

High Efficiency Power Combining of Ka-Band TWTs for High Data Rate Communications

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ABSTRACT

Future NASA deep space exploration missions are expected in some cases to require telecommunication systems capable of operating at very high data rates (potentially 1 Gbps or more) for the transmission back to Earth of large volumes of scientific data, which means high frequency transmitters with large bandwidth. Among the Ka band frequencies of interest are the present 500 MHz Deep Space Network (DSN) band of 31.8 to 32.3 GHz and a broader band at 37-38 GHz allocated for space science [1]. The large distances and use of practical antenna sizes dictate the need for high transmitter power of up to 1 kW or more. High electrical efficiency is also a requirement.

The approach investigated by NASA GRC is a novel wave guide power combiner architecture based on a hybrid magic-T junction for combining the power output from multiple TWTs [1,2]. This architecture was successfully demonstrated and is capable of both high efficiency (90-95%, depending on frequency) and high data rate transmission (up to 622 Mbps) in a two-way power combiner circuit for two different pairs of Ka band TWTs at two different frequency bands. One pair of TWTs, tested over a frequency range of 29.1 to 29.6 GHz, consisted of two 110-115W TWTs previously used in uplink data transmission evaluation terminals in the NASA Advanced Communications Technology Satellite (ACTS) program [1,2]. The second pair was two 100W TWTs (Boeing 999H) designed for high efficiency operation (>55%) over the DSN frequency band of 31.8 to 32.3 GHz [3].

The presentation will provide a qualitative description of the wave guide circuit, results for power combining and data transmission measurements, and results of computer modeling of the magic-T and alternative hybrid junctions for improvements in efficiency and power handling capability. The power combiner results presented here are relevant not only to NASA deep space exploration missions, but also to other U.S. Government agency programs.

- [1] E.G. Wintucky et al., "Ka-Band Technology Developments for Space Communications at the NASA Glenn Research Center," Proc. 10th Ka and Broadband Communications Conf., Vicenza, Italy, pp. 501-508, Sep. 30-Oct. 2, 2004.
- [2] E.G. Wintucky et al., "Waveguide Power Combiner Demonstration for Multiple High Power Millimeter Wave TWTAs," Fifth IEEE Inter. Vacuum Electronics Conf., Monterey, CA, pp. 98-99, April 27-29, 2004.
- [3] N.R. Robbins et al., "High Power, High Efficiency 32 GHz Space Traveling wave Tube," Fifth IEEE Inter. Vacuum Electronics Conf., Monterey, CA, pp. 261-262, April 27-29, 2004.

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2005 Tri-Service Vacuum Electron Device Workshop (TVED 2005)

