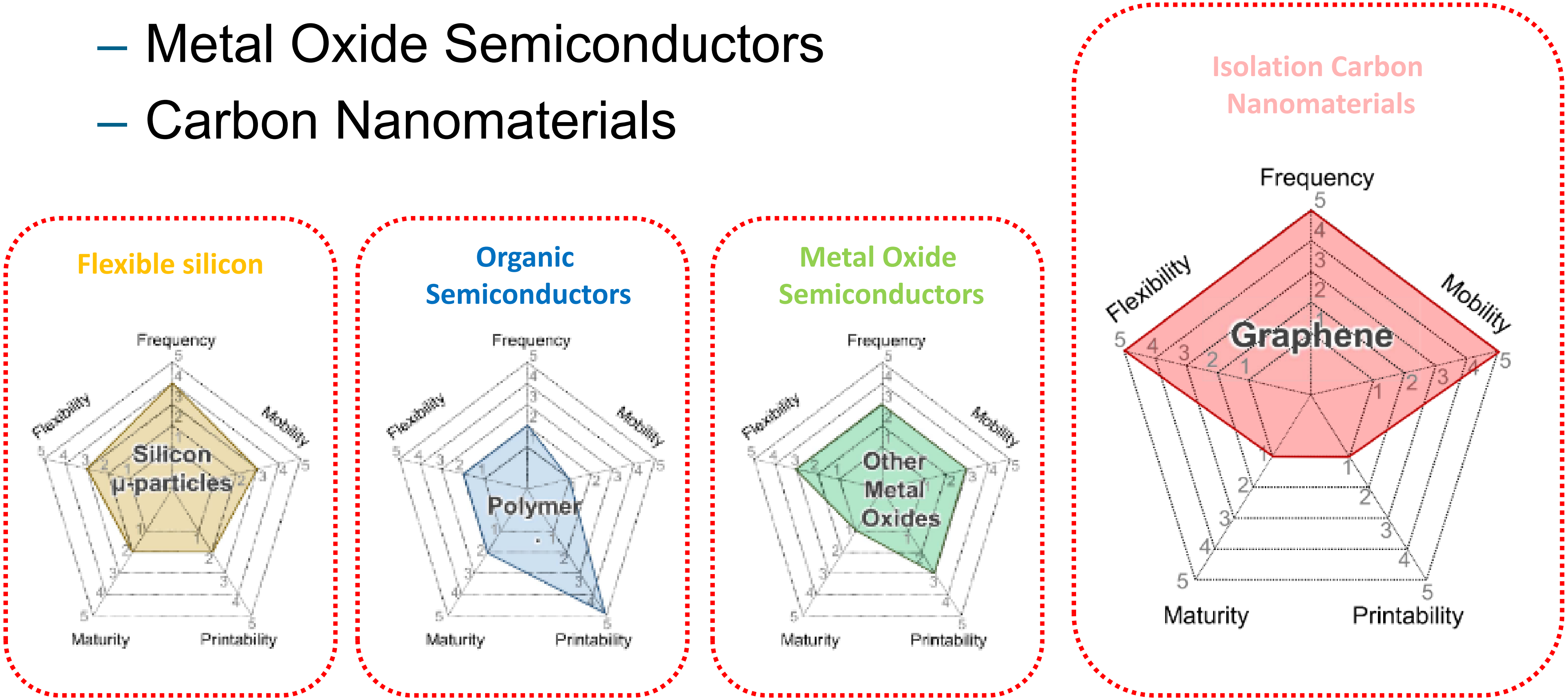


Graphene-based RF devices on HR Silicon

Schwierz, F. Graphene transistors: status, prospects, and problems. Proc. IEEE 6, 770–775 (2013)

Introduction

- Many semiconductor materials
  - Flexible silicon
  - Organic semiconductors
  - Metal Oxide Semiconductors
  - Carbon Nanomaterials

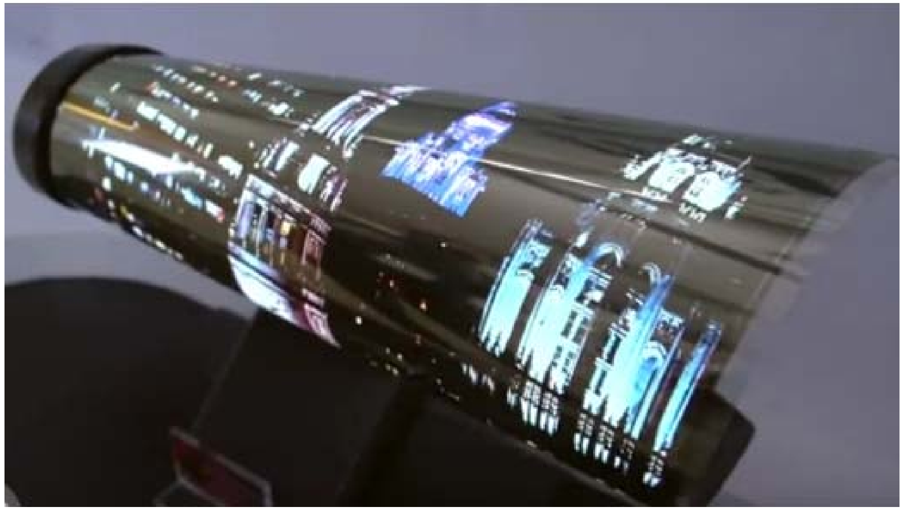


[3]

Main semiconductor materials for flexible circuits

Flexible electronics

- Bendable displays
- Health care applications
- Wearable devices
- Biomedical applications



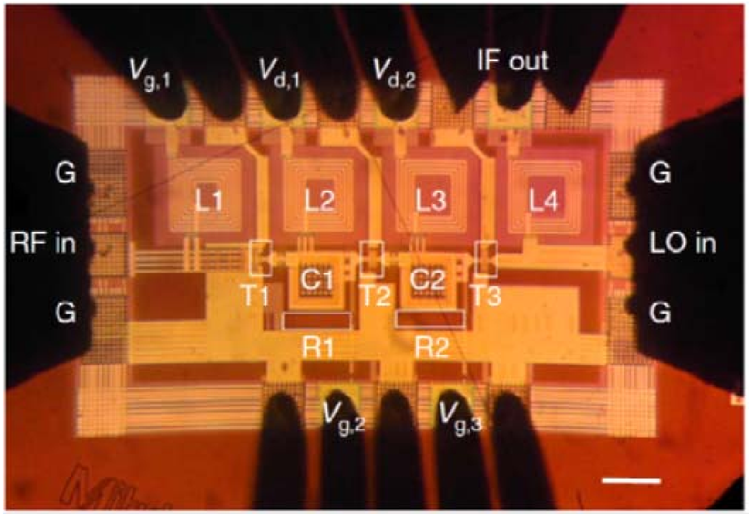
OLED rollable display [1]

Health care and wearable communication [2]

State-of-the-art Graphene-based circuits

Ref.	Scheme	f_{RF} (GHz)	f_{LO} (GHz)	Conversion Gain (dB)	Remarks
[1]	GFET mixer	2	1.01	-24	Single transistor
[2]	AM Demodulator	2.45	2.45	-35	Single transistor
[3]	AM Rx Frontend	4.3	4.3	-10	3 transistors
				High loss	Repeatability!

[1] O. Habibpour, et. al., “A Subharmonic Graphene FET Mixer,” *IEEE Electron Device Lett.*, vol. 33, no. 1, pp. 71–73, 2012.
[2] M. N. Yogeesh, et. al., “Towards the design and fabrication of graphene based flexible GHz radio receiver systems,” presented at the 2014 IEEE/MTT-S International Microwave Symposium - MTT 2014, 2014, pp. 1–4.
[3] S.-J. Han,et. al., “Graphene radio frequency receiver integrated circuit,” *Nature Communications*, vol. 5, Jan. 2014.

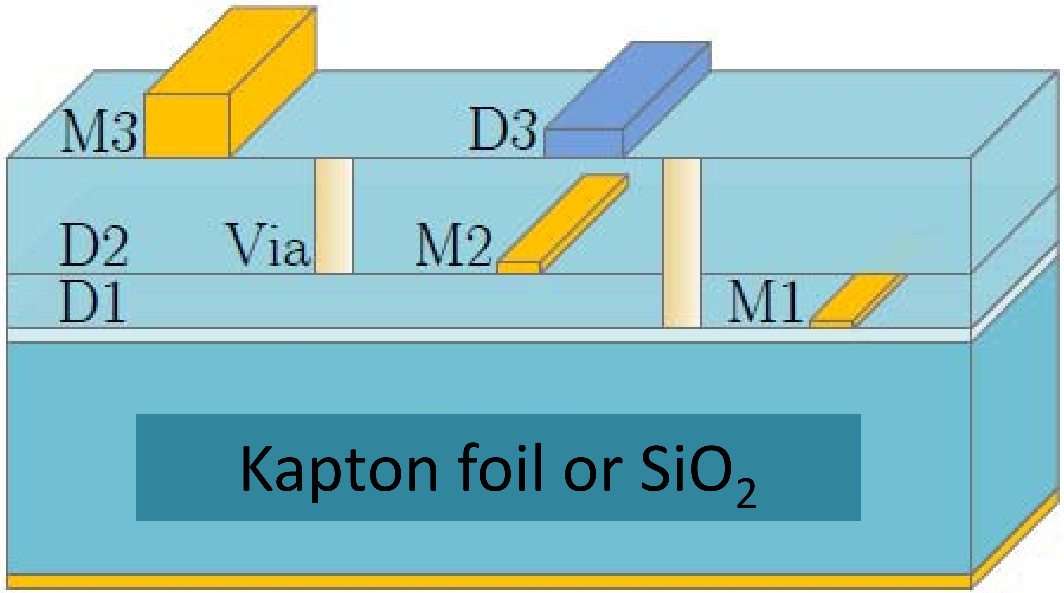


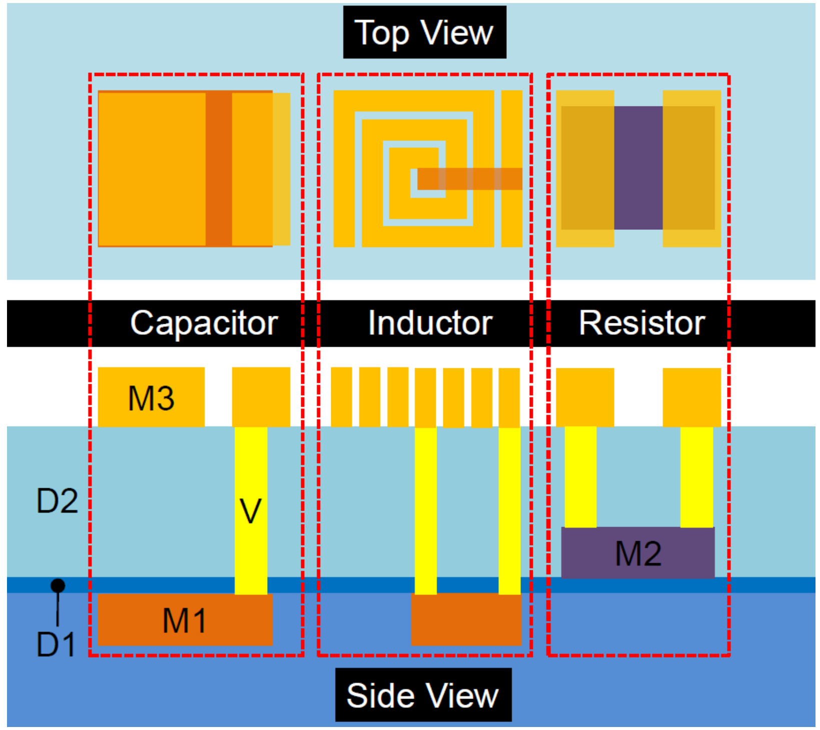
S.-J. Han,et. al., “Graphene radio frequency receiver integrated circuit,” Nature Communications, vol. 5, Jan. 2014.

