Development of Gallium Nitride Monolithic Microwave Circuits for the Modular Dual-Band Ku/Ka Antenna Tile with Digital Calibration (K-Tile)

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Outline

1) Purpose and Objective
2) Background
   - Ka-band (26.5-40 GHz) 35.5 GHz radar front end
   - Why Gallium Nitride (GaN)?
3) Status of GaN MMIC development
   - New GaN Ka-band monolithic microwave integrated circuits (MMICs)
4) Summary
5) Acknowledgement

Purpose and Objective

- This talk reviews Ka-band (35.5 GHz) GaN MMICs being developed for the ACT13 project "**Modular Dual-Band Ku/Ka Antenna Tile with Digital Calibration (K-Tile).**" The Principle Investigator is Jim Hoffman.
- **Purpose:** Advance Earth science knowledge by developing new microwave sensors for high-resolution satellite observations of rainfall and soil moisture and extending TRMM-type measurements to high latitude. Ku/Ka band frequencies are main candidates for measuring the 3D structure of cloud and precipitation dynamics. Ku-band (12.4-18 GHz) for interior cloud convection processes and Ka-band for solid/liquid mixed phase hydrometeors and light precipitation dynamics.
- **Objective:** Develop new Ka-band (35.5 GHz) MMICs to enable radar transceiver unit cells (K-tile) that can be stacked in various compact configurations for agile electronically scannable radar arrays (airborne – drones, aircraft; space – cubesats, satellites)

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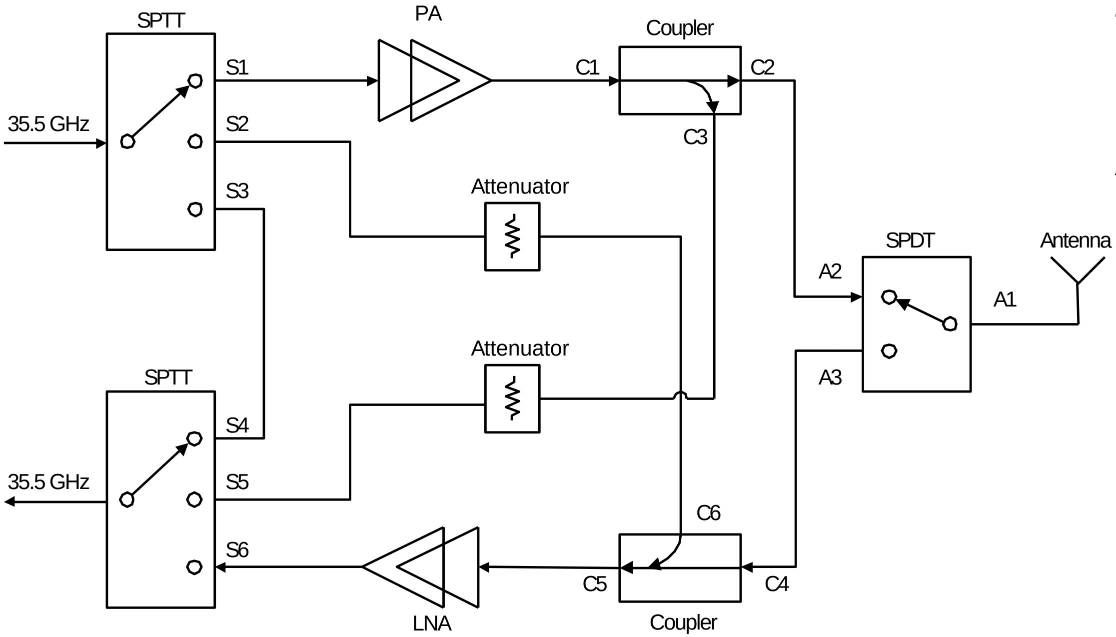
Background

- Ka-band 35.5 GHz radar front end circuit unit cell schematic



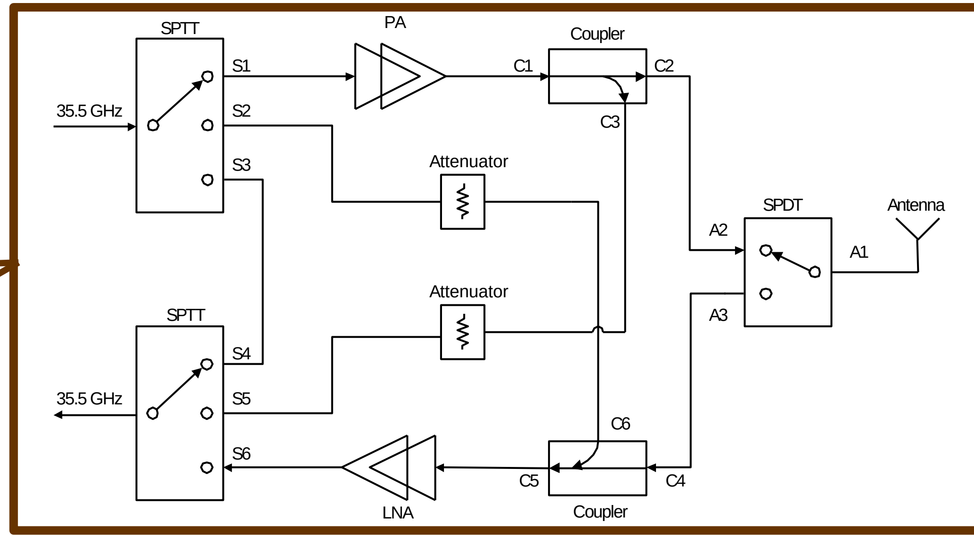
Transmit Path:
S1,C1,C2,A2,A1
Receive Path:
A1,A3,C4,C5,S6

