Methods to Achieve Competitive Solid State Replacement of Traveling Wave Tube Amplifier (TWTA) Implementations

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- The semiconductor industry continues to mature higher frequency and higher power device technologies and geometries into MMICs with multi-watt performance. Efficient, novel combination of these devices enables the promise of successfully high power, solid state power amplifier (SSSPA) solutions that can supplant traveling wave tube amplifiers (TWTAs) in many applications.
- This presentation discusses the merits and challenges, along with the disadvantages of replacing tubes with SSPAs. Several architectures, including traditional printed circuit board, non traditional three dimensional circuit board, waveguide, and spatial combining are presented along with specific strengths and weaknesses of each approach.
- Performance results of several non-traditional combining methods are presented.

Vacuum Electron Devices (VEDs) have defined high power microwave capability

- TWTAs and other vacuum devices have historically been used to provide high power microwave amplification
  - Narrow and Broad Band
  - Watts to Megawatts
  - Frequencies to >100 GHz

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Tube Advantages

- High Power, frequency and bandwidth
  - Limited alternatives
- High Efficiency
- Compact power to volume ratio
- Tolerant of high ambient temperatures
- Low Current – small wire diameters
- Effective Pulse – Low Duty Factor, High Peak Power
- Radiation resistant (Space)

TWTA Disadvantages

- Dwindling supply base
  - CPI
  - L3
  - Thales
  - E2V
  - Teledyne
- Perceived Reliability and Robustness Issues
  - Degassing
  - Repair Costs
- Single Point Failure
- High Voltage Power Supplies

TWTA Disadvantages

- High Thermal Noise Output
- Warm Up Time
- Poor inherent linearity
  - AM-AM and AM-PM
- Poor Stability over time
- Storage – Degassing issues
- Difficult to Repair
- Poor Gain/Power Flatness vs Frequency

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Search for Alternatives

- Search for RF and microwave high power alternative technologies has existed since tubes were first used
  - IMPATT (**IMP**act ionization **A**valanche **T**ransit-**T**ime)diodes
  - Bipolar Junction Transistors (BJT)
  - LDMOS (**Laterally diffused metal oxide semiconductor)**
  - **GaAs FETS (Gallium Arsenide Field Effect Transistors)**
    - **MESFETS (metal semiconductor field effect transistor)**
    - **PHEMT (***pseudomorphic* **High electron mobility transistor)**
  - **GaN FETS (Gallium Nitride FETS)**
    - **PHEMT**

Alternatives

- Microwave Power Modules (MPMs)
- Single High Power Solid State devices
- Combined Solid State Implementations
  - Circuit Combined
    - Radial
    - PCBA
      - Planar
      - 3 D
  - Spatial Combined
    - Free Space
    - Rectangular Waveguide
    - Coaxial

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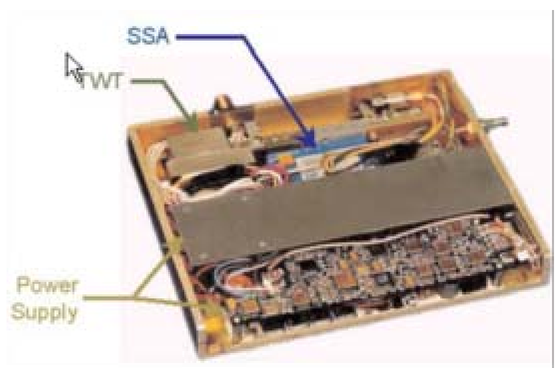
Microwave Power Modules (MPMs)

- Combines solid state driver with TWTA output
- Improves Noise and Stability, and linearity

- Still Includes high Voltage Power supply with additional complexity of low voltage supply
- 33% Typ. Efficiency
- 20 dB Noise figure



5:1 Reduction in Size
5:1 Reduction in Weight
100:1 Reduction in Noise
50% improvement in efficiency
--L3

High Power 20-170W
Narrow Band S,C,X,Ku,Ka,Q
Wide Band
2-8, 4.5-18, 6-18, 18-40, 40-46 GHz
Small Size
100Watts in 770 cc, 1.75 kG

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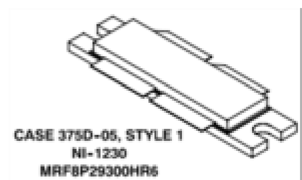
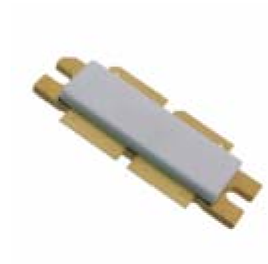
Standalone Solid State devices

- Typically Narrow band and Pulse Operation
- Very High Powers limited to 3.5 GHz and Below
  - Radar
- Field Proven
- Robust





MRF6VP121KH
965-1215 MHz
1000 W
50 V
56% Efficient
128µS, 10% DF

MRF8P29300H
2.7-2.9 GHz
320 Watts Peak
100µS, 10% DF

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Device Technology

- GaN (Gallium Nitride) Key Capability Enabler
  - High RF power density
  - Higher Breakdown voltages
    - >400V reported, typically 120-150V
  - Associated higher impedance and lower capacitance
    - Broader bandwidth
  - Higher junction temperature capability
    - 230°-280°

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GaN MMIC Activity

- Cree
  - 2-6 GHz 25W
  - 2.7-3.5 GHz 75 W
  - 5.5-8.5 GHz 25W
  - 8-11 GHz 25W
- Triquint
  - 30MHz-3GHz 10W
  - 14-16 GHz 20W
  - 2-18 GHz 10W
- Numerous proprietary and government sponsored parts
- Numerous wireless communication parts
  - RFMD, MACom Tech, etc.

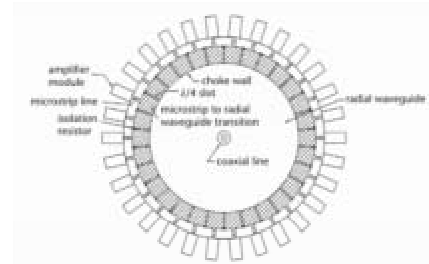
Progress, but still not enough power at microwave frequencies!

Power Combined Amplifiers

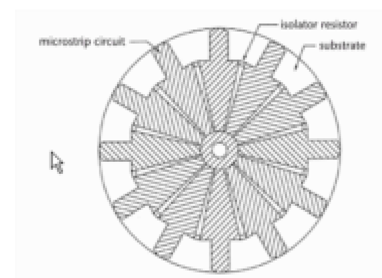
- Fundamental Challenges and Trade Spaces
  - Impedance transformation
  - Bandwidth
  - Loss or combining efficiency
  - Thermal management
  - Phase and amplitude balance
  - DC Bias distribution, isolation and balance
  - Mechanical complexity

Circuit Combined Amplifiers

Radial Power Combiners



- High multiple combining
  - 50 or more combining elements possible
- High Power Handling
- Narrow Band (<20%)@ 90% Combining Efficiency (Radial Waveguide)
- High Loss for Microstrip radial combiners
- Radial Waveguide challenging to Model
- Challenging to fabricate
- Hybrid Approach has practical applications
  - Adequate thermal management



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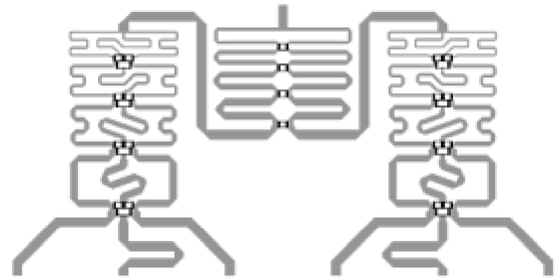
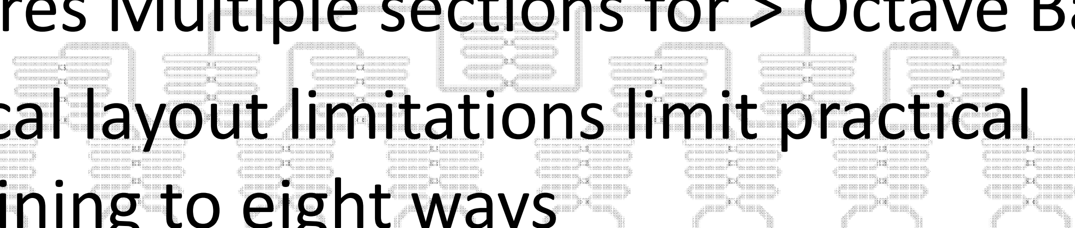
Planar Printed Circuit Combined Amplifiers



- Corporate Feed
  - Wilkinson or Quadrature Hybrid Coupled
  - Typically 2^N Way Splitting and Combining
  - Requires Multiple sections for > Octave Bandwidth
  - Physical layout limitations limit practical combining to eight ways

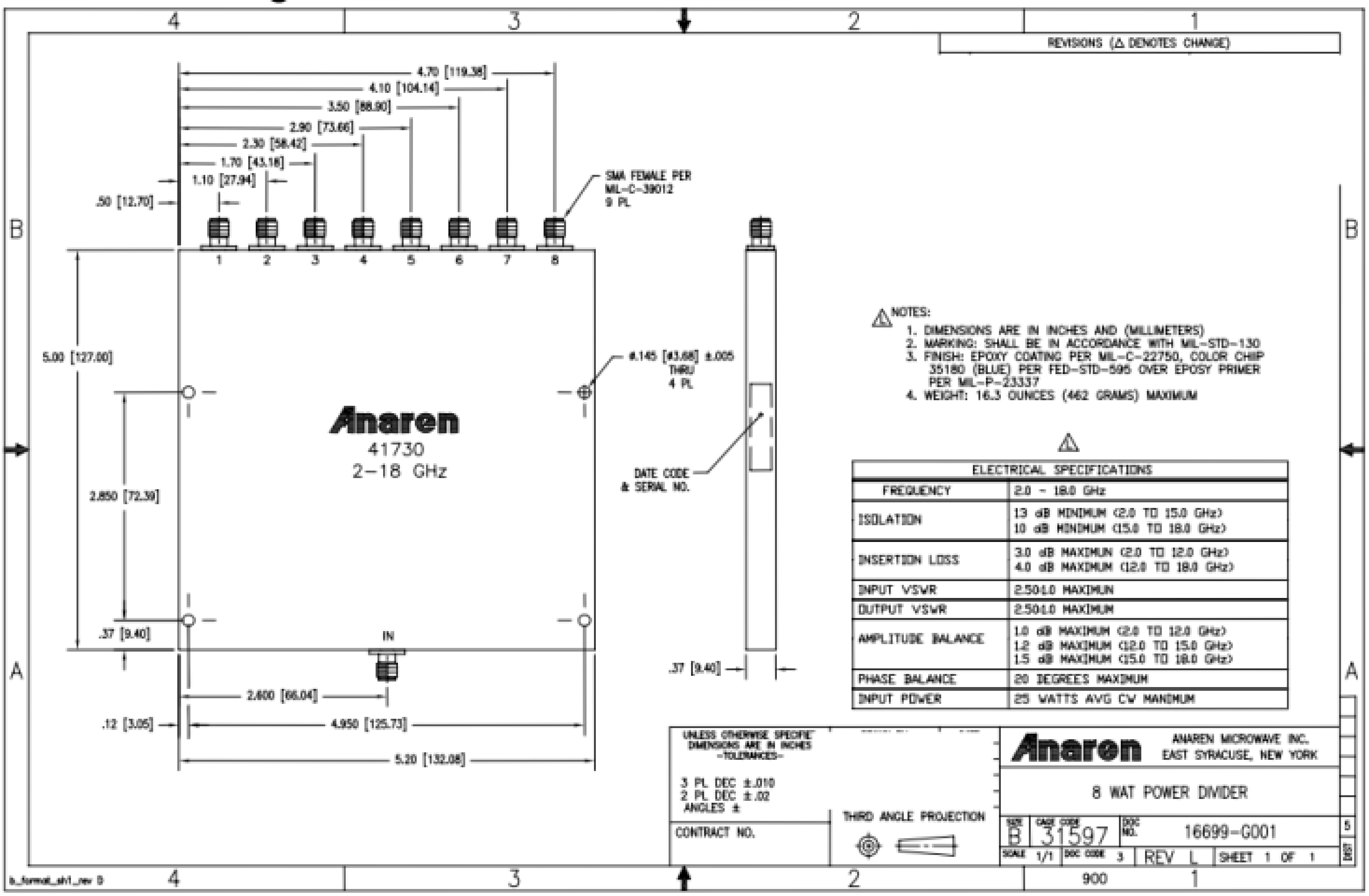


- Simple Fabrication
- Excellent Thermal path to planar surface
- Readily Calculated or Modeled

Commercial 8 Way Splitter

NOTES: *Input power with load VSWR of 1.20:1*
Electrical and Mechanical Specifications subject to change without notice

Outline Drawing



ELECTRICAL SPECIFICATIONS	
FREQUENCY	2.0 – 18.0 GHz
ISOLATION	13 dB MINIMUM (2.0 TO 15.0 GHz) 10 dB MINIMUM (15.0 TO 18.0 GHz)
INSERTION LOSS	3.0 dB MAXIMUN (2.0 TO 12.0 GHz) 4.0 dB MAXIMUM (12.0 TO 18.0 GHz)
INPUT VSWR	2.50:1.0 MAXIMUN
OUTPUT VSWR	2.50:1.0 MAXIMUN
AMPLITUDE BALANCE	1.0 dB MAXIMUM (2.0 TO 12.0 GHz) 1.2 dB MAXIMUM (12.0 TO 15.0 GHz) 1.5 dB MAXIMUM (15.0 TO 18.0 GHz)
PHASE BALANCE	20 DEGREES MAXIMUM
INPUT POWER	25 WATTS AVG CW MAXIMUM

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Three Dimensional PCBA Combined Amplifiers

- Overcomes the planar PCB layout limitations
- Requires multiple transformation to achieve broad bandwidth.
- Complex mechanical and challenging thermal structure.