13-15 September 2005

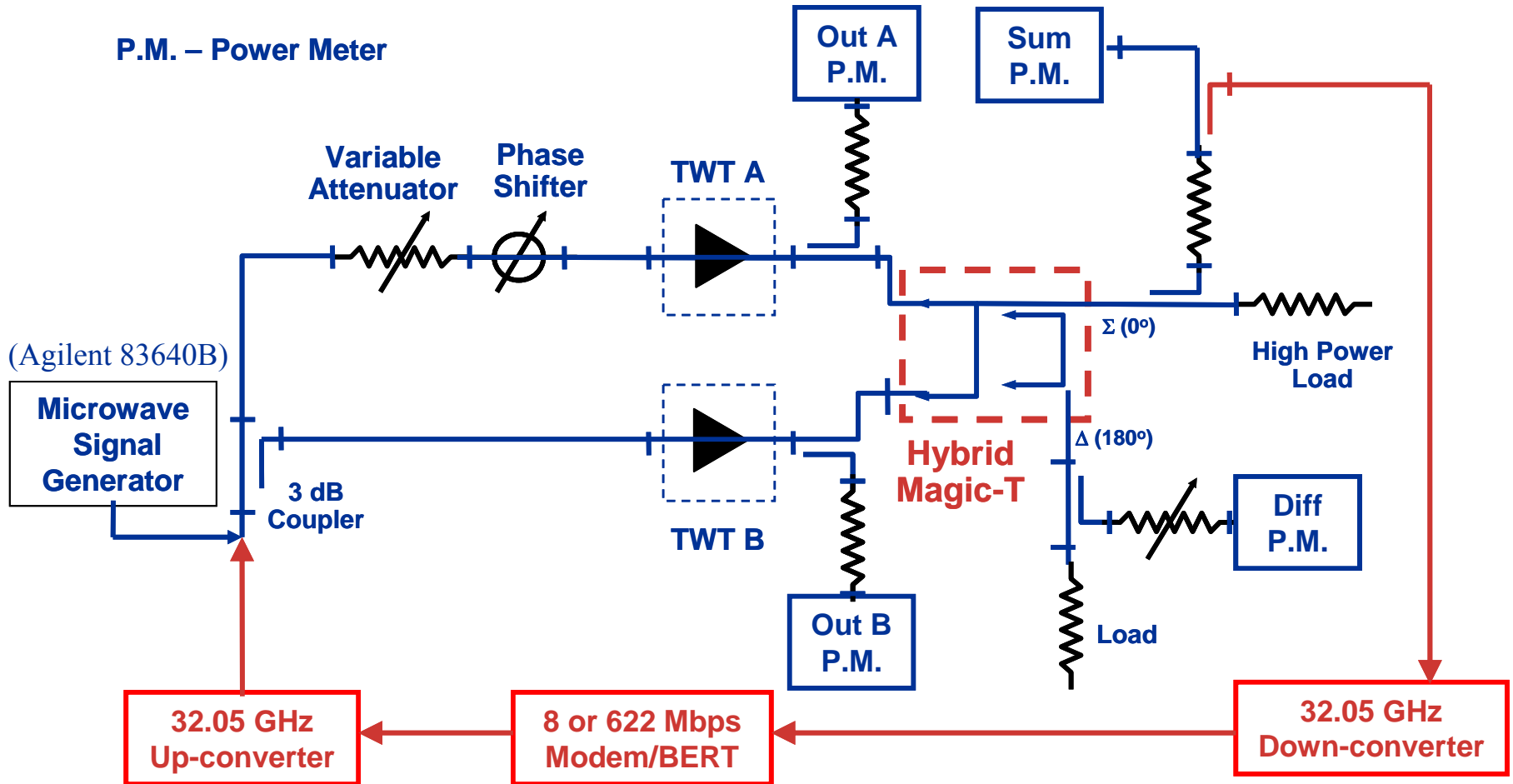
Albuquerque, NM

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Objectives and Approach

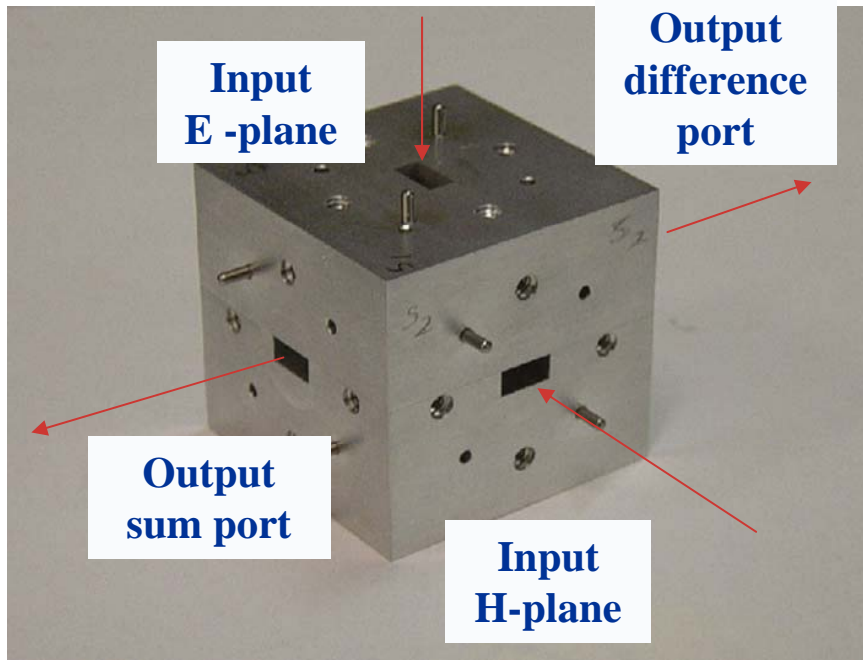
- **Demonstration of high efficiency power combining of multiple high power Ka-band TWTs for potential generation of 1000 W of RF power**
 - **Two-way wave guide power combiner circuit based on hybrid junction magic-T for combining power output from multiple TWTs**
 - **Two 110-115 W ACTS TWTAs – 500 MHz BW (29.1-29.6 GHz)**
 - **Two 100W Boeing space TWTs (999H) – 500 MHz DSN BW (31.8-32.3 GHz)**
- **Demonstration of high data transmission rates of >10 Mbps (error-free or low BER) for future NASA deep space exploration missions**
 - **8 Mbps (BPSK and QPSK) – ACTS TWTAs and Boeing 100W TWTs**
 - **622 Mbps (QPSK) - Boeing 100W TWTs**
- **Computer modeling of hybrid junctions for improvements in efficiency and power handling**
 - **CST Microwave Studio modeling and design for optimization of transmission characteristics of magic-Ts and alternative hybrid junctions**

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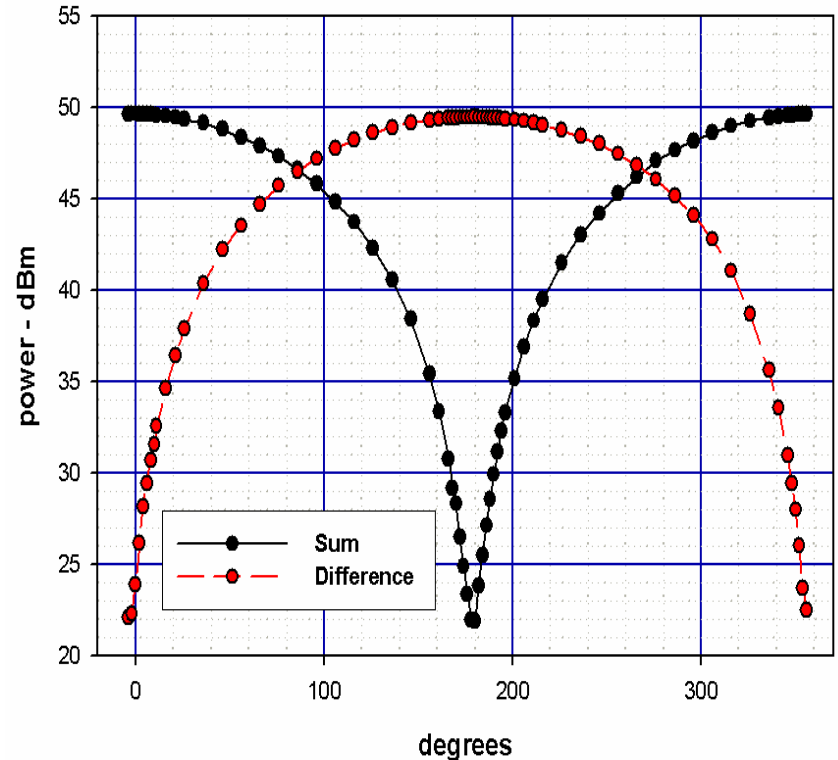
Two-way TWT power combiner circuit

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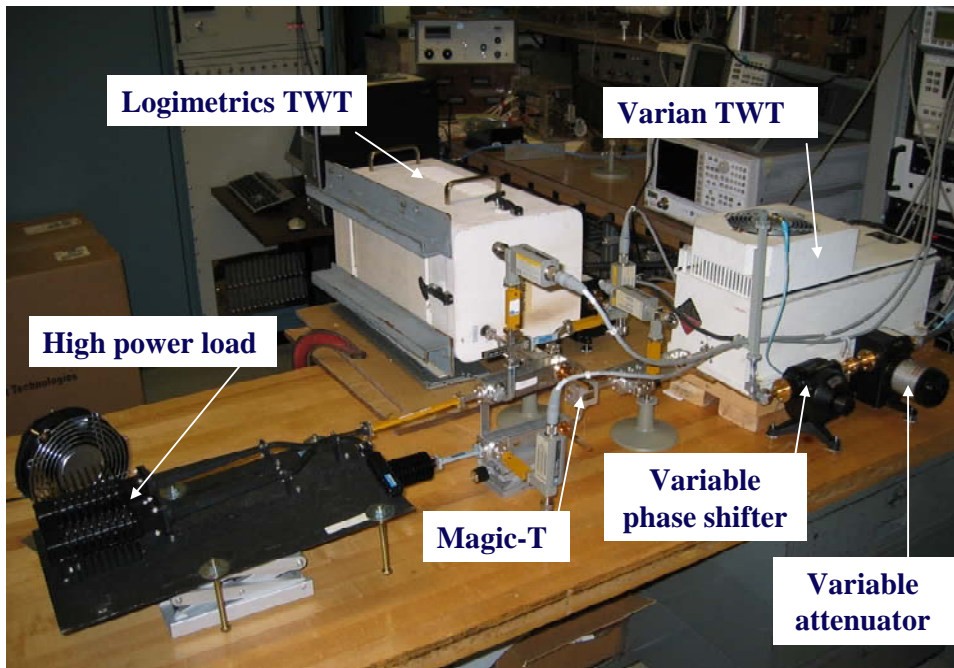
Hybrid Magic Tee

