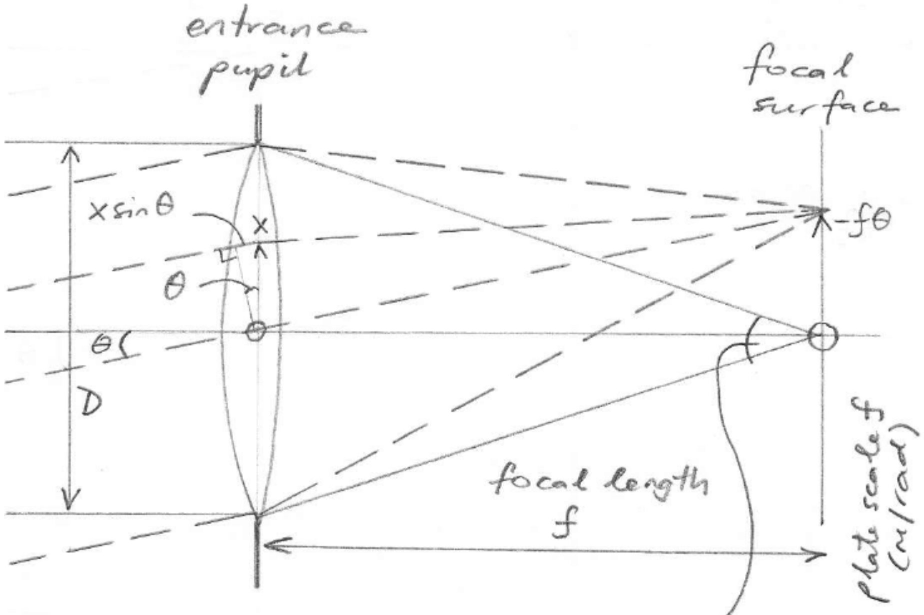
Telescopes & detector coupling

S. Padin

Telescope basics



aperture defines which rays are accepted, sets angular resolution + point source sensitivity

$\frac{D}{f} = \frac{1}{F}$

F = focal ratio at image

Image formation

At −fθ on focal surface, telescope coherently adds rays from direction θ.

for a source at ∞ (Fraunhofer diffraction) $\sin\theta = \theta$

$$\underset{\text{image}}{E(\theta)} = \int_{-D/2}^{D/2} \underset{\text{aperture}}{E(x)}\, e^{-i\frac{2\pi}{\lambda}x\theta}\,dx$$

$$E(\theta) \overset{FT}{\longleftrightarrow} E(x)$$

Telescope is a Fourier Transform machine

Amplitude response to a point source on axis

$$E(\theta) = \int_{-D/2}^{D/2} \frac{1}{D}\, e^{-i\frac{2\pi}{\lambda}x\theta}\,dx = \frac{\sin \frac{2\pi}{\lambda}\frac{D}{2}\theta}{\frac{2\pi}{\lambda}\frac{D}{2}\theta}$$

1st null at $\frac{2\pi}{\lambda}\frac{D}{2}\theta = \pi$, $\theta = \frac{\lambda}{D}$

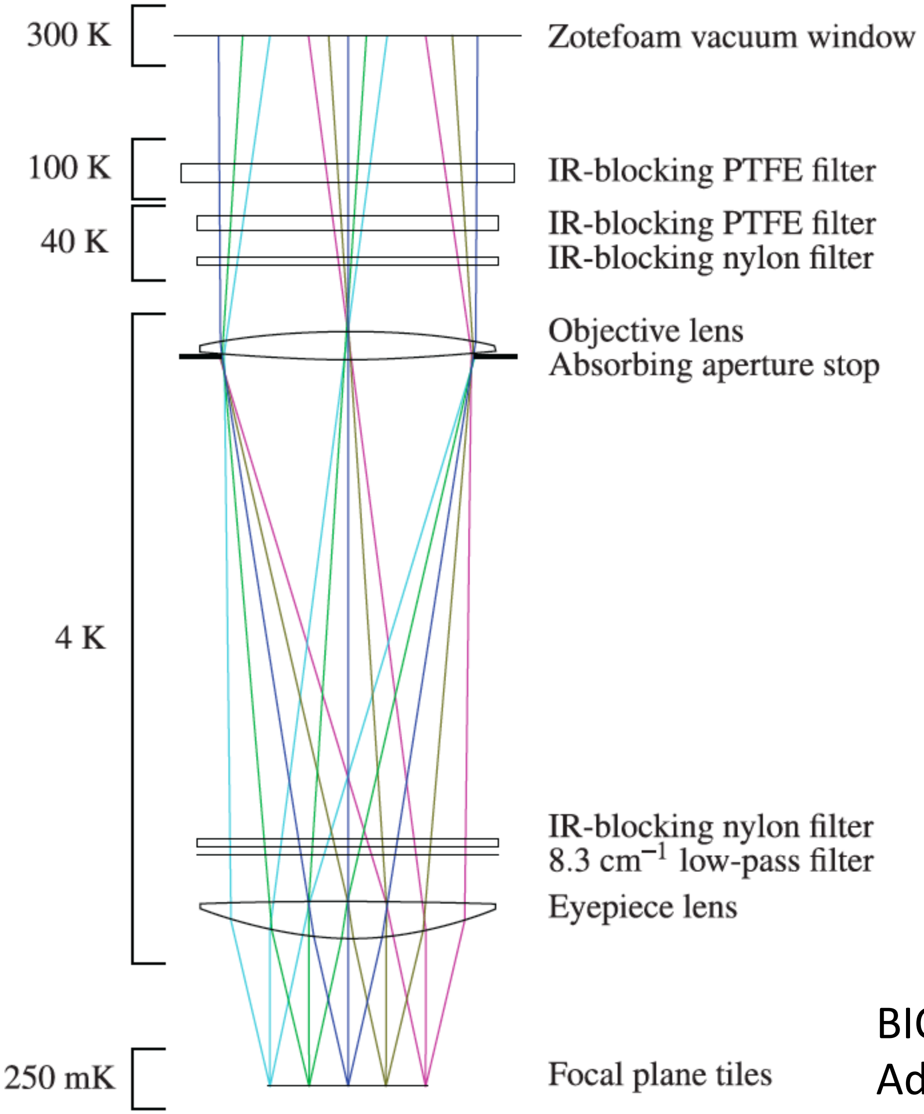
Beam (power)

$$B(\theta) = E(\theta)E^*(\theta) = FT\left[E(x) \otimes E(x)\right]$$

autocorrelation theorem

see Bracewell, "The FT + its Applications"

Refractor

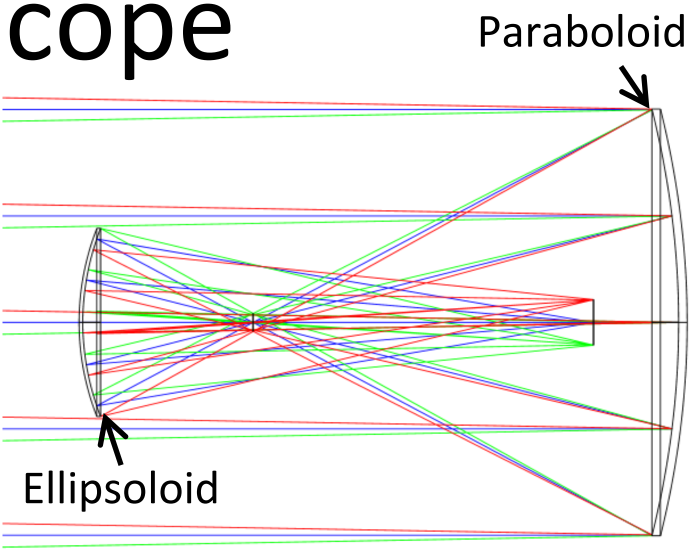


OK for small CMB telescopes
No blockage
Compact
Can achieve wide FOV
Lenses are lossy; must be cooled

BICEP2
Ade et al., ApJ, 792 2014

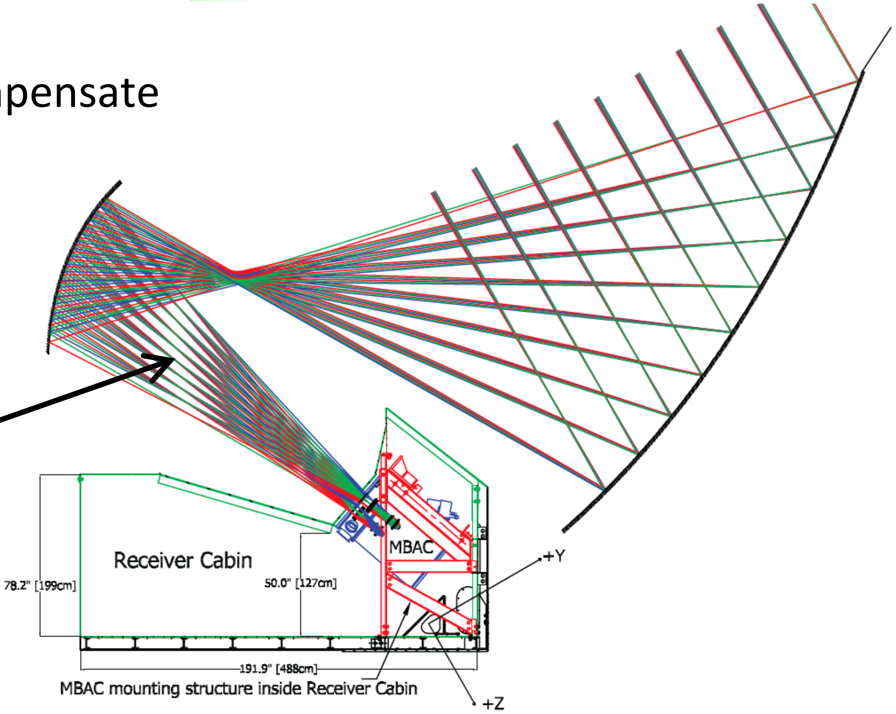
Gregory telescope

- Classical
  - Centered design
  - Perfect imaging on axis; diffraction limited over a modest FOV (~2° at λ>1mm for a 5m)
- Aplanatic
  - Shaped surfaces to correct coma
- Offset
  - No obscuration; low scattering
    - In centered designs, secondary blockage is typically a few %
  - Dragone form has tilted secondary to compensate astigmatism