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Spatially Combined Amplifiers

- Spatial power amplification is the method of coherently combining the power of many amplifying devices using free space or air as the power dividing/combining medium within a guided wave structure
- Sometimes referred to as Quasi-Optical combining
  - Makes use of similar techniques used to combine power in the optics industry

Arrays

- The original concept for spatially combining power
- Uses multiple apertures or antennas fed with multiple amplifiers to produce a composite free space field strength greater than that of a single antenna or amplifier
- Bandwidth limited by antenna/aperture characteristics
- Useful only for radiational structures
- Highly Efficient

Waveguide Combiners

- Uses Waveguide splitters, combiners, “Magic Tees”, couplers, in a mechanical configuration to achieve combining
- Can be excessively large at low frequencies
- Awkward to implement
- Limited to BW of Waveguide
- Excellent Power Capacity

History of Spatial Combining

- Earliest known use prior to WWII – Uda
  - Tubes and Dipole antennas
- Grid Amplifier – Rutledge 1991
- Substantial work at several universities in mid 1990s – notably
  - University of Colorado at Boulder
  - University of Michigan
  - North Carolina State University
  - University of California at Santa Barbara
  - California Institute of Technology

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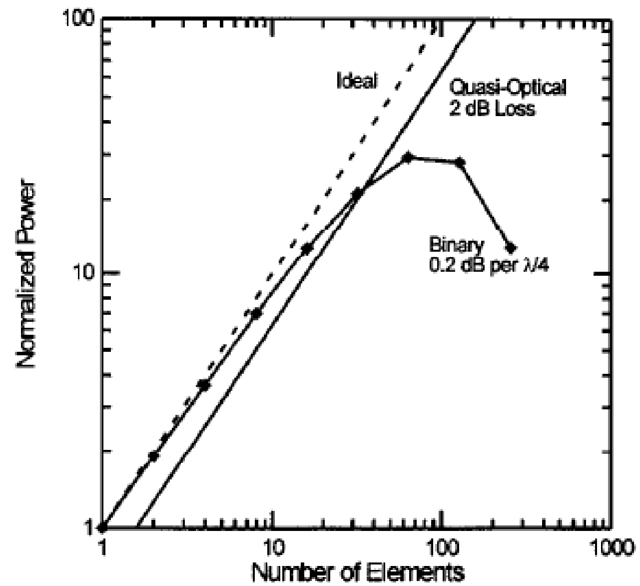
General Characteristics

- Efficiently combine large numbers of amplifiers
  - Loss is independent of number of combined elements
  - > 8 devices
  - > 90% combining efficiency
- Inherently low loss structure
- Graceful degradation on failure
- Low voltage operation
- Solid State reliability
- Good phase noise characteristics



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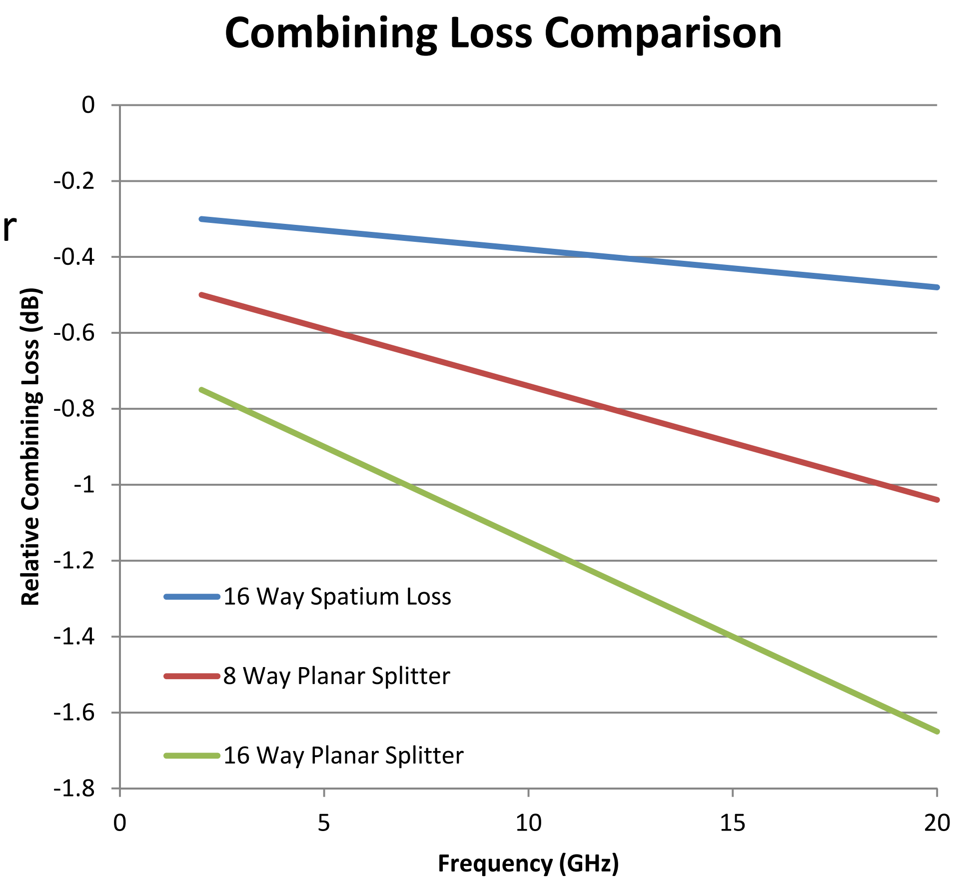
Spatial Power Combining

Spatial Power Combining Features
Minimal Loss
Minimal Variation vs. Frequency
Significantly Better Performance over frequency than other combining method

Lower Loss means more power transmitted, less wasted in heat

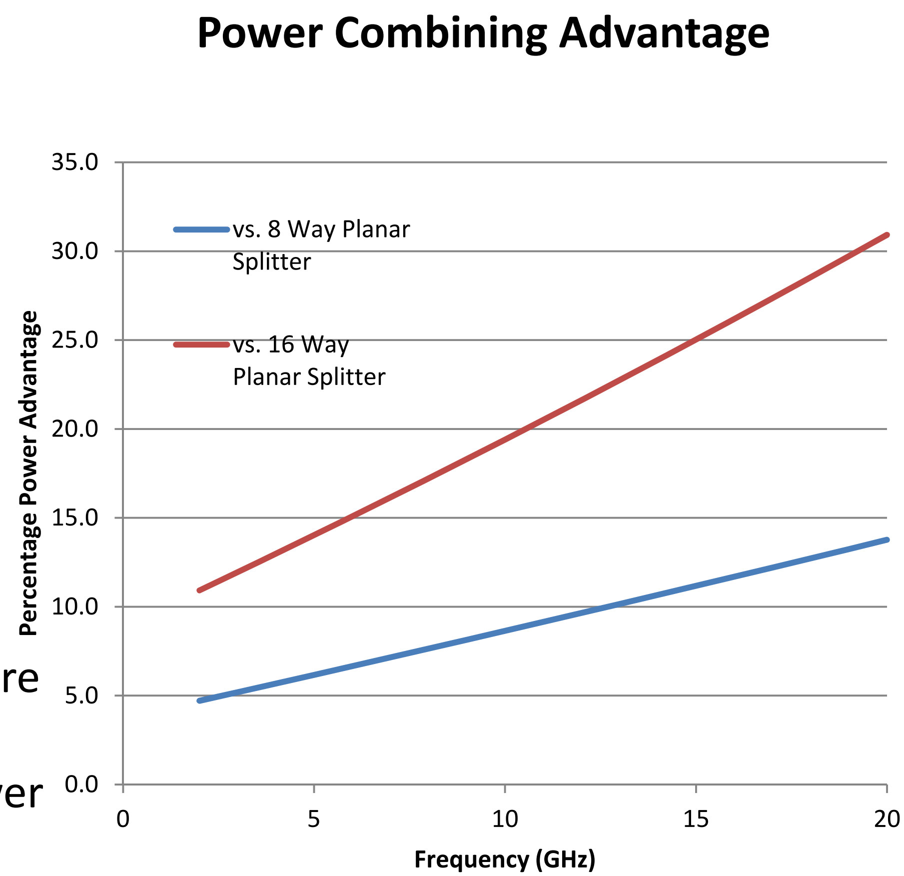


Percentage Improvement

Spatial Combining yields significantly more output power than planar combining methods at high combination factors

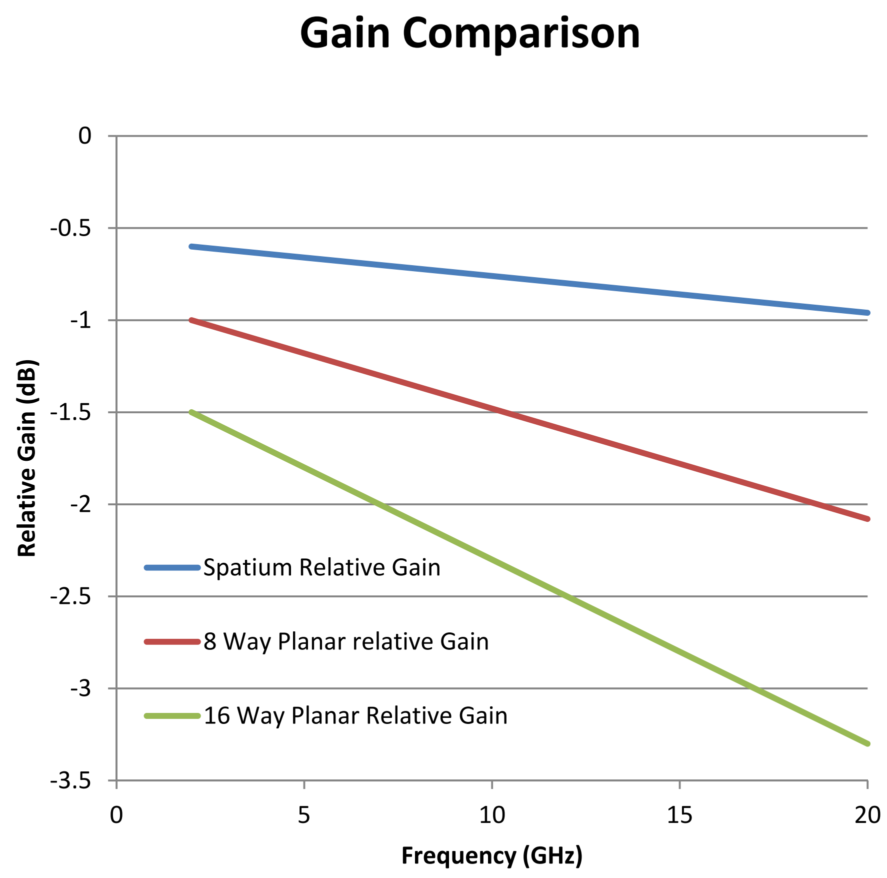
Up to 14% better than 8 Way Planar
Up to 32% Better than 16 Way Planar

More Efficient Combining means a more efficient amplifier
   More RF Power for Same Prime Power
or
   Same RF Power for Less Prime Power



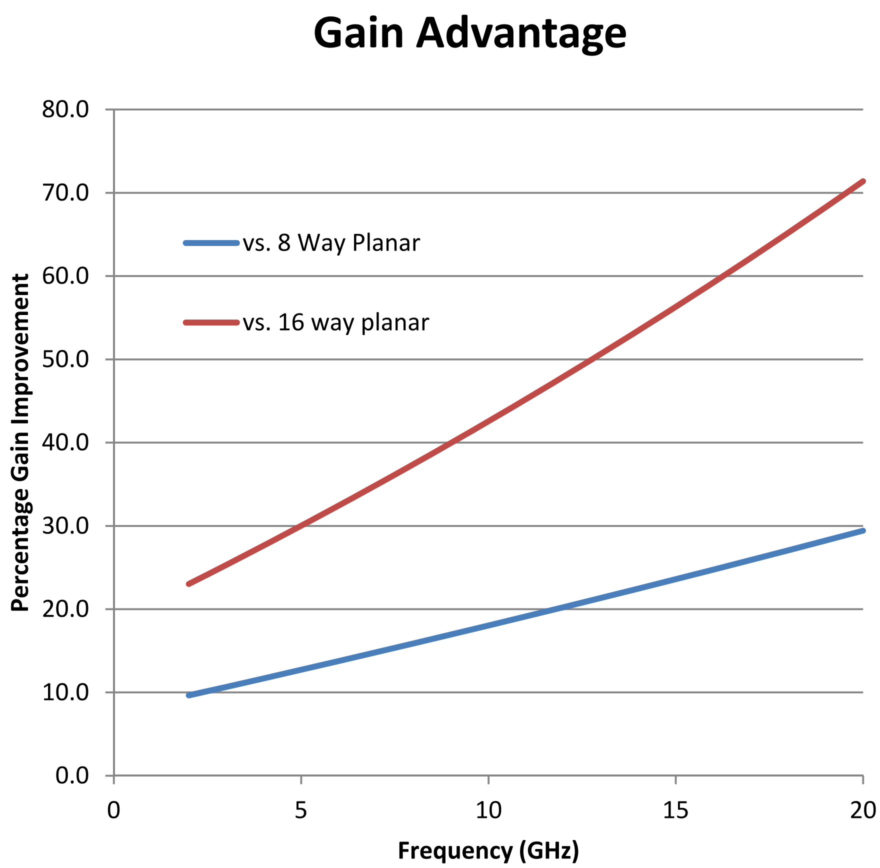
Gain Advantage

Spatially combined amplifiers have higher relative gain
- Fewer stages required
- Fewer failure mechanisms
- Reduced power requirements for drivers



Gain Advantage

Spatial combining can have as much as more than 70% more gain magnitude than competing combining technologies



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Requirements

- High efficiency compact radiation elements
  - Microstrip or other suitable launch element
- Compact moderate power amplifiers (MMICs)
- Method to maximize reverse isolation (S12)
- Bias distribution schema
- Thermal management methodology

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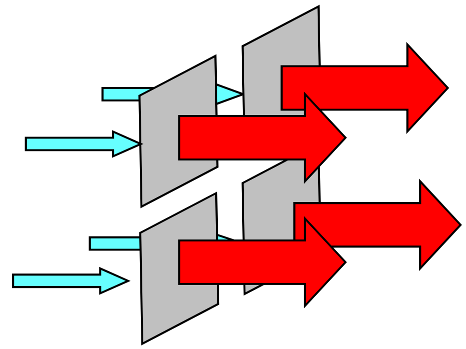
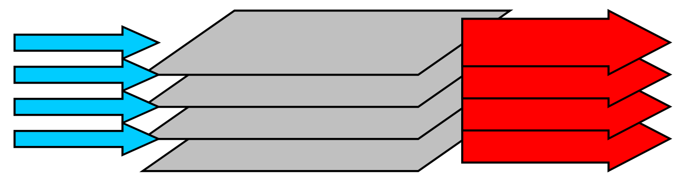
Practical Architectures

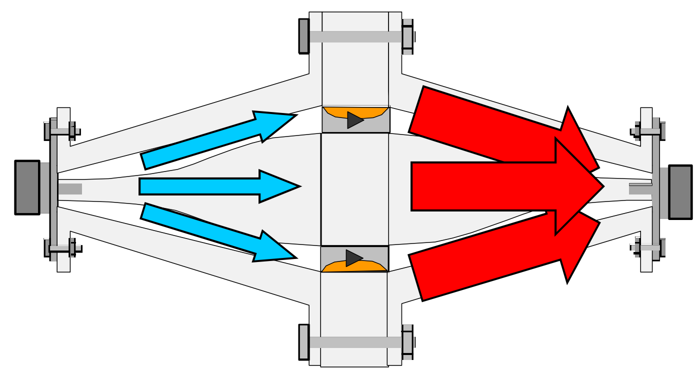
- Grid Amp



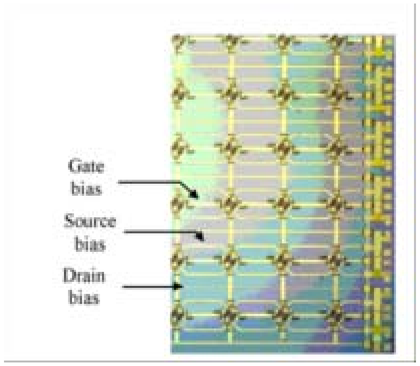
- Tray Amp



- Coaxial Waveguide Amp



Grid Amp



Two dimensional Array in a waveguide structure

Limited Power Dissipation	Inner devices suffer from heat concentration and poor thermal path (Exception – reflective grid amp)
Generally Narrower Bandwidth	Bandwidth determined by antenna structure - Typically patch or dipole
Good for higher frequencies (millimeter wave and above)	Tolerance defined by photolithography or other semi conductor techniques
Non Linear	Non-uniform field distribution in rectangular wave guide
Potentially large number (100s) of devices can be combined fabricated from single monolithic device	Excessive device numbers can be yield buster, but potentially very cost effective for high volume applications
Can be configured as a reflection (1 Port) amplifier	