- The goal is to implement the 6 components that consists of the radar RF front end: power amplifier (PA), low noise amplifier (LNA), single pole double throw switch (SPDT), single pole triple throw switch (SPTT), voltage controlled attenuator (VCA) and coupler
- Calibration circuitry included in the front end
- LNA during transmit should not be damaged or pushed into saturation for phase and amplitude stability

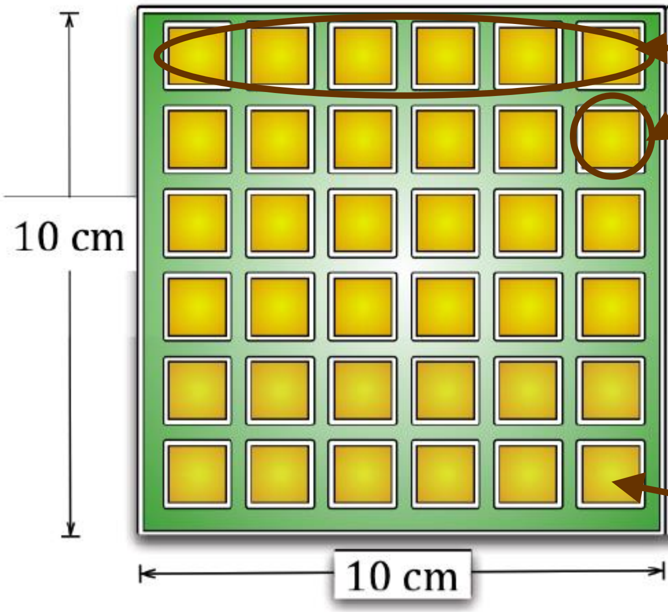
Background

- K-Tile

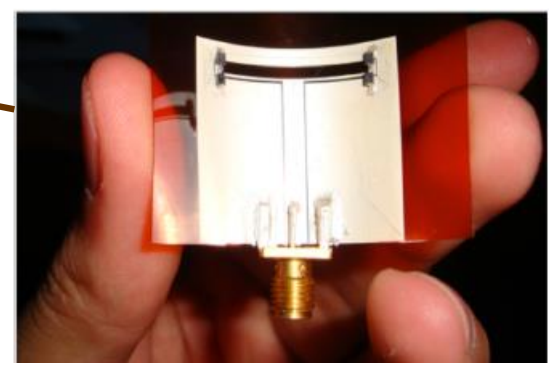
K-Tile Ka-Band Transceiver Front End



K-Tile
6x6 patch array aperture



Printed Patch Antenna



Why Gallium Nitride (GaN)?

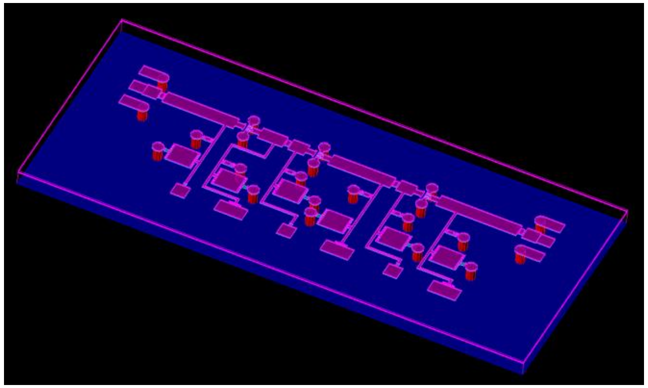
- High power density is due to its intrinsic large band gap => high voltage swing capability => higher efficiency
- High frequency operation is enabled by transistor scaling to reduce gate length and epitaxial layer thicknesses => reduce electron transit time through the transistor
- SiC substrate has higher thermal conductivity than other presently practical semiconductor materials => improve thermal management
- Physically robust material => higher temperature operation, can withstand higher power/voltage handling => more reliable for extreme environment operation

Semiconductor		Gallium Nitride	Silicon Carbide	Indium Phosphide	Gallium Arsenide	Silicon
Bandgap	eV	3.49	3.25	1.35	1.42	1.12
Breakdown Field	MV/cm	3.3	3	0.5	0.4	0.3
Electron Mobility	$cm^2/V*s$	1,000-2,000	700	5,400	8,500	1,500
Thermal Conductivity	W/(cm*K)	2.0	4.5	0.68	0.54	1.56
Dielectric Constant	εr	9	10	12.5	12.8	11.8

D. Runton et al., *“History of GaN: High-Power RF Gallium Nitride (GaN) from Infancy to Manufacturable Process and Beyond,”* IEEE Microwave Magazine 2013.
http://www.aps.org/units/fiap/meetings/presentations/upload/khan.pdf