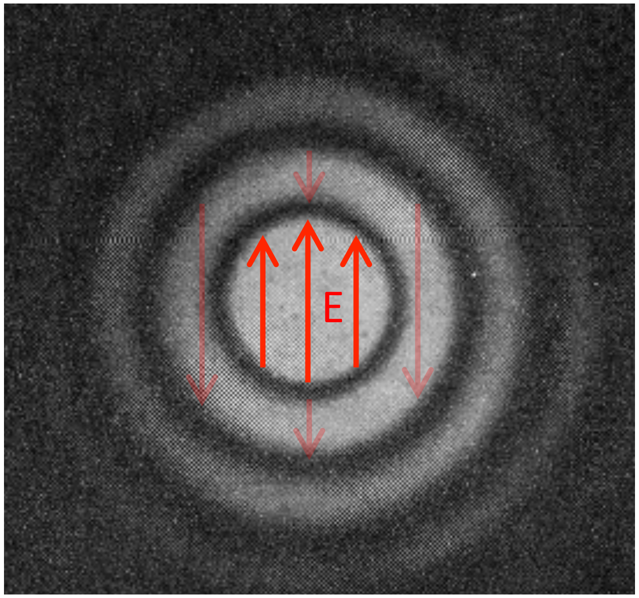
ACT is an offset, aplanatic Gregory
with a tilted secondary
Fowler et al., Appl. Optics, 46 2007

Gregory has an real exit pupil;
can use for a chopping flat



For an overview of CMB telescopes, see
Hanany et al., in Planets stars & stellar systems
2013 DOI 10.1007/978-94-007-5621-2_10

Airy pattern



Field amplitude

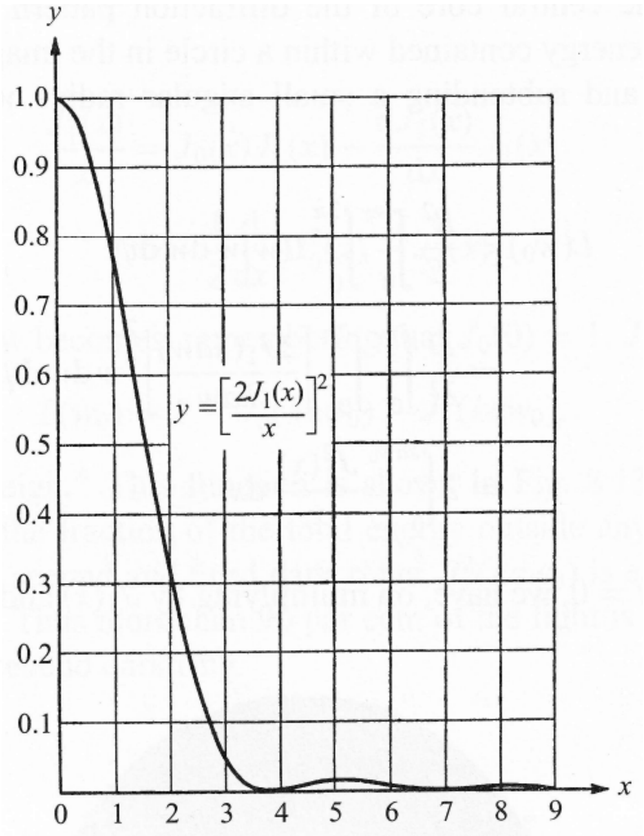
$$E(\theta) = \frac{2J_1\left(\frac{2\pi}{\lambda}\frac{D}{2}\theta\right)}{\frac{2\pi}{\lambda}\frac{D}{2}\theta}$$

1st null $\frac{2\pi}{\lambda}\frac{D}{2}\theta = 1.22\pi$

$$\theta = 1.22\frac{\lambda}{D}$$

half power $\frac{2\pi}{\lambda}\frac{D}{2}\theta = 1.6165$

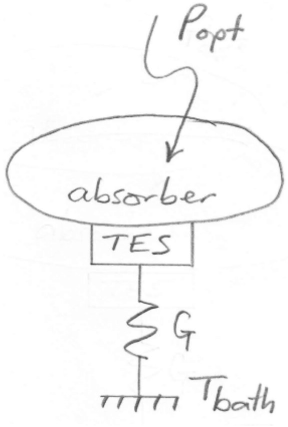
$$\theta = 0.515\frac{\lambda}{D}$$



Need to couple this intensity/field pattern to a detector with well-defined polarization and frequency range.

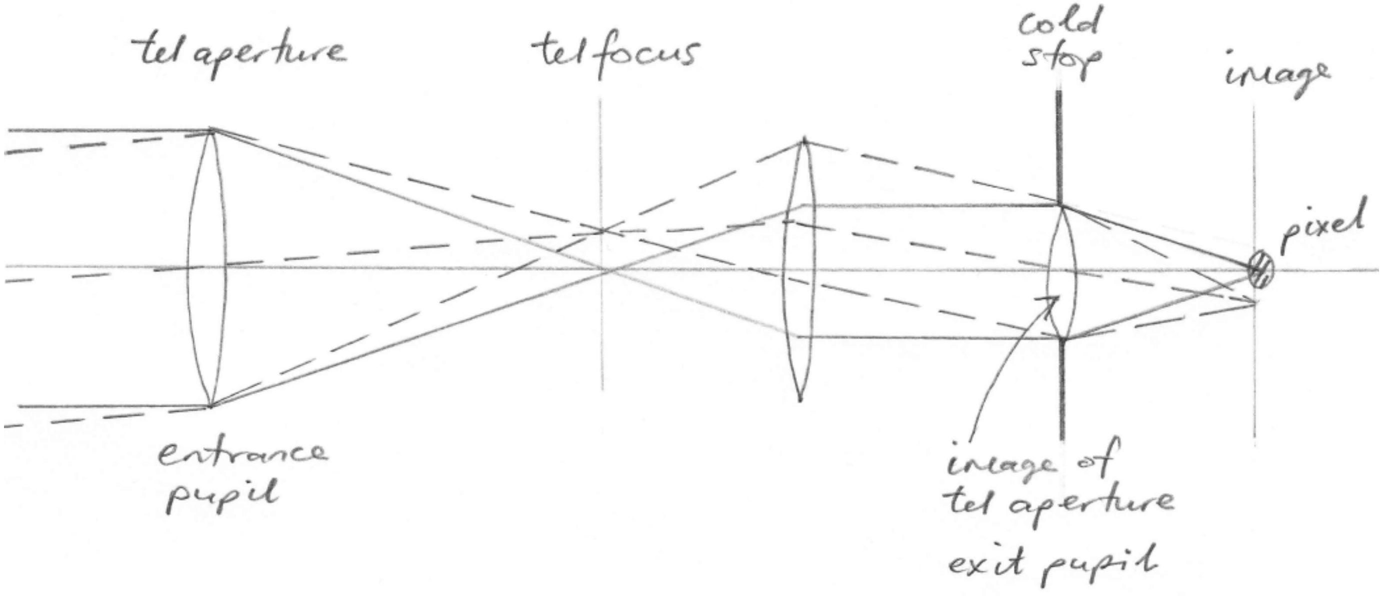
Born & Wolf, Principles of Optics
Airy, Trans. Camb. Philosophical Soc., 5 1835

Direct absorption



e.g., CCDs, many far-IR cameras, some KIDs

Pixel is an absorbing patch in the focal plane
    Responds to incident intensity
Define frequency band and polarization using “free space” components
    e.g., mesh filters, wire grids
Broad angular response ~π sr
    Need a cold pupil stop (“Lyot stop”) to control coupling to telescope



Pixel size

For uniform aperture illumination, Airy pattern $\mathrm{FWHM}_{tel} \approx \lambda/D$ (rad)

- In distance units, $\mathrm{FWHM}_{tel} \approx f\lambda/D = F\lambda$ (meters)