- Input ports – 3 dB coupling to output ports, 90 deg phase shift
- Sum port – input powers add in phase
- Difference port – phase cancellation of input powers

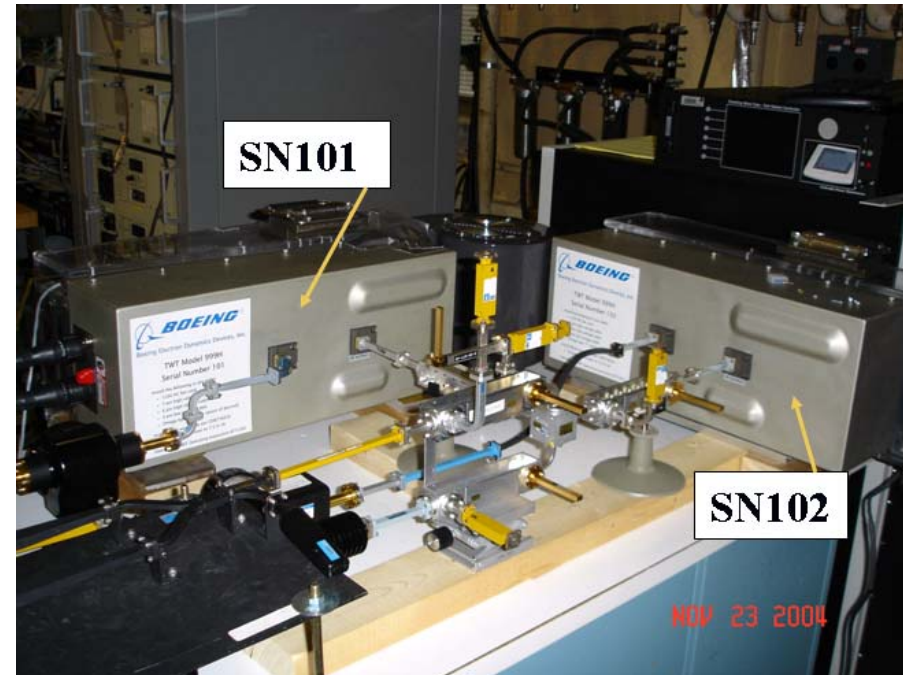


Sum and difference power variations with change in phase

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**Power combiner test bed for
ACTS 100W TWTAs**



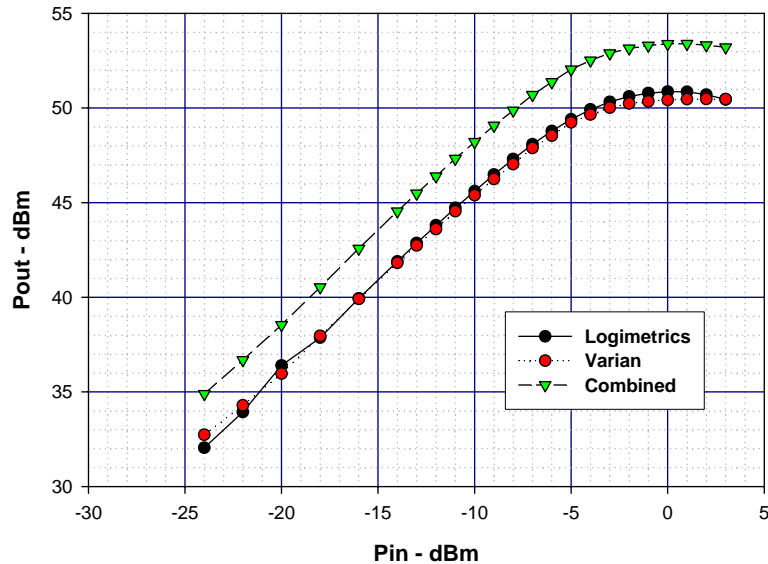
**Power combiner test bed for
Boeing 999H 100W TWTs**

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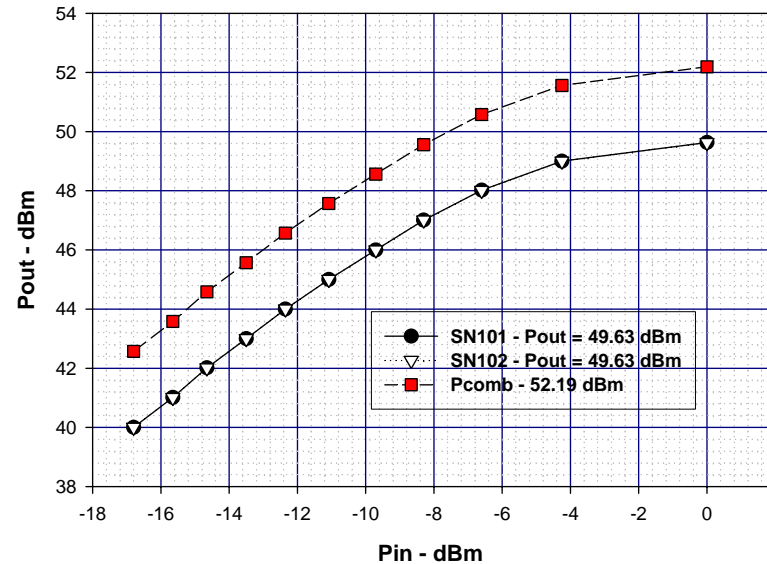
Power/efficiency measurements

