Planar Transmission Line Technologies

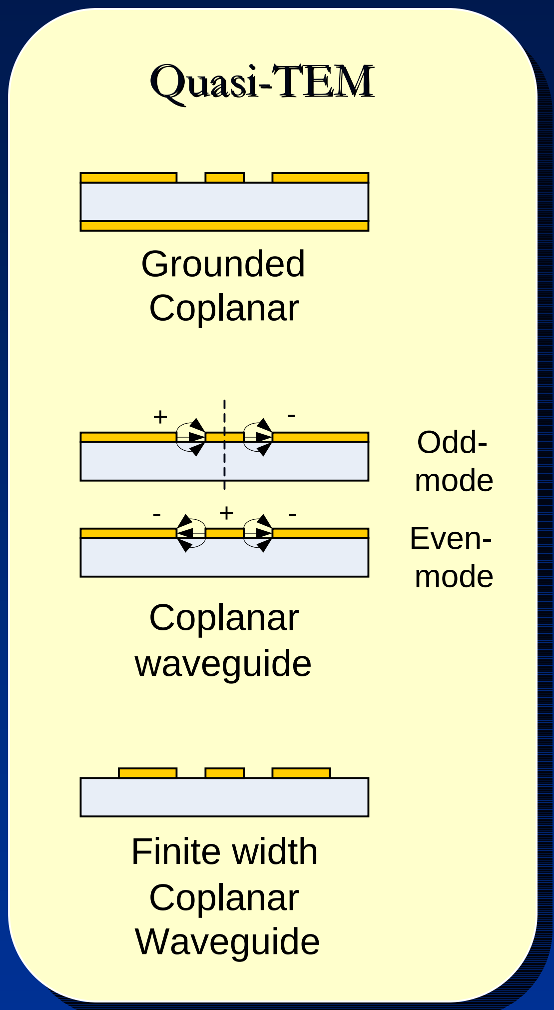
CMB Polarization Technology Workshop
NIST/Boulder

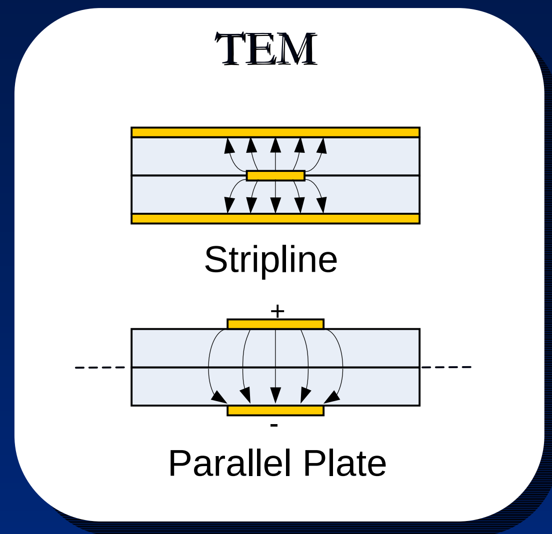
Edward J. Wollack
Observational Cosmology Laboratory
NASA Goddard Space Flight Center
Greenbelt, Maryland

Overview

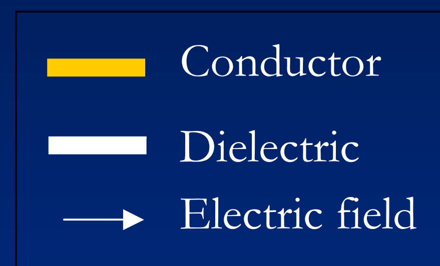
- Selected Planar Transmission Line Topologies
- Planar Transmission Line Applications
- Example: Planar Microwave Filters
- Component Repeatability
- System Level Considerations
- Technical Readiness Level (TRL)
- Future Development Milestones

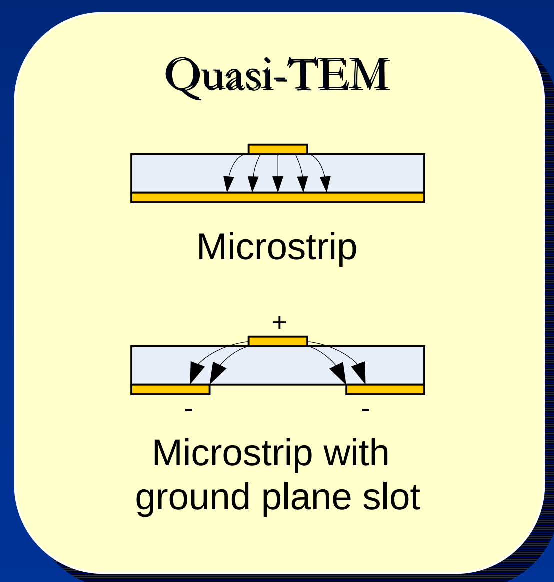
Planar Transmission Lines

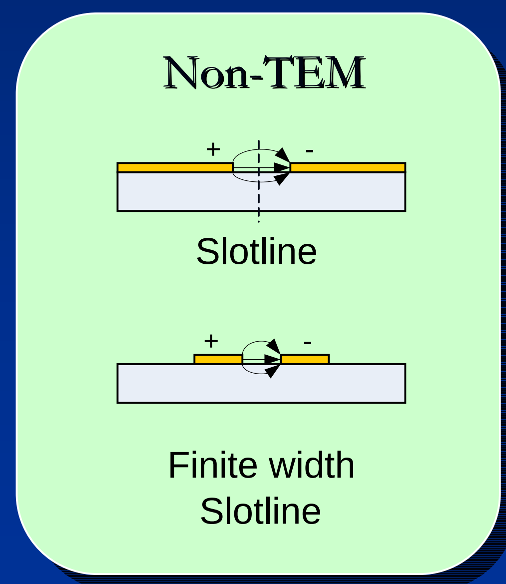




- Phase Velocity
- Impedance Level
- Number Propagating Modes
- Field Configuration





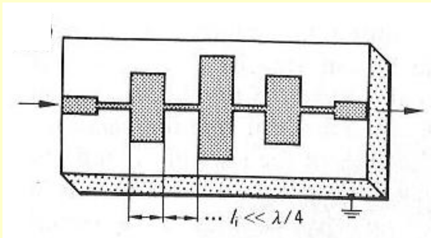


Planar Transmission Lines: Characteristics and Applications

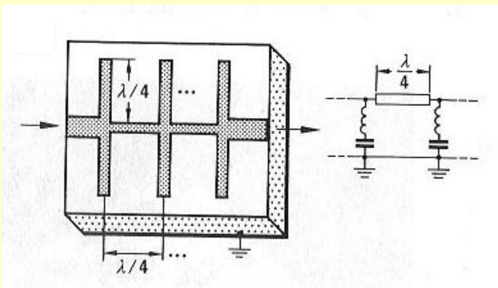
	Relative Loss	Impedance $[Z_o]$	Typical Sensor Circuit Examples:
Strip Line	Medium	~0.1 – 1	Blocking Filters
Parallel-Plate Line	Low	~0.4 – 1.6	Antennas, Transitions
Microstrip Line	Low	~0.2 – 1.4	Filters, Hybrids, High Q-Resonators
Coplanar Waveguide	Low	~0.6 – 2	Filters, Hybrids, High Q-Resonators
Microstrip Line with ground plane slot	Medium	~0.6 – 1.8	Antennas, Resonance Suppression, Filters, Transitions
Slotline	High	~1.2 – 2.4	Antennas, Phase Shifters
Finite-Width Slotline (i.e., Edge-Coupled Line)	Highest	~1.2 – 3	Antennas, Transitions, Power Combiners

Planar Microwave Filters

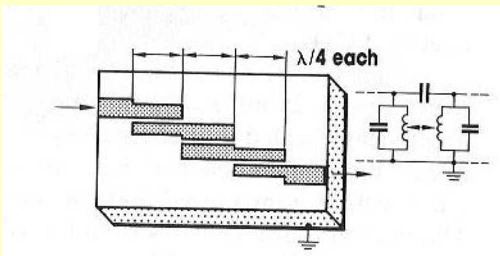
Lumped Element Filter



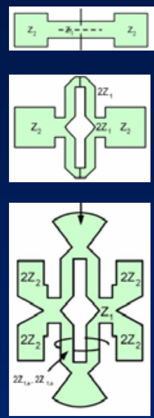
Quarterwave Band-stop Filter

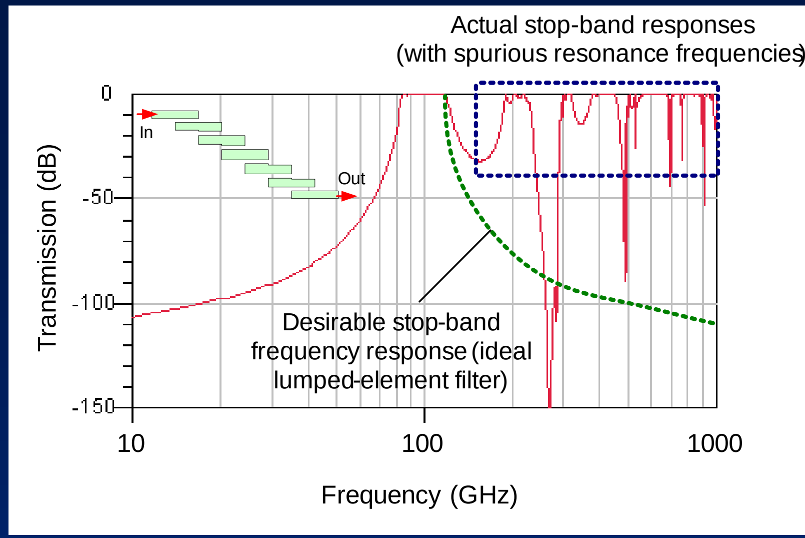


Coupled-Line Band-pass Filter



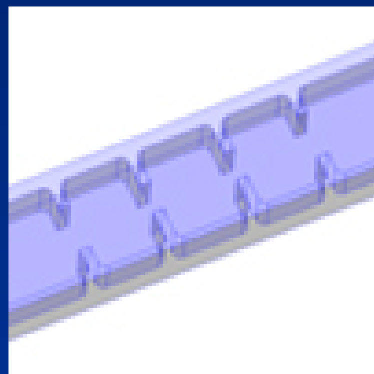
Source: R. K Hoffman, "Handbook of Microwave Integrated Circuits," Artech House, 1987.

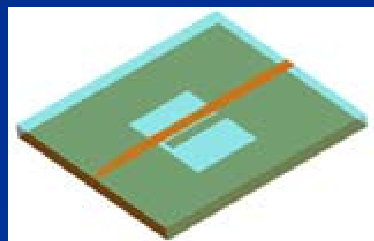


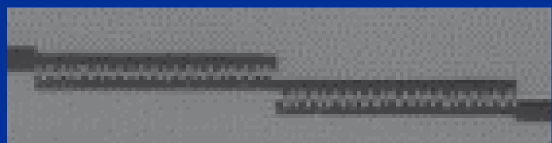


Methods to control spurious response and radiation

- Extending fundamental propagation mode bandwidth:
  - Limit width/length ratio
  - Thin dielectric
- Suppress undesired modes:
  - Symmetric design
  - Packaging
  - Transmission zeros insertion
  - Transmission line alteration
  - Stepped impedance line
  - Defected ground structure
  - Wiggly coupled lines
  - Other…







Filter Designs: Band-Pass

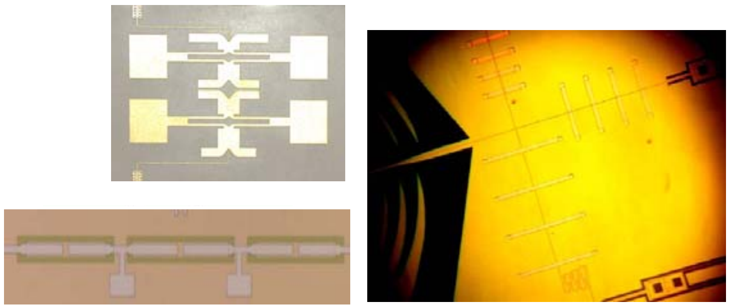


Figure 1. *Upper left:* The layout of a resonant stepped impedance filter (GSFC/GATech [2]); *Lower left:* A lumped element filter with CPW inductors (JPL, [4]); *Right:* A triplexer (3-element filter bank) connected to a broad band antenna (UC Berkeley, [1]).

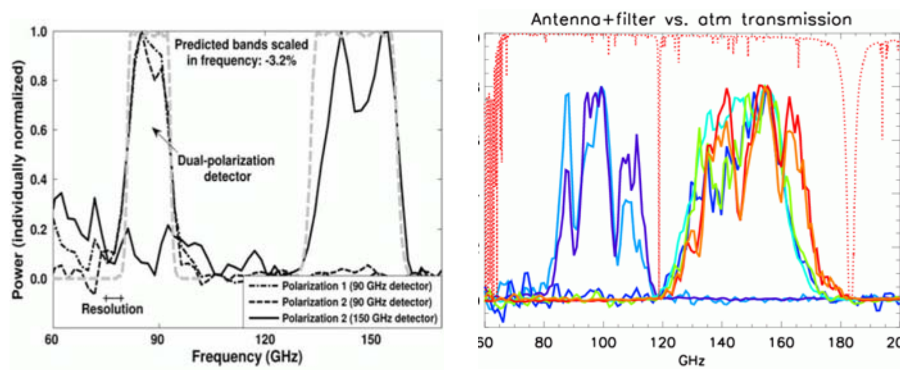


Figure 3. FTS Spectra for integrated antenna+filters, from the Berkeley group (*Left*), and the JPL group (*Right*). Devices for 90 and 150GHz bands are shown. All spectra are normalized individually. The red curve in the right panel indicates atmospheric transmission at ballooning altitudes.