Status of Ka-Band (35.5 GHz) Radar MMICs in Development

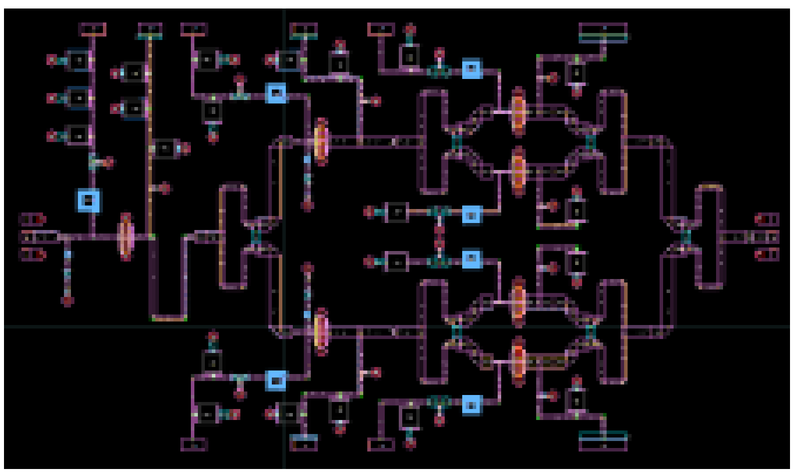
- Design in Qorvo foundry process GaN15
  - For amplifiers and switches up to 40 GHz
  - GaN high electron mobility transistors (HEMTs) with 0.15 µm gate lengths
  - GaN epitaxy grown on silicon carbide substrate with through wafer vias
  - Multi-metal layer process
  - Integrated thin film metal-insulator-metal (MIM) capacitors and resistors
  - Power density: 4.5 W/mm at 30 GHz
  - Reliability: 10M hours at 200C and 28V (MTTF where Idmax changes by 10%)
  - 100 mm wafer size
- All preliminary circuit designs are complete and layouts have been drawn up
  - Electromagnetic simulations are continuing to examine proximity effects and for verification

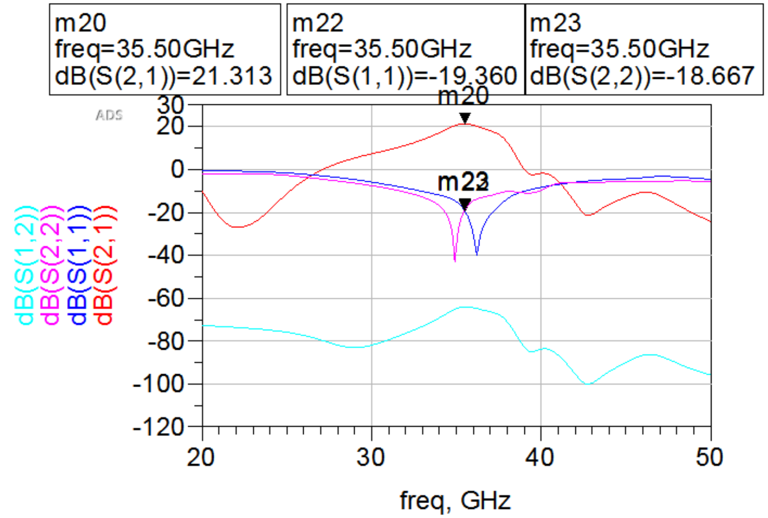


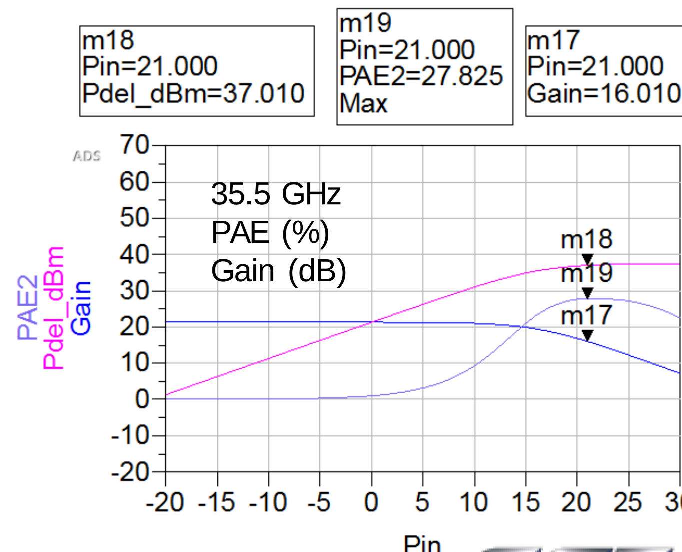
GaN MMIC Amplifiers

GaN Power Amplifier

- 3-Stage amplifier
- 8x50um gate width GaN HEMTs
- Wilkinson power divider/combiners
- 35.5GHz: Pout,max 37dBm (5W), PAE 27.8%, Gain 16 dB
- Total drain bias at Pout, max 18V, 978mA
- At lower DC bias: 4W output power, 18V, 447mA