- **AM-AM measurements**
 - **Manual variation of input power (20 dBm range) and phase for power/phase balance into magic-T**
 - **Power measurements made with Agilent dual power meters (E4419B)**
 - **Offsets based on network analyzer (Agilent E8363B) measurements of insertion losses**
 - **Accuracy of power/efficiency measurements critically dependent on calibration accuracy (0.1 dBm ~ 2.3%)**
 - **Power measurement results shown only for center frequencies of ACTS (29.35 GHz) and DSN (32.05 GHz) frequency bands**
 - **Output powers shown for Boeing TWTs are actual powers going into magic-T and reflect power loss in directional couplers used for power meter measurements. Actual saturated powers are about 50.2 dBm.**
 - **Efficiencies are for center and band edge frequencies for each frequency band**

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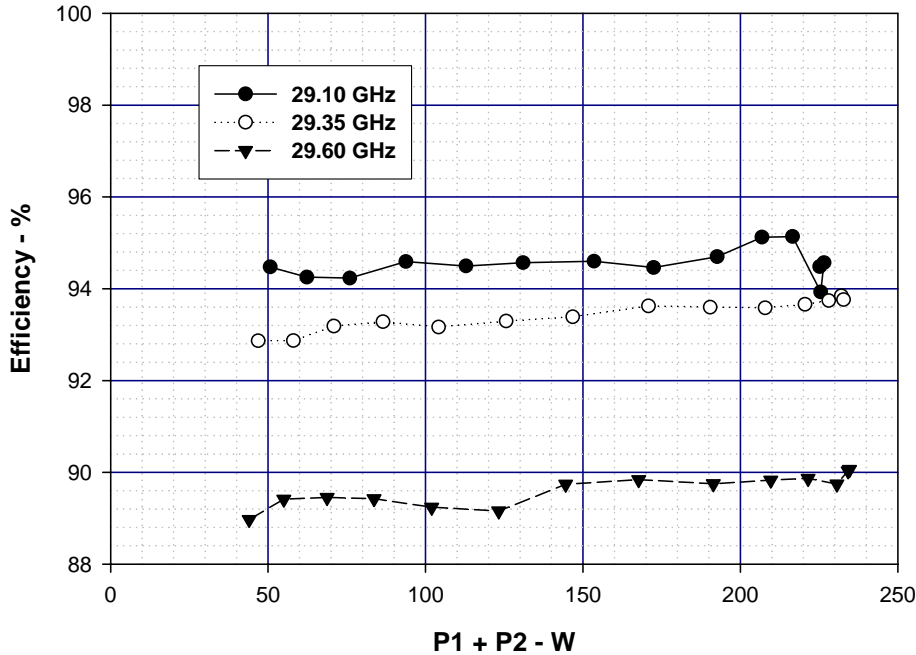


**ACTS TWTA and combined
output powers at 29.35 GHz**

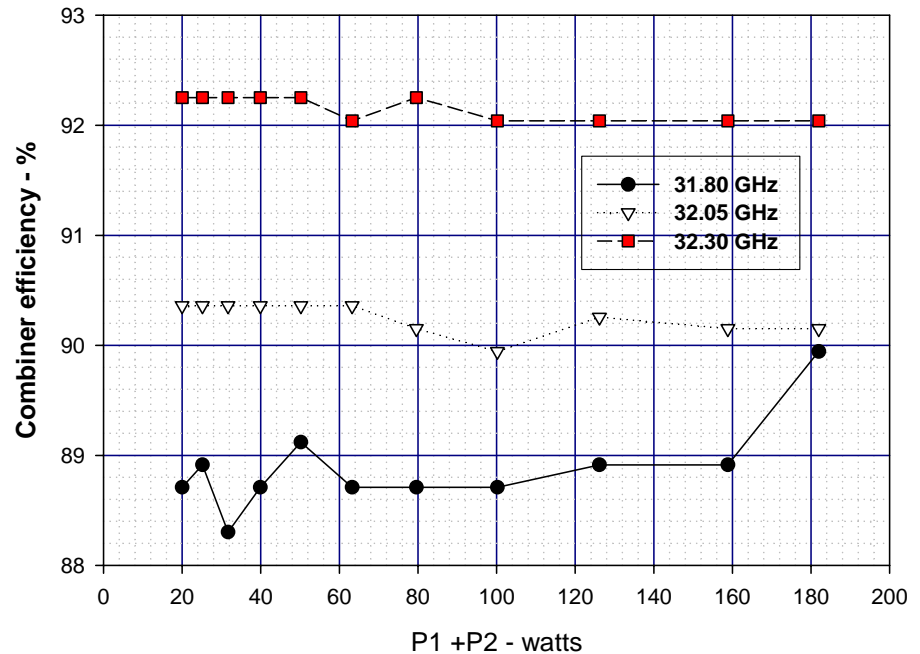


**Boeing TWT and combined
output powers at 32.05 GHz**

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(a) ACTS TWTAS



(b) Boeing TWTS

Power combining efficiencies for (a) ACTS TWTAS and (b) Boeing TWTS at center frequencies and 500 MHz band edges