Outline

- MMIC process development
- Graphene electron devices
- Millimetre-wave Graphene-based power detectors
- Microwave-wave Graphene-based mixers and frequency multipliers
- Micro- and millimetre-wave Graphene receiver frontends
- Summary and Outlook

MMIC process on any substrate





3 Dielectric layers:

- D1: 5 nm TiO2 (diodes, varactors) or 5-10 nm Al2O3 (transistors)
- D2: 90nm Al203 (encapsulation, capacitors)
- D3 500 nm SU8 (inductors)

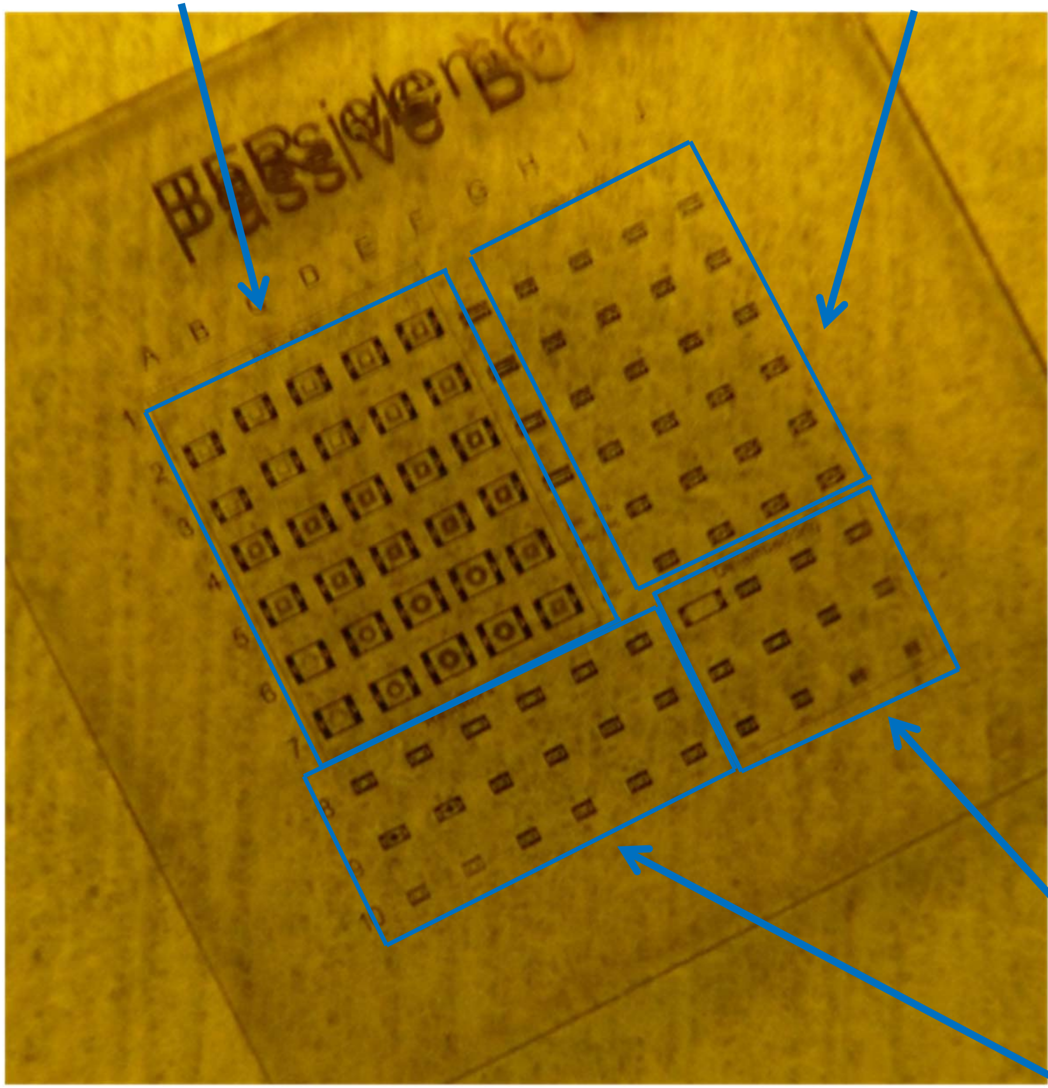
4 Metal layers:

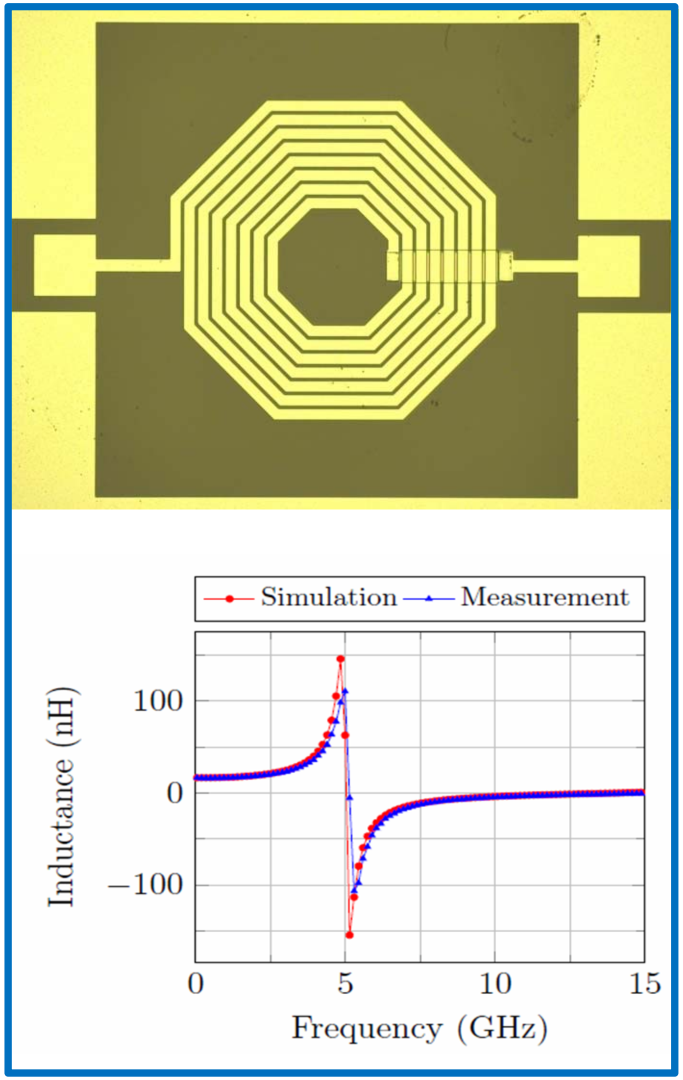
- M1: 100nm Al (gate electrode, passives)
- M2a: 20 nm Nickel (graphene contacts)
- M2b: 110 nm TiN (resistors)
- M3: 2µ Al (passives, interconnects)

Graphene is between D1 and M2, and can be used in diodes, varactors or/and transistors.

A. Askar, A. Hamed, M. Saeed, A. A. Sagade, D. Neumaier, and R. Negra, "Graphene-based MMIC process development and RF passives design," German Microwave Conference, 2015, pp. 299–302. DOI: 10.1109/GEMIC.2015.7107813

Evaluation chip on 500 µm quartz substrate





A. Askar, A. Hamed, M. Saeed, A. A. Sagade, D. Neumaier, and R. Negra, “Graphene-based MMIC process development and RF passives design,” German Microwave Conference, 2015, pp. 299–302. DOI: 10.1109/GEMIC.2015.7107813

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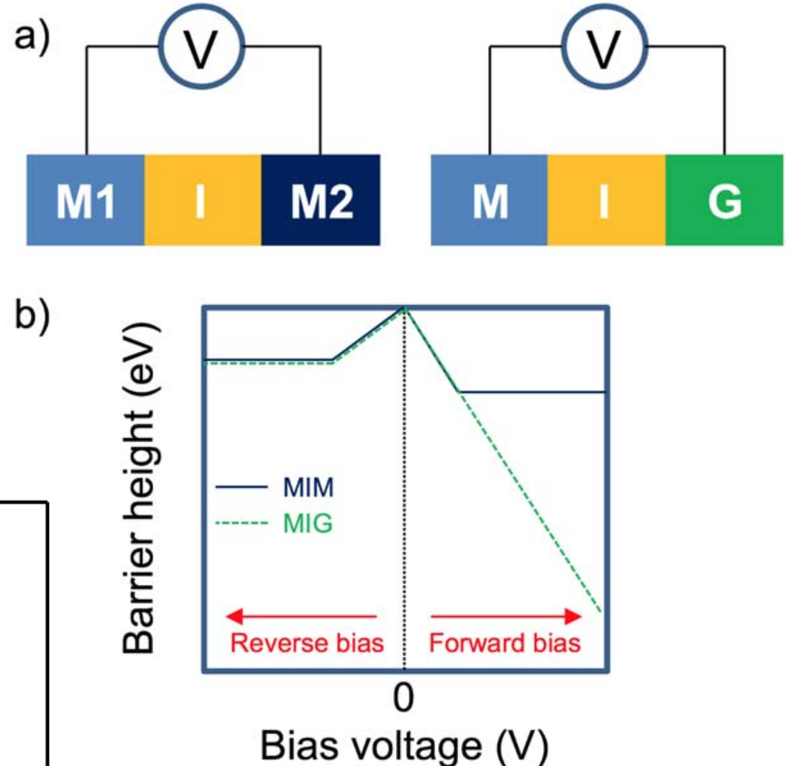
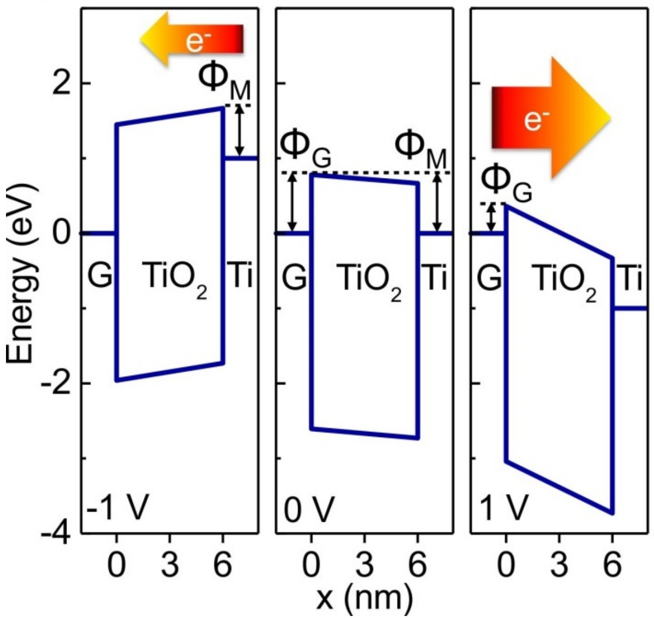
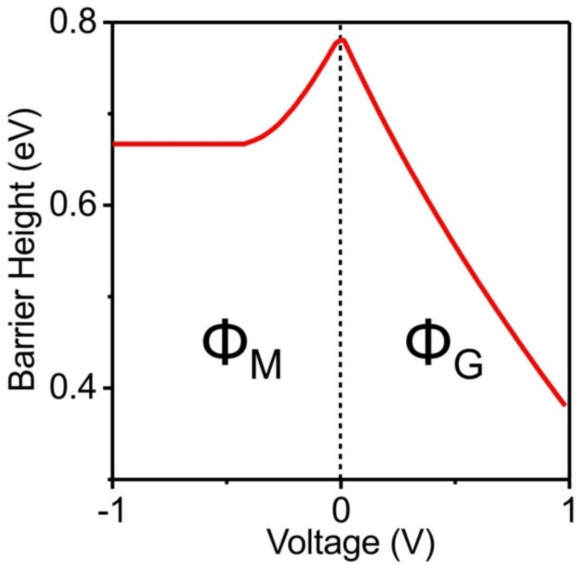
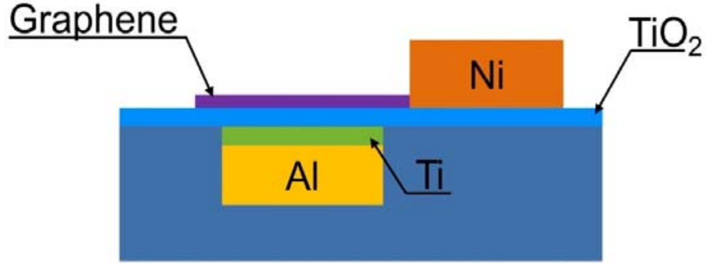
Metal-Insulator-Graphene diode