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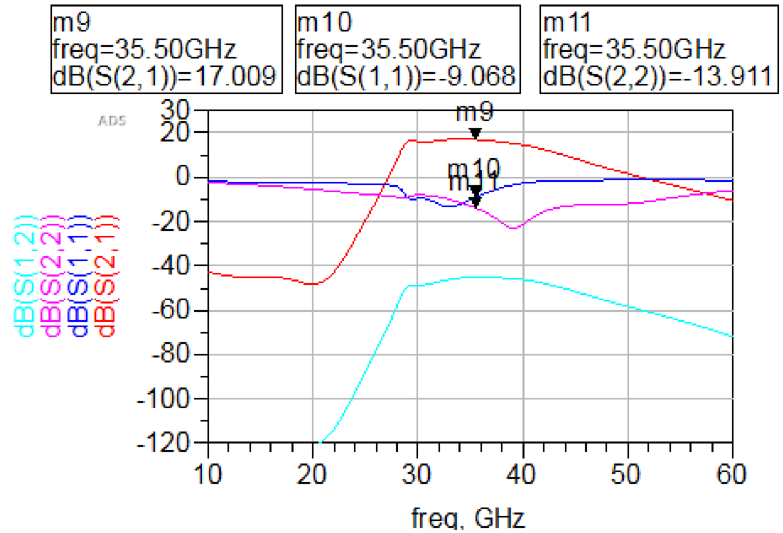
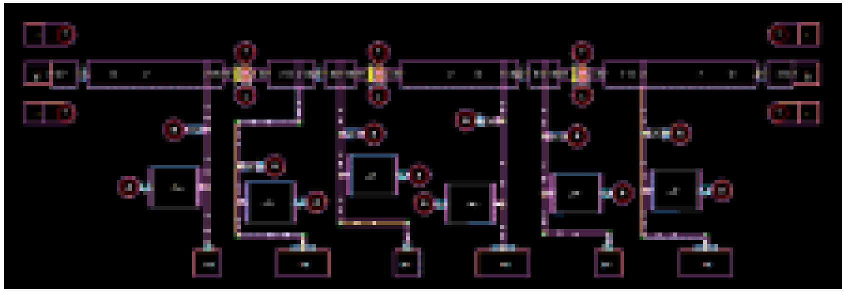
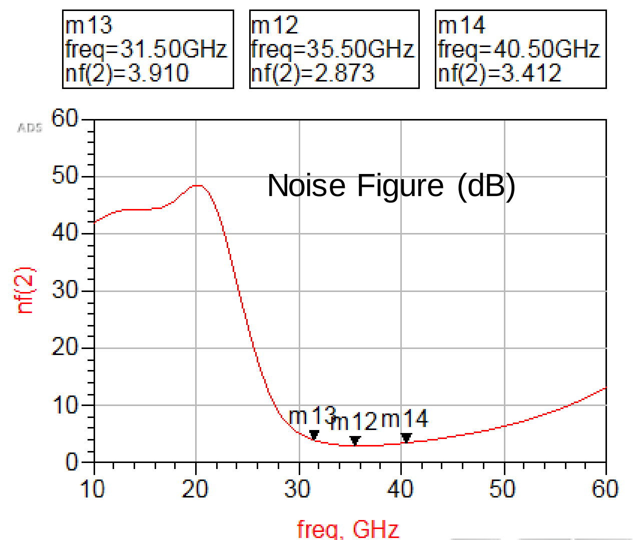
GaN MMIC Amplifiers

GaN Low Noise Amplifier (LNA)

- 3-Stage amplifier
- 4x25um gate width GaN HEMTs
- 35.5GHz: Gain 17dB, Noise Figure 2.9dB
- Total drain bias 10V, 30mA







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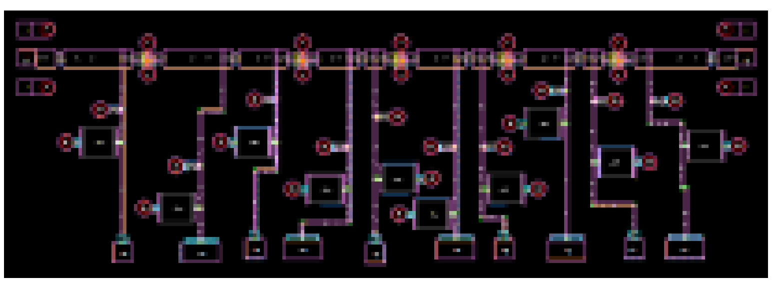
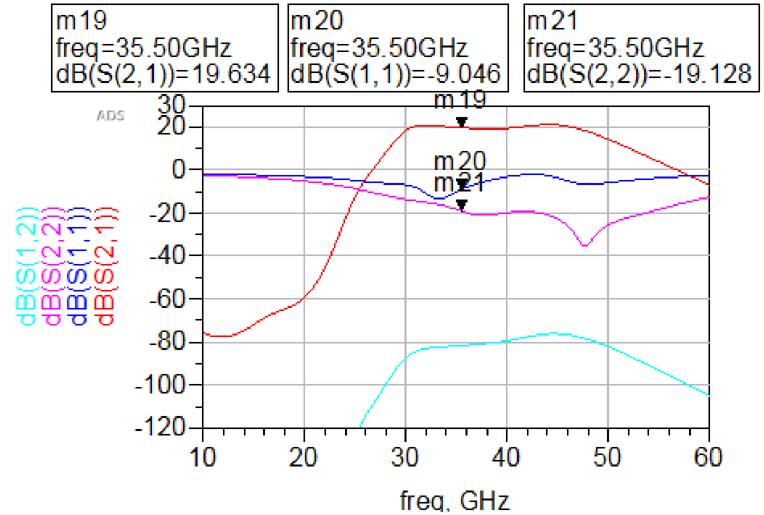
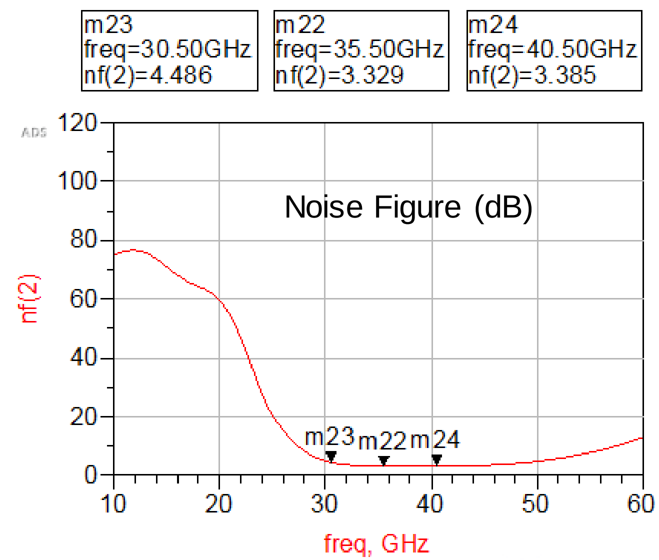
GaN MMIC Amplifiers