$0.5F\lambda$ pixels Nyquist sample the image

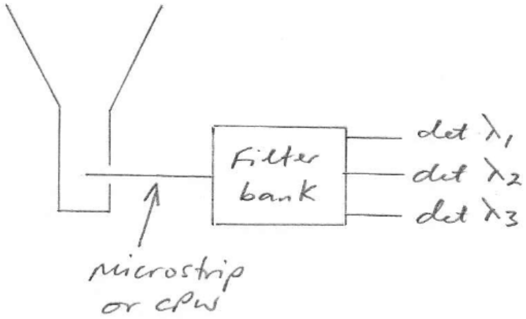
- Max mapping speed for extended sources; ~3× faster than $2F\lambda$ horns
- Need lots of detectors
- Good solution if detectors are cheap

Image is convolved with pixel footprint, so large pixels degrade angular resolution

- $\mathrm{FWHM}_{map} \sim \mathrm{FWHM}_{tel} \times (1+1/p^2)^{1/2}$ where p=number samples across FWHM
  - e.g., $0.5F\lambda$ pixels, p=2, 12% wider beam
    - $F\lambda$ pixels, p=1, 41% wider beam

Horn coupling

e.g., radio telescopes (EVLA, ALMA etc.), many CMB cameras



Horn responds to a specific field distribution

Use transmission line components to define frequency band(s) and polarization

- e.g., waveguide/microstrip filters, OMTs
- Flexible, often complicated, may be lossy

Angular response can be matched to telescope output beam

- In this case, don't need a cold stop

Horn size

2Fλ horn

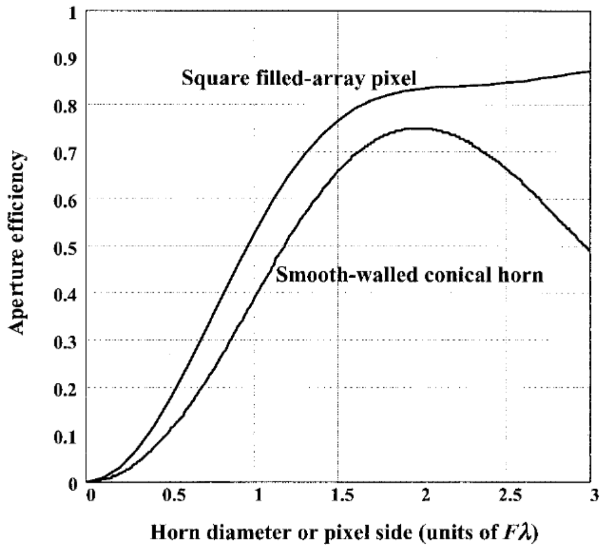
- Full width of horn beam=$2\lambda/D_h$=1/F (rad)
  - matches full width of telescope output beam
- Max coupling efficiency
- Does not degrade angular resolution of telescope
- Need multiple pointings to Nyquist sample the sky with an array of 2Fλ horns
- Good solution for photometry of known point sources, or if number of detectors limited by $$$

Larger horn has narrower beam, so coupling efficiency decreases

- This does not happen with direct absorbers, but large horns and large absorbers both degrade angular resolution

Smaller horn has broad angular response, so lower coupling to telescope output beam

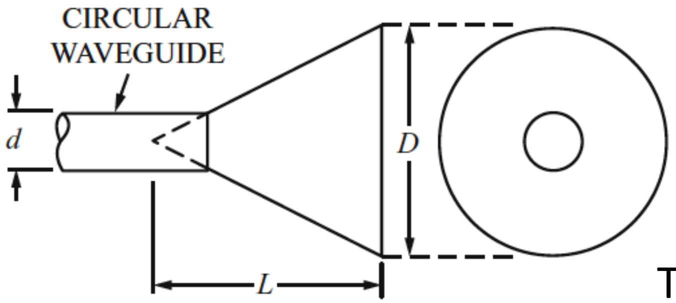
- Sky sampling closer to Nyquist, so faster mapping speed
- Need a cold stop

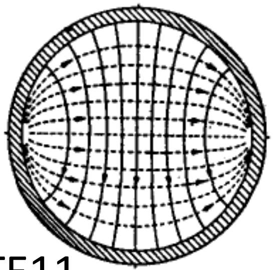


Griffin et al.,
Appl. Opt., 41 2002

Conical horn

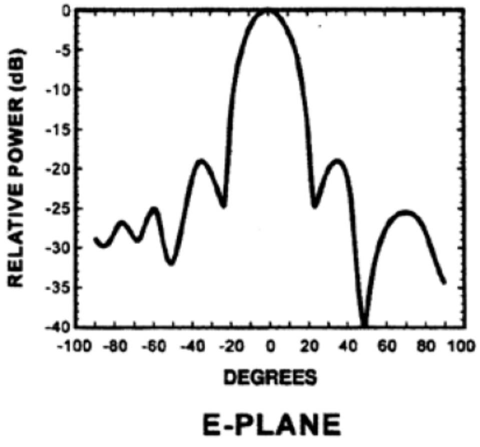
Horn expands modes

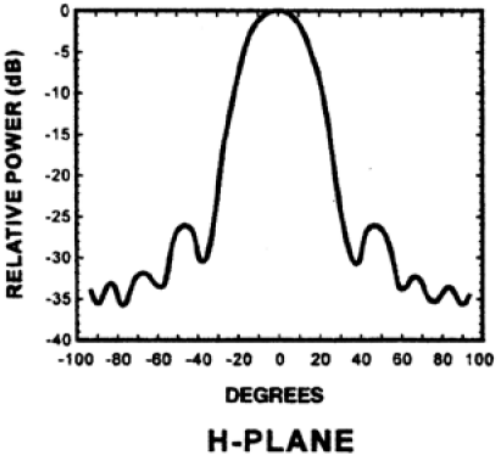




TE11
E solid, H dashed

Millitech CHA





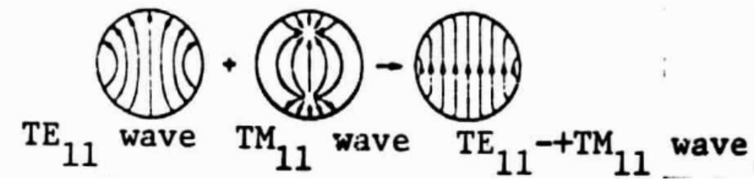
Usually drive only the lowest-order mode, TE11
- Roughly matches field at telescope focus
- Different beamwidths in E & H
  - May be OK if horn over illuminates a cold stop
  - e.g., SPT-SZ
- Poor xpol

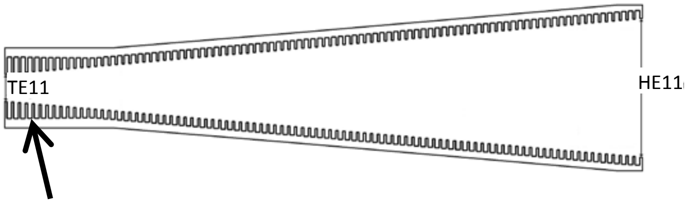
For horns, need aperture $D_h > \sim 1.5\lambda$
- With F=1-3 (typical for CMB cameras), $D_h > 1.5\text{-}0.5F\lambda$

For ~flat phase, horn aperture must be in far field of throat
- Requires horn length $L_h > 2D_h^2/\lambda$, so a horn with $D_h = 2F\lambda$ should have $L_h > 8F^2\lambda$

Corrugated horn

Combine TE11 and some TM11 with the right phase to give HE11





Mode converter generates ~15% TM11

HE11 has almost pure transverse E with roughly Gaussian profile

- Good match to field at telescope focus
- Gives symmetric beam with low xpol

HE11 can propagate in a corrugated horn

- At wall, $E_{\text{parallel}} \neq 0$, $H_{\text{normal}} \neq 0$ is OK
  - λ/4 grooves make impedance at wall infinite (shorted λ/4 transmission line is an open); typically >6 grooves/λ

Clarricoats & Olver, Corrugated Horns for Microwave Antennas 1983
Granet & James, Antennas. Propag. Magazine, 47 2005
Clarricoats & Saha, Proc. IEE, 118 1971
Thomas, AP-26 1978

Smooth-wall profiled horn

Combine TE11 with higher-order modes to give desired field distribution at aperture

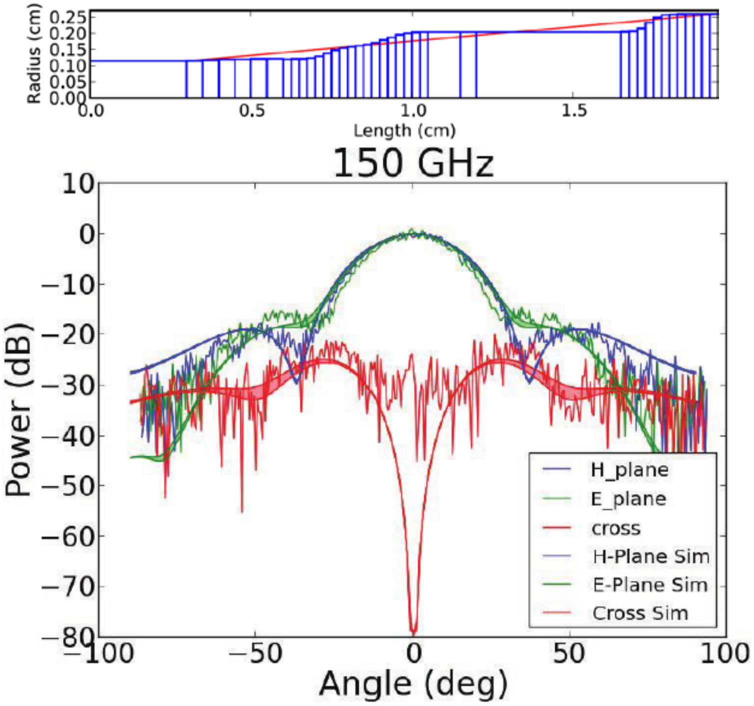
Fairly recent development because extensive modeling is needed