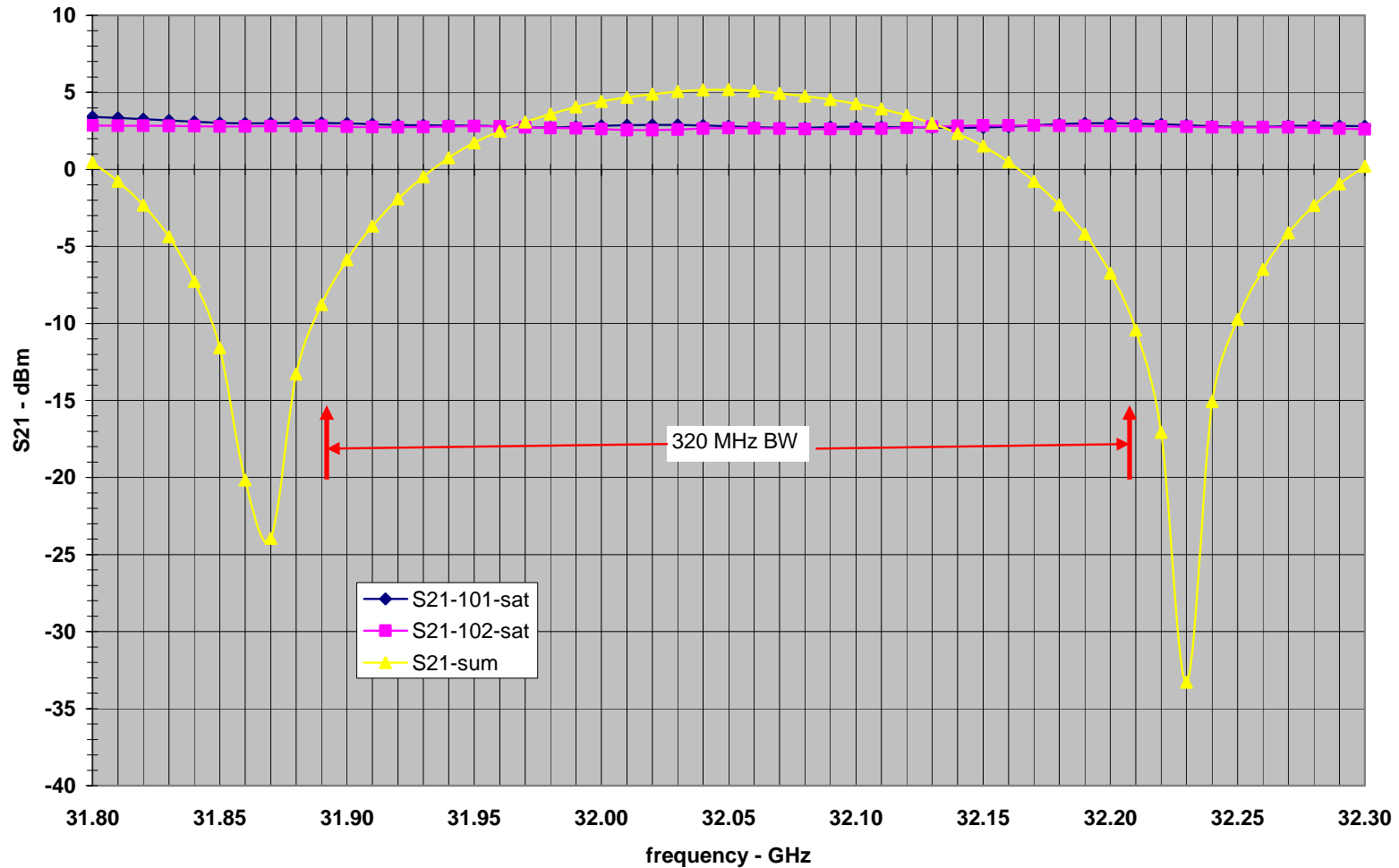
High Efficiency Power Combining of Ka-Band TWTs for High Data Rate Communications

Demonstration of data transmission

- **Error-free transmission of 8 Mbps, BPSK and QPSK, (Comstream Digital Modem, CM701) successfully achieved with both ACTS and Boeing TWT combiner circuits**
 - **No correction required for differences in phase-vs-frequency ($d\phi/df$) between RF output of the two TWTs (narrow BW of signal & small dependence of peak of combined power on phase)**
- **Low BER (2.4×10^{-8}) 622 Mbps QPSK successfully demonstrated (Synthesis Research 622 BitAlyzer) with mod-1 for Boeing TWT combiner circuit**
- **Correction required for 622 Mbps because of large phase imbalance at magic-T over signal BW (311 MHz BW – QPSK)**
 - **Initially $d\phi/df = 0.991$ deg/MHz**
 - **Added wave guide: mod 1 – 0.147 deg/MHz, mod 2 – 0.018 deg/MHz**
- **Useful bandwidth of magic-T for data transmission shown to be at least 3 GHz**
 - **Gain ripple of combined power output < 1 dBm and equal to or less than outputs of individual TWTs**

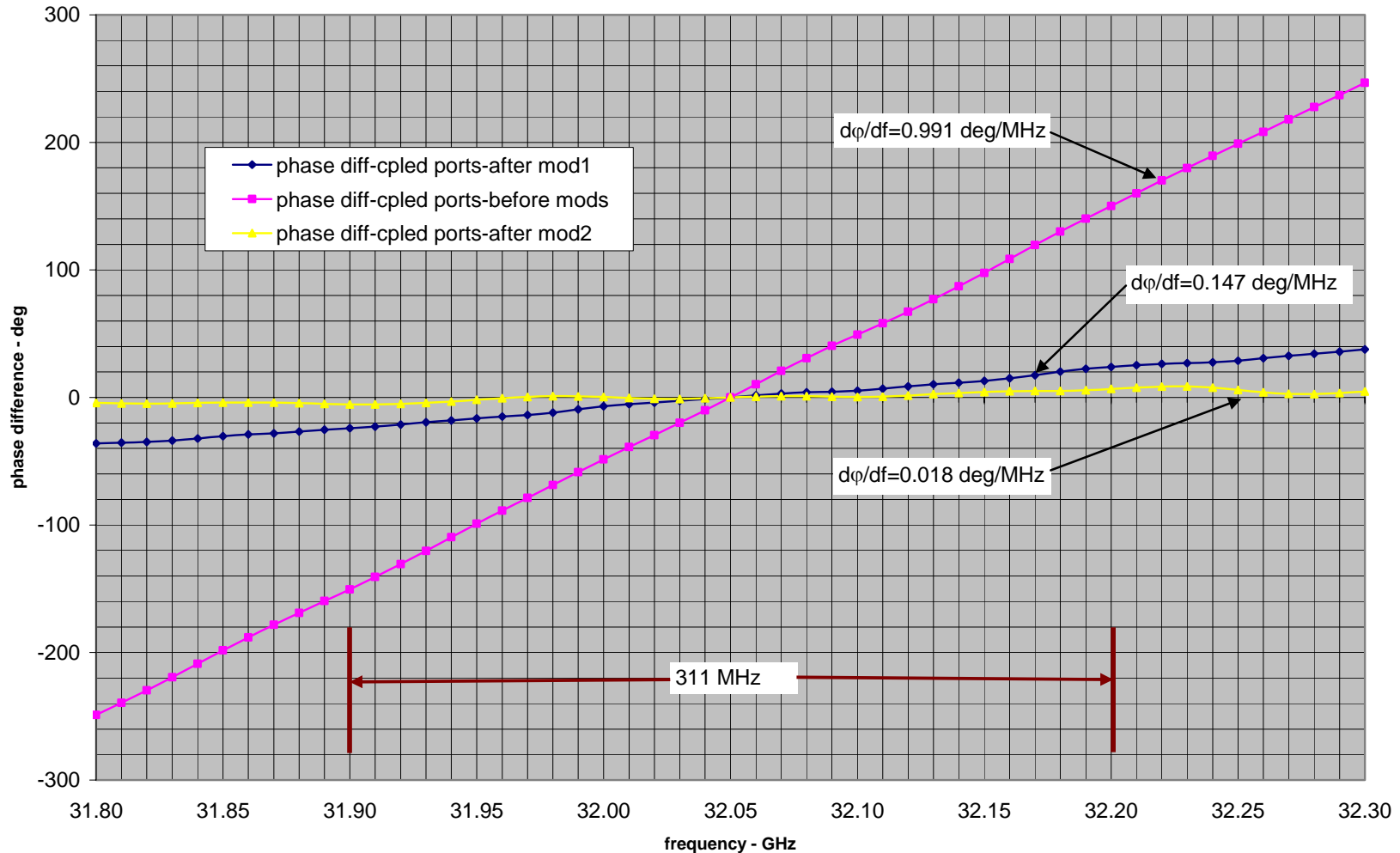
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S21 comparison - Initial results before circuit modification
FRQpowcompF1S (chart 2)