GaN Broadband LNA

- 5-Stage amplifier
- 4x20um and 4x25um gate width GaN HEMTs
- 35.5GHz: Gain 19.6dB, Noise Figure 3.3dB
- Drain bias 10V, 46mA



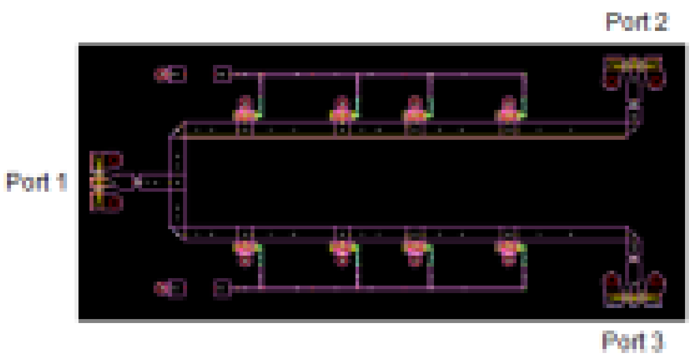




GaN MMIC Switches

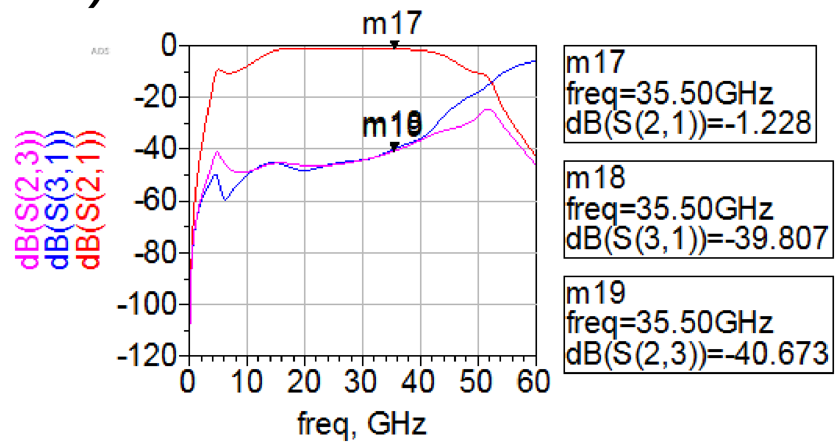
GaN Single Pole Double Throw (SPDT)

- 4 HEMT per branch shunt to ground configuration
- 3x100um gate width GaN HEMTs
- 35.5GHz: Insertion Loss -1.2dB,
  Isolation -40 dB, Match S11,22 < -23 dB
- Gate voltage: -20V off-state, 0V on-state

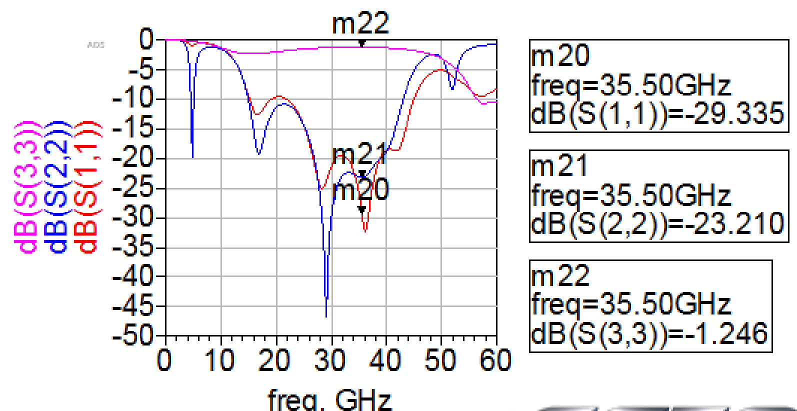


Port 1 and 2 On-State, Port 3 Off-State

Loss S21 and Isolations S31,23 (dB):



Port Match (dB):