- Structure: Same as MIM-diode
- Concept: Bias induced barrier lowering
- Substrate embedded electrode
- Higher nonlinearity and asymmetry







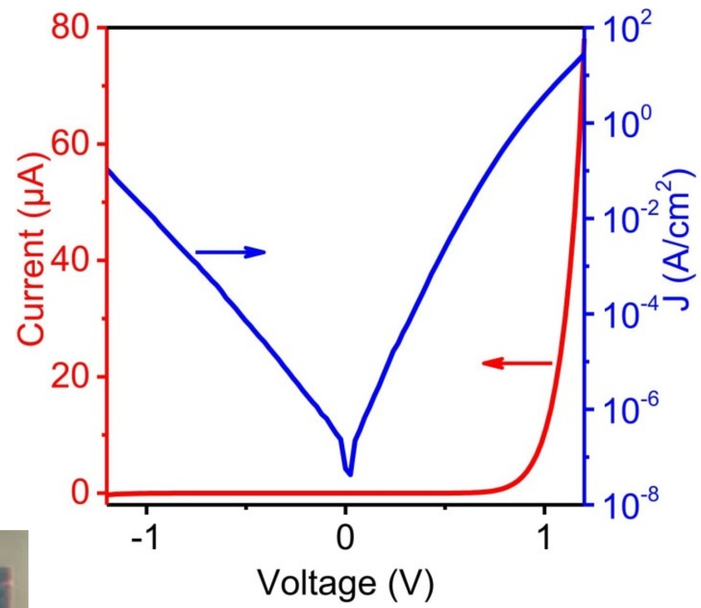


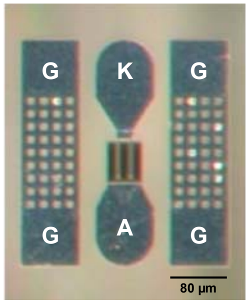
M. Shaygan, Z. Wang, M. S. Elsayed, M. Otto, G. Iannaccone, A. H. Ghareeb, G. Fiori, R. Negra, and D. Neumaier, “High performance metal–insulator–graphene diodes for radio frequency power detection application,” Nanoscale, vol. 9, pp. 11944–11950, Sep. 2017, DOI: 10.1039/C7NR02793A.

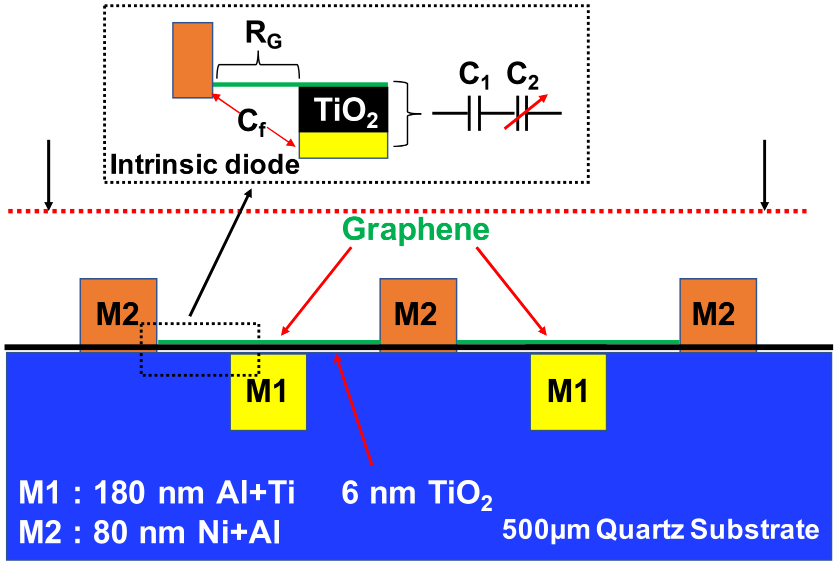
M. Saeed, A. Hamed, Z. Wang, M. Shaygan, D. Neumaier, and R. Negra, “Zero-bias 50-dB dynamic range linear-in-dB V-band power detector based on CVD graphene diode on glass,” IEEE Trans. Microw. Theory Techn., vol. 66, no. 4, pp. 2018–2024, Apr. 2018, DOI: 10.1109/ TMTT.2018.2792439.

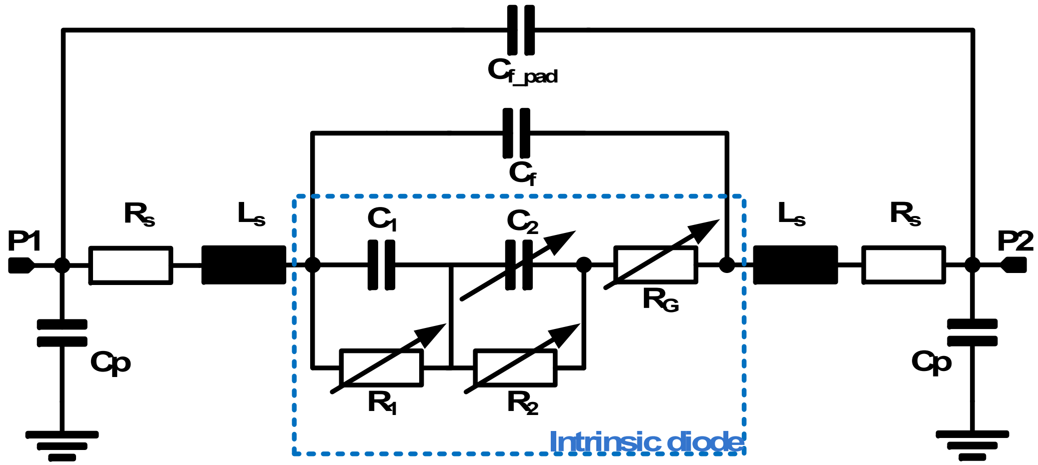
Metal-Insulator-Graphene diode / varactor

- Characterisation: DC & S-parameters
- Physical design considerations
- Measurements demonstrate
  - On current density up to 280 mA/mm^2
  - Asymmetry up to 520
  - Nonlinearity up to 15 at 0.7 V
  - Responsivity up to 24 A/W at 0.2 V