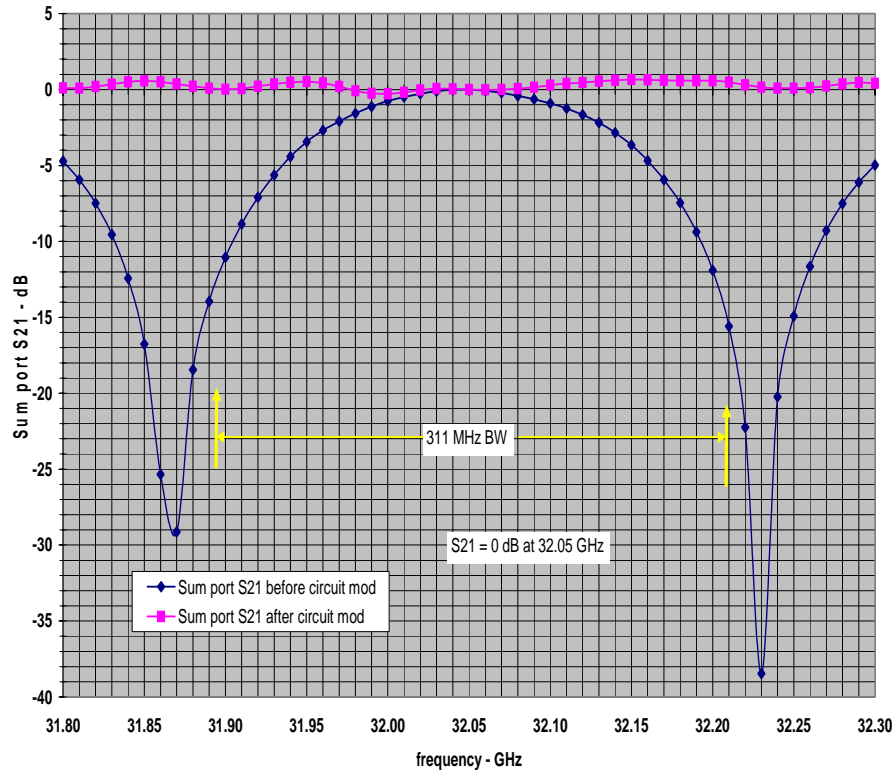
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Phase difference comparison - before and after circuit mods
FrqSwp_compare1 (chart 9)

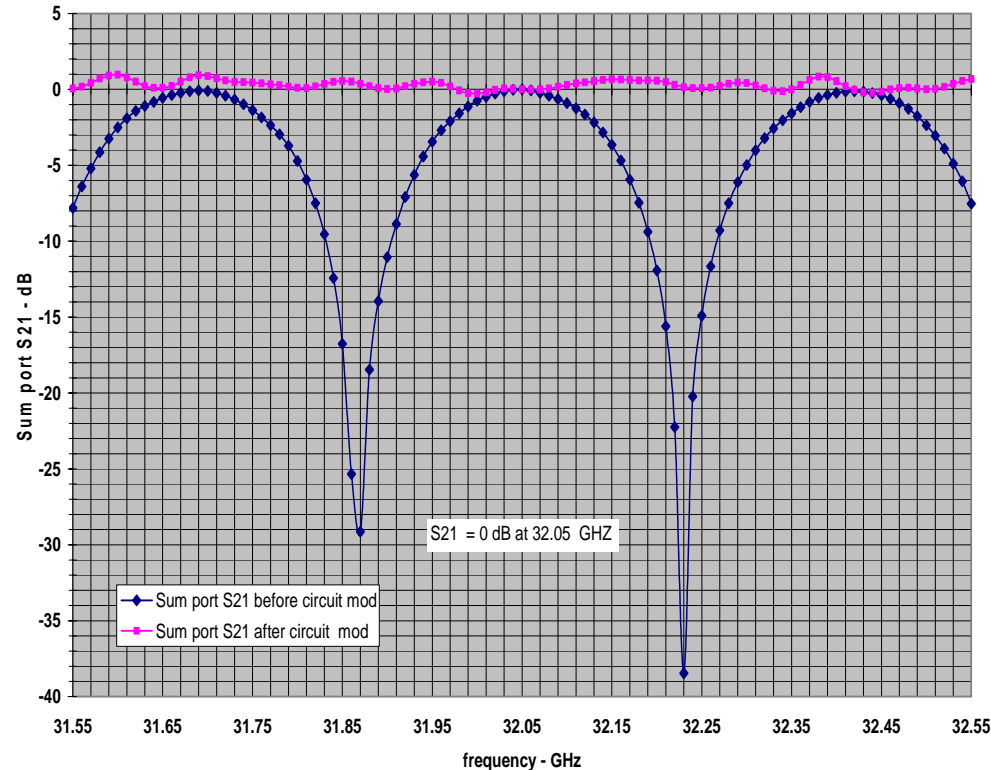


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Comparison of sum port S21 before & after circuit modification
FrqSwp_compare1 (chart 2)