Does not require infinite impedance at wall

Smooth wall is easy to make, less $

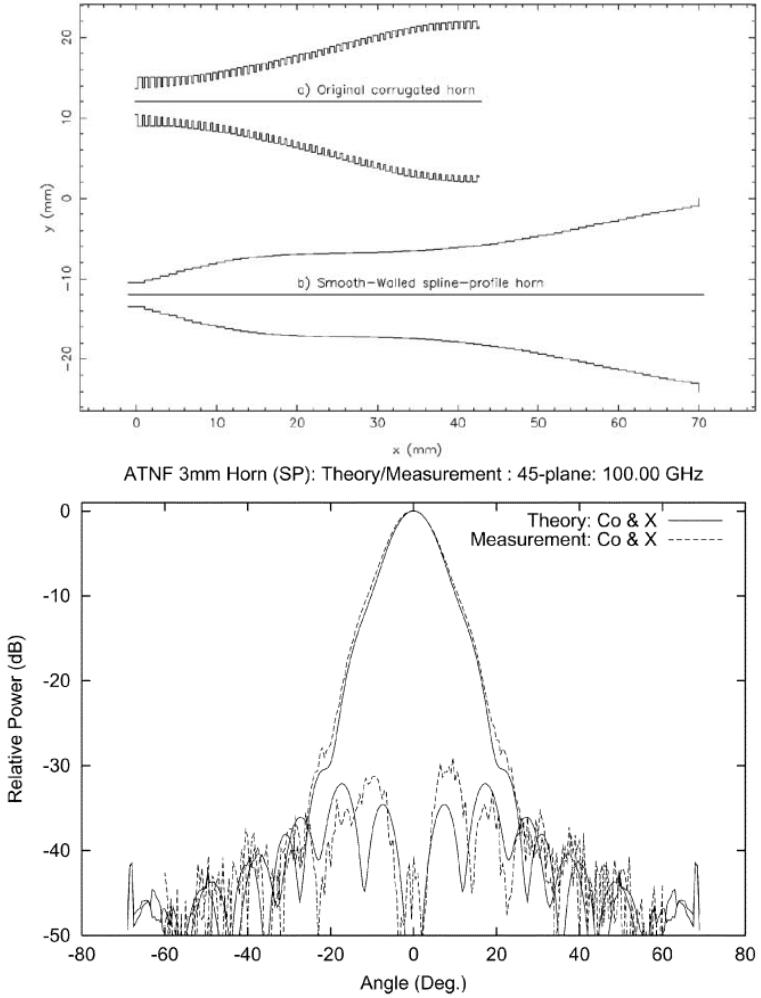
Good beam symmetry and xpol

Tends to be longer than corrugated horn



AdvACTpol 90/150GHz horn

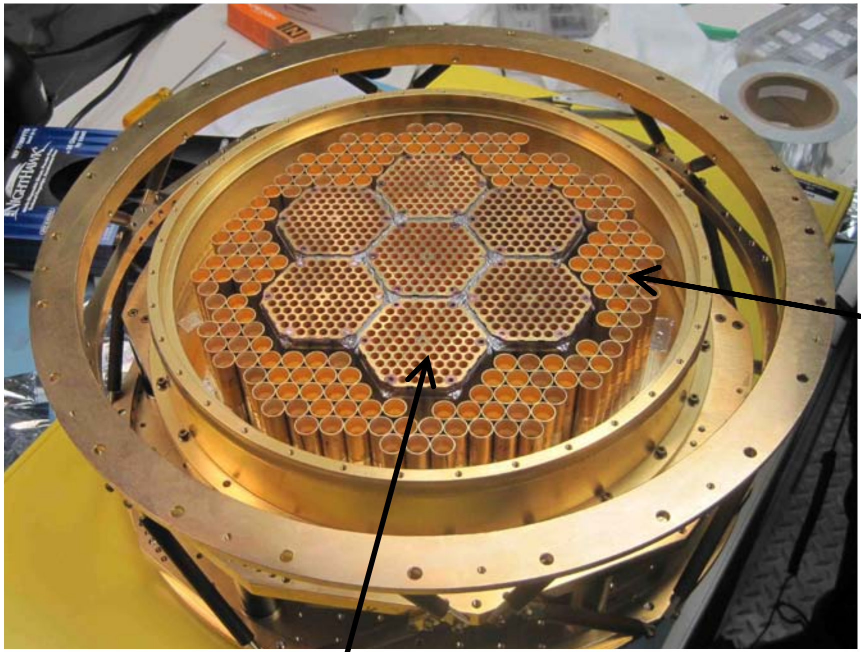
Simon et al., SPIE 991416 2016

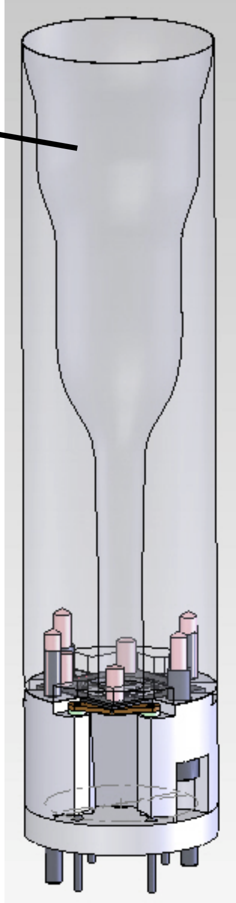


Granet et al., AP-52 2004

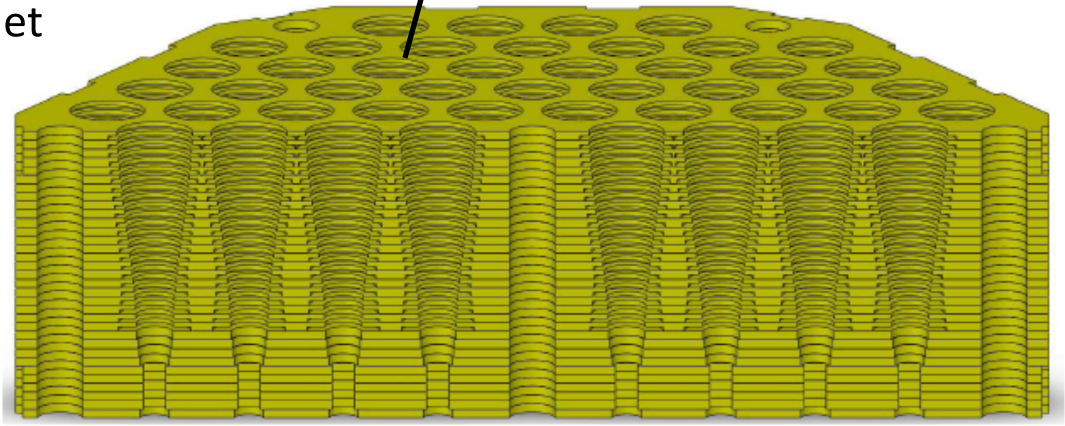
SPTpol horns

Profiled smooth-wall horns at 90GHz.
2.3Fλ
Machined in Cu with profiled reamer, then Au plated.



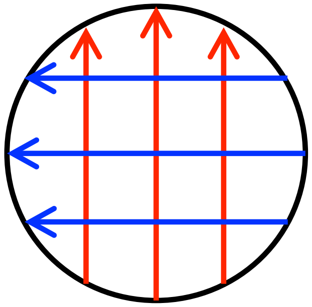


Corrugated platelet horns at 150GHz.
1.6Fλ
Stack of micro-machined Si wafers, Cu/Au plated.