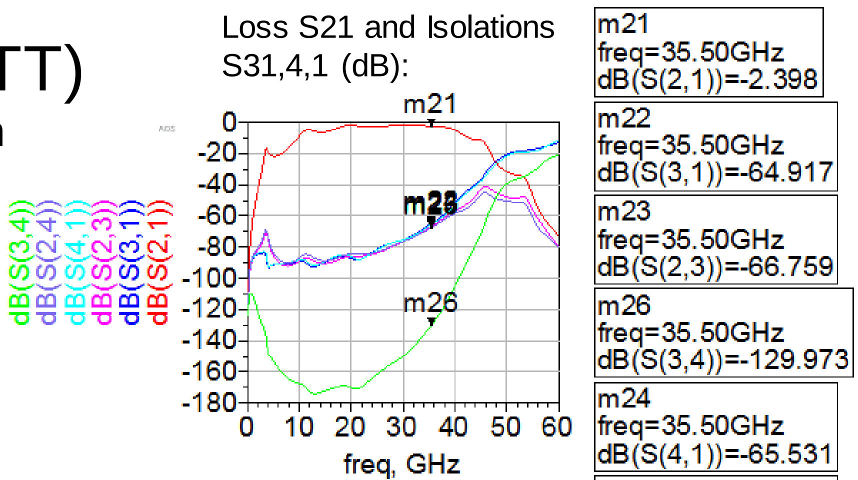


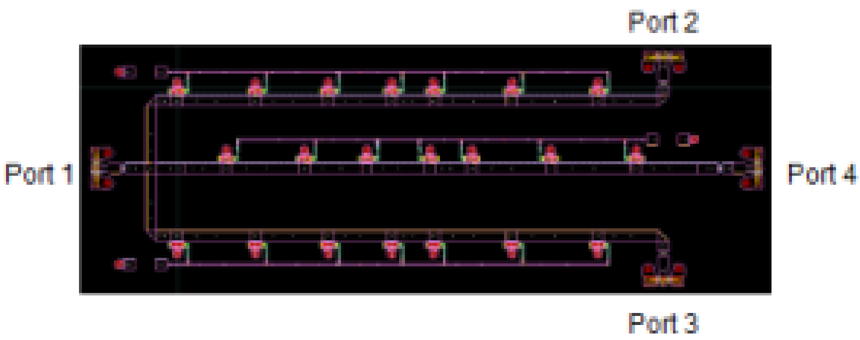
GaN MMIC Switches

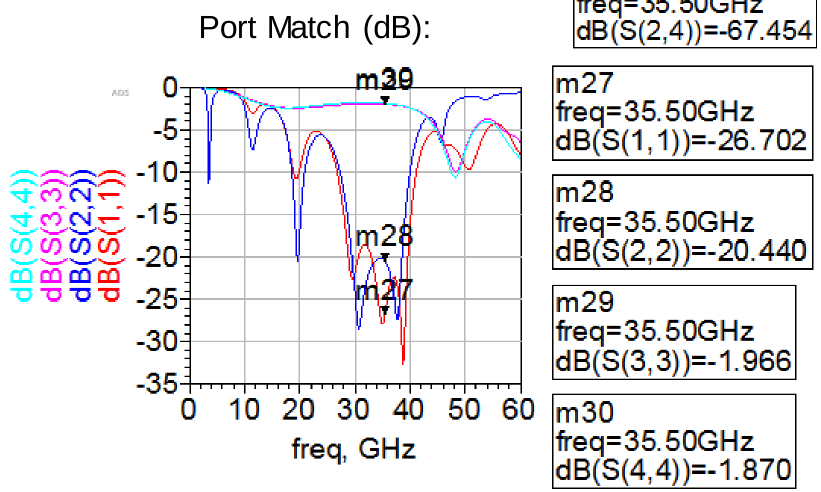
Port 1 and 2 On-State, Port 3 and 4 Off-State

GaN Single Pole Triple Throw (SPTT)

- 7 HEMT per branch shunt to ground configuration
- 3x100um gate width GaN HEMTs
- 35.5GHz: Insertion Loss -2.4dB,
  Isolation -65dB, Match S11,22 < -20 dB
- Gate voltage: -20V off-state, 0V on-state







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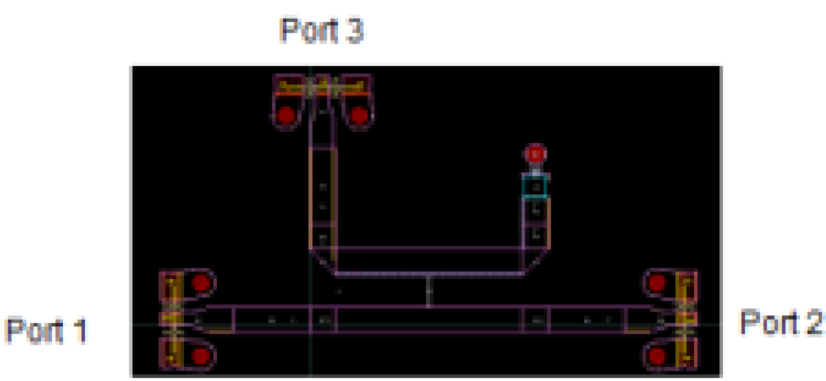
MMIC Coupler

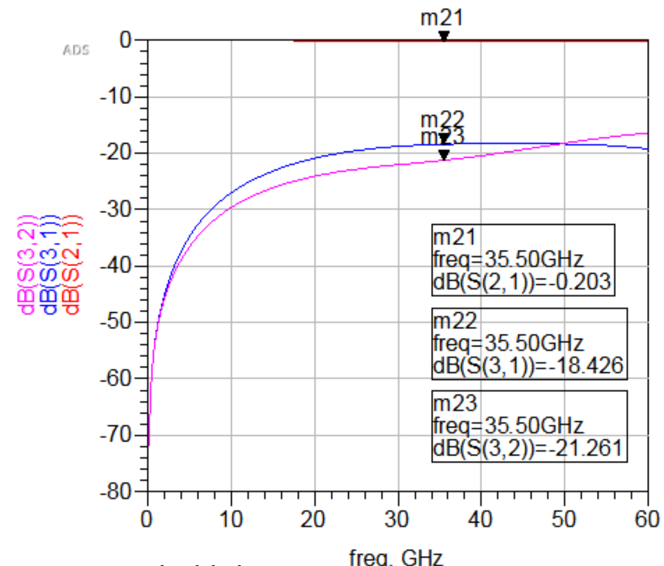
Microstrip Quarter Wave Coupler

- Input Port 1, Output Port 2, Coupled Port 3
- 35.5GHz: Insertion Loss (S21) -0.2dB, Coupling (S3,1) -18dB, Directivity is 2.8 dB, Port match about -30 dB

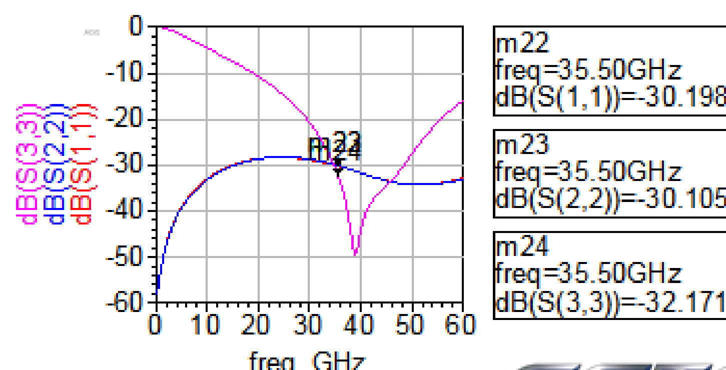


Thru Ports 1 to 2, Coupling Port 3

Loss S21 and Coupling S31 (dB):