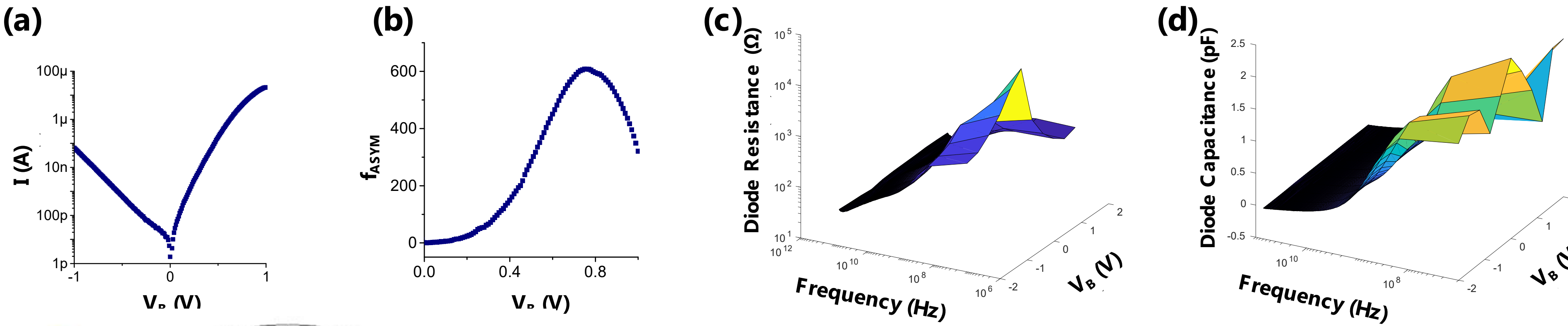


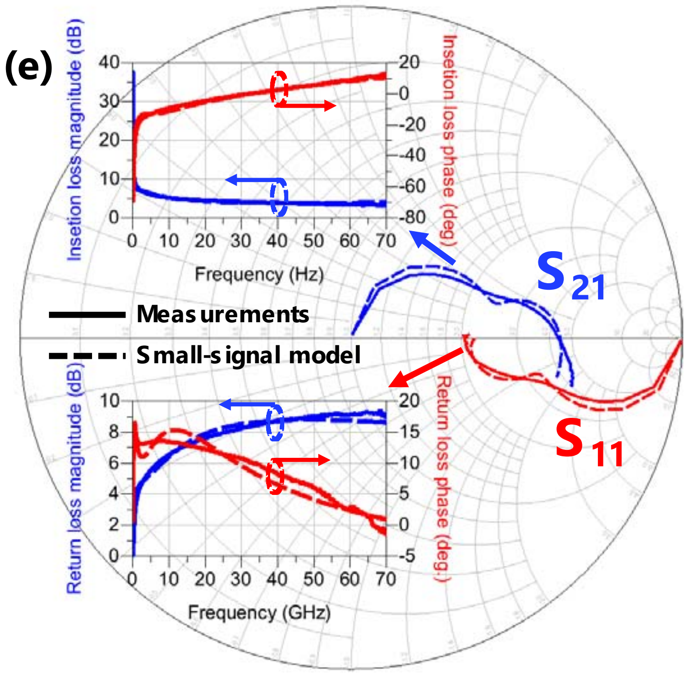






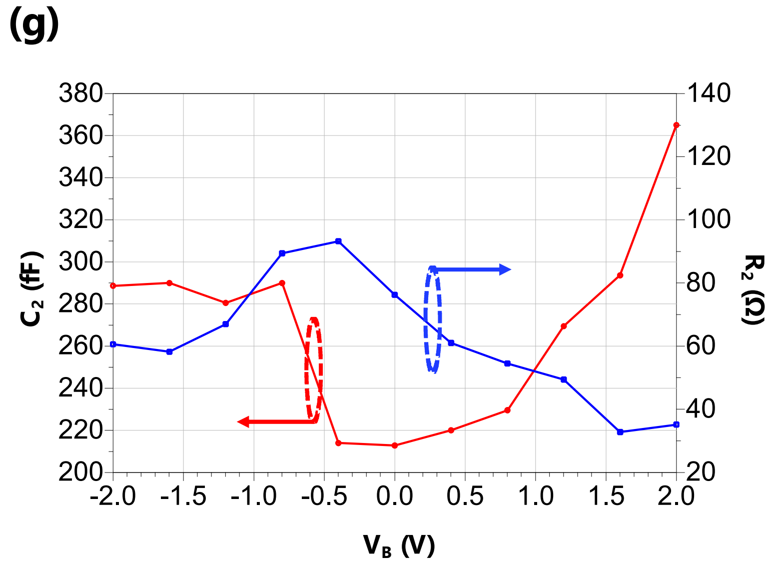
Metal-Insulator-Graphene diode





(f)

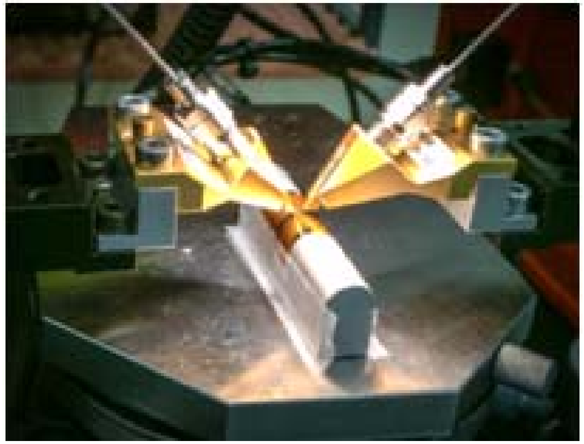
Component	Value	Unit
C_p	5.4	fF
R_s	5.1	Ω
L_s	19	pH
C_{f_pad}	1.1	fF
C_f	7.8	fF
C_1	2	pF
R_G (@0V)	40	Ω
R_1 (@0V)	17	kΩ
C_2 (@0V)	212	fF
R_2 (@0V)	76	Ω

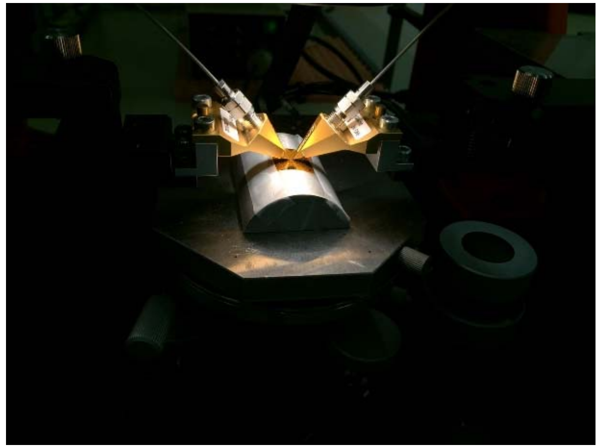


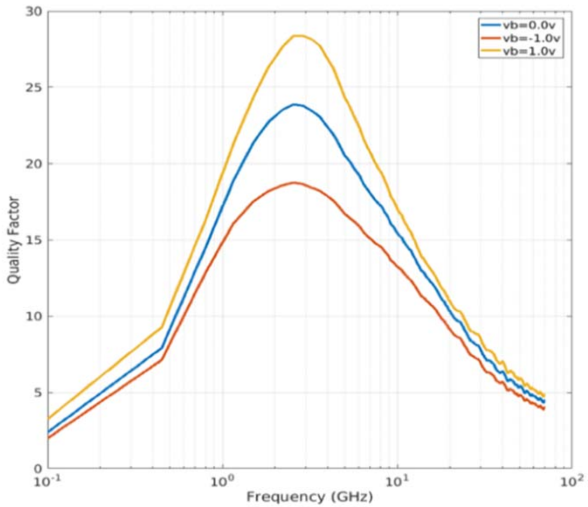
M. Saeed, A. Hamed, Z. Wang, M. Shaygan, D. Neumaier, and R. Negra, “Metal-Insulator-Graphene Diode Mixer based on CVD Graphene-on-Glass,” *IEEE Electron Device Lett.*, pp. 1–1, 2018. DOI: 10.1109/LED.2018.2838451

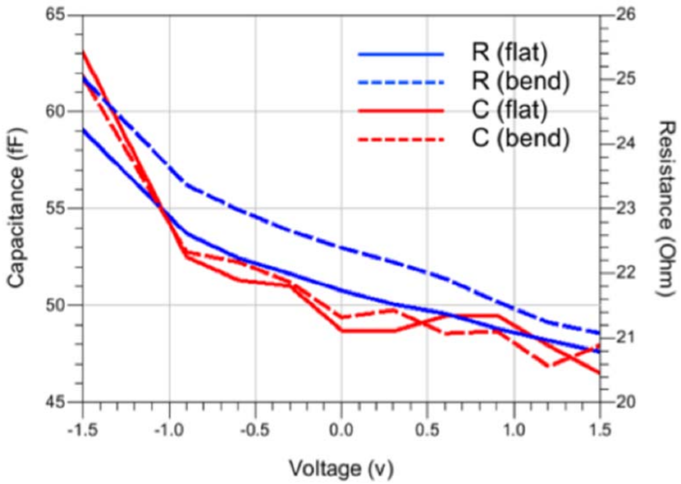
Flexible Graphene varactor

- Varactor operation up to at least 70 GHz
- CVD based process
- Measurements demonstrate
  - Low resistance
    - → High quality factor
    - → Matching
  - Only 2% variation at 5 mm bend radius









M. Saeed, A. Hamed, C.-Y. Fan, E. Heidebrecht, R. Negra, M. Shaygan, Z. Wang, and D. Neumaier, "Millimeter-wave graphene-based varactor for flexible electronics," European Microwave Integrated Circuits Conference, 2017, pp. 117-120. DOI: 10.23919/EuMIC.2017.8230674

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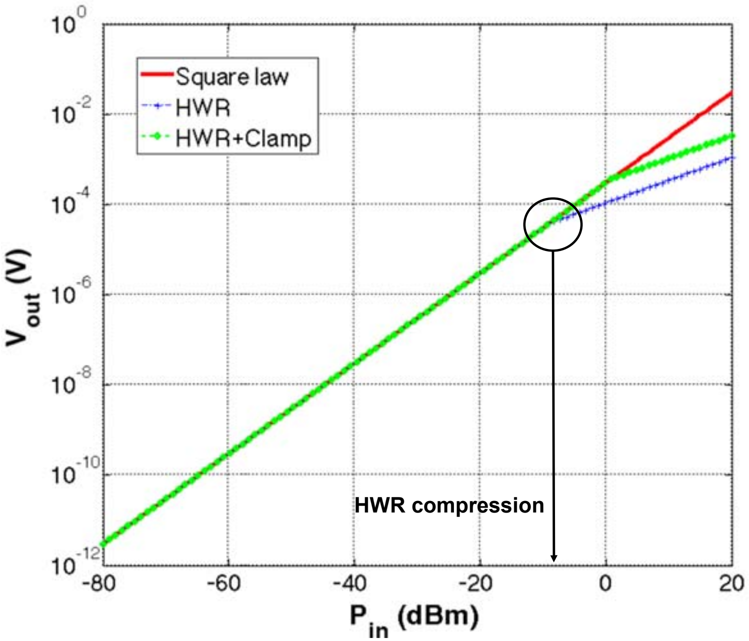
Linear-in-dB V-band power detector

- Linear-in-dB with 50 dB dynamic range
- Tangential signal sensitivity better than -50 dBm
- 15 V/W responsivity at 60 GHz
- Measurements from 40-70 GHz



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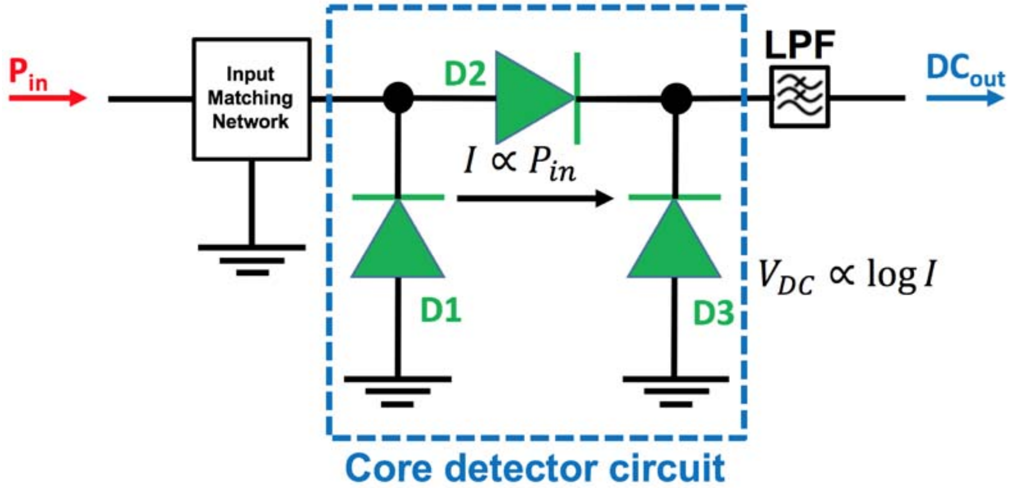
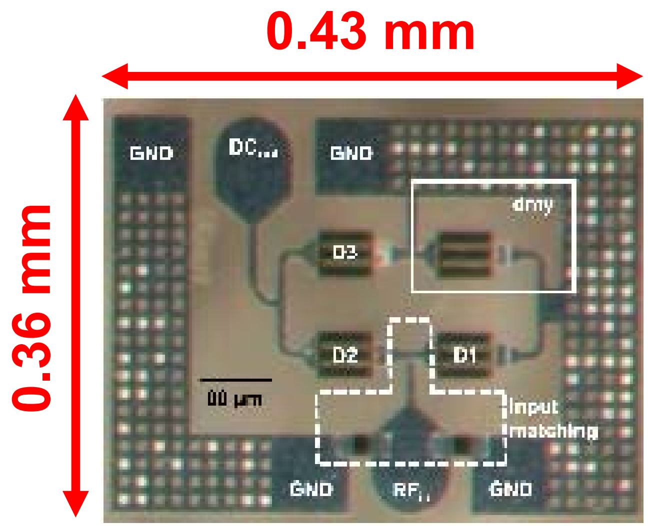
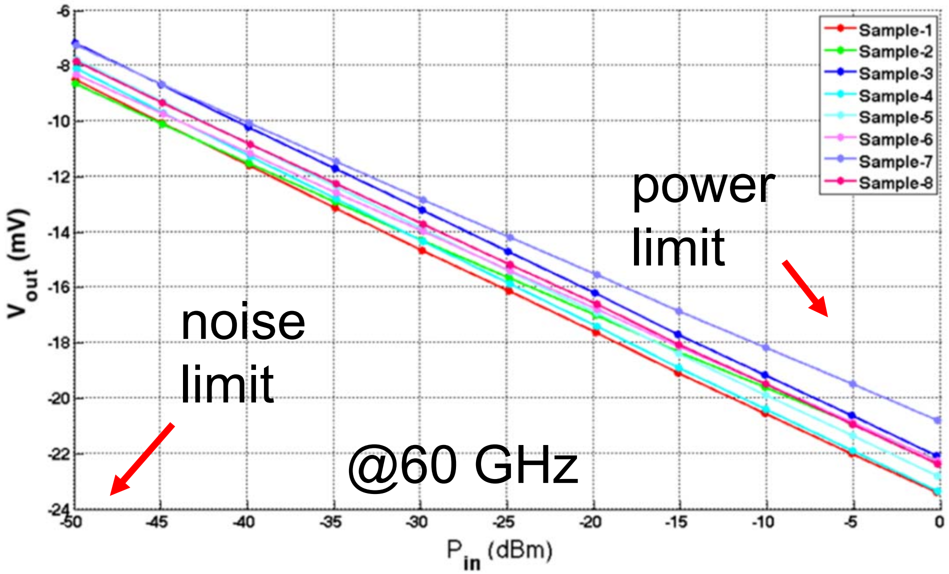