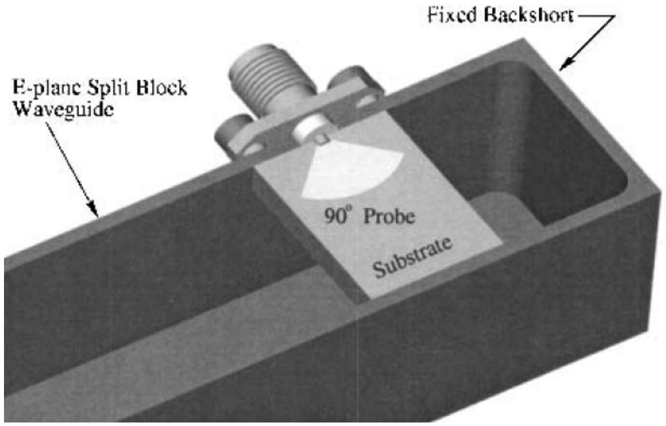


Orthomode transducer

Couples 2 orthogonal TE11 modes in circular guide to, e.g., mstrip

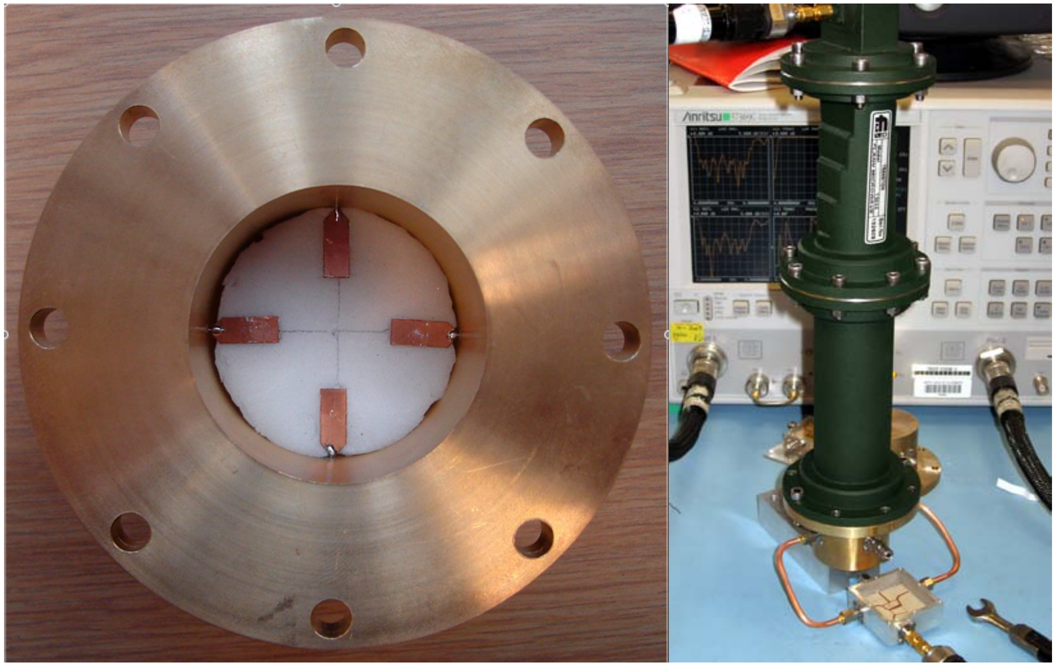


Simple transition for 1 polarization has a probe and a λ/4 backshort. Requires good ground connection at guide wall.



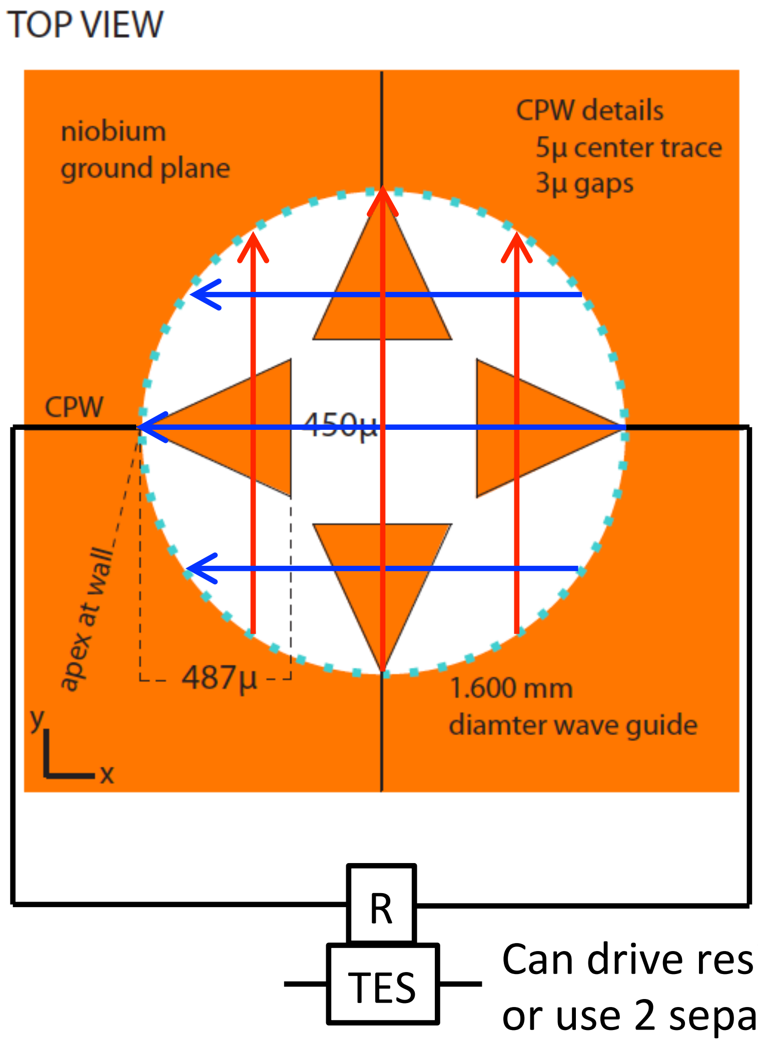
Kooi et al., Int J IR mm waves, 24 2003

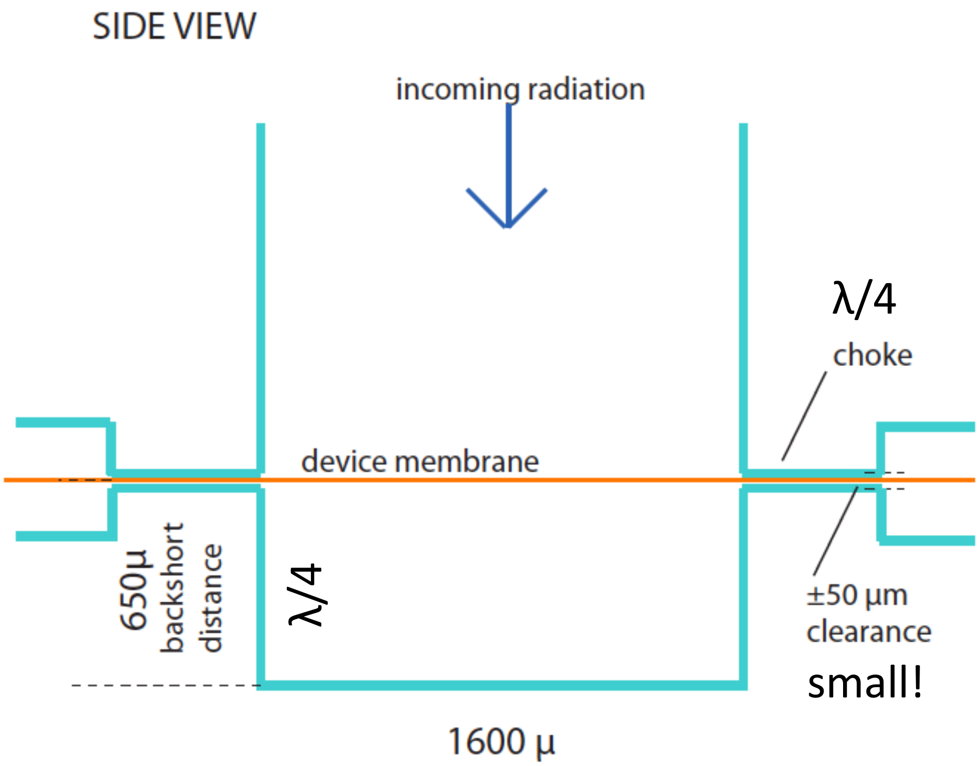
4 probes give good symmetry, low xpol



OMT for C-BASS
Grimes et al., El Lett, 43 2007

OMT with differential output



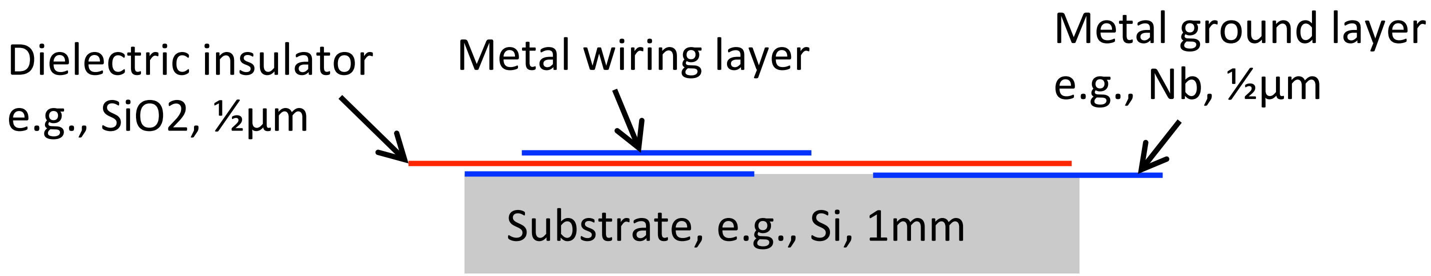


McMahon et al., LTD13 2009
Yoon et al., LTD13 2009

Can drive resistor differentially (SPT-3G)
or use 2 separate resistors (ACTpol)

Planar antennas

Printed metal structures on a dielectric substrate



Dielectric insulator
e.g., SiO2, ½µm

Metal wiring layer

Metal ground layer
e.g., Nb, ½µm

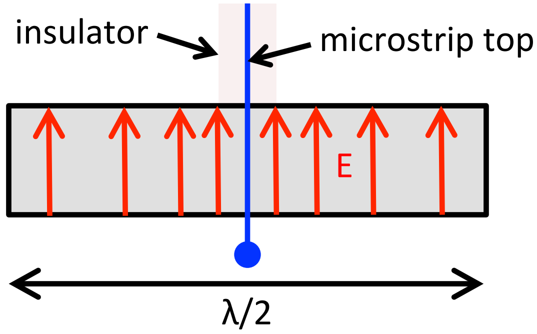
Substrate, e.g., Si, 1mm

Easy to integrate planar antennas, filters, detectors etc. on wafer

Cover most of the substrate with ground, leaving holes only where there are antennas; feed signals from the ground side
- Reduces stray light
- Natural configuration for slot antennas

Slot antennas

Single slot



Slot length sets frequency; feed position sets Z.

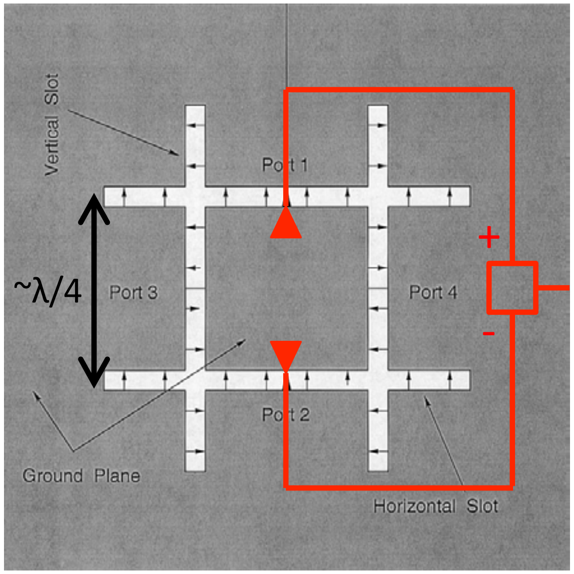
Z~30Ω; easy to feed.

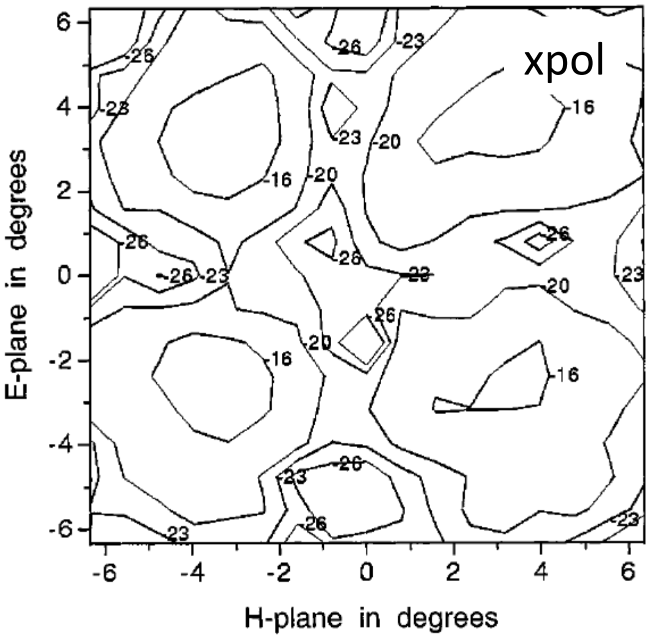
Fairly narrow band, ~10% .

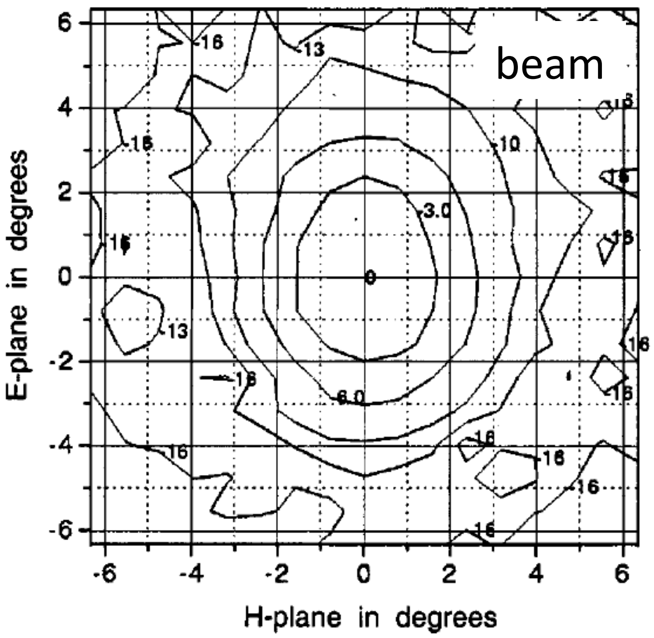
Slots are easy to design and fabricate.
Widely used for test structures.

Twin slot
Slot spacing controls beam shape.

550GHz twin slot
Chattopadhyay et al., MTT-48 2000
Also see Zmuidzinas & LeDuc MTT-40 1992



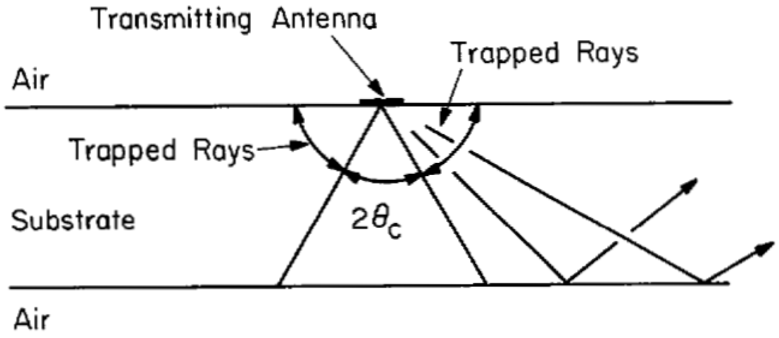




Effect of the substrate

Reflection at substrate/air interface

- For normal incidence $R=|(n-1)/(n+1)|^2$
- e.g., Si e=11.7, n=3.42
- R=0.3; need AR coating



Trapped rays (Rutledge & Muha, AP-30 1982)

- Make substrate thin, e.g., SiN membrane
- Add a lenslet so rays always hit the substrate/air interface at small angles

Most of the power is in the substrate

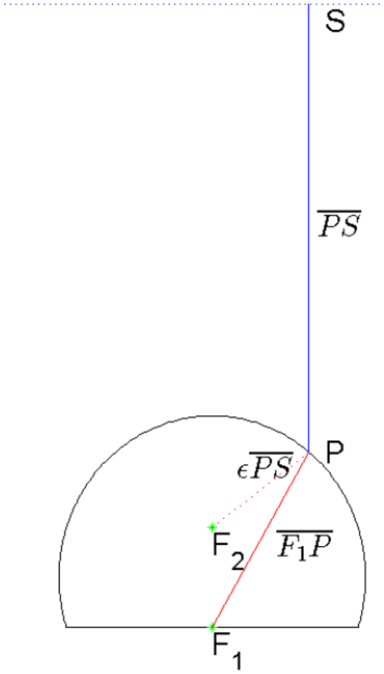
- Lower wave impedance in the substrate
  - $Z=E/H=(\mu/\varepsilon)^{1/2}$, $Z_0=377\Omega$, Z scales with 1/n, where $n^2=e=\varepsilon/\varepsilon_0$
  - Poynting vector $\mathbf{S}=\frac{1}{2}\mathbf{E}\times\mathbf{H}$, $\langle S\rangle=E^2/(2Z)$
- Field transmission coefficient $t_{\text{air to substrate}}=2/(1+n)$, $t_{\text{substrate to air}}=2n/(1+n)$
  - Response of antenna to E in substrate is ~n times higher than to E in air

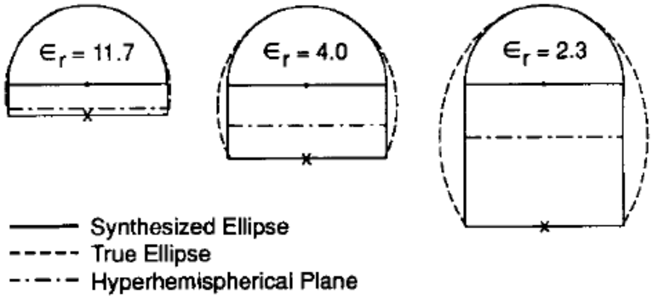
Lenslets

Lenslet improves coupling to a planar antenna on thick substrate

- No trapped rays
- Power in the dielectric is ~n^3 higher than in air
- Concentrate rays if absorber/antenna is smaller than Airy pattern