Port Match (dB):



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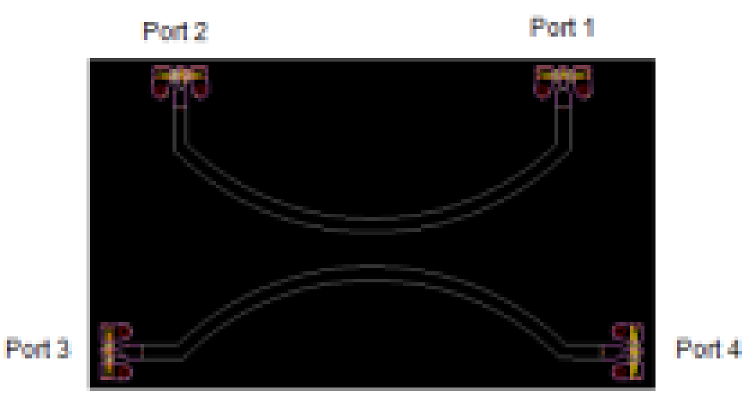
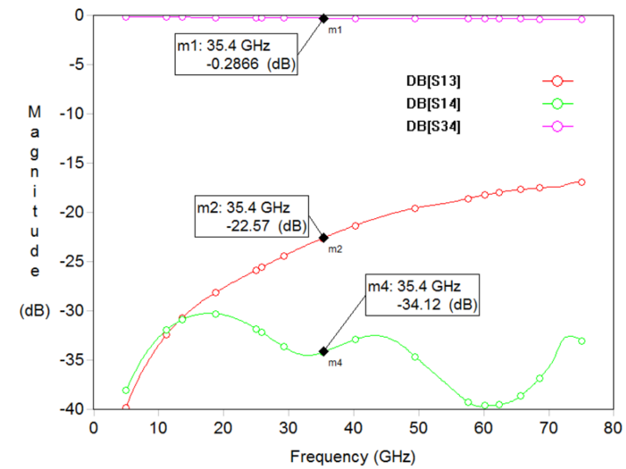
MMIC Coupler

Microstrip 'Arc' Coupler

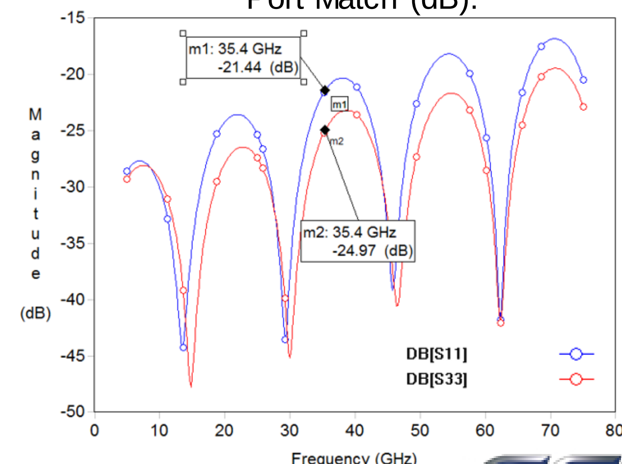
- For improved directivity (Morgan and Weinreb 2003)
- Input is Port 3, Coupled port is Port 1, Output is Port 4, Isolated port is Port 2
- 35.4GHz: Insertion Loss (S21) -0.3dB, Coupling (S3,1) -22.6dB, Directivity is 11.6 dB, Port match better than -21dB,



S-Parameters
Input Ports 3, Output Port 4, Coupling Port 1, Isolated Port 2



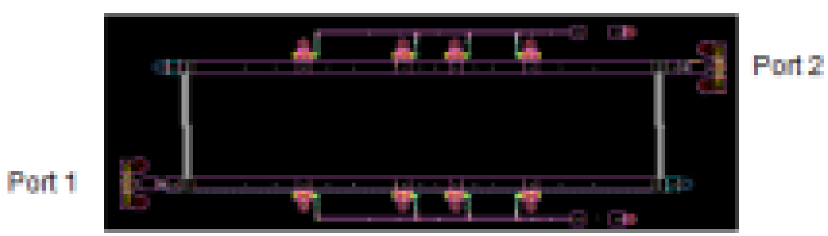
Port Match (dB):