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Tray Amp

Enhanced Thermal Path	Individual thermal conduction paths
Limited Bandwidth	Bandwidth limited by waveguide cutoff and moding – requires new mechanical design for each waveguide size
Non-Linear	Non Linear due to non-uniform field distribution in rectangular waveguide
Mechanically Simple	Multiple, stacked machined or cast units
Effective as feedmount amplifier	Transmitter can be mounted at antenna minimizing feed losses
Modular	Potentially Field Reparable

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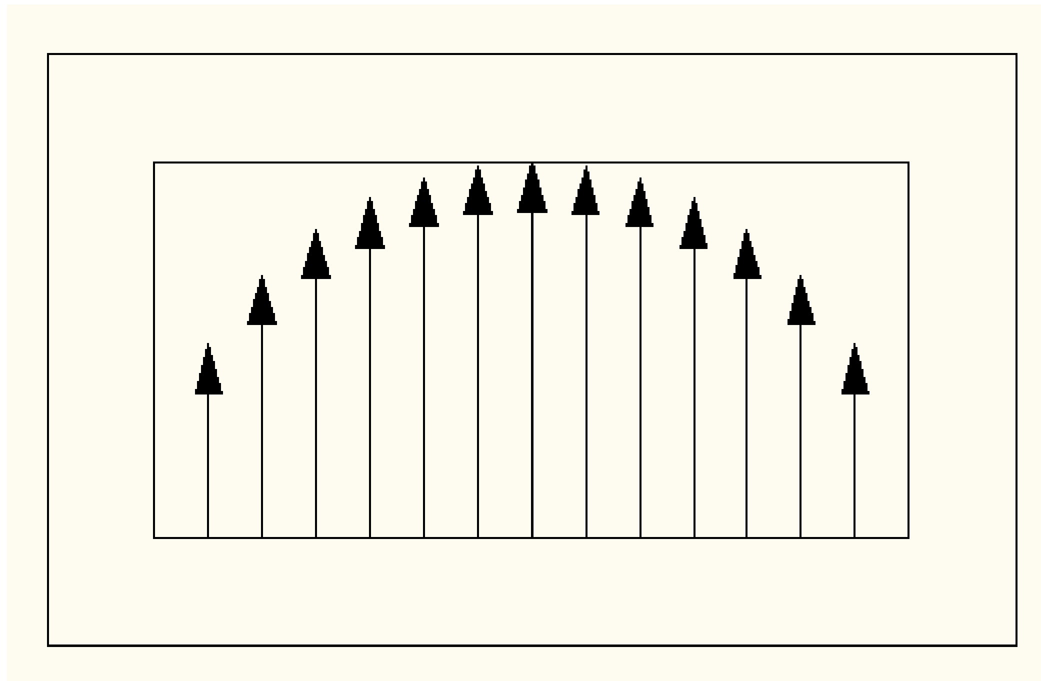
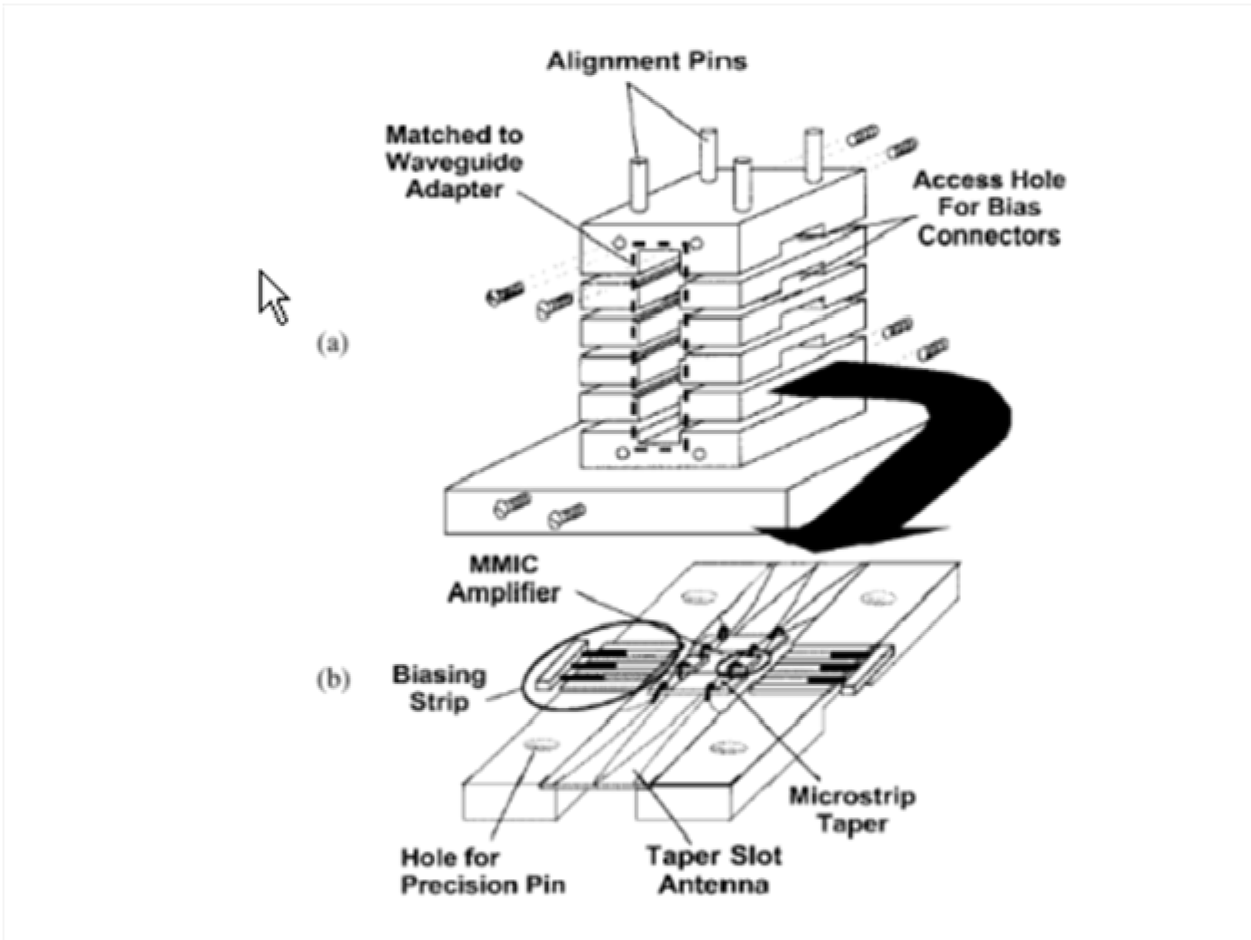
Rectangular Waveguide

- Rectangular waveguide has non uniform E-Field distribution



Dominant TE_{10} mode field strength

Notional Tray Amplifier

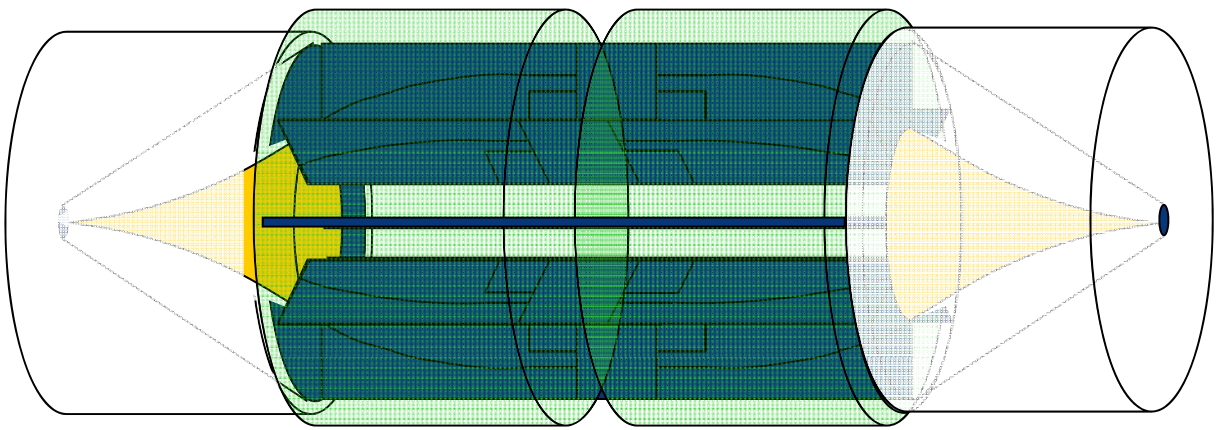


Coaxially Combined Amplifier

Linear/Efficient	Uniform Field Distribution in TEM Mode
Broadband	Multi-Octave Bandwidth
Coaxial Interface	
Thermally Efficient	
Use available devices/technologies	Design Reuse
High Output Powers	Potentially kW+
Modular	Potentially Field Reparable
Effective as feedmount amplifier	Transmitter can be mounted at antenna minimizing feed losses

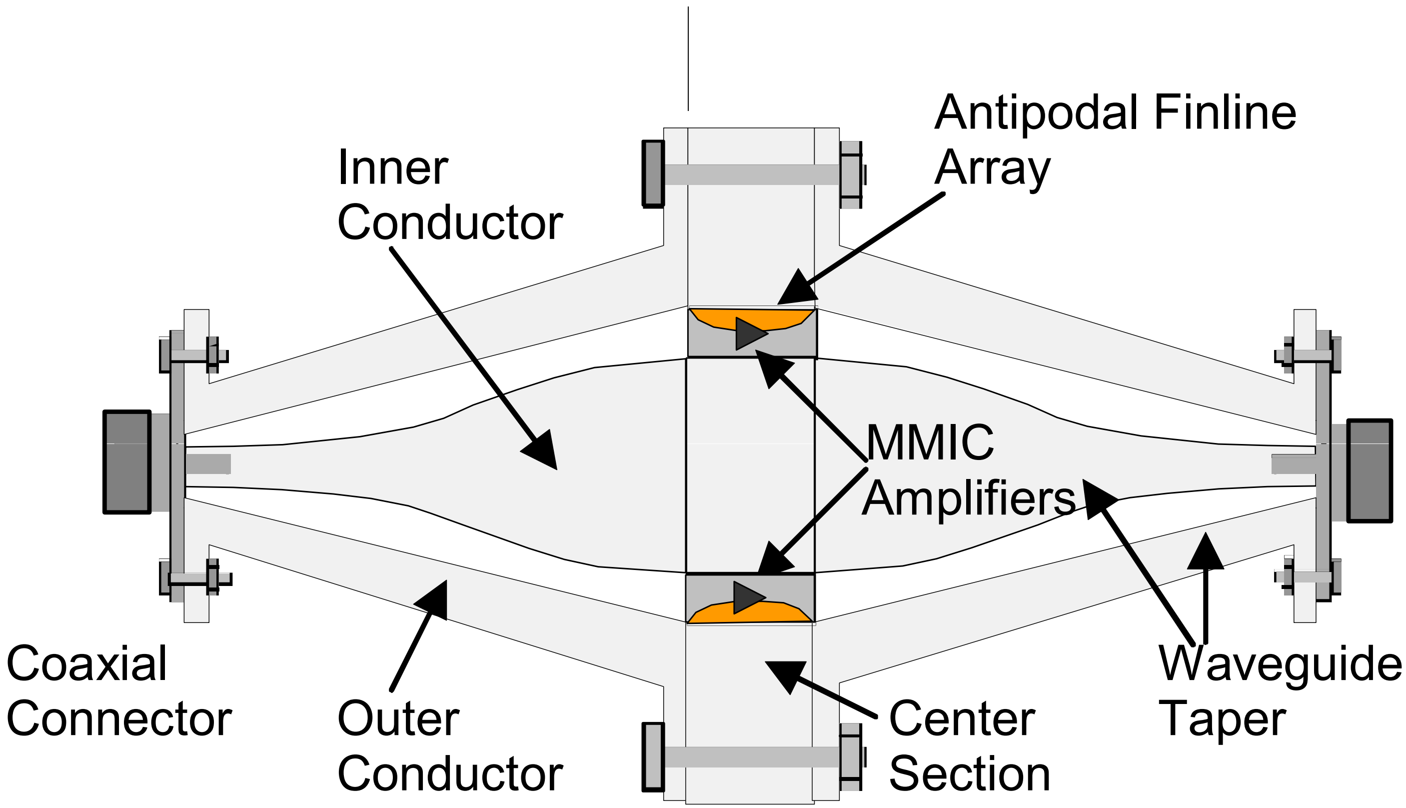
Spatium™

Physical Structure

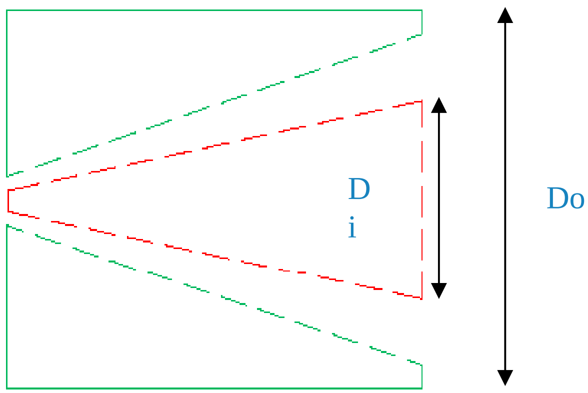


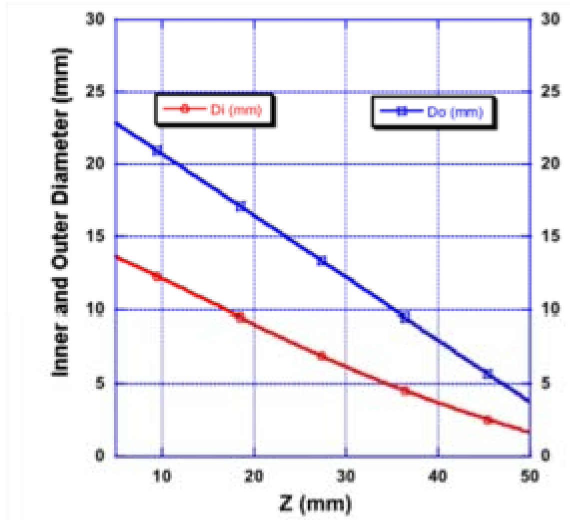
- Tapered Coaxial Transformer Feed
- Multiple Antipodal Finline Antenna Elements
- Tapered Coaxial Transformer Feed
- Outer Conductor of Coaxial Waveguide