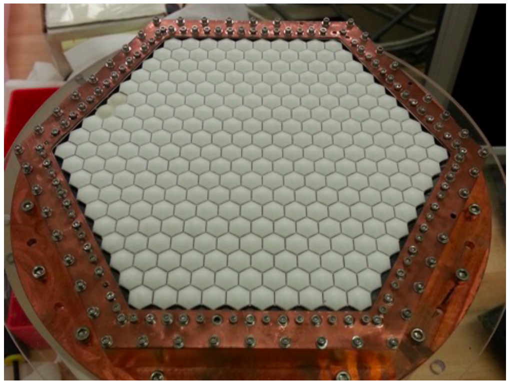
Use elliptical lens to focus a collimated beam



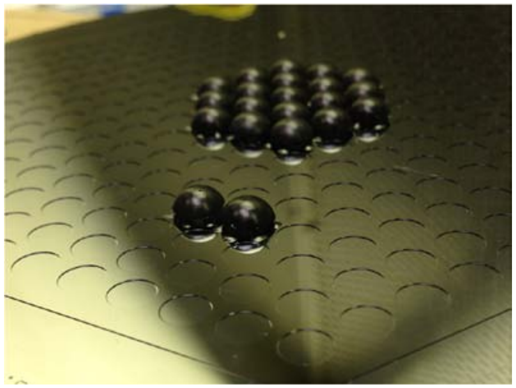


Make an elliptical lens by stacking
a hemisphere on a plate
Rebeiz, Proc. IEEE, 80 1982

Elliptical lens focuses plane wave
to a point at the far focus
eccentricity=1/n
O'Brient thesis 2010



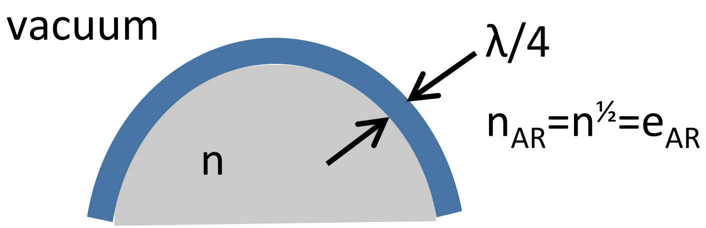
SPT-3G lenslet array

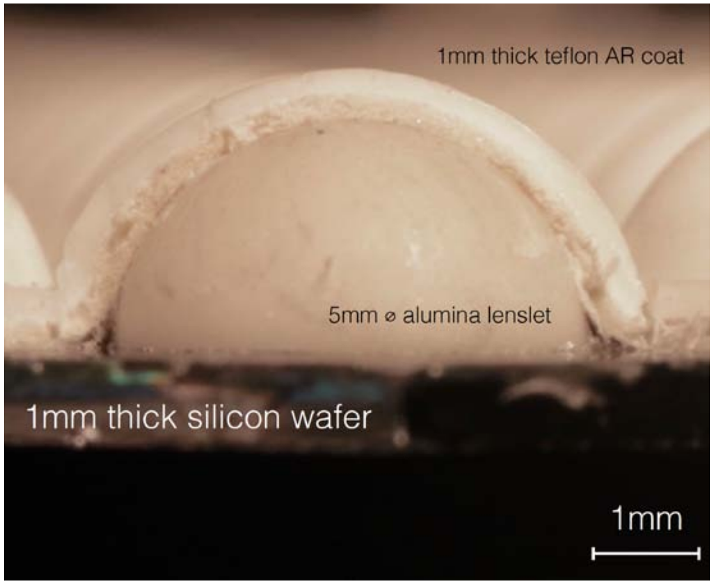


PB lenslets on seating wafer, Suzuki thesis 2013

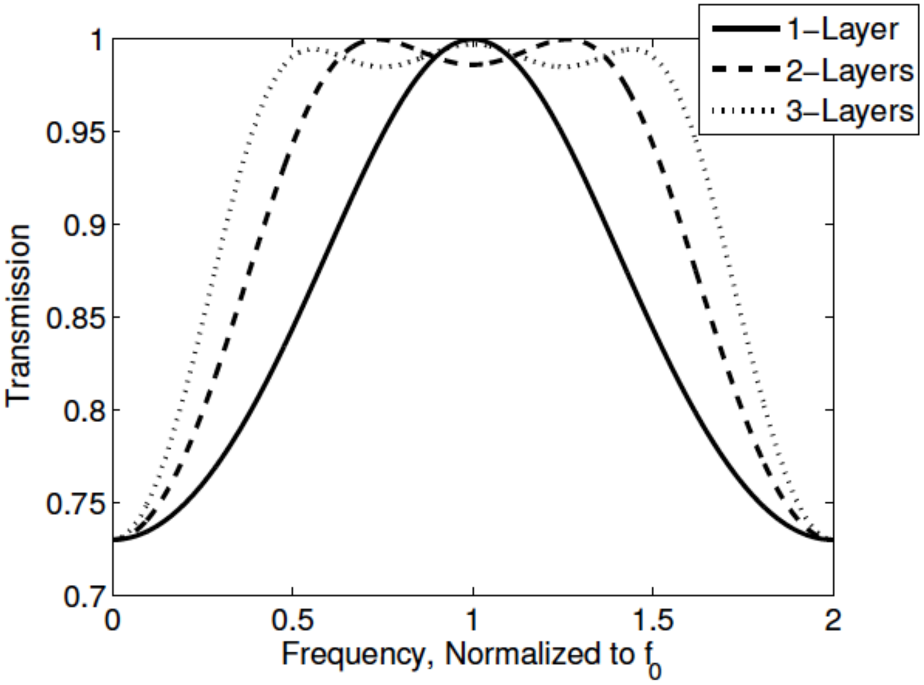
AR coatings for lenslets

Single-layer AR coating





SPT-3G Alumina lenslet with 2 layers ceramic-loaded teflon and 1 layer ePTFE



Calculated transmission for AR coatings on alumina (e=10)