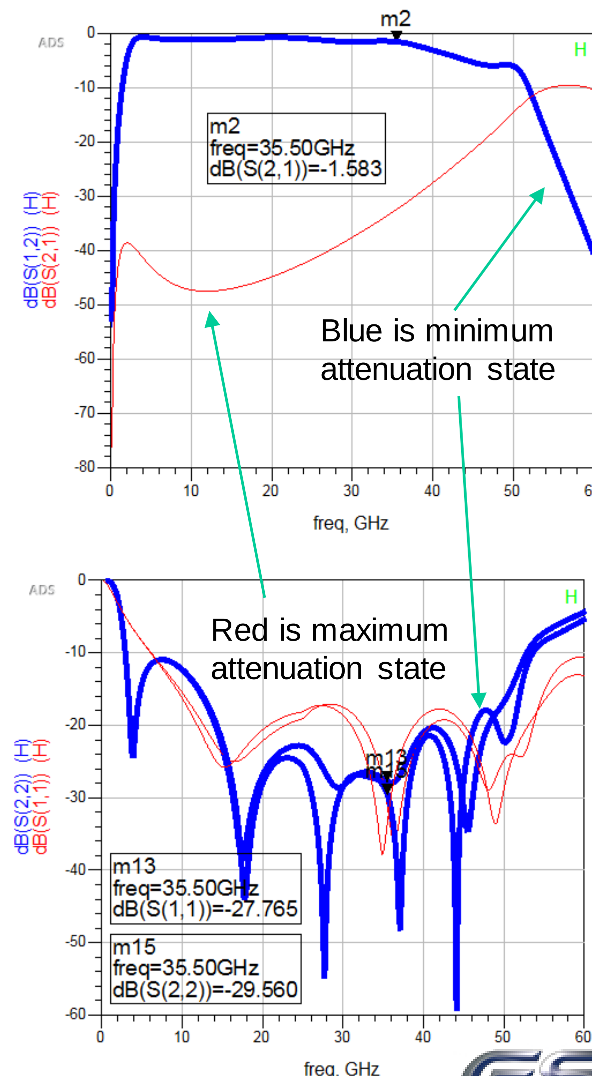
GaN MMIC Attenuator

Voltage Controlled Attenuator

- Consists of two microstrip branch lines with 4 GaN HEMTs shunt to ground for continuous voltage control attenuation
- Lange couplers are used to improve match
- VCA HEMT gate control lines are biased,
    - 0V for maximum attenuation S21 -32.4 dB, with match S11,22 of better than -31dB
    - -20V for minimum attenuation S21 -1.58 dB with match S11,22 of better than -27 dB

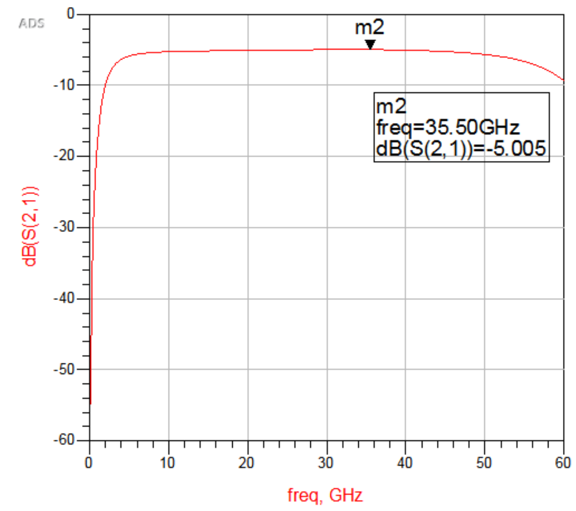


S-Parameters



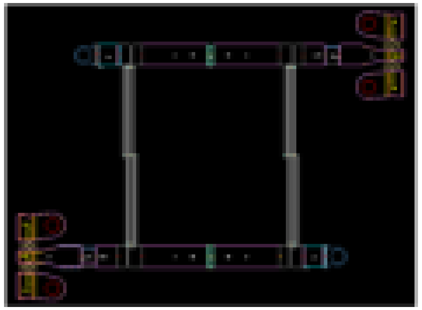
GaN MMIC Attenuator

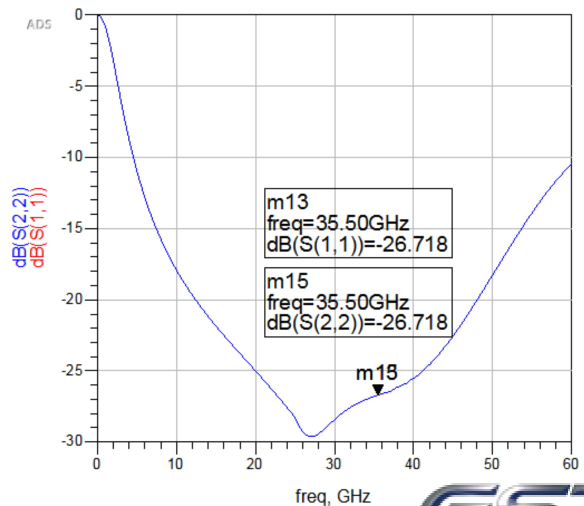
S-Parameters



Fixed Value 5 dB Attenuator

- Consists of two microstrip branch lines with series thin-film resistors to achieve fixed 5 dB attenuation
- Lange couplers are used to improve match S11,22 of better than -26dB
- Fixed attenuators are simpler to use and won't fluctuate with voltage bias supply compared to VCA





Summary

- We are supporting the advancement of Earth science by developing microwave electronic components for an new Ka-band radar that can improve high-resolution airborne and/or satellite observations of rainfall and soil moisture.
- Ku/Ka band frequencies are main candidates for measuring the 3D structure of cloud and precipitation dynamics. Ku-band (12.4-18 GHz) for interior cloud convection processes and Ka-band for solid/liquid mixed phase hydrometeors and light precipitation dynamics.
- Specifically in this task we are developing new Ka-band (35.5 GHz) MMICs to enable a radar transceiver unit cell (K-tile) that can be stacked in various compact configurations for agile electronically scannable radar arrays (for airborne – drones, aircraft; space – cubesats, satellites) to enable characterization of large atmospheric volumes in the least amount of observation time.
- GaN semiconductor is chosen for implementation of MMICs because of its highest power density and highest efficiency capability for semiconductor power amplifiers at Ka-band.
- Six MMIC circuits that will form the K-tile Ka-band radar front end have been simulated and physically drawn for layout: PA, LNAs, SPDT, SPTT, attenuators and couplers.
- The MMIC designs are being further analyzed and improved with electromagnetic simulations and will be fabricated in the near future.

Acknowledgement

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