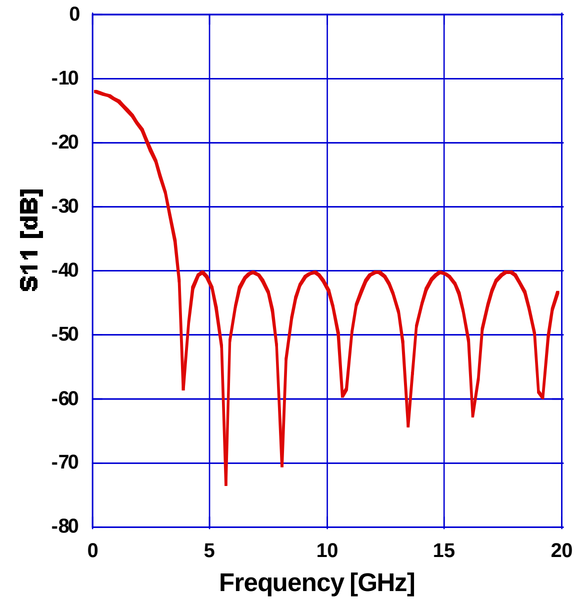
Cross Section



Waveguide Transition







$$\Gamma_{in}(f) = \frac{1}{2}\int_0^{\theta_t} e^{-j\theta}\frac{d}{d\theta}\ln\left(\frac{Z(\theta)}{Z_0}\right)d\theta$$

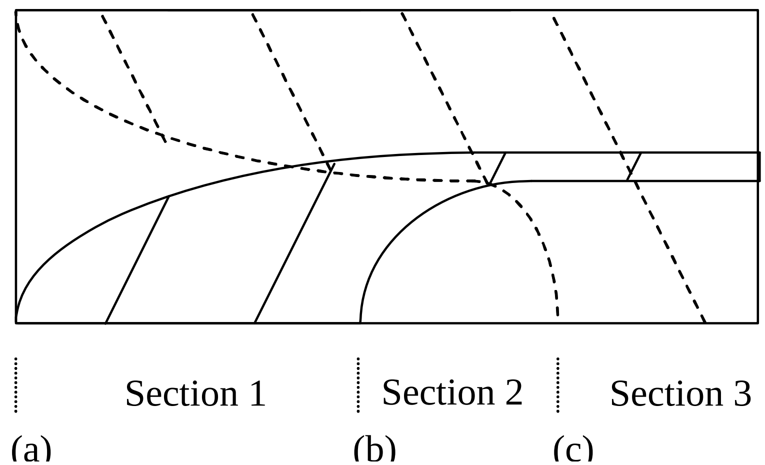
$$\theta_t = 2\beta L$$

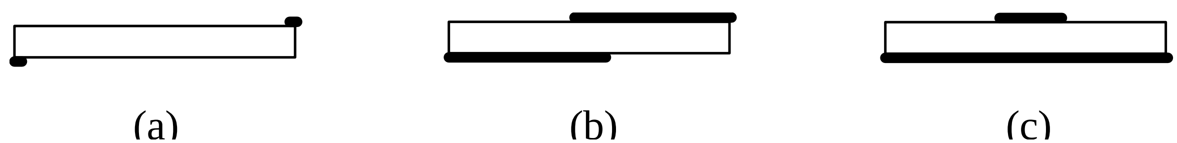
B is the propagation constant
Θt is the *round* trip phase delay to a point Z along the taper
L is the taper length

Synthesized applying small reflection theory of TEM transmission lines

Antipodal Finline Transition to Microstrip

•Based on Antipodal Finline Vivaldi Antenna (Antipodal Tapered Slot Antenna or ATSA)
•Exponential Tapered Profile for nearly constant impedance across broad bandwidth (>10:1)
•Microstrip to ATSA transition should be 3-5 λ
•Transition from an imbalanced transmission line to a balanced radiation element incorporating a polarization rotation





Transforms from 480 Ohms Radiation Element to 50 Ohm microstripline

Paired Microstrip Design

- 0.010” Taconic TSM-DS
  - Dk 2.85 DF .0010 @ 10 GHz

  - Ag Plate – 0.5 oz Cu

$$Z_0 = \frac{\eta_0}{\sqrt{\varepsilon_r}} \left\{ \frac{a}{b} + \frac{1.0}{\pi} \ln 4 + \frac{\varepsilon_r + 1.0}{2\pi\varepsilon_r} \ln \left[\frac{\pi e \left(a/b + 0.94 \right)}{2.0} \right] + \frac{\varepsilon_r - 1.0}{2\pi\varepsilon_r^2} \ln \frac{e \pi^2}{16.0} \right\}^{-1} \Omega \left(a/b > 1 \right)$$

Formula for Paired strip transition from microstrip to radiation element
Z_0 = the characteristic impedance,
e_r = the dielectric constant of the substrate,
e_0 = the characteristic impedance of free space (377 Ω),
a = the width of the paired line × 0.5, and
b = the thickness of the dielectric substrate × 0.5.

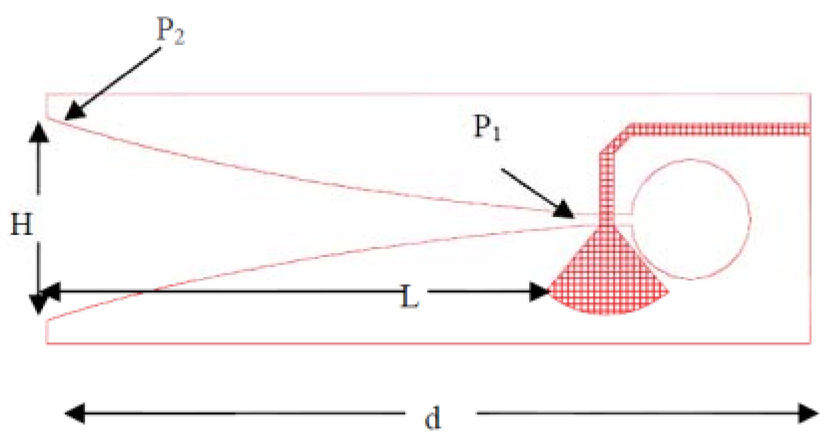
Taper Design

R is defined as the opening rate
Points P1(x1,y1) and P2(x2,y2) are the two end points of the taper profile.
P1 is the point where the slotline starts to flare
x2 – x1 is the flare length L

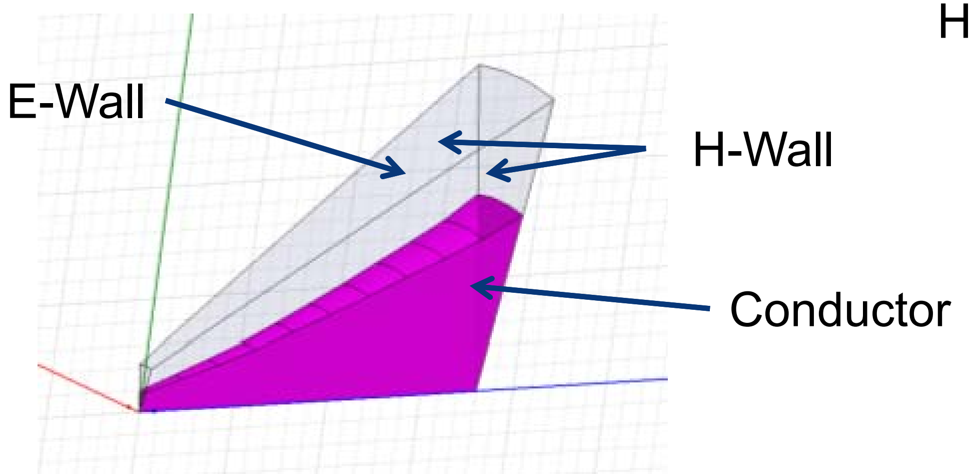
$$y = c_1 e^{Rx} + c_2$$

$$c_1 = \frac{y_2 - y_1}{e^{Rx_2} - e^{Rx_1}}$$

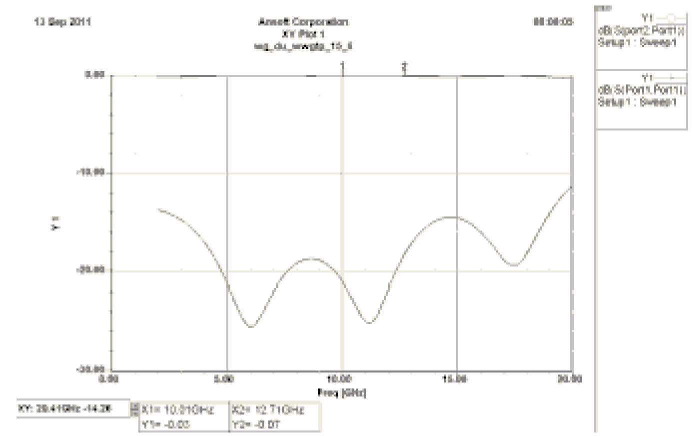
$$c_2 = \frac{y_1 e^{Rx_2} - y_2 e^{Rx_1}}{e^{Rx_2} - e^{Rx_1}}$$