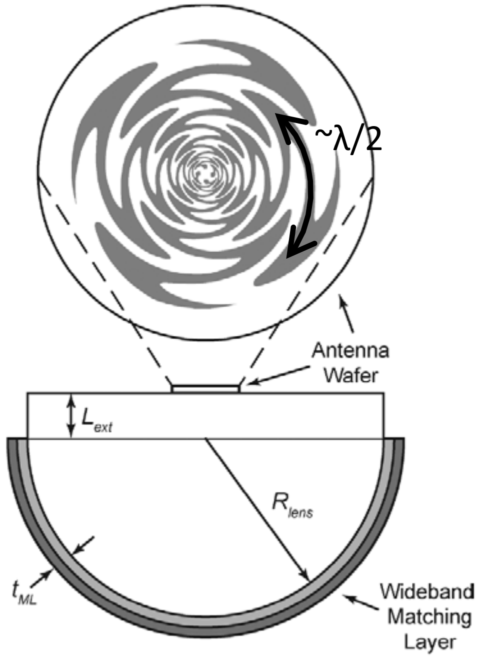
All layers λ/4 at f_0

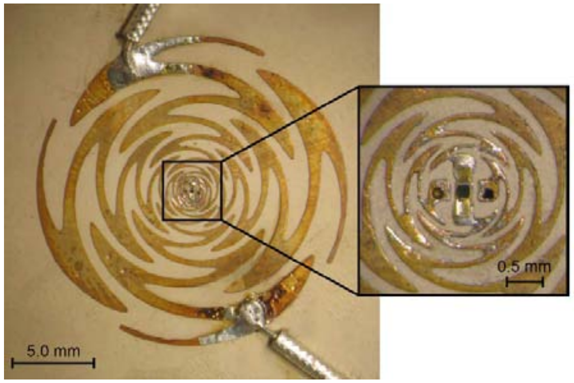
layers	e
1	3.2
2	2,5
3	2,4,7

Suzuki thesis 2013

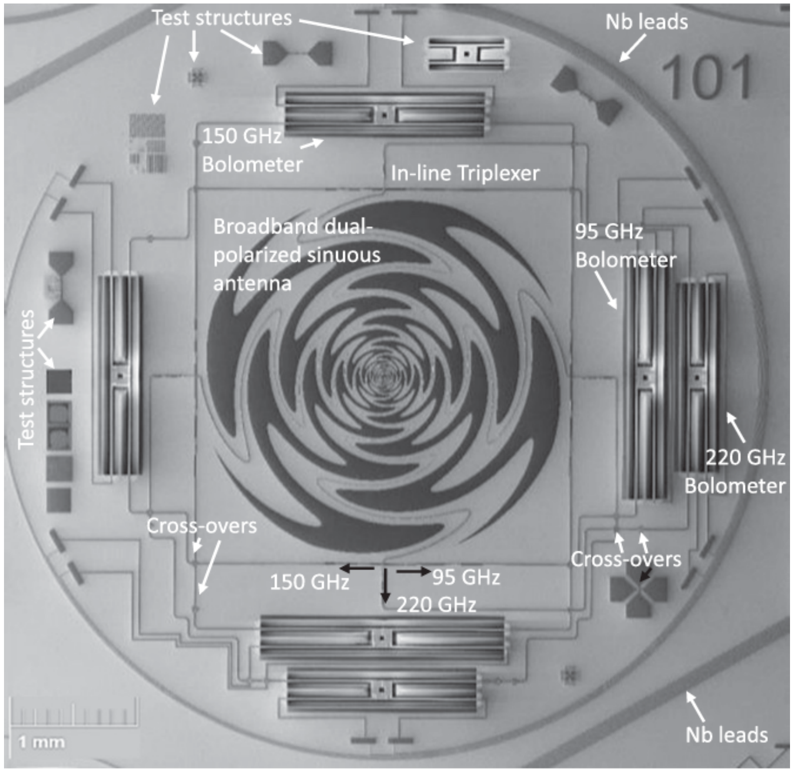
Sinuous antenna

Very wide bandwidth

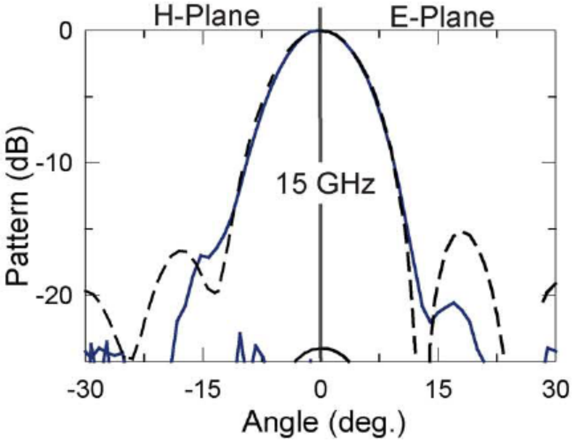


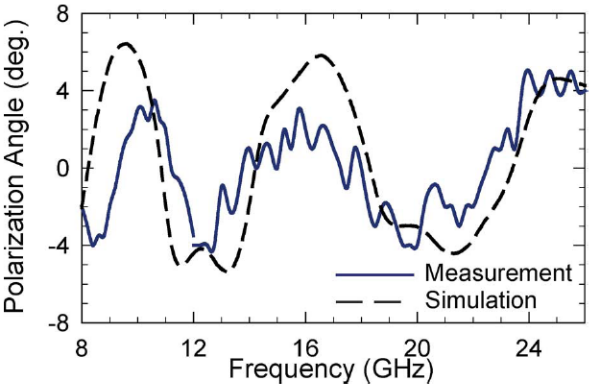


6-24GHz prototype antenna with diode detector at center
Edwards et al., AP-60 2012
Also see
O'Brient thesis 2010
Suzuki thesis 2013



SPT-3G sinuous slot

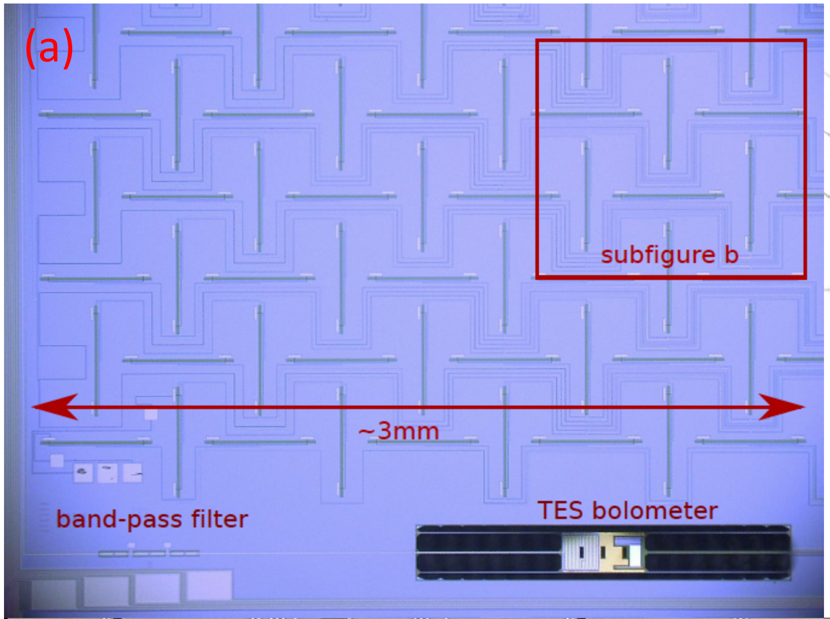
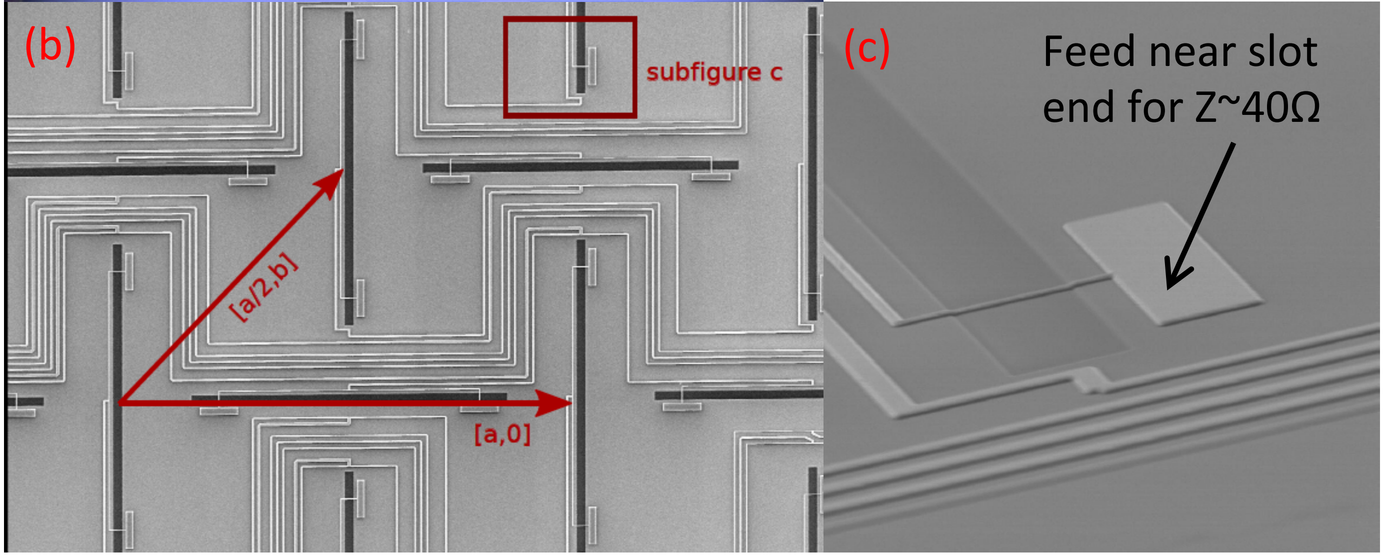


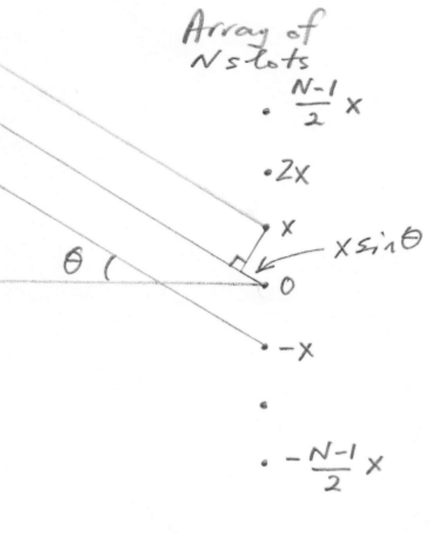


BICEP2/Keck 8×8 slot array
Ade et al., Ap.J., 812 2015

Phased arrays

Good control of angular response



Amplitude pattern

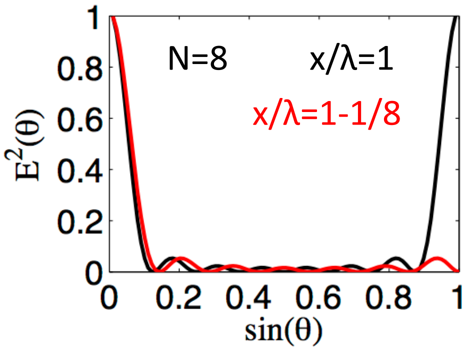
$$E(\theta) = \sum_{M=-\frac{N-1}{2}}^{\frac{N-1}{2}} e^{-i\frac{2\pi}{\lambda}Mx\sin\theta}$$

$$= \frac{\sin(N\pi\frac{x}{\lambda}\sin\theta)}{\sin(\pi\frac{x}{\lambda}\sin\theta)}$$

1st grating lobe at $\sin\theta = \frac{\lambda}{x}$

lobe width ~ $\frac{\lambda}{Nx}$

avoid lobe by making $x<\lambda(1-\frac{1}{N})$



Optical coupling summary

Direct absorption
- ½Fλ pixels give high mapping speed
- Wide angular response; need cold stop
- Stray light is a serious problem
- Multi-band pixels not so easy

Antenna coupling

Horn
- Small beam shape and polarization errors; "gold standard for feeds"
- Good control of stray light; some leaks at horn/wafer interface
- Limited bandwidth for simple horns

Planar antenna
- Can be very wide band
- Wide angular response; need lenslets and cold stop or phased array
- Easy to integrate on detector wafer

See CMB-S4 technology book http://xxx.lanl.gov/abs/1706.02464