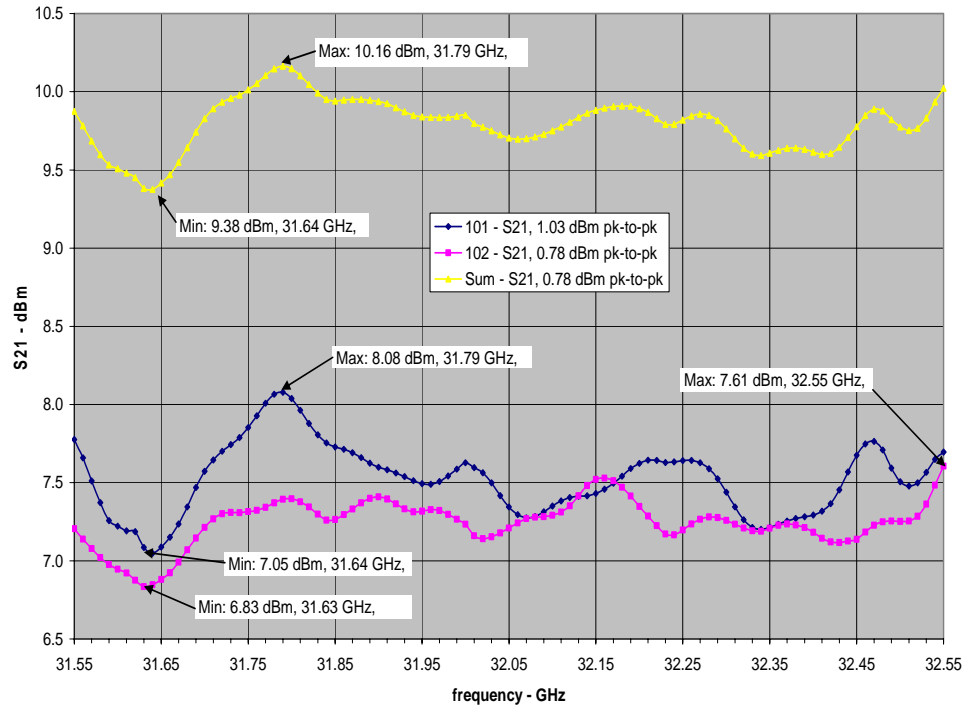


Comparison of sum port S21 before & after circuit modification
FrqSwp_compare1 (chart 1)

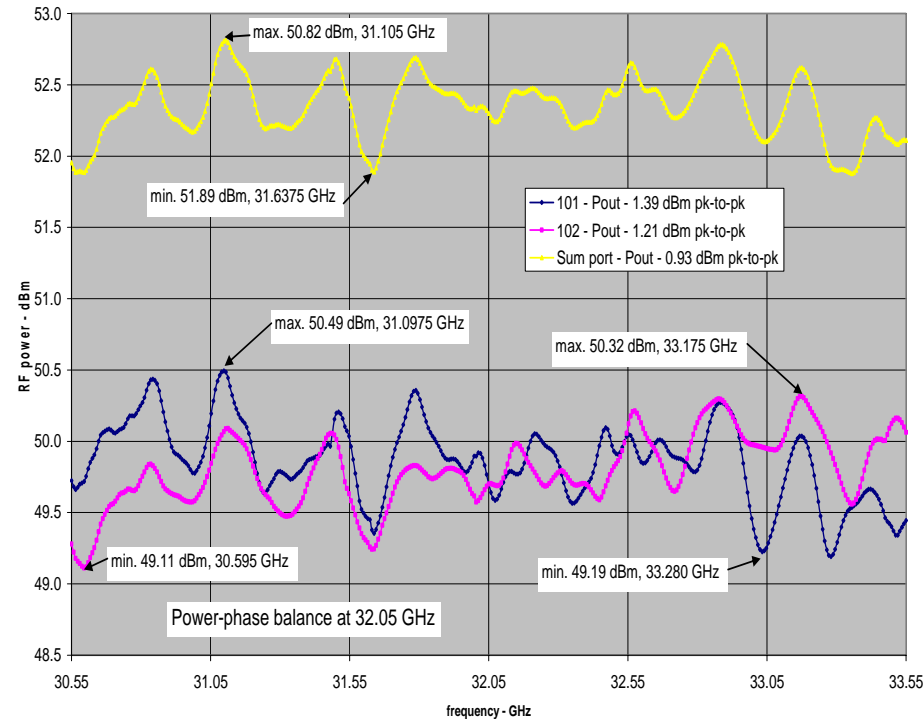


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S21 comparison - 101,102, sum (1 GHz BW)
PowComp 6-22-05 (chart 1)



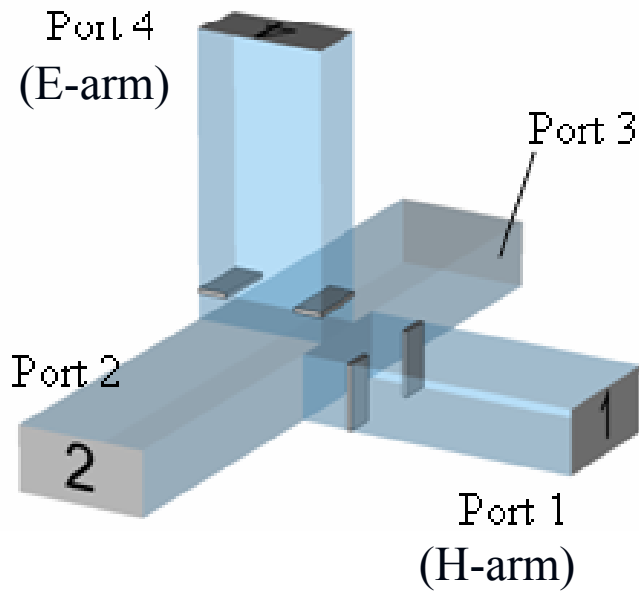
Power vs frequency - 3 GHz frequency sweep
Comp fs 3GHz 6-28-05 (chart 1)



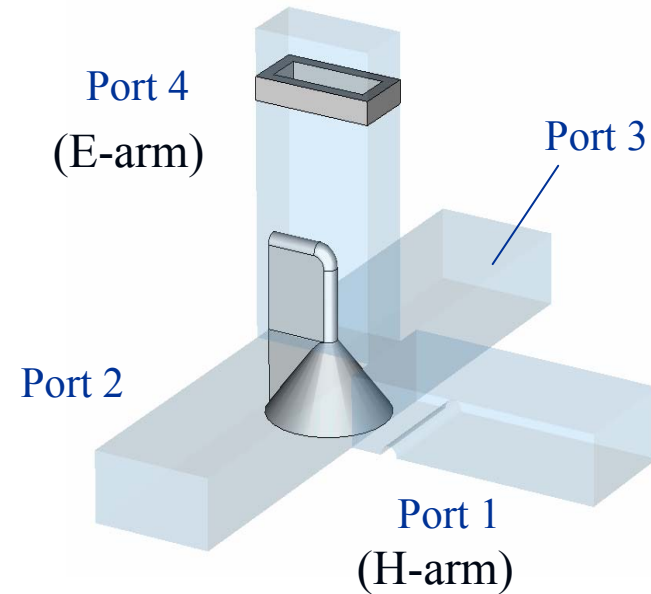
High Efficiency Power Combining of Ka-Band TWTs for High Data Rate Communications