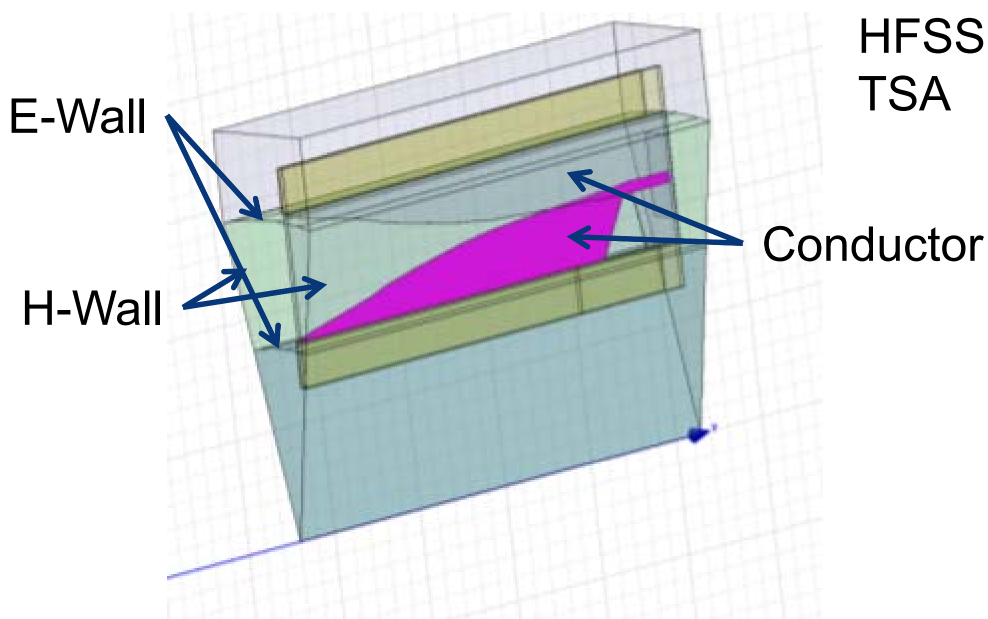


HFSS Simulation of Structure

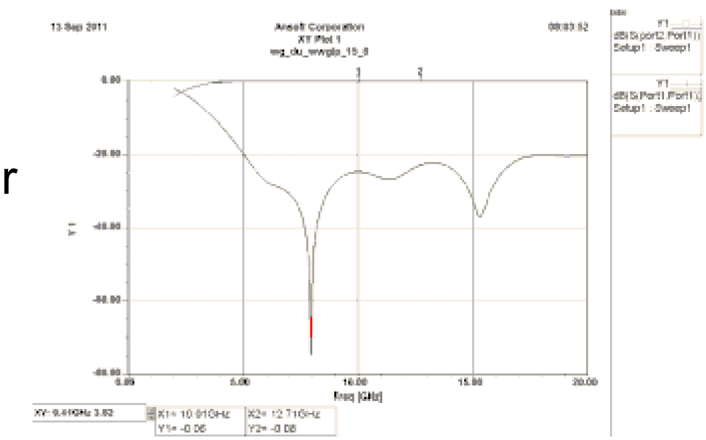


HFSS simulated coaxial transition

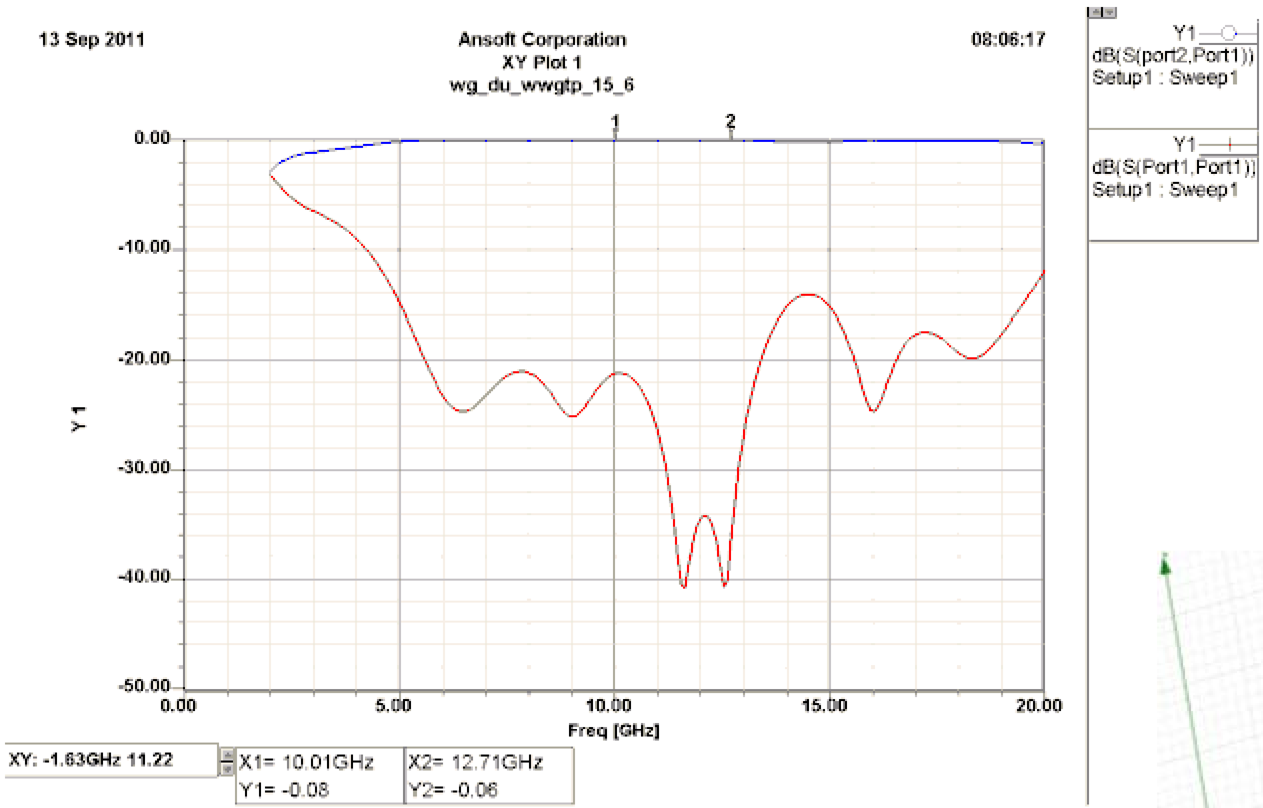


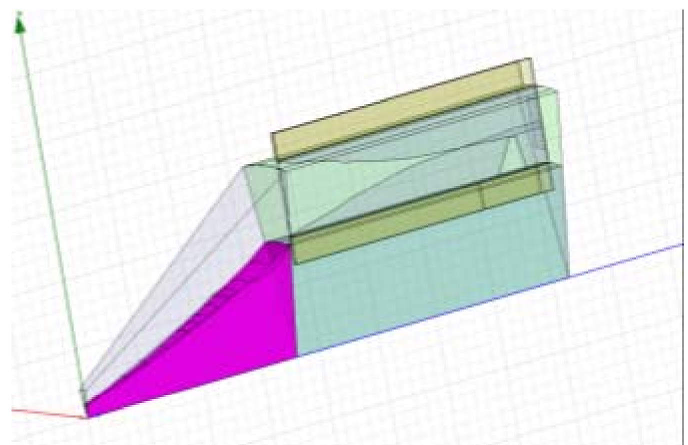


HFSS simulated Microstrip to Antipodal TSA

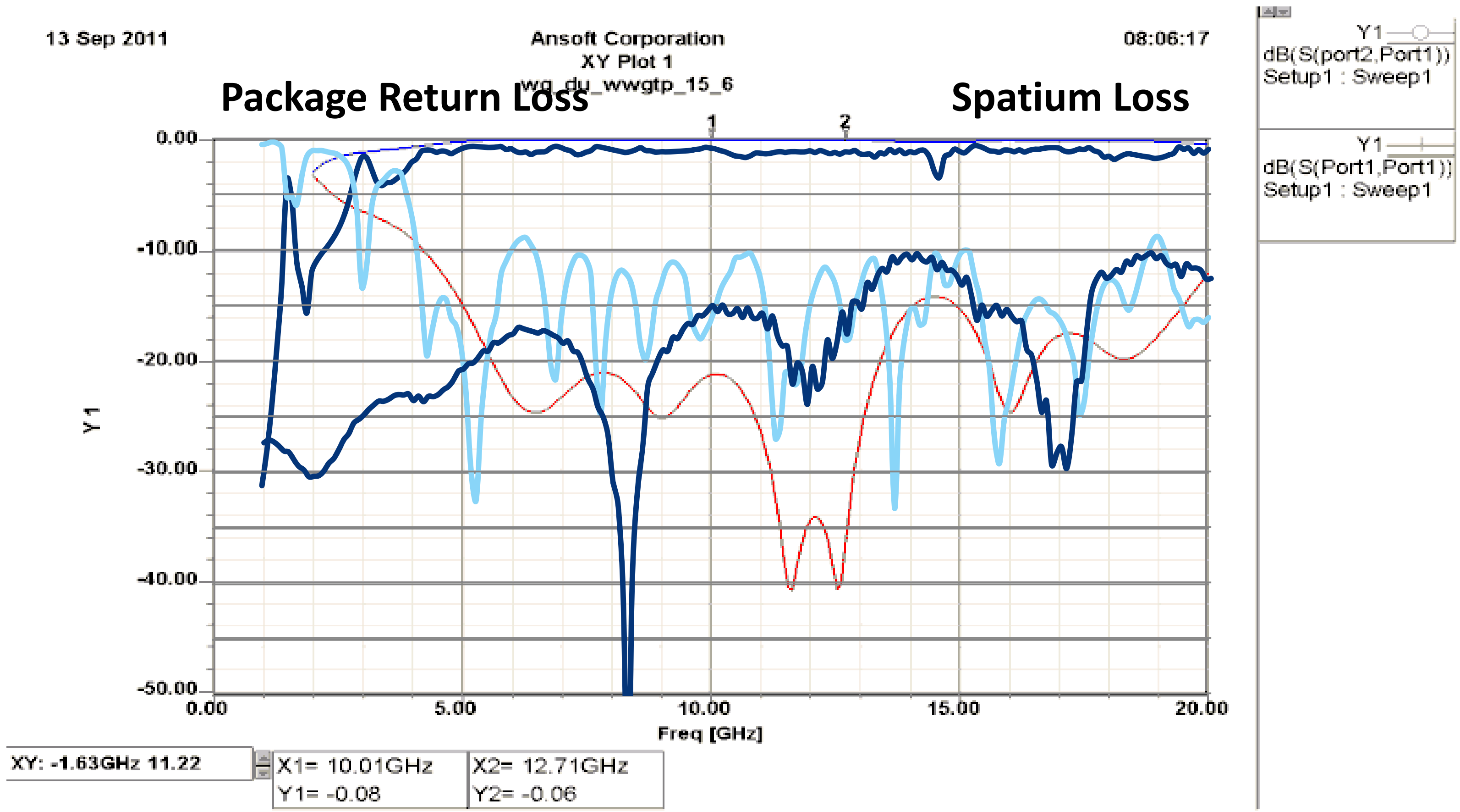


Composite Model

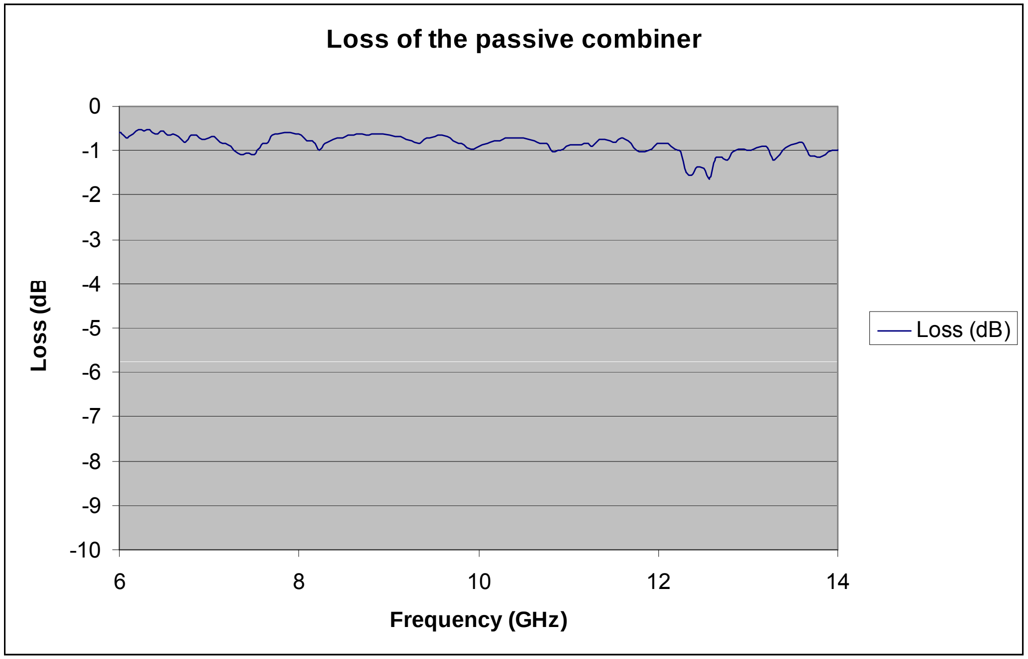




Measured Performance



Combining Efficiency



- Input/Output antennas are connected with a through line
- Port to port insertion loss is measured, 0.6 to 1 dB back to back loss from 8 to 12 GHz
- Output section only has a maximum 0.5 dB loss, corresponding to 90% combining efficiency

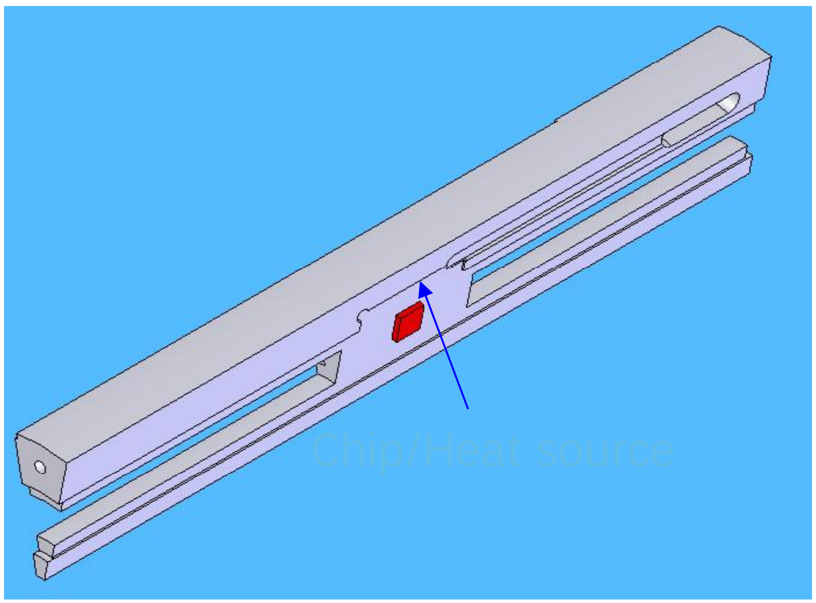
Characterisitics

- Inter-element isolation
  - 10 log (# of elements) dB
  - No isolation resistors
  - During normal operation isolation in even mode is determined by phase and amplitude balance of the elements.
- Graceful Degradation
  - Failure of element Output power reduces by: 10 log [(# elements operational)/(Total # elements)]^2 dB (10 log [(n-1/n)^2]) dB

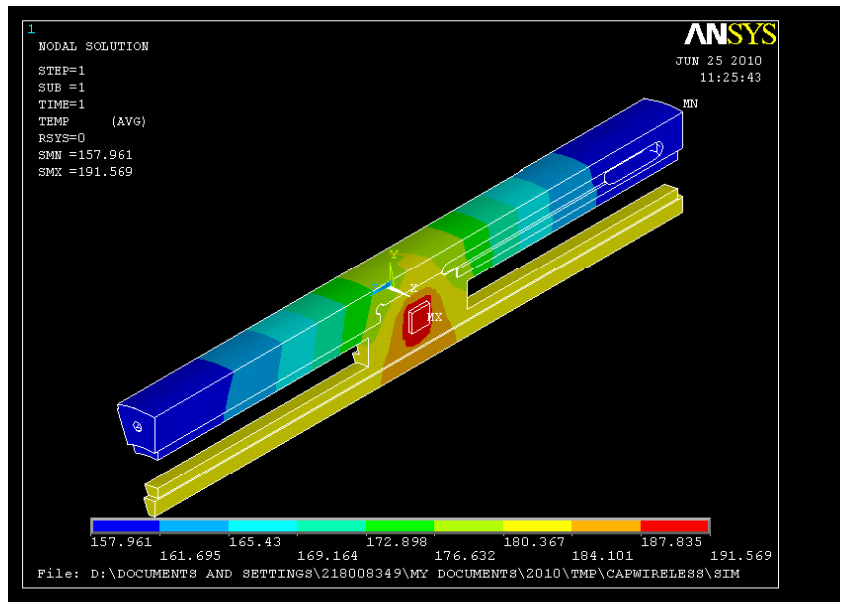
Thermal Performance

Boundary conditions:

1) Heat source: Chip Input Power = 60W,
2) Heat dissipation: Only one the curved surface.
   Heat transfer coefficient h= 250W/m^{2}K
3) Ambient: T = 25 C

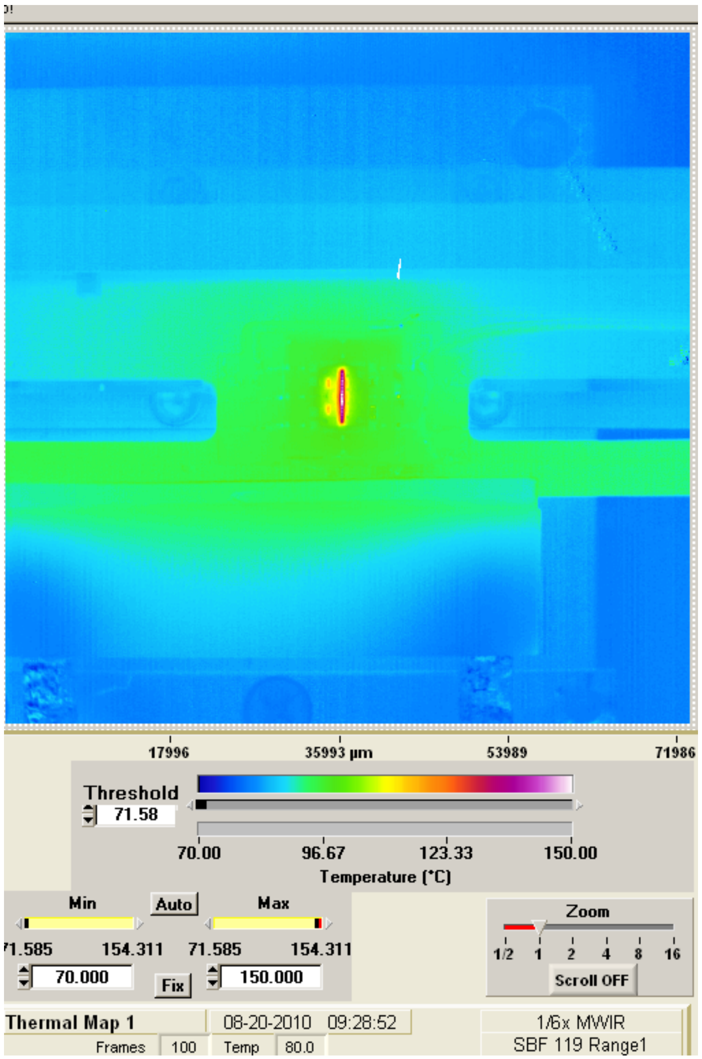


Chip size: 0.2”x0.2”



Tmax = 192 C (underneath chip)
Tmin = 158 C (outer surface of wedge)
ΔT = 34C

Thermal Measurements

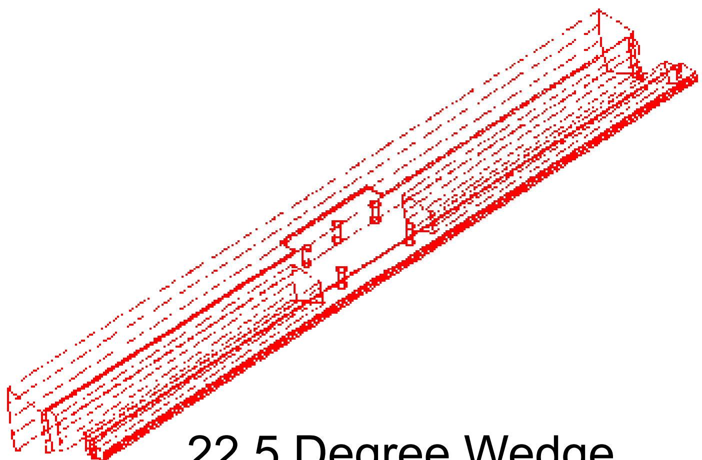


30W Dissipated Power

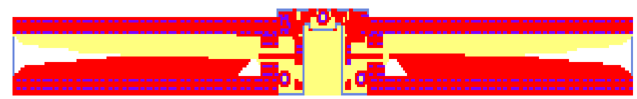
~20° C Rise from outer surface to backside of package