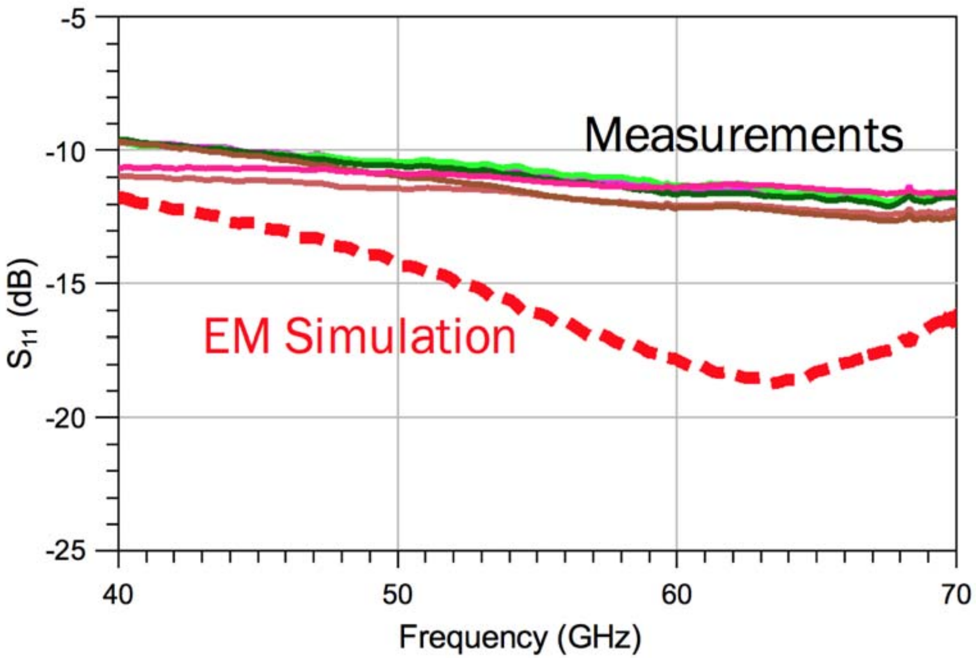
M. Saeed, A. Hamed, Z. Wang, M. Shaygan, D. Neumaier, and R. Negra, "Zero-bias 50-dB dynamic range linear-in-dB V-band power detector based on CVD graphene diode on glass," IEEE Trans. Microw. Theory Techn., vol. 66, no. 4, pp. 2018–2024, Apr. 2018, DOI: 10.1109/ TMTT.2018.2792439.

Linear-in-dB V-band power detector

- Measurements: S-parameter
  - Only 0.15 mm^2 including PADs
  - S_{11} better than -9.5 dB from 40-70 GHz
  - CVD advantage of repeatability







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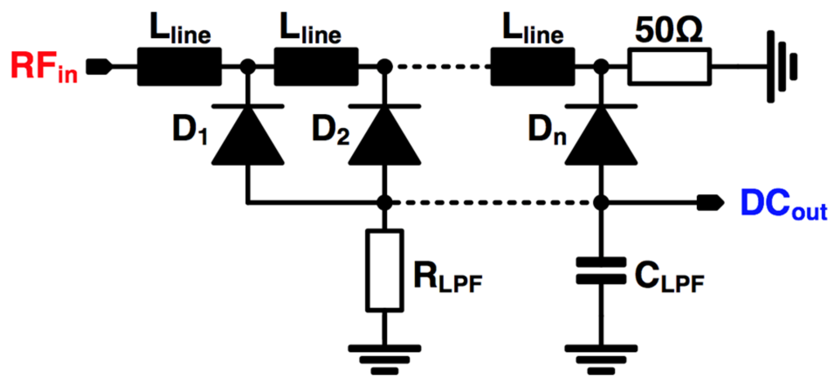
Distributed power detector

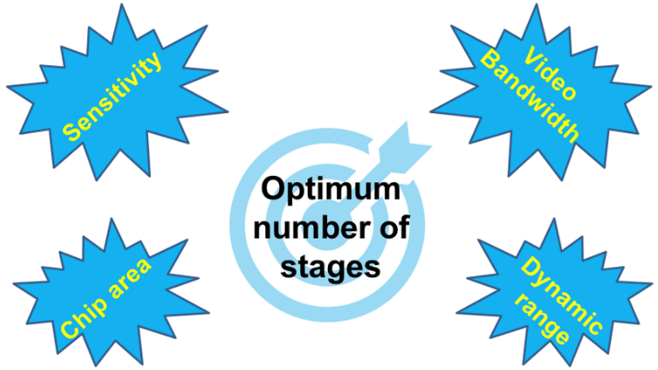


✓ Wideband input matching!

➢ Number of stages!

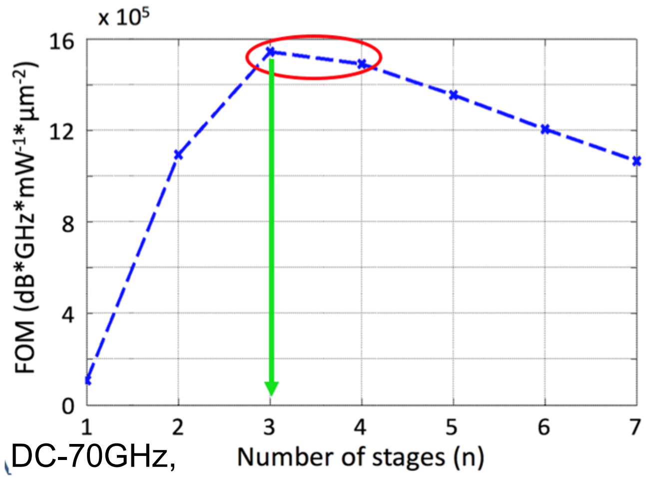
✓ Design optimisation

➢ Proposed figure-of-merit (FOM)



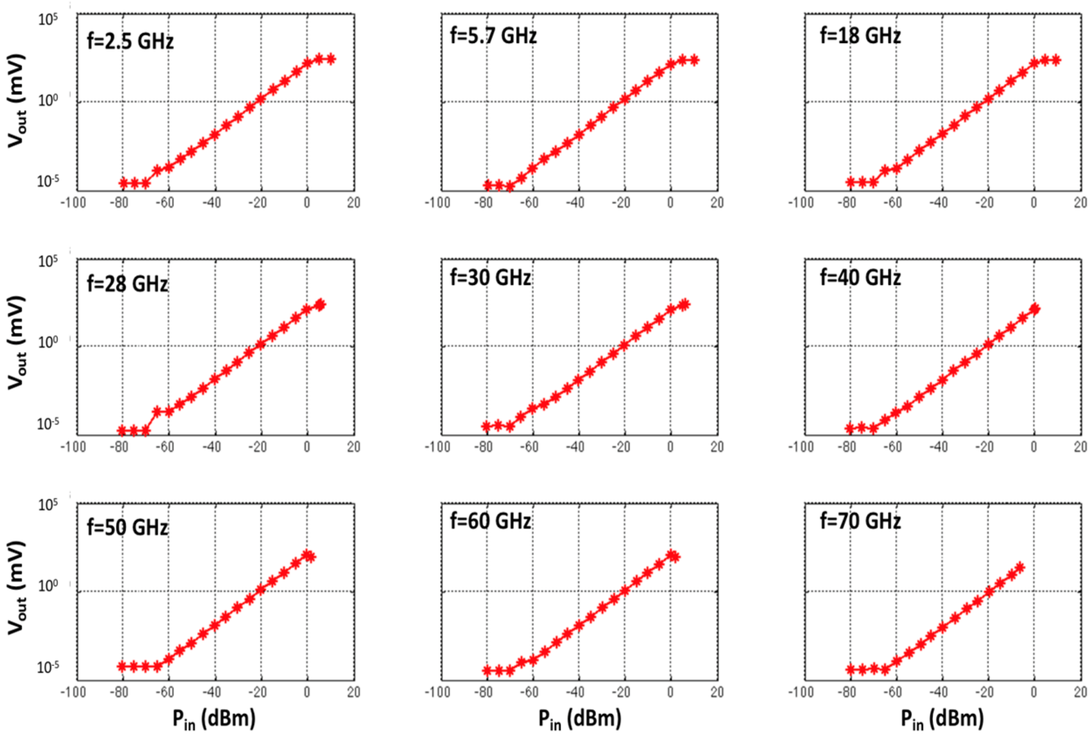
$$FOM(n) = \frac{DR(n) \times VBW(n)}{TSS(n) \times A(n)}$$

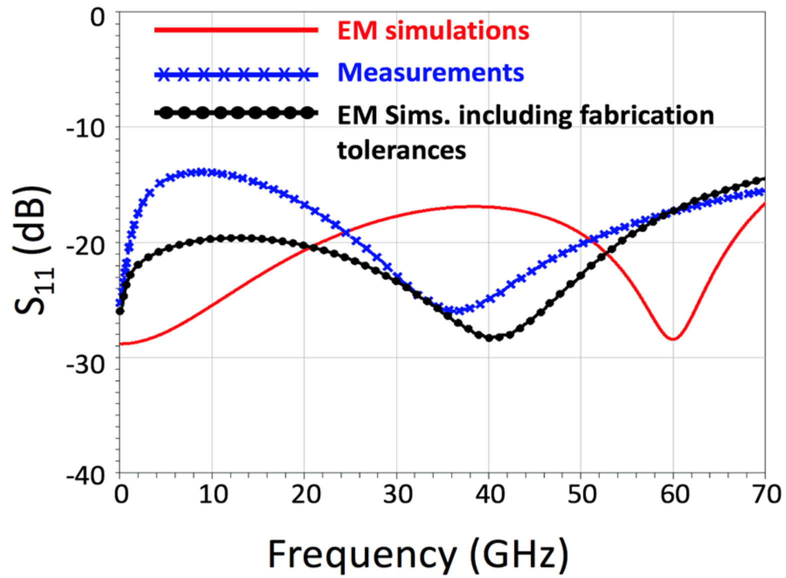
- Dynamic range **DR(n)**
- Tangential signal sensitivity **TSS(n)**
- Video bandwidth **VBW(n)**
- Chip area **A(n)**

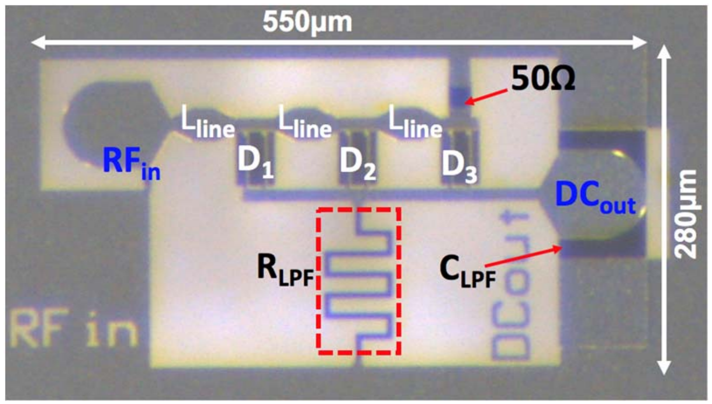


M. Saeed, A. Hamed, S. Qayyum, Z. Wang, M. Shaygan, D. Neumaier, and R. Negra, "0.15 mm 2, DC-70GHz, Graphene-Based Power Detector with Improved Sensitivity and Dynamic Range," IEEE/MTT-S International Microwave Symposium - IMS 2018, 2018, pp. 1519–1522. DOI: 10.1109/MWSYM.2018.8439262

Prototype validation







- ✓ 0.15 mm^2 chip area including pads
- ✓ Excellent measured dynamic range and minimum detectable signal sensitivity
- ✓ Measurement equipment limitations
- ✓ Fabrication process tolerances!

M. Saeed, A. Hamed, S. Qayyum, Z. Wang, M. Shaygan, D. Neumaier, and R. Negra, “0.15 mm 2, DC-70GHz, Graphene-Based Power Detector with Improved Sensitivity and Dynamic Range,” IEEE/MTT-S International Microwave Symposium - IMS 2018, 2018, pp. 1519–1522. DOI: 10.1109/MWSYM.2018.8439262

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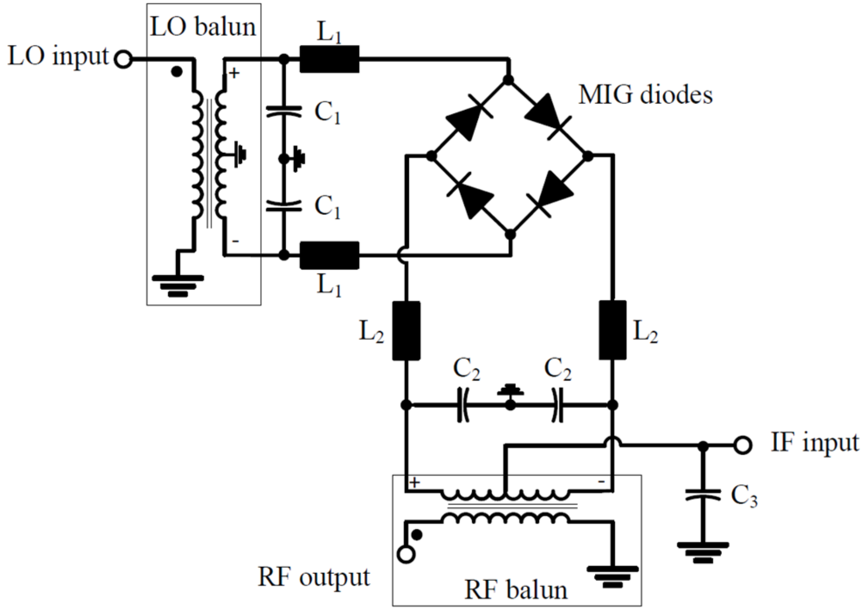
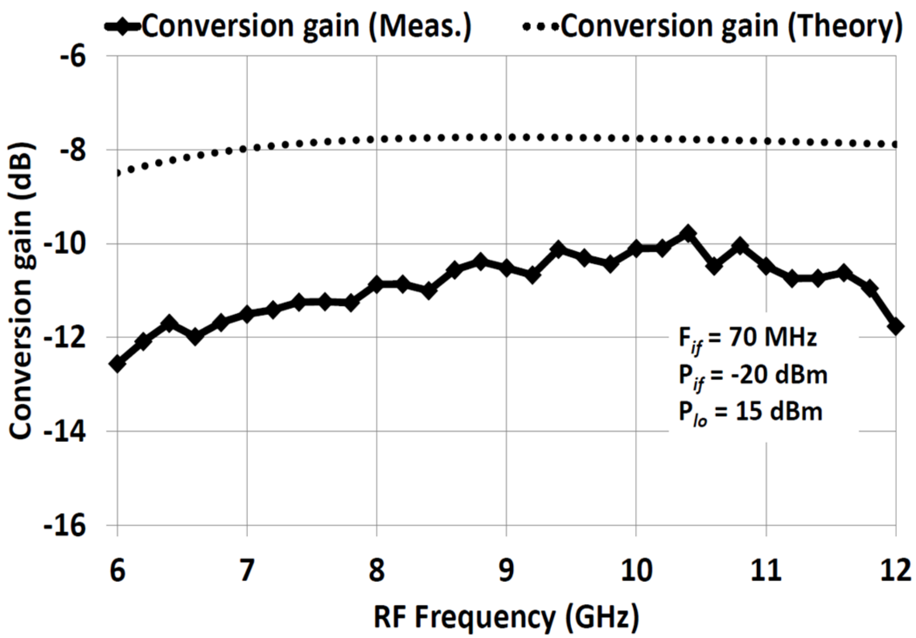
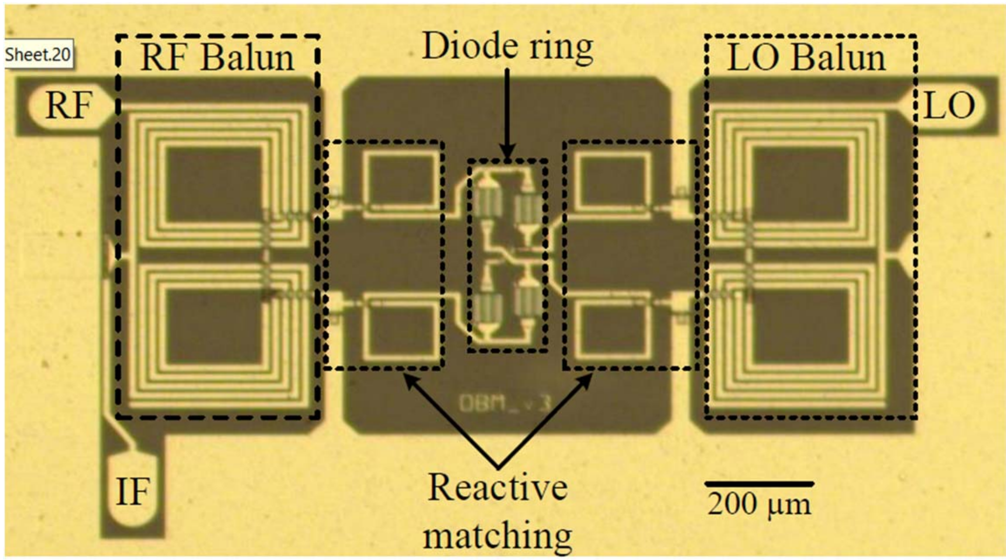
Graphene diode-based double-balanced mixer

- Fully integrated mixer
- Ring mixer core: 4x MIG diodes, CVD-graphene enables repeatability
- MMIC process: Reactive matching, LO & RF balun



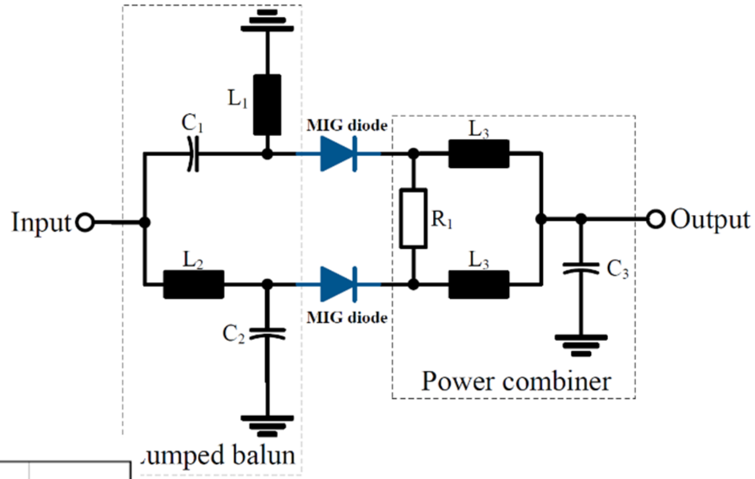


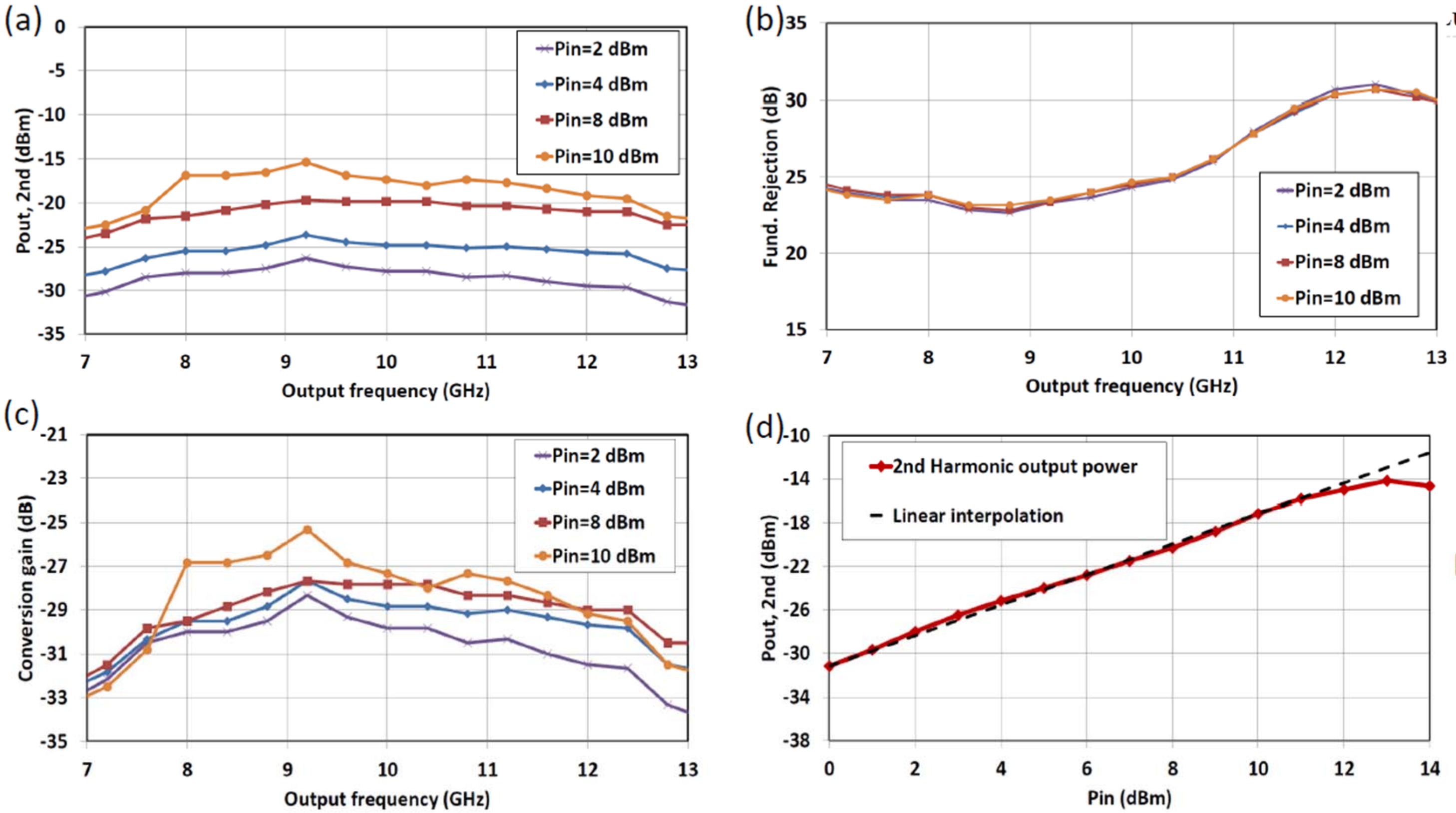


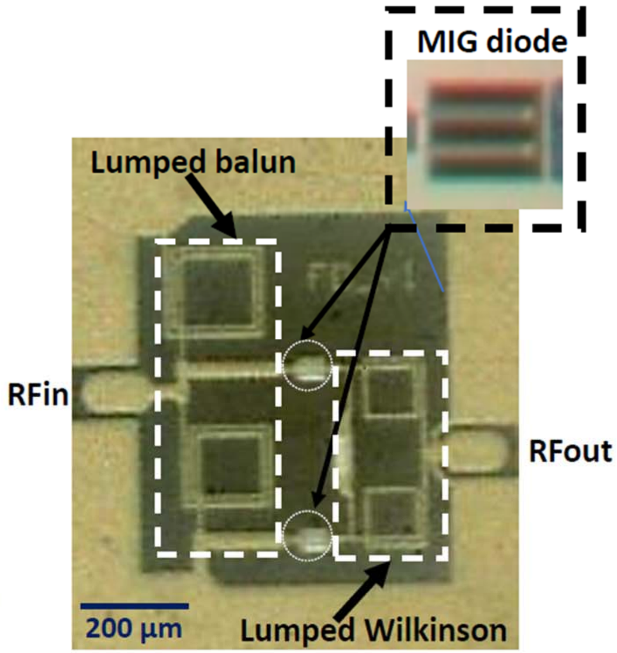
A. Hamed, M. Saeed, Z. Wang, M. Shaygan, D. Neumaier, and R. Negra, “6–12 GHz MMIC Double-Balanced Upconversion Mixer based on Graphene Diode,” IEEE/MTT-S International Microwave Symposium - IMS 2018, 2018, pp. 674–677. DOI: 10.1109/MWSYM.2018.8439211

Graphene diode-based balanced frequency doubler

- Fully integrated frequency doubler
- Core: 2x MIG diodes, CVD-graphene enables repeatability
- MMIC process: lumped balun and combiner







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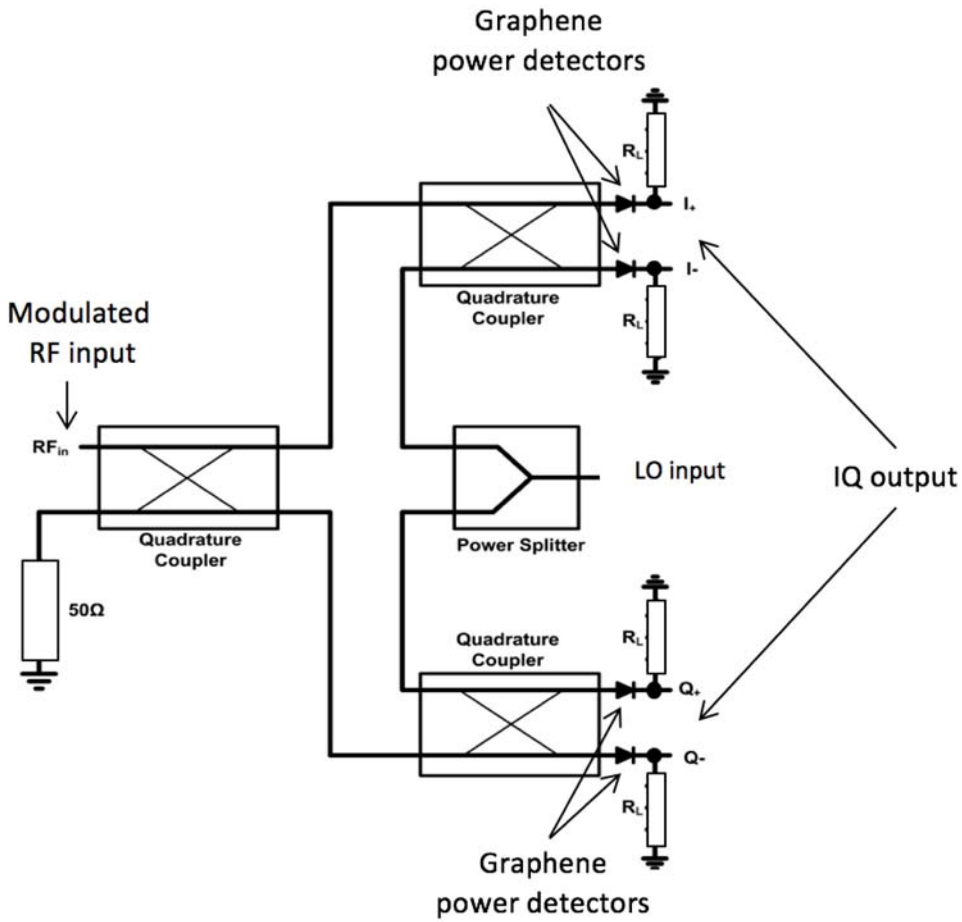
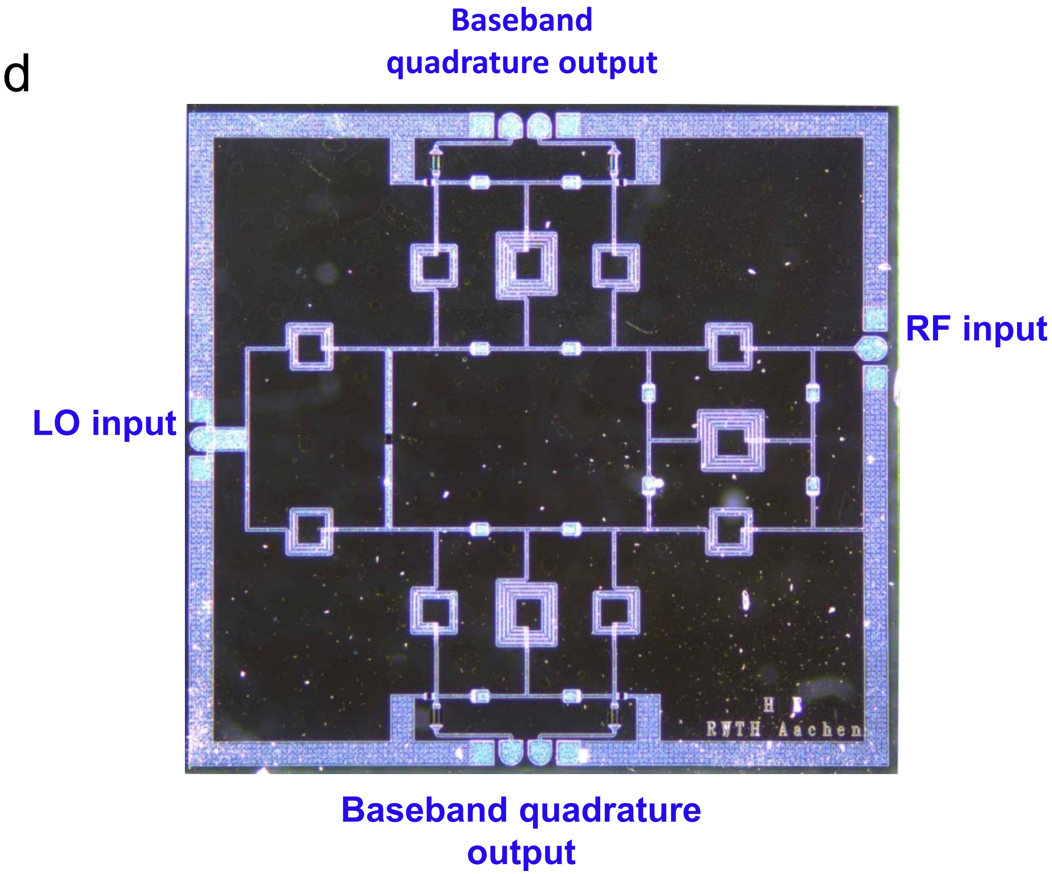
Six-port receiver: concept of operation

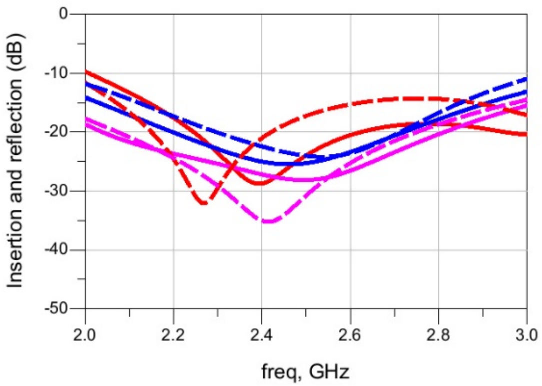
- Full-fledged receiver frontend based on passive six-port junction and power detectors
- Linear addition of complex RF signal with reference LO signal with quadrature phase shifts
- Low complexity, low cost and wideband implementation
- Output calibration to compensate for power detectors nonlinearity

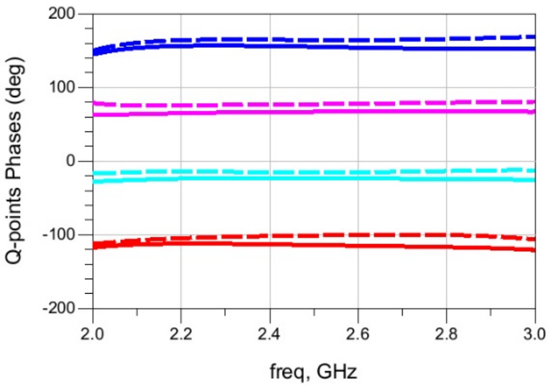


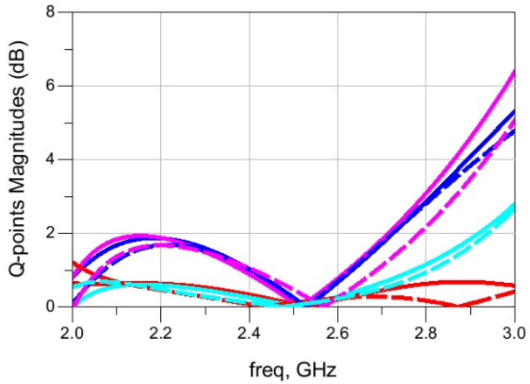
WiFi six-port receiver frontend on Quartz

- Fully integrated IQ receiver frontend
  - 2.1 GHz – 2.7 GHz
- Based on MIG diode detectors
- Lumped-element-based couplers
- Differential IQ baseband outputs





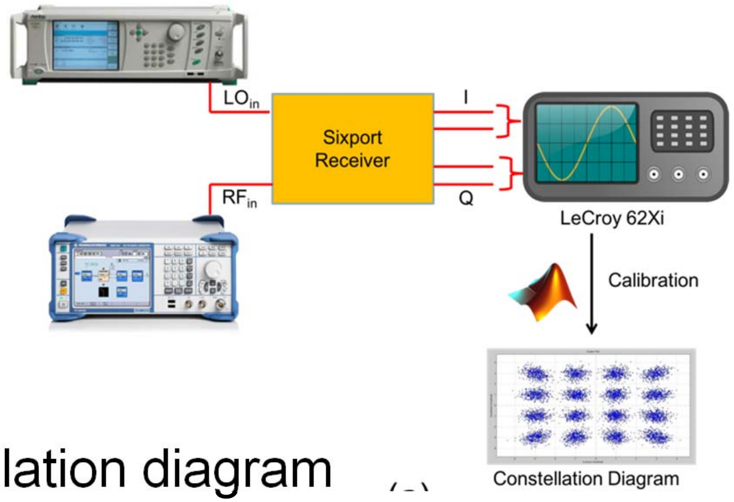




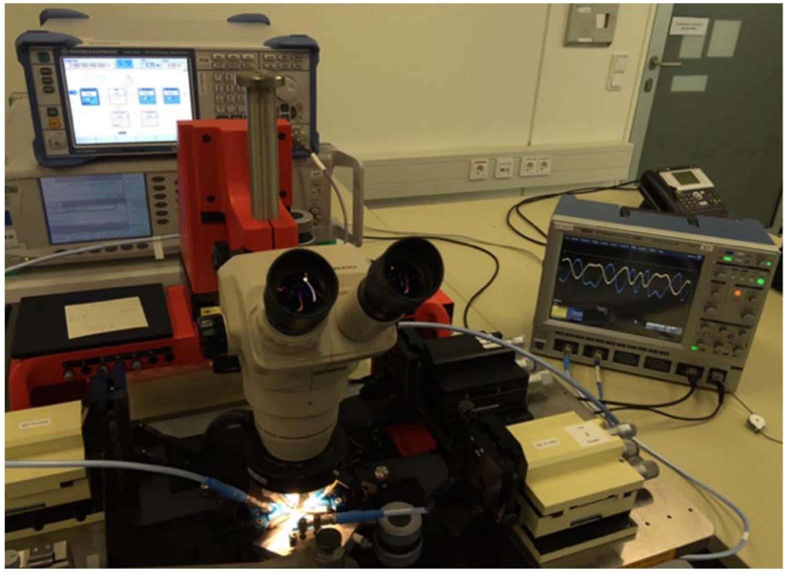
M. Saeed, A. Hamed, Z. Wang, M. Shaygan, D. Neumaier, and R. Negra, "Graphene integrated circuits: new prospects towards receiver realisation," Nanoscale, vol. 10, no. 1, pp. 93–99, 2018, DOI: 10.1039/ c7nr06871a

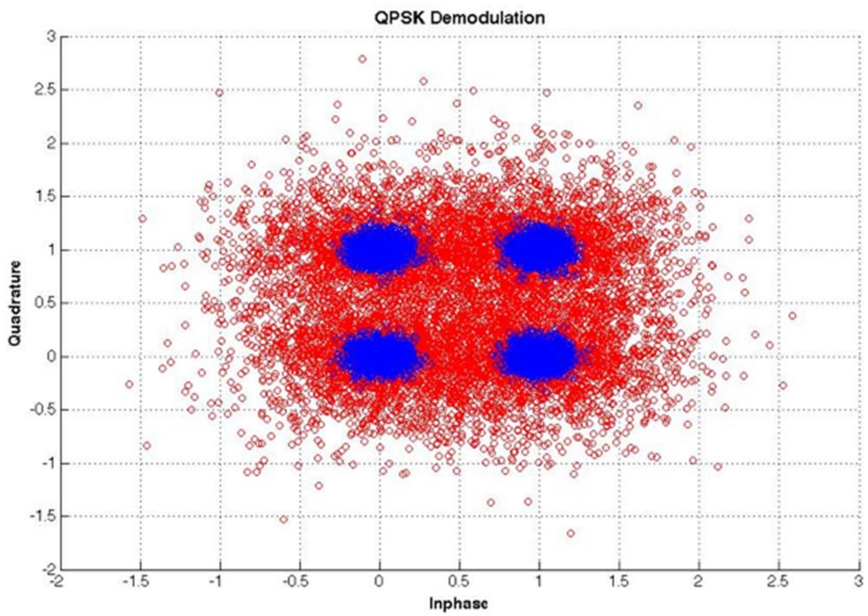
WiFi six-port receiver frontend on Quartz

- On-wafer probing measurement setup
  - RF power = -15 dBm
  - LO power = 0 dBm
  - 20 Mbps QPSK modulated signal



- Calibration algorithm applied for better constellation diagram

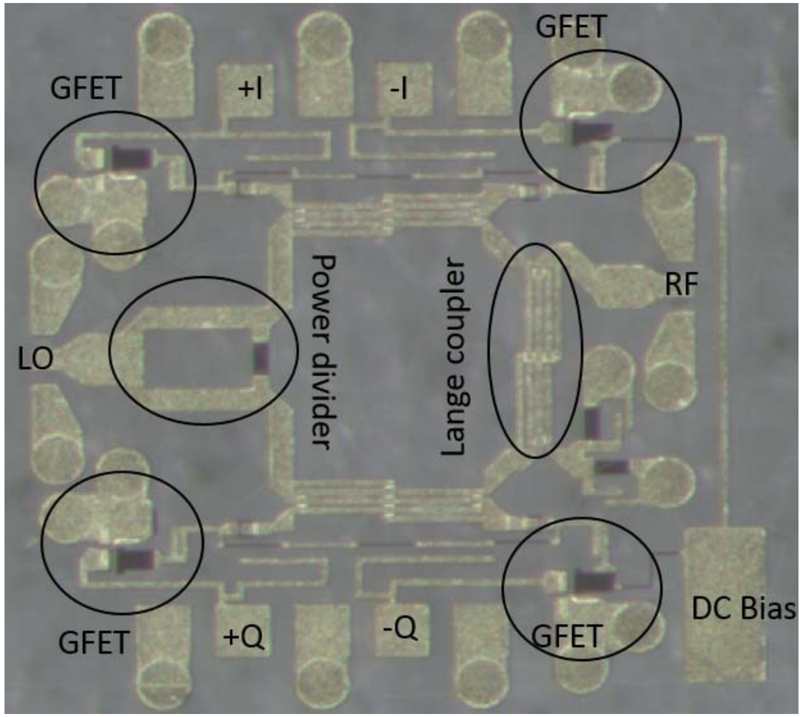


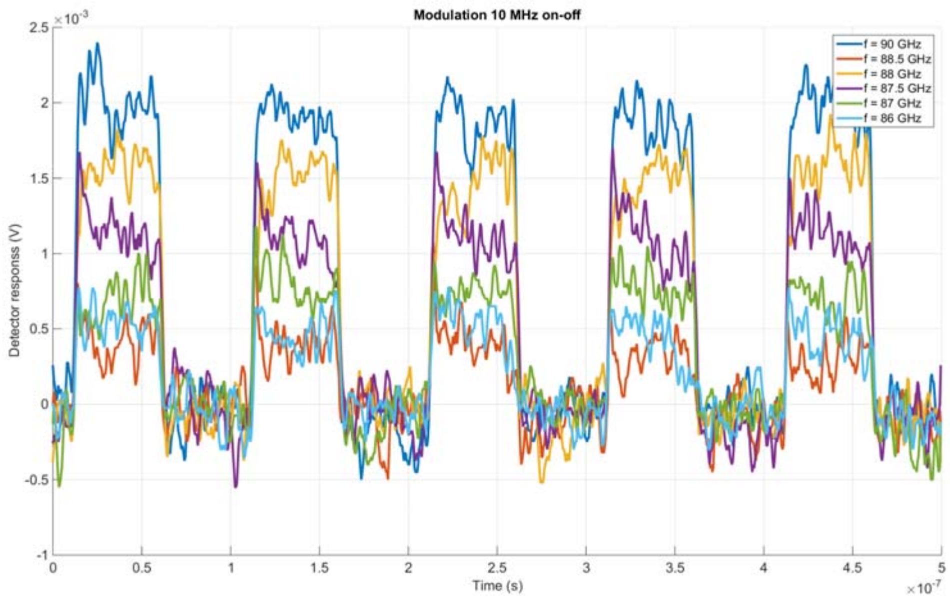


M. Saeed, A. Hamed, Z. Wang, M. Shaygan, D. Neumaier, and R. Negra, “Graphene integrated circuits: new prospects towards receiver realisation,” Nanoscale, vol. 10, no. 1, pp. 93–99, 2018, DOI: 10.1039/ c7nr06871a

W-band six-port receiver frontend on SiC

- Fully integrated IQ receiver frontend
  - 70 GHz – 110 GHz
- Based on GFET power detectors
- Single-ended RF and LO input signals
- Differential IQ baseband outputs
- Single dc bias pads for all detectors
- On-wafer probing measurement setup





- Successful demodulation of 10 Mbps OOK signal from 86 GHz to 90 GHz

A. Hamed, O. Habibpour, M. Saeed, H. Zirath, and R. Negra, “W-Band Graphene-Based Six-Port Receiver,” *IEEE Microw. Wireless Compon. Lett.*, pp. 1–3, 2018. DOI: 10.1109/LMWC.2018.2808416

Summary and Outlook

- Substrate independent, Graphene-based thin-film MMIC
- Graphene-based diodes enabling at least up to millimetre-wave integrated circuits and systems
- Wideband millimetre-wave power detectors based on MIG diode
- Six-port concept is proposed and utilized to implement WiFi and W-band receiver frontends
- Receiver frontends on both rigid and flexible substrates are in fabrication
- Further improvement in GFET is crucial to enable more Graphene-based application