- **Preliminary computer aided design and modeling of high power Ka-band 4-port hybrid junctions using CST Microwave Studio**
 - **Objectives: Improvement of efficiency and power handling capability**
 - **Design goals:**
 - **Center frequency of 32.05 GHz (500 MHz BW), WR28 waveguide**
 - **Hybrid junctions: Magic Tee, Folded E-plane Tee, Rat Race**
 - **Use of elements appropriate for powers ranging from hundreds of watts to kilowatts**
 - **Optimization of S-parameters – matching of ports**
 - **3 dB insertion loss**
 - **Minimum of 15 dB reflection loss**
 - **Minimum of -40 dB isolation loss**

High Efficiency Power Combining of Ka-Band TWTs for High Data Rate Communications

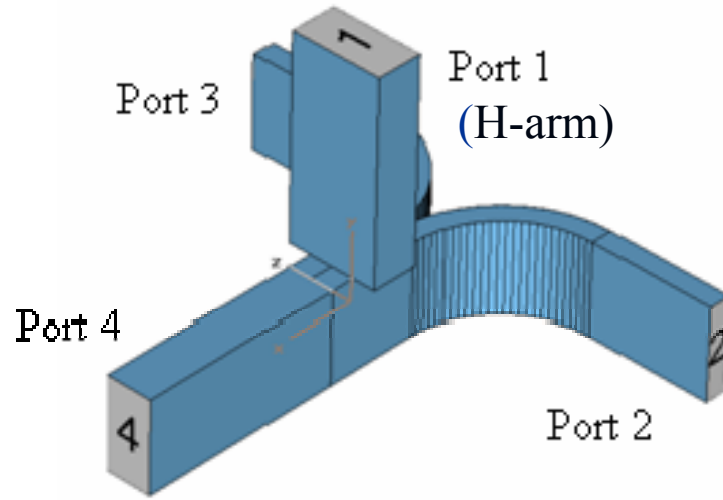


**Magic Tee matched by
inductive windows**

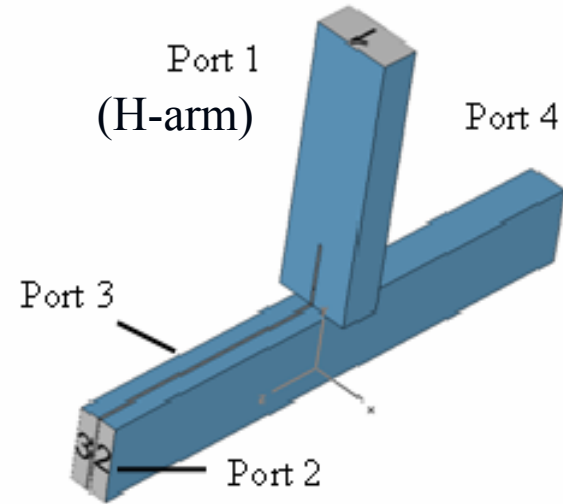


**Magic Tee matched by cone-
fin structure**

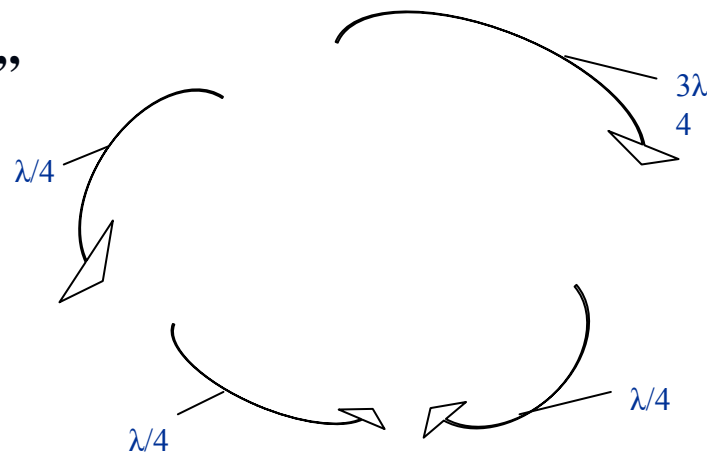
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**Folded E-plane Tee
“Split Co-linear arms”**



**Folded E-plane Tee
“Common wall”**



“Rat Race” hybrid ring

High Efficiency Power Combining of Ka-Band TWTs for High Data Rate Communications

Comparison of simulated transmission characteristics of the different hybrid junctions (WR28 wave guide) over a frequency range of 31.8 to 32.3 GHz

Hybrid Junction	Insertion Loss		Reflection Loss		Isolation
	S ₂₁ dB	S ₂₄ dB	S ₁₁ dB	S ₄₄ dB	S ₄₁ dB
Magic Tee (inductive windows)	-3.072	-3.17	-24.17	-14.48	-76.4
Magic Tee (cone-fin)	-3.156	3.426	-15.44	-9.823	-136.3
Folded E-Plane Tee (common wall)	-3.203	-3.124	-13.72	-15.9	-151.4
Folded E-plane Tee (split collinear arms)	-3.068	-3.073	-14.84	-19.17	-140.6
Rat Race	-3.569	-3.467	-10.2	-10.42	-27.38

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Conclusions

- **Two-way Ka-band wave guide power combiner circuit based on magic-T hybrid junction can provide high power (> 200 W) at high efficiency ($>90\%$).**
 - **Readily extendable to combine 4 or 8 TWTs (binary configuration)**
- **Magic-T can support high data rate transmission rates of at least 622 Mbps at low BER.**
 - **Wave guide circuit easily modified to compensate for output phase imbalances ($d\phi/df$) of TWTs**
 - **Useful bandwidth for high data transmissions rates can be extended to at least 3 GHz.**
- **Computer modeling of magic-T and other hybrid junctions shows improvements in efficiency (lower insertion, return and isolation losses) and power handling capability are possible.**
 - **Folded E-plane hybrid junctions very well suited for high power applications. (Robust, easily fabricated, relatively inexpensive)**