Copper wedges

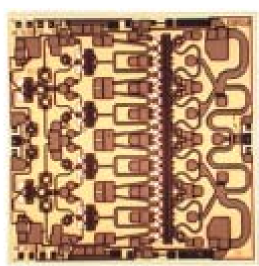
Tray Components



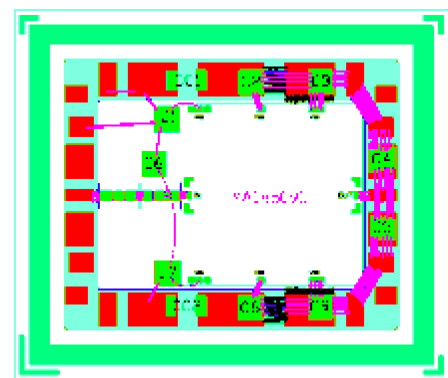
22.5 Degree Wedge



Laminate antipodal finline circuit



MMIC amplifier



HTCC power amplifier module

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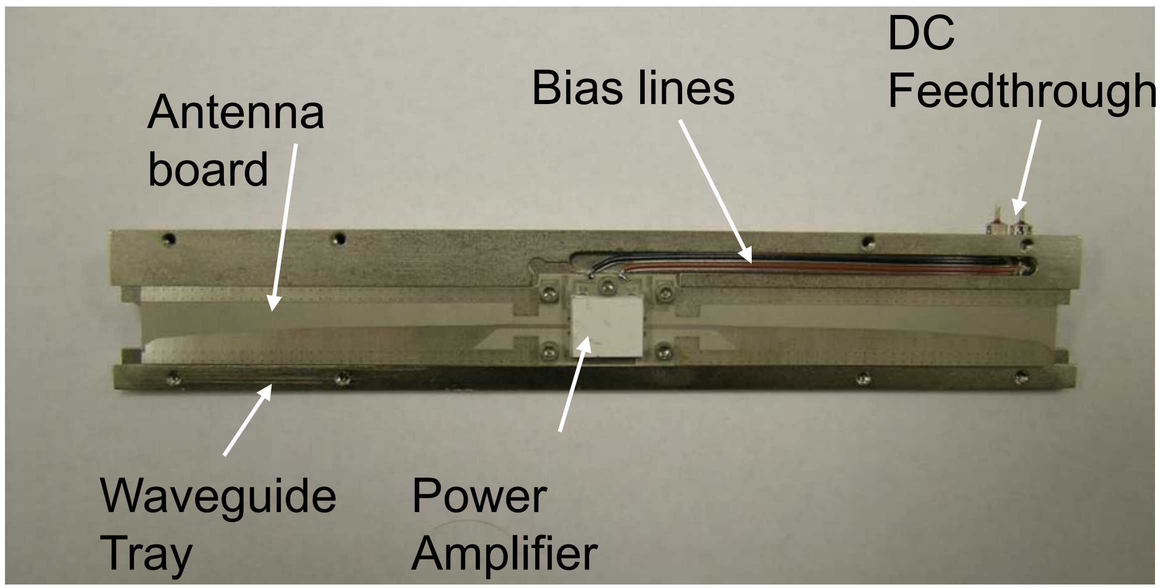
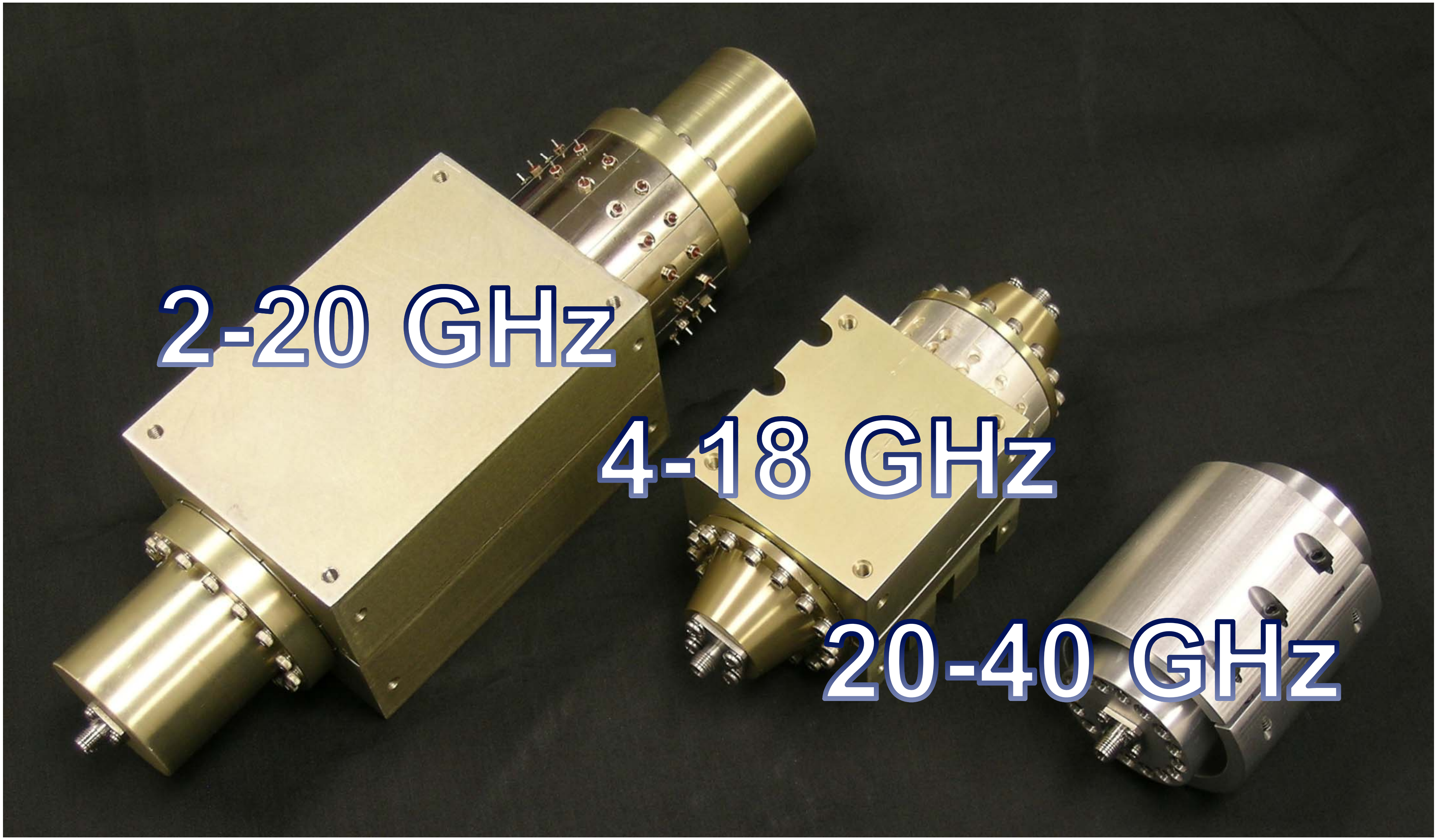
Assembled Circuit Tray





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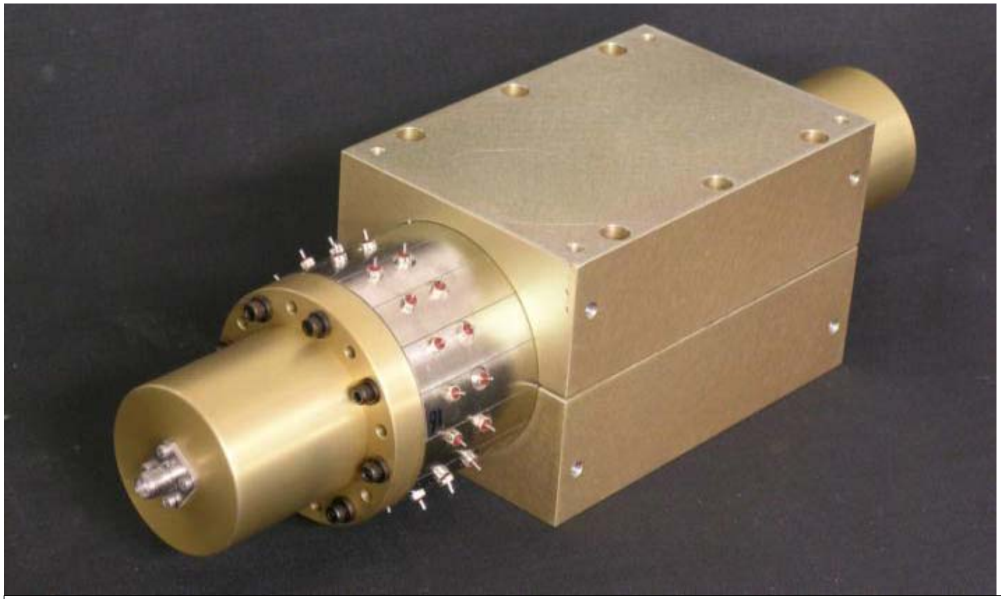
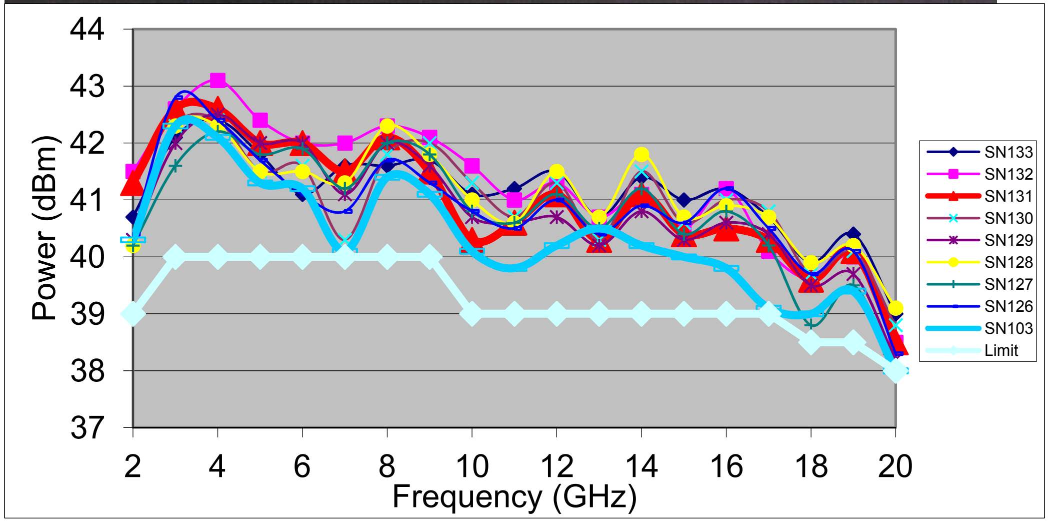
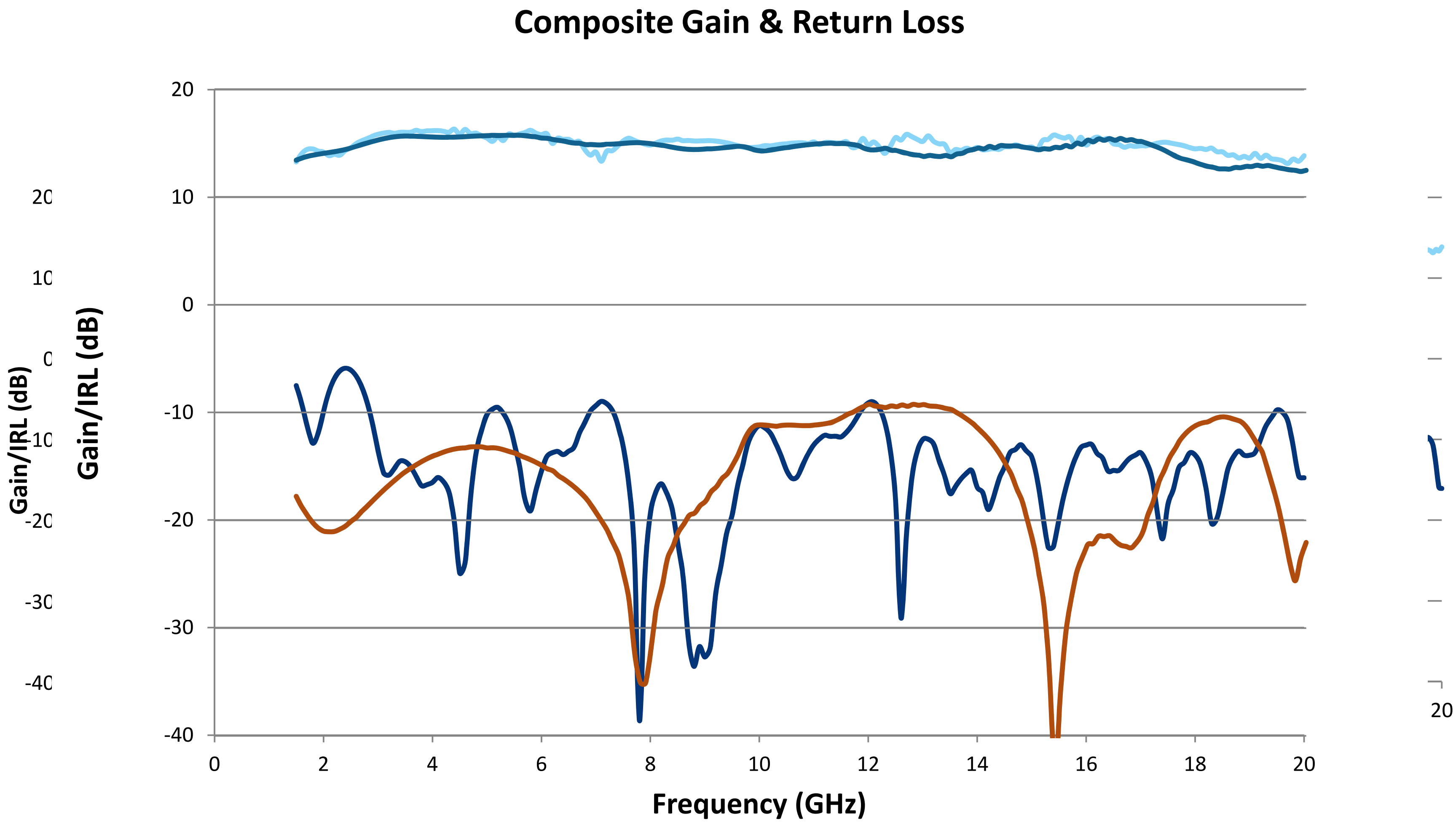
2-20 GHz Amplifier



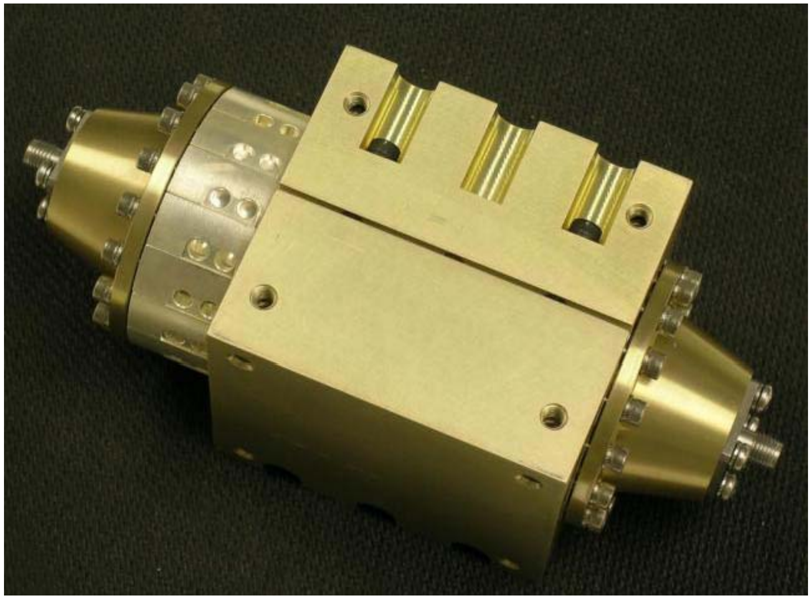


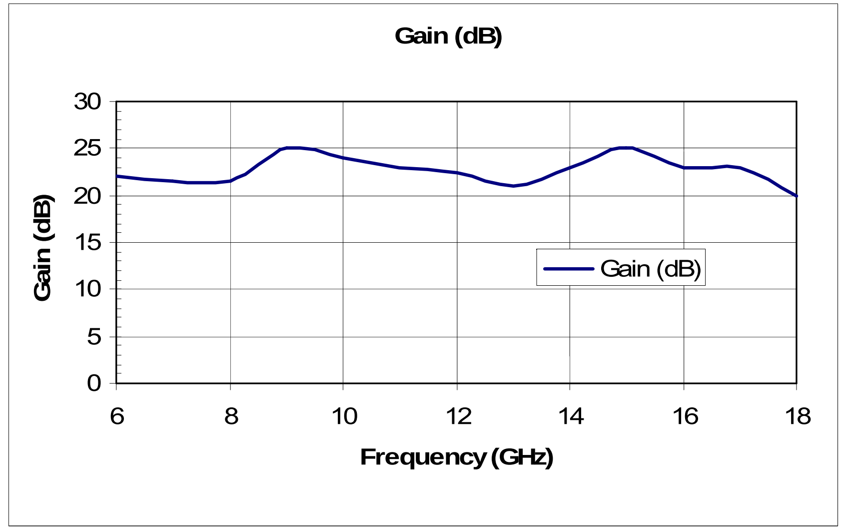
CHPA0220-2

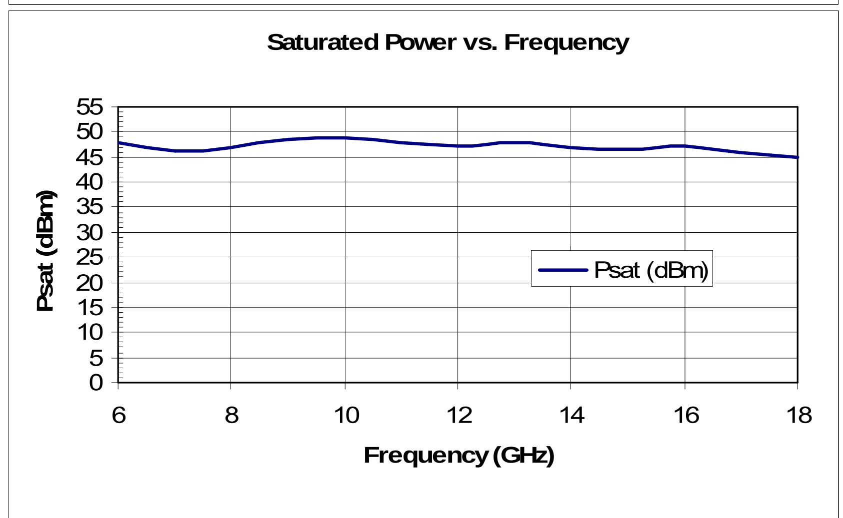


Composite Gain & Return Loss
20
10
0
-10
-20
-30
-40
Gain/IRL (dB)
0
2
4
6
8
10
12
14
16
18
20
Frequency (GHz)

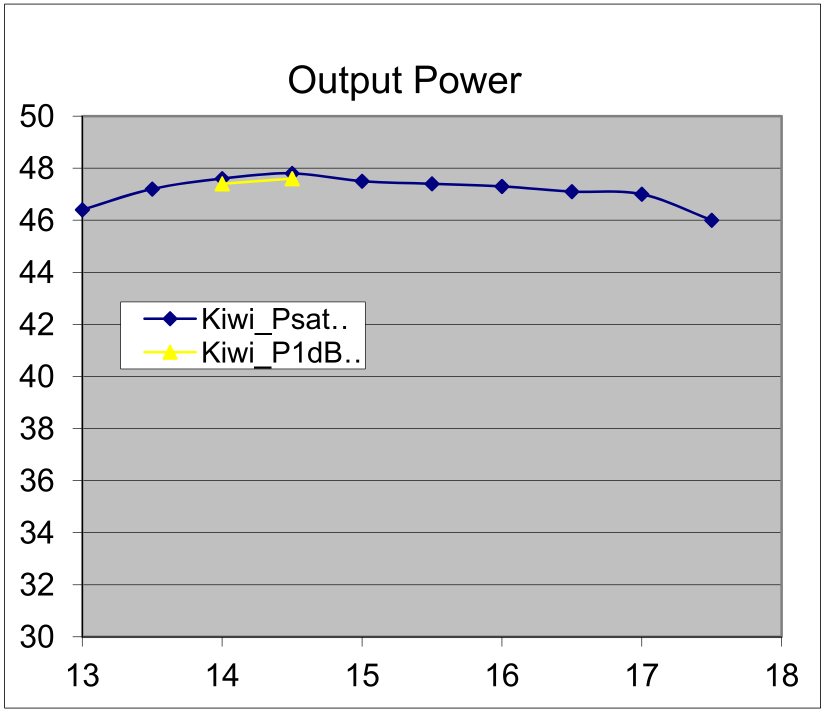
6-18 GHz

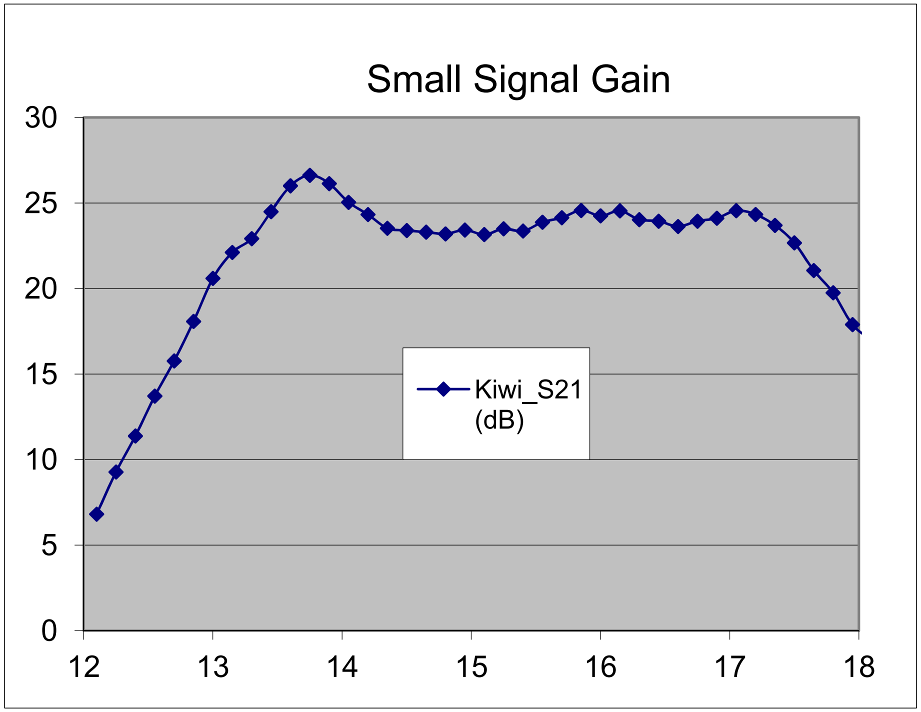



Gain (dB)
30
25
20
15
10
5
0
6
8
10
12
14
16
18
Gain (dB)
Frequency (GHz)
Gain (dB)


Saturated Power vs. Frequency
55
50
45
40
35
30
25
20
15
10
5
0
6
8
10
12
14
16
18
Psat (dBm)
Frequency (GHz)
Psat (dBm)

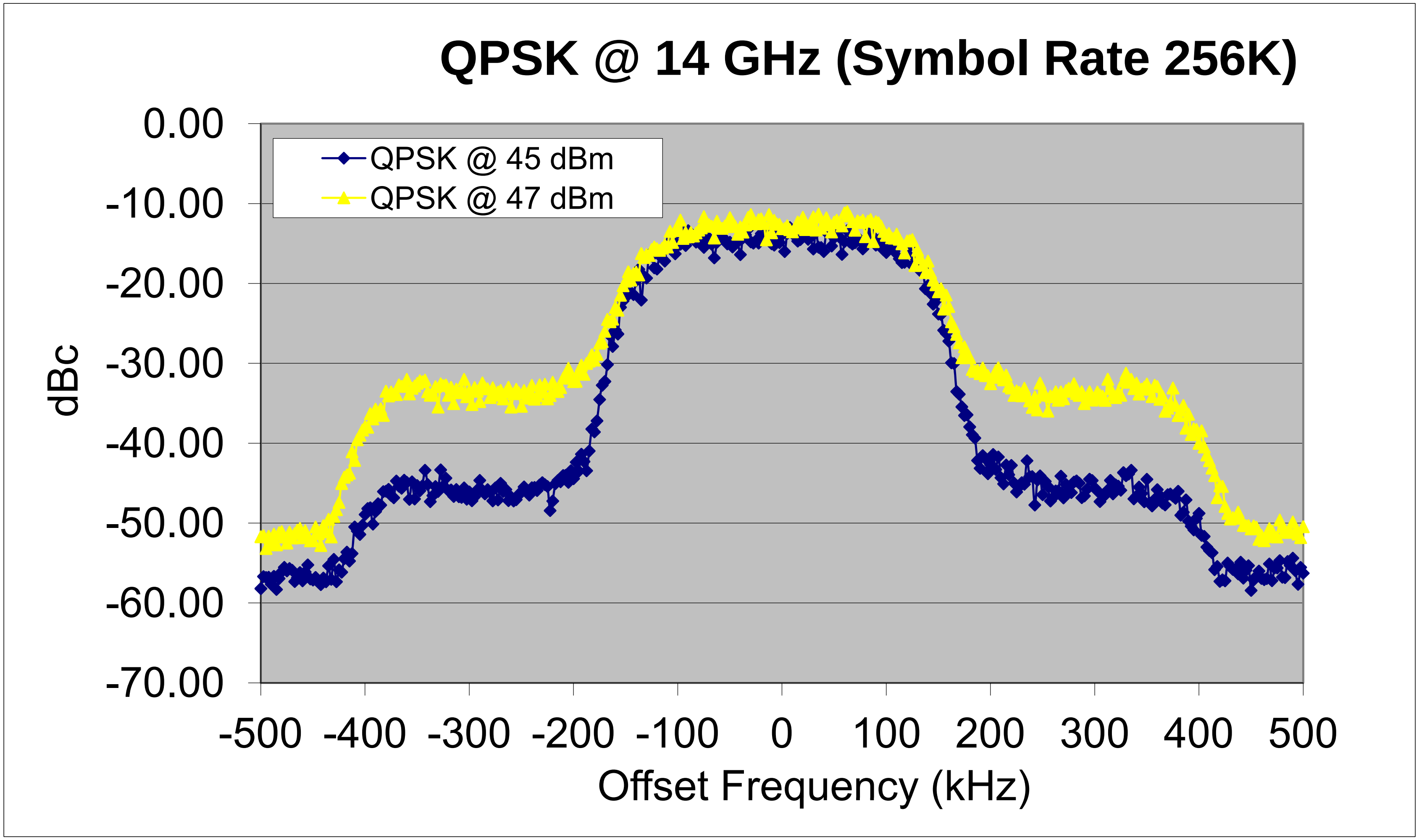
Ku Band Spatium Power





Configured as BUC	Freq (GHz)	Pin (dBm)	Pout (dBm)	Gain	MainAmp DC Power (W)
@P1dB	14	-27.5	47	74.5	245
	14.5	-24	47	71	245
@-26 dBc, 1x symbol rate offset	14	-29	46	75	240
	14.5	-25.5	46	71.5	240
@-30 dBc, 1x symbol rate offset	14	-30	45	75	235
	14.5	-26.5	45	71.5	235

Ku Band Spectral Regrowth



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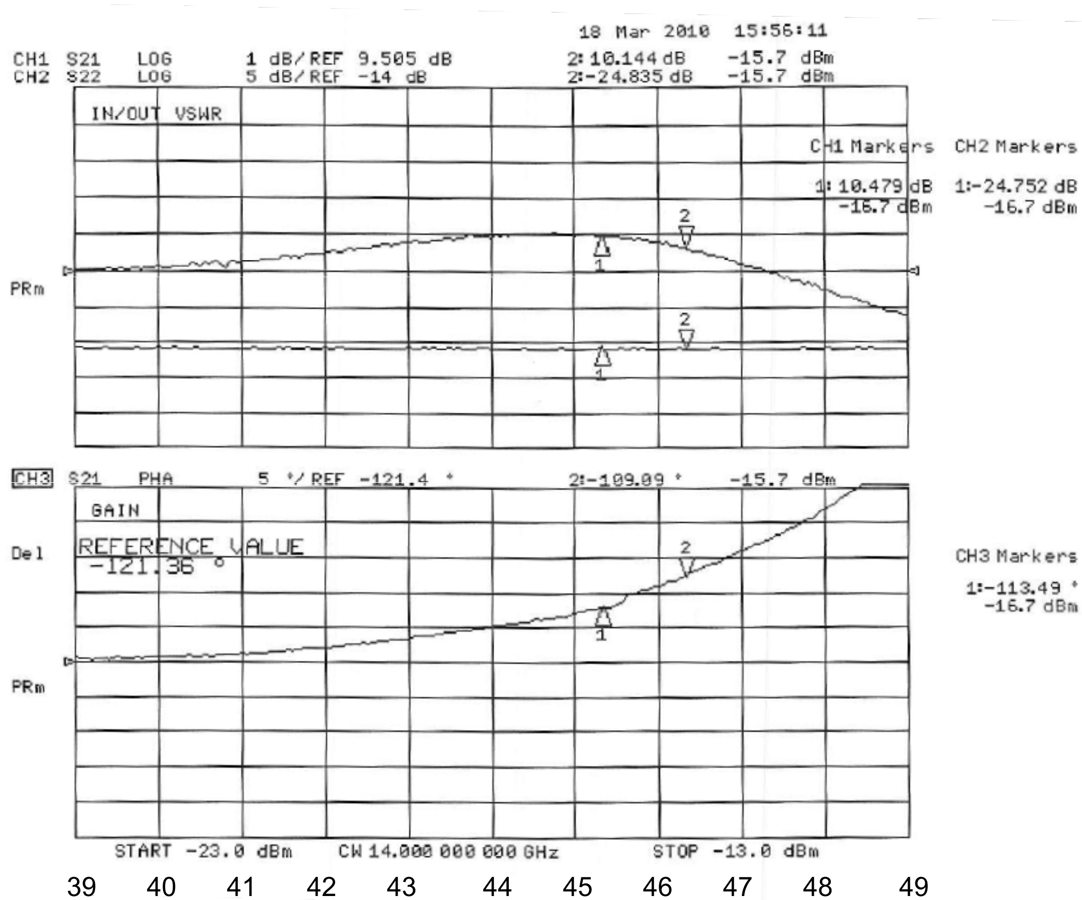
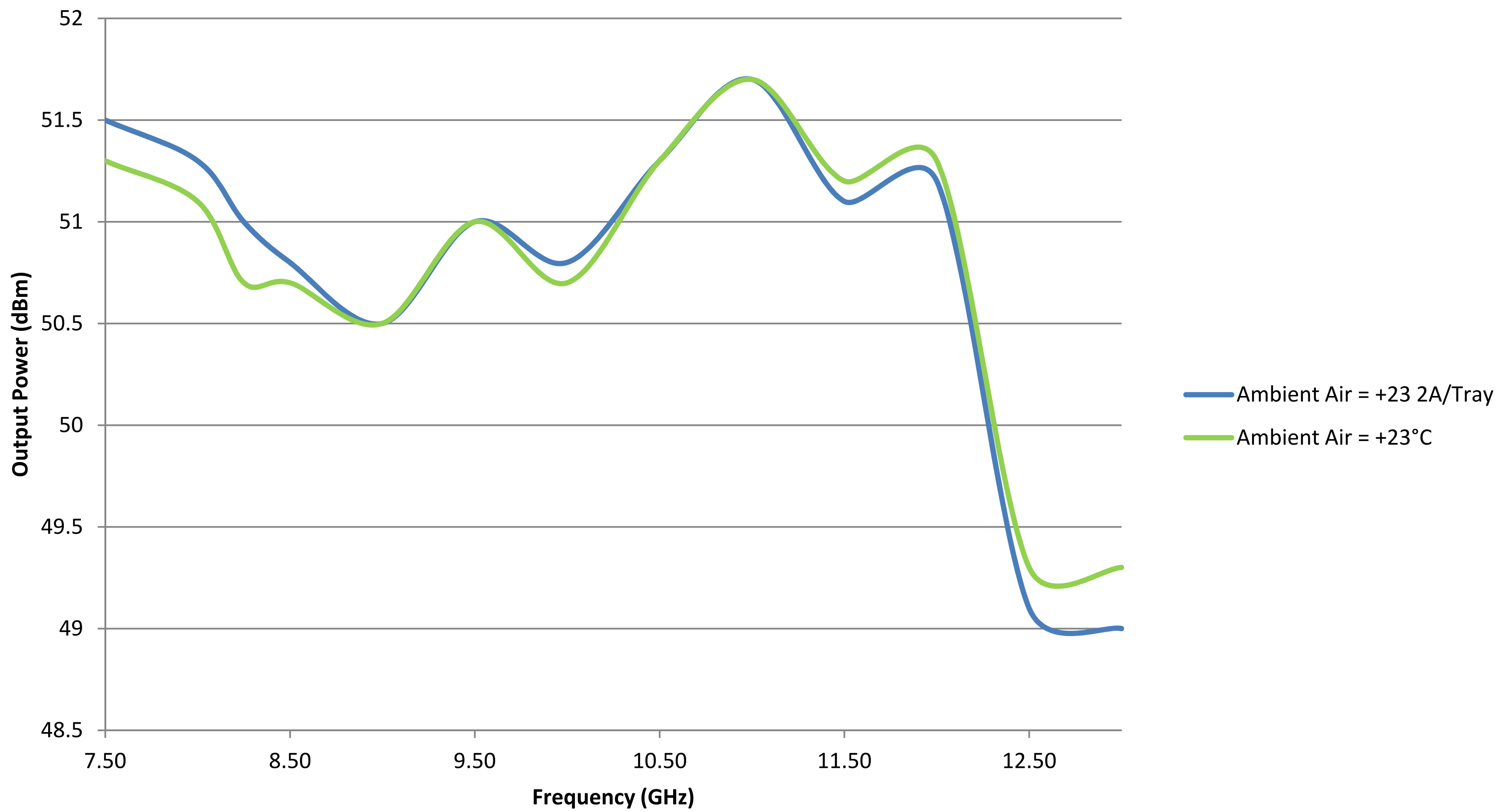
AM-AM & AM-PM


18 Mar 2010 15:56:11
CH1 S21 LOG 1 dB/ REF 9.505 dB 2:10.144 dB -15.7 dBm
CH2 S22 LOG 5 dB/ REF -14 dB 2:-24.835 dB -15.7 dBm
IN/OUT VSWR
CH1 Markers
1:10.479 dB
-16.7 dBm
CH2 Markers
1:-24.752 dB
-16.7 dBm
PRm
CH3 S21 PHA 5 °/ REF -121.4 ° 2:-109.09 ° -15.7 dBm
GAIN
REFERENCE VALUE
-121.36 °
Del
CH3 Markers
1:-113.49 °
-16.7 dBm
PRm
START -23.0 dBm CW 14.000 000 000 GHz STOP -13.0 dBm
39 40 41 42 43 44 45 46 47 48 49

Example X Band Performance



Ka Band

Eagle Spatium Power Measurements 6/7/11

Vd = 6.0V Id = 1.5A per MMIC

f (GHz)	P1dB (dBm)	Current (A) @ P1dB
30.0	45.3	34.3
30.5	44.7	33.8
31.0	44.4	33.4

Two-Tone Measurements
Linear Power is defined as the total average power of the
two tones spaced 20MHz apart when the IM3 products are 25.5dBc.

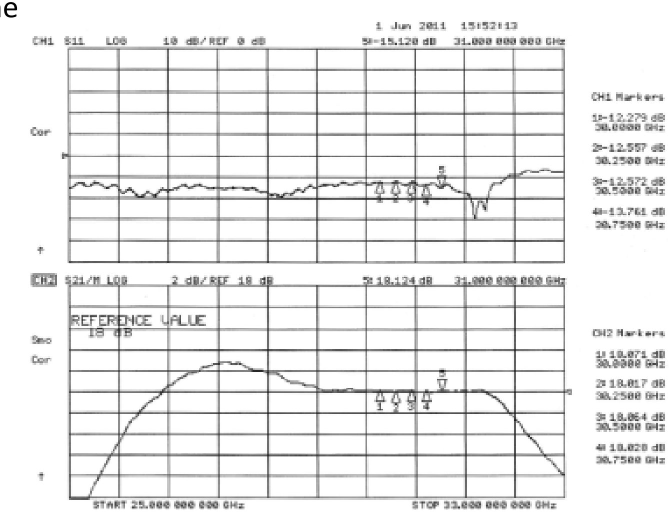
f (GHz)	Max Linear Power (dBm)
30.0	41.4
30.5	40.9
31.0	39.8

Vd = 6.0V Id = 1.8A per MMIC

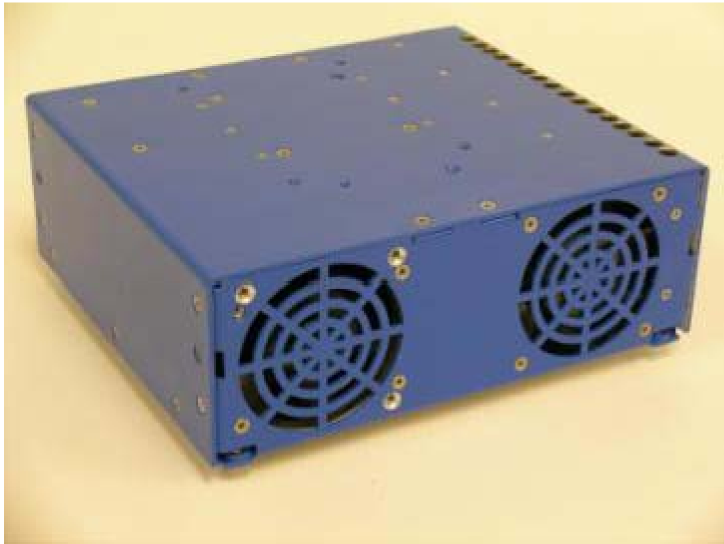
f (GHz)	P1dB (dBm)	Current (A) @ P1dB
30.0	45.4	36.4
30.5	44.8	36.3
31.0	44.4	36.1

Two-Tone Measurements
Linear Power is defined as the total average power of the
two tones spaced 20MHz apart when the IM3 products are 25.5dBc.

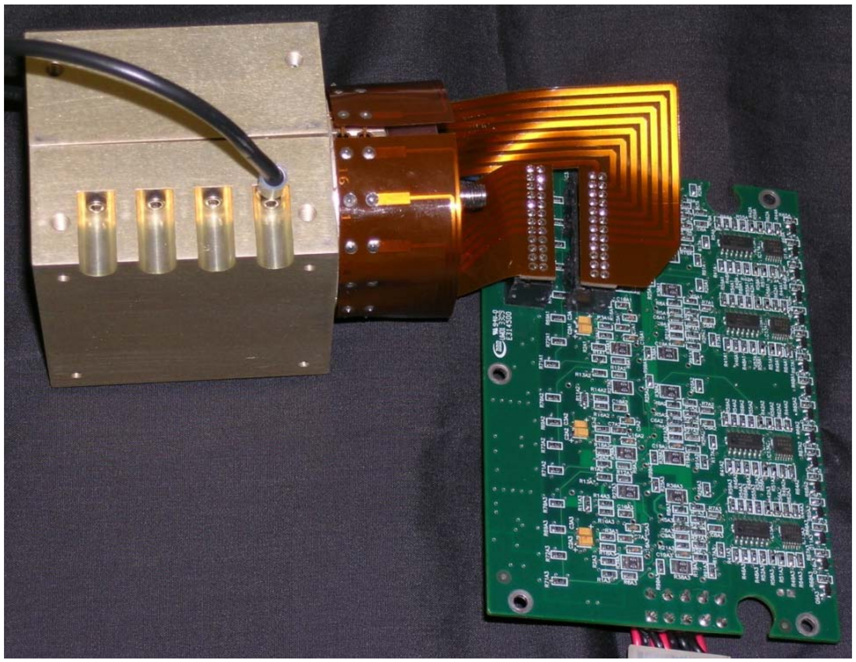
f (GHz)	Max Linear Power (dBm)
30.0	42.1
30.5	41.7
31.0	40.3

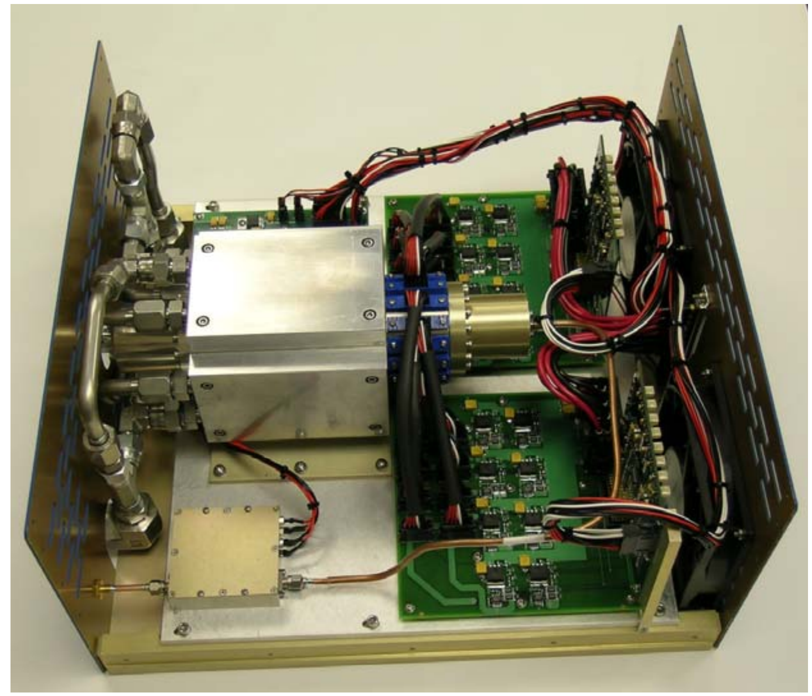


CAP WIRELESS



CAP WIRELESS



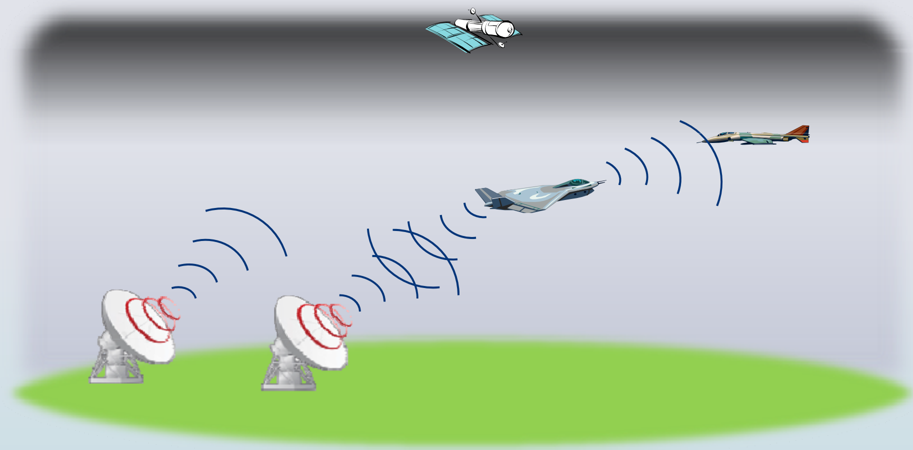


Summary

- Classic Legacy Microwave Performance achievable with tubes is rapidly giving way to solid state high performance alternatives.

Spatium™

Solid State Spatially Combined Microwave and Millimeter Wave Power Amplifiers



Features

Frequency 2-40+ GHz

RF Power to 100s of Watts

Low Voltage <50 Volts

Fault Tolerant – No Single Point Failure

Convection, Conduction or Liquid Cooling

Low Thermal Noise Power
Low Phase Noise

No Warmup Required

Pulse or CW

Linear or Saturated Operation

Applications

Satellite Communication

Data Link

Electronic Warfare (EW)

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