Corrugated Platelet Feed Arrays for Millimeter-Wave Imaging

CMB Polarization Technology Workshop
NIST/Boulder

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Why Corrugated Feed Arrays?

- CMB Polarization detection and Flight (COBE, WMAP, Plank) heritage:

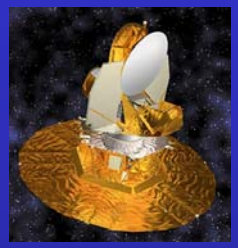
DASI

CBI

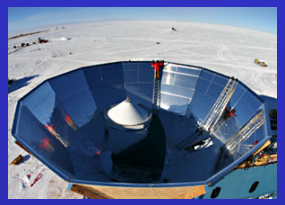
Boomerang

CAPMAP

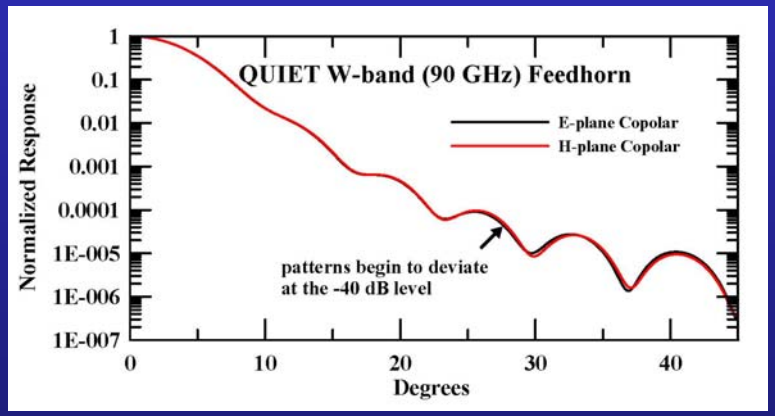
WMAP



QUAD



- Well Defined Illumination Function
  - Superior Beam Symmetry
    - Equal E and H-Plane Response
    - Low Cross Polarization (<-30 dB)
  - Low Sidelobe Response

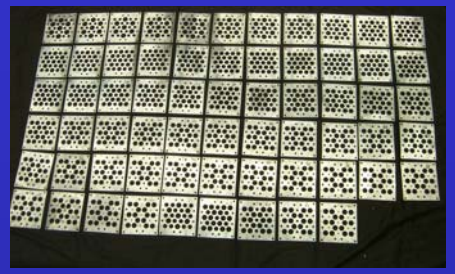


- High Coupling Efficiency
  - Broad (>30%) Bandwidth
  - Low Insertion Loss
  - Low Return Loss

- Corrugated feeds are compatible with high performance polarization diplexing and microstrip based filtering approaches, waveguide cutoff minimizes RFI, and provide natural separation of IR and millimeter wave filtering needs

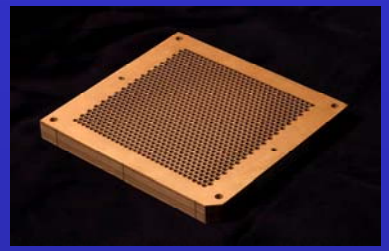
- Large numbers of corrugated feeds can be fabricated together in the form of platelet feed horn arrays in order to increase packing density and reduce fabrication costs.

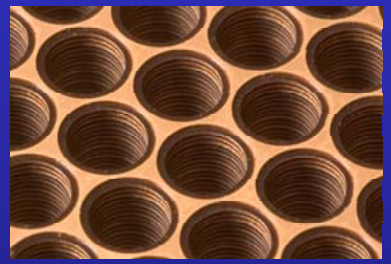
What is a Platelet Array?



A 7 element prototype array for use at 90 GHz was manufactured out of AL6061-T6 on a CNC mill and bonded together using transient liquid phase diffusion bonding. (J. Gundersen)

- A platelet array typically consists of a number of thin metal sheets with a common hole pattern with varying hole sizes on the different sheets. When these sheets are bonded together, a large array of corrugated feed horns can be formed.
- A variety of different metals have been used (e.g. copper, aluminum), a variety of metal removal techniques have been used (e.g. CNC machining, chemical etching), and a variety of different bonding procedures have been used.
- Platelet arrays have been manufactured for use at millimeter and sub-millimeter wavelengths.
- The manufacturing process allows for a great deal of flexibility. Hence light-weighting the arrays is straightforward to implement and thermal-mechanical interfaces are straightforward.
- Platelet arrays can be manufactured in a cost effective manner (~5-10 times cheaper than electroformed versions) while preserving the superior performance and similar mass/horn of electroformed equivalents.





A 1020 element prototype array for use at 400 GHz (WR2.2) was manufactured out of copper, the metal was removed using chemical etching and the platelets were bonded together using diffusion welding. (E. Wollack)

Advantages of Platelet Arrays:

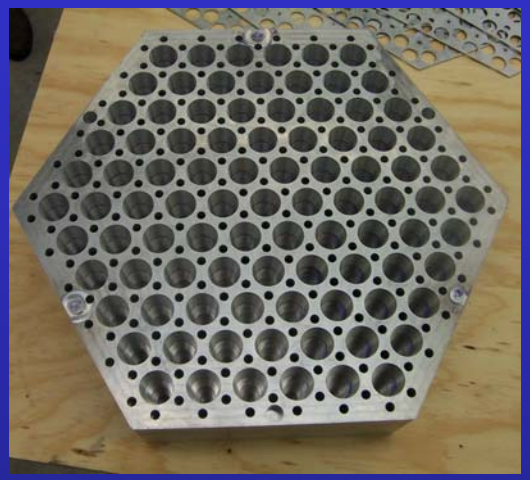
- Platelet arrays of corrugated feeds use a well established machining/fabrication processes for metallic structures which are compatible with reliable cryogenic end use.
- Platelet arrays of corrugated feeds represent a viable technological path toward large number of detector elements in a focal plane.
- Platelet arrays of corrugated feeds provide a well controlled and repeatable illumination pattern that enables desired return loss, beam shape, spill, and instrument polarization response.
- Platelet arrays of corrugated feeds are compatible with high performance polarization diplexing and microstrip based filtering approaches, they provide a natural waveguide cutoff to minimize RFI, and they allow a natural separation of IR and millimeter wave filtering needs.
- The theoretical predictions and analysis tools for platelet array performance are very mature.

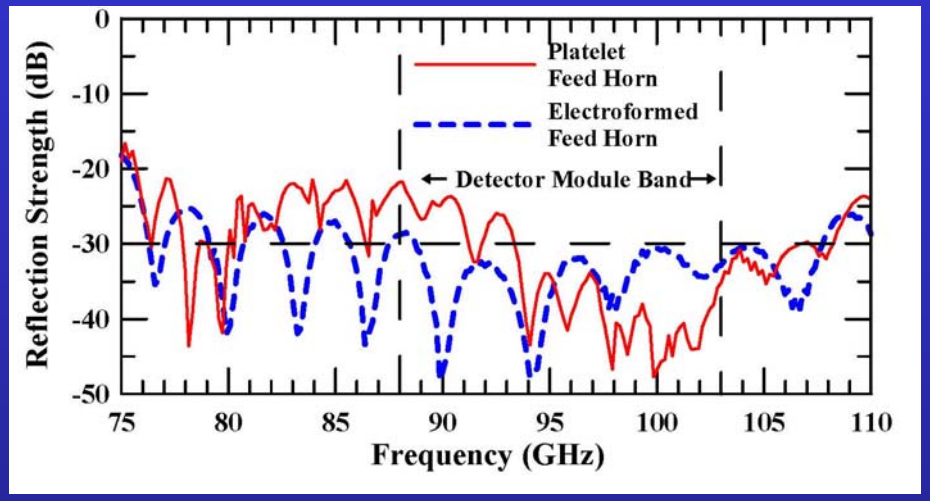
Disadvantages of Platelet Arrays:

- Relatively high metal mass/volume used in conventional approach requires lightening to produce more optimal component for space borne application, however, this material can provide shielding from ionizing radiation
- The simplest array realization requires flat focal surface. As in all antenna illumination approaches the f/ and number of optimally performing detectors pixels coupled in specification of the design. The total optical throughput may push one toward a system configuration with multiple optical assemblies to achieve the requisite number of pixels on sky.
- The detector coupling structures are waveguide based. As a result, the packaging requirement can be more demanding than planar array based approaches
- Depending upon system implementation, quasi-optical IR blocking filters may be required after feed illumination definition in order to achieve the desired thermal environment for the detector.
- Coupling to HE_{11} mode has lower total efficiency and sampling than uniform illumination. This fundamental tradeoff between optical through put and image quality is desirable to control measurement systematics.

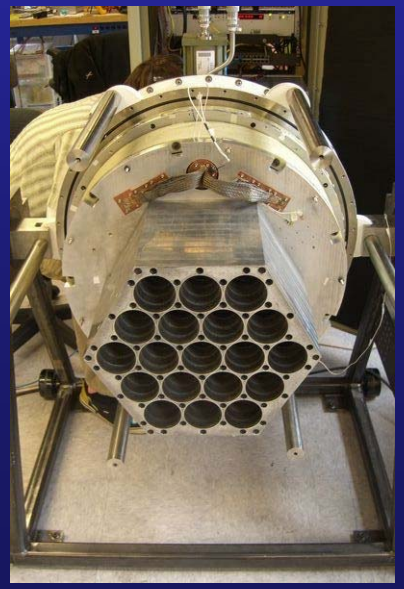
Example: QUIET Platelet Arrays

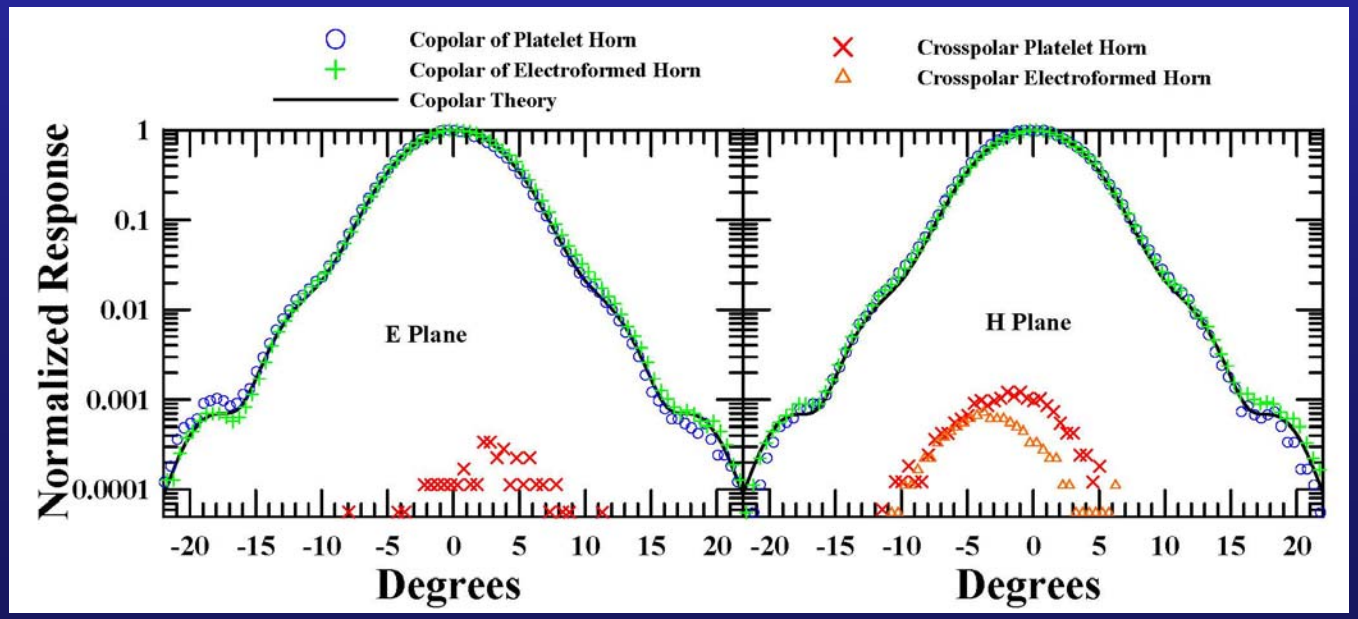
91-Element W-band Array



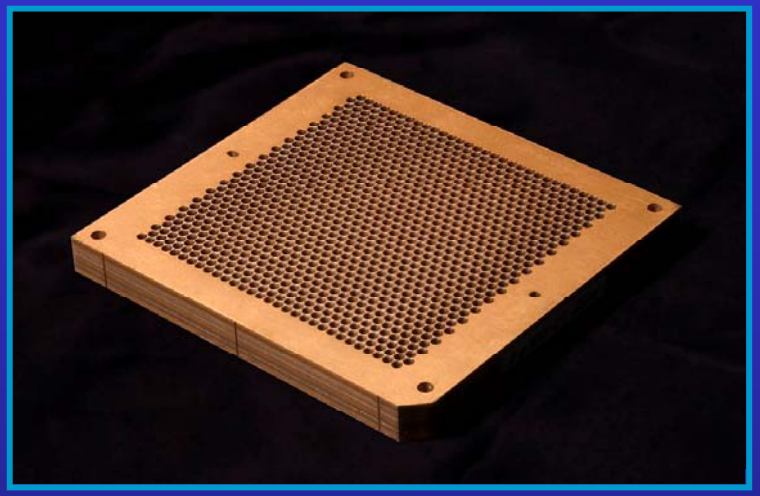


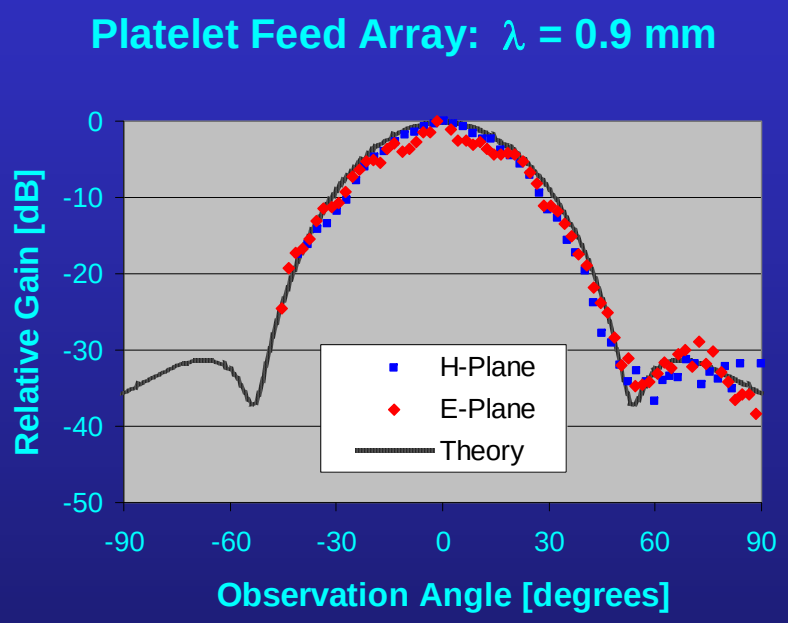
19-Element Q-band Array





Example: WR2.2 Platelet Array





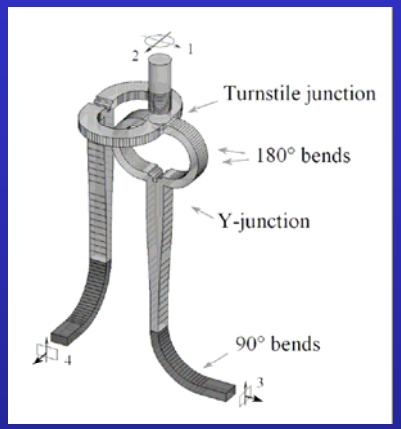
Return Loss for elements sampled better than 20 dB across test band…

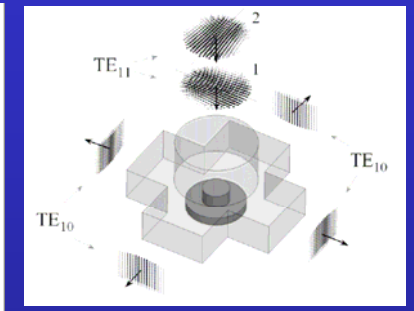
Technology Readiness…

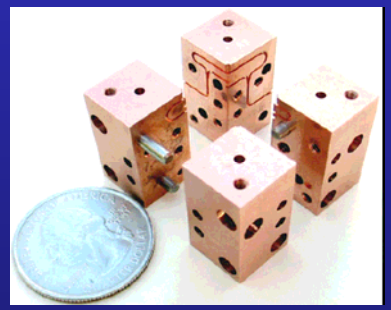
- The technical readiness of platelet feed array structures when used in conjunction with cryogenic coherent receiver systems is at level five or higher.
- For bolometric imaging systems the interface between the platelet array and the detector forces one to assign a lower level of readiness for the technology. Laboratory efforts in this area are underway and a TRL of ~3-to-4 is estimated for the approach at the present time.
- The resources required use this technology are dominated by detector and system level costs associated with fielding instruments which utilize and validate this technology.

Waveguide OMTs: Symmetric Designs

Turnstile (Dicke 1948)



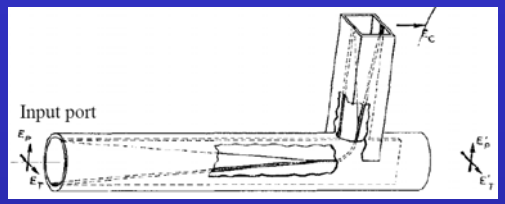




Navarrini &Plambeck (2006)

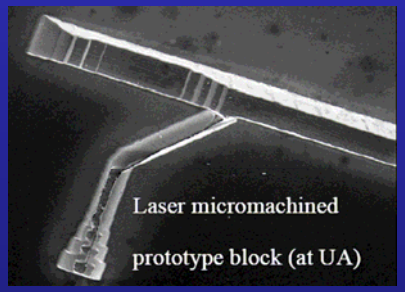
Pisano et al. (2007)

Finline (Robertson 1955)



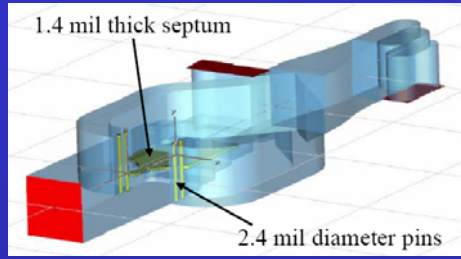
Robertson (1955)

Chattopadhyay & Carlstrom (1998)

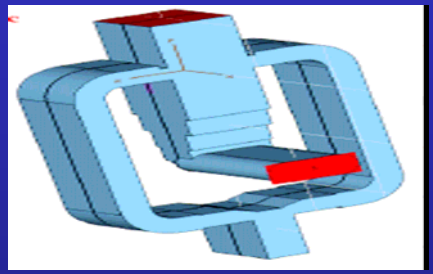


Groppi et al. (2006)

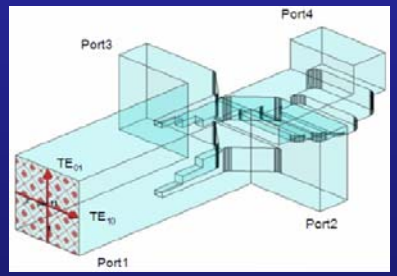
Folded-Turnstile (Boifot 1990)



Wollack (1996)



Narayanan and Erickson (2002)



Dunning (~2006)

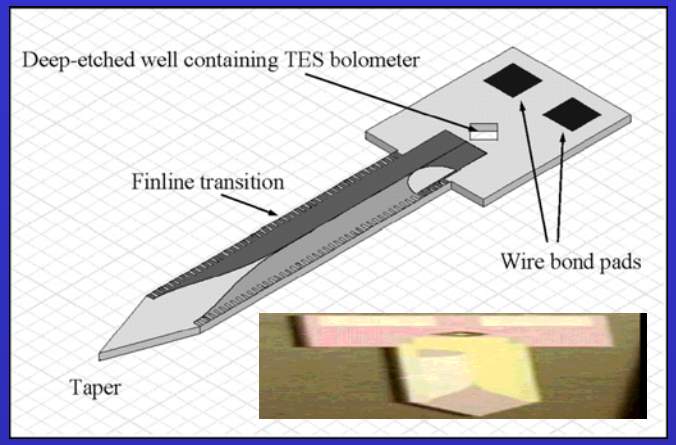
Technical Readiness Level > 5

In Radioastronomy symmetric OMTs have demonstrated the best overall system performance at microwave thru mm-wavelengths

- In forms shown here design does not address the required transition to detector or beam forming functions…
- Block topologies can complicate coupling between waveguide and chip… would like power combiner bends on silicon rather than in metal housing…
- Planar solutions retaining these desirable properties are presently underdevelopment…

Waveguide Transitions: Standard 2:1 Guides

North et al. (2007)



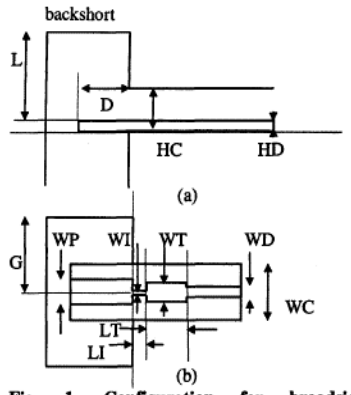


Fig. 1. Configuration for broadside transition. (a) View of WG narrow wall (b) View in direction of propagation away from backshort

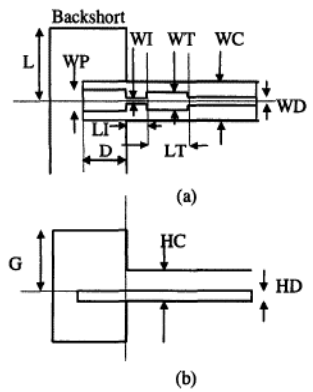


Fig. 2. Configuration for longitudinal transition. (a) View of WG narrow wall (b) View in direction of propagation towards backshort.

Leong & Weinreb (1999)

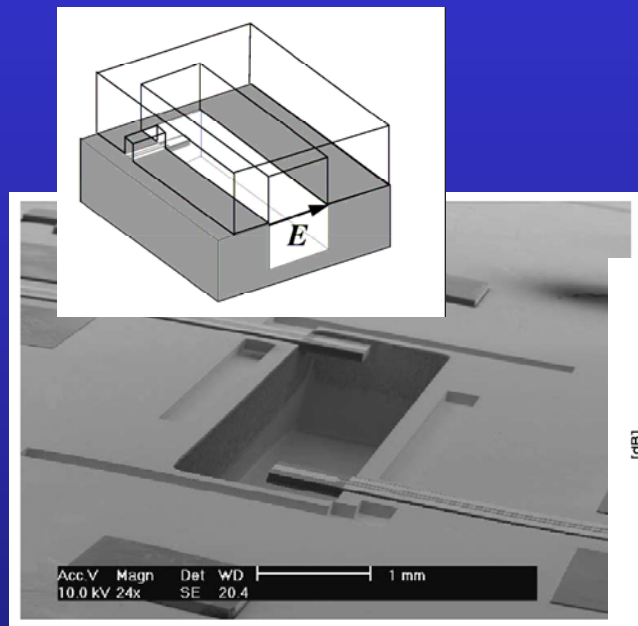


Fig. 9. SEM of a bottom half of a micromachined waveguide with pro placed in the cradle. The alignment block is also seen.

Lee et al. (2004)

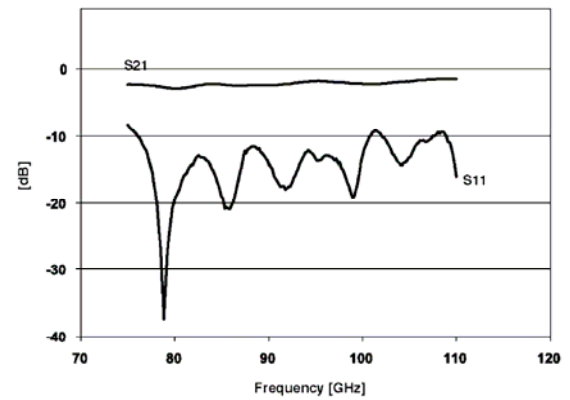


Fig. 10. Measured results of a back-to-back FGC to micromachined silicon DRIE waveguide transition.

Technical Readiness Level ~ 5

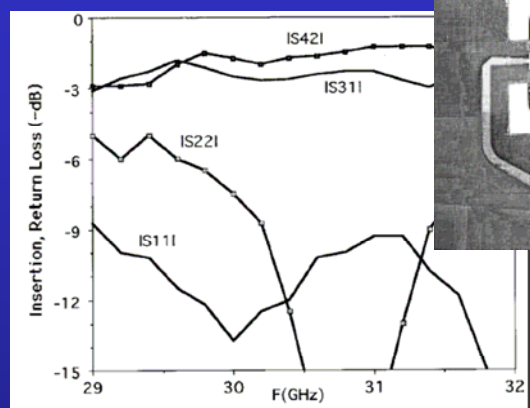
[1] Y.-C. Leong and S. Weinreb, " "Full Band Waveguide-to-Microstrip Probe Transitions, 1999, MTT-S, pp. 1435-1438.

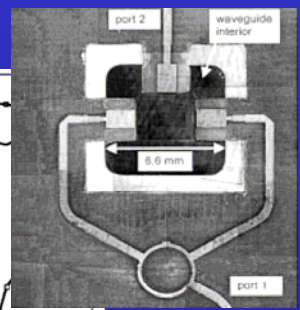
[2] Y. Lee, et al., "Fully Micomachined Finite-Ground Coplanar Line-to-Waveguide Transitions for W-Band Applications", 2004, IEEE MTT, 52, 3, p. 1001.

[3] C. E. North et al., "CLOVER – Measuring the CMB B-mode polarisation," 18th Int. Symp. on Space Terahertz Technology, Pasadena, CA, USA, 2007.

[4] G. Yassin, et al., "A 350 GHz SIS Antipodal Finline Mixer", 2000, IEEE MTT, 48, 662.

Waveguide OMTs: Planar Turnstile





Jackson (2001)

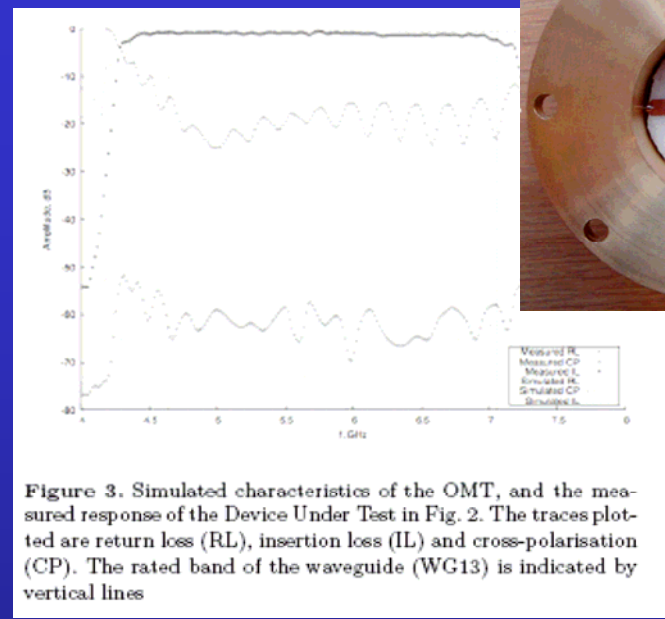
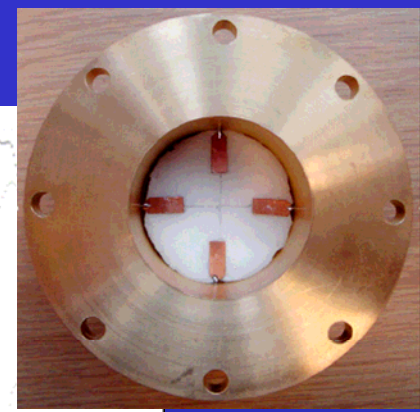
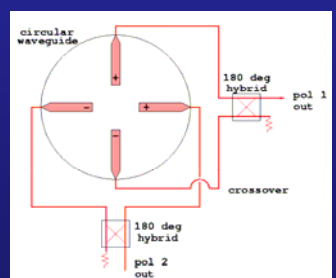


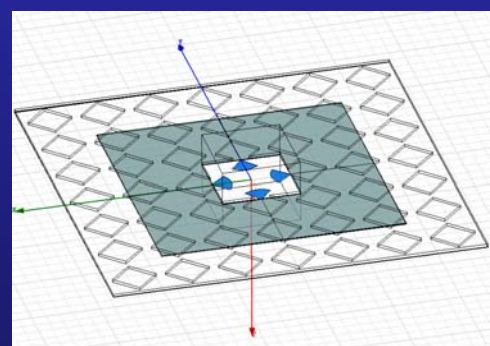
Figure 3. Simulated characteristics of the OMT, and the measured response of the Device Under Test in Fig. 2. The traces plotted are return loss (RL), insertion loss (IL) and cross-polarisation (CP). The rated band of the waveguide (WG13) is indicated by vertical lines

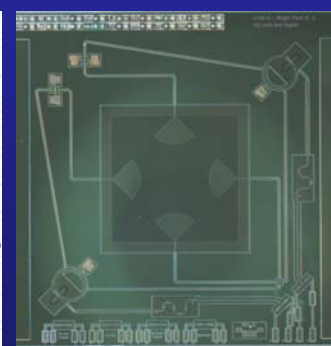


Grimes, et al. (2007)



Engargiola & Plambeck (2003)





NASA/GSFC

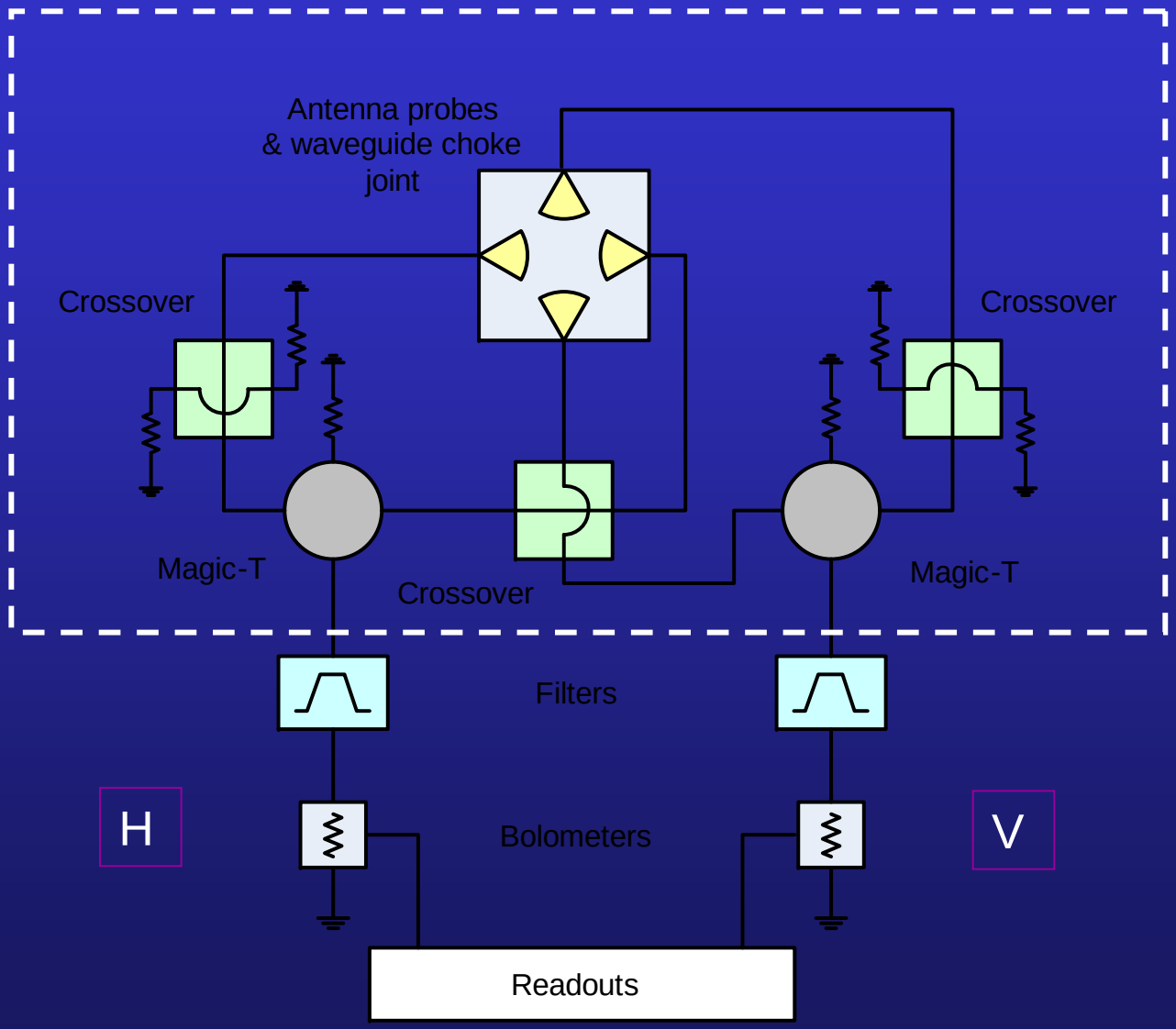
Technical Readiness Level ~ 2-3

[1] Engargiola, G. and Plambeck, R.L., "Test of a Planar L-Band Orthomode Transducer in Circular Waveguide," 2003, Review of Scientific Instruments, Vol. 74, No. 3, pp. 1380—1382.

[2] Jackson, R.W., "A Planar Orthomode Transducer," 2001, IEEE Microwave and Wireless Components Letters, Vol. 11, No. 12, pp. 483—485.

[3] P.K. Grimes, O.G. King, G. Yassin, and M.E. Jones, "Compact Broadband Planar Orthomode Transducer", 2007, astroph-0709.1777.

Symmetric Waveguide Sensor Block Diagram



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- Emerson, D.T. and Payne, J.M., “Multi-Feed Systems for Radio Telescopes,” 1995, Astronomical Society of the Pacific Conference Series, Vol. 75.
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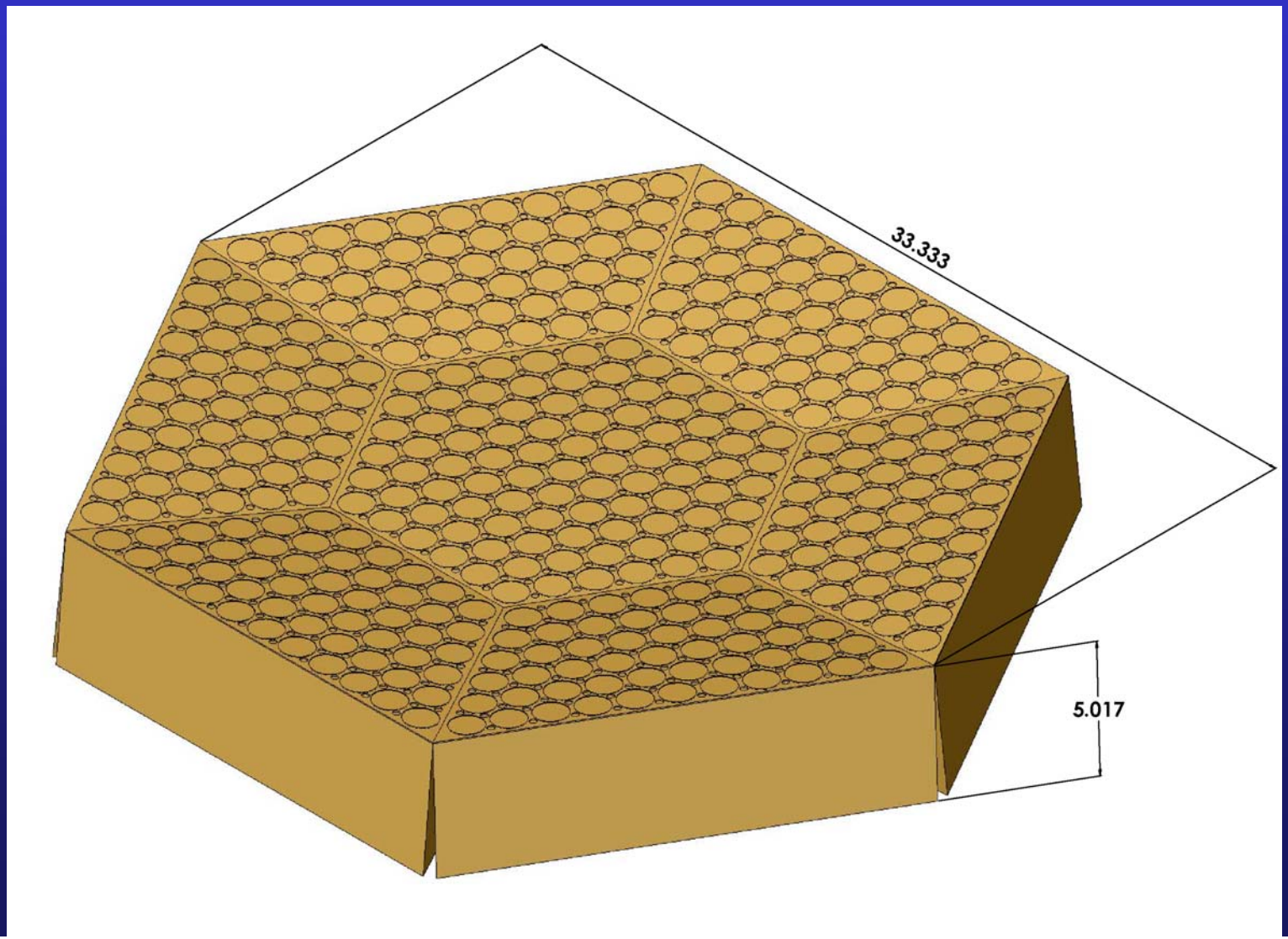
- P.J.B. Clarricoats and A.D. Olver, “Corrugated Horns for Microwave Antennas,” 1984, Peter Peregrinus Ltd., London UK.

Corrugated Feed Fabrication Survey:

Fabrication Technique	Construction	Freq [GHz]	Emission	Array	Mech / Thermal Stability
Direct Machining	Single Metal Block	<100	uniform	-	good
	Plunge EDM (low f/)	<300	high	NxN	good
	Split Metal Block	<1000	pol	1xN	ok
Negative Processing	Metal Casting	<30	high	-	good
	Rosin Split Block / Vapor Deposit Metal	<300	pol	-	poor
	Metal Electroform	<1000	uniform	-	good
	Silicon Split Block / Vapor Deposit (Walker 2003)	<1000	pol	1xN	ok
Stacked Washers	Isolated Epoxy Bond (Staggs 1996)	<3	pol	-	poor
	Eutectic Solder Bond (Bersaneli 1992)	<10	pol	-	good
	Aluminum Dip Braze Bond	<10	uniform	-	good
	Thermal Contraction Joint	<30	pol	-	N/A
	Plated Carbon Fiber Composite (Kogut 2001)	<30	pol	-	ok
	Electroformed Bond (Dragone 1976)	<100	high	-	good
	Laminated Etch Platelets	<300	uniform	NxN	ok
	Diffusion Bond Platelets (Haas 1993)	<1000	uniform	NxN	good
Other Hybrids…	Electroform Throat / Machine Flare (Erickson 1992)	<300	uniform	-	good

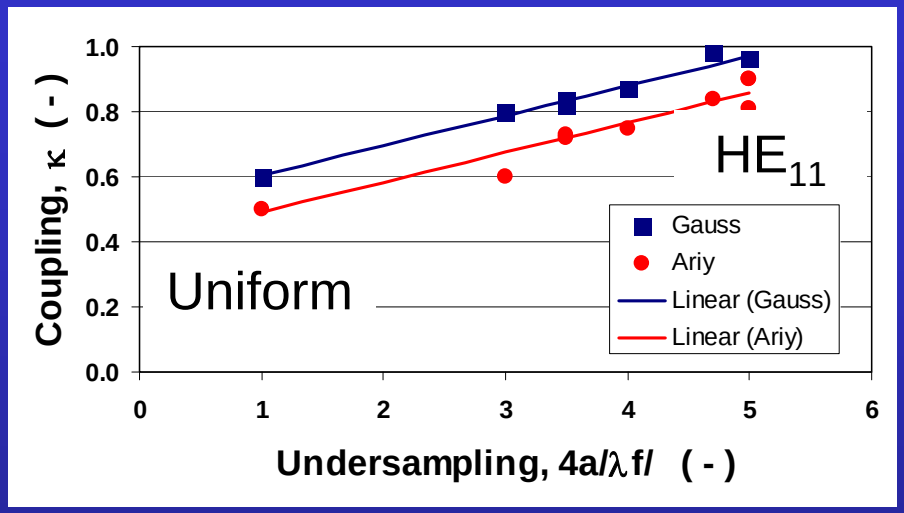
Towards Larger Arrays: 397-Element W-Band Array



Platelet Feed: Design Considerations

- Tolerances relative to wavelength more critical than absolute dimensions. Simulation indicate ~1/100 wavelength deviations are tolerable between ring/slots and feed axis in flare section from a mode conversion perspective, however, must be tighten for low cross-pol applications…
- Consistency of dimensions are critical – an abrupt unintended shift in profile is undesirable – smoothly changing profiles is fabrication goal. Base plate with sufficient stiffness is required to control flatness upon cooling array structure.
- Each section needs to be mated firmly to the next section – gaps may result in a discontinuity in the current flow that in turn can distort field configuration…
- To control loss for the metallic interior wall of the feed to have high surface conductivity and be smooth. For cryogenic applications additional benefits may be achieved by employing pure metal alloys…

Feed Coupling and Undersampling



Coupling efficiency:

$$\kappa = \frac{\left|\left\langle E_{apt} \middle| E_{feed} \right\rangle\right|^2}{\left\langle E_{apt} \middle| E_{apt} \right\rangle \left\langle E_{feed} \middle| E_{feed} \right\rangle}$$

where...

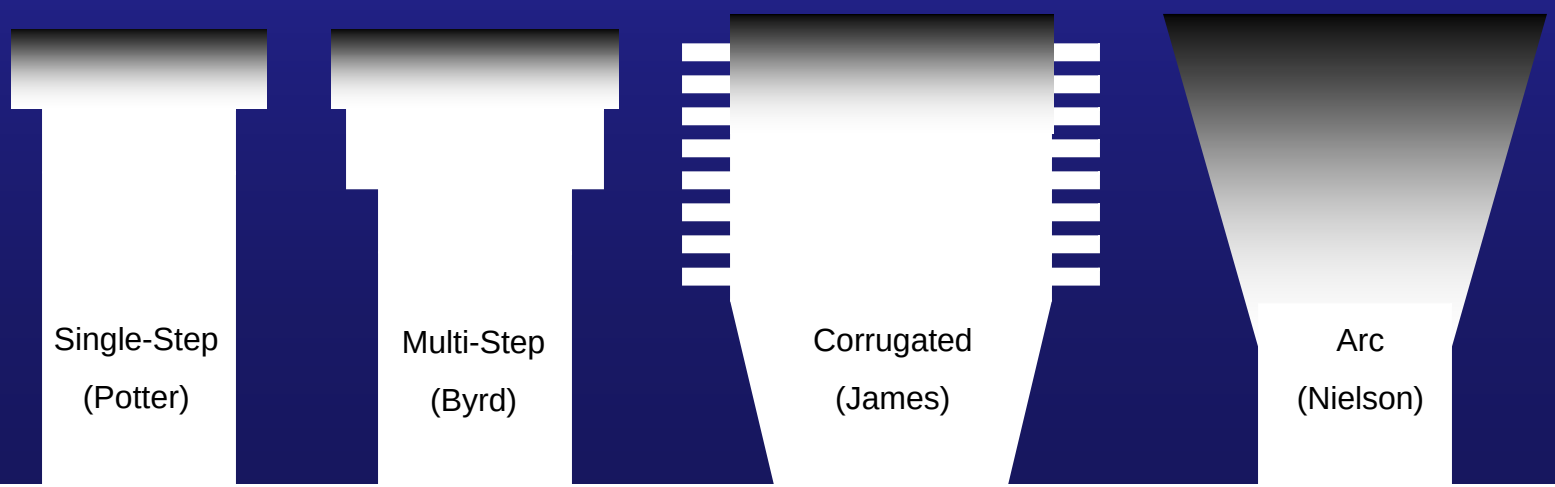
$$E_{apt}(\pi r / \lambda f/) = \begin{cases} \text{Ariy Function for Ariy Disk Coupling...} \\ \text{Gaussian for Gausian Beam Coupling...} \end{cases}$$

Feed Type:	Gaussian Coupling (-)	Match (w/a)	Airy Coupling (-)	Under-Sampling (4a/lam/f#)	Co-Pol Content (-)	Fractional BW (df/f)	Number Modes (-)
3D - structures							
Corrugated	0.98	0.64	0.84	4.7	1	0.8	2
Potter	0.96	0.59	0.81	5	0.99	0.2	2
Conical	0.87	0.77	0.75	4	0.96	0.3	2
Diagonal	0.84	0.86	0.73	3.5	0.91	0.4	2
Hard	0.82	0.89	0.72	3.5	1	0.2	2
Self-Scaling		--			0.5	--	2
2D - planar							
Uniform	0.6	--	0.5	1	0.5	0.4	2
Dual-Dipole	0.96	--	0.9	5	0.97	0.4	2
Dual-Slot	0.96	--	0.9	5	0.97	0.4	2
TSA	0.8	--	0.6	3	0.8	0.5	1
Self-Scaling		--			0.5	--	1

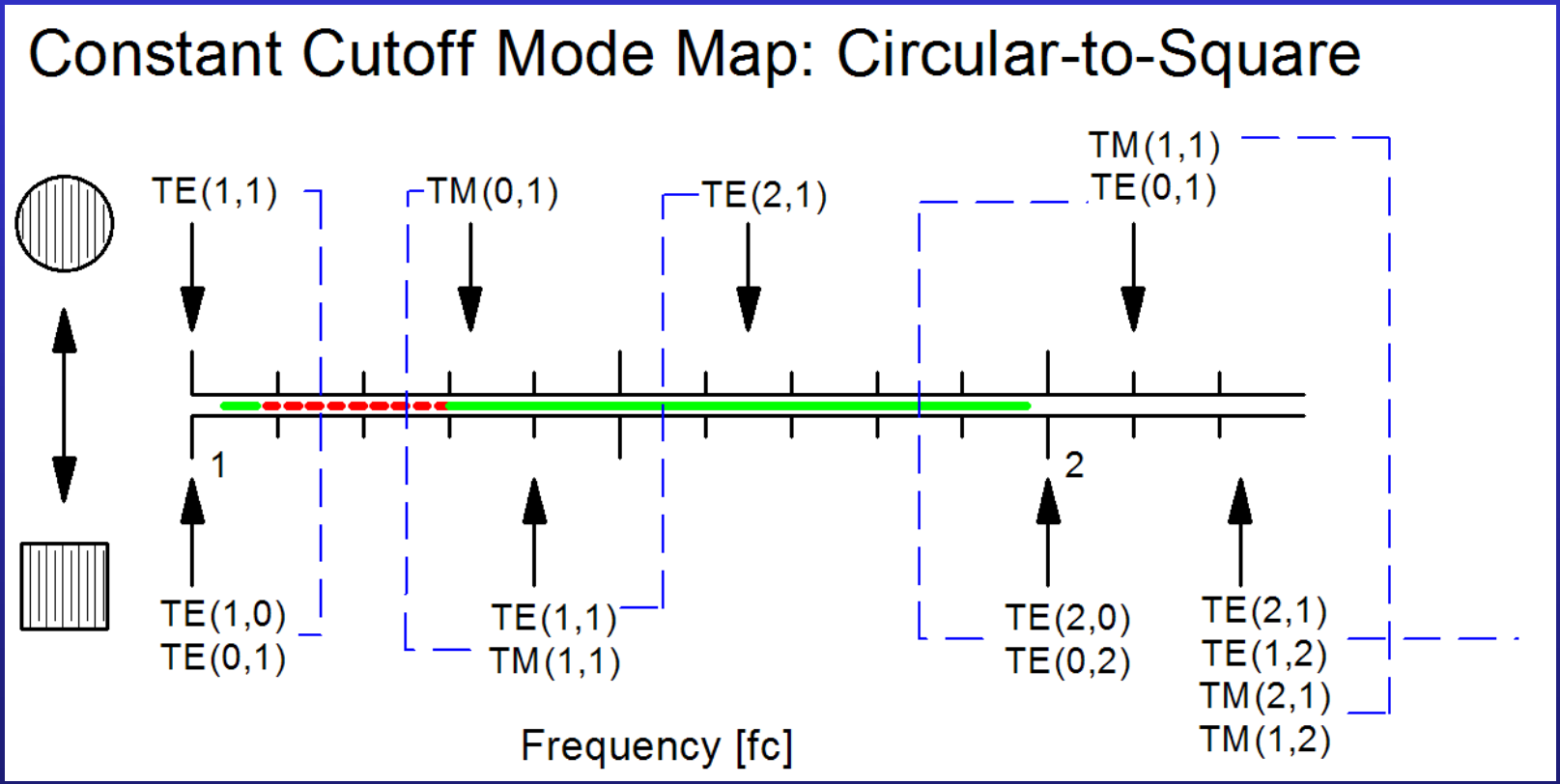
Recall: Aperture acts as a low-pass spatial filter with a cut-off angular frequency of ~D/λ. Thus, the angular Nyquist sampling rate is ~λ/2D…

Variation on a Theme: HE_{11} Feeds

- HE_{11} Feed Structures can be viewed as Transitions from Waveguide to Freespace
  - Stepped → Corrugated Surface → Continuously Profiled
  - Discrete Modal Excitation → Continuous Mode Converters
- Expand Aperture via Flare to Set Beam Angular Scale
  - Diffraction > Geometric Angle → Frequency Dependent Beam
  - Diffraction < Geometric Angle → Frequency Independent Beam



When is a Circle a Square?



Planar Antenna Element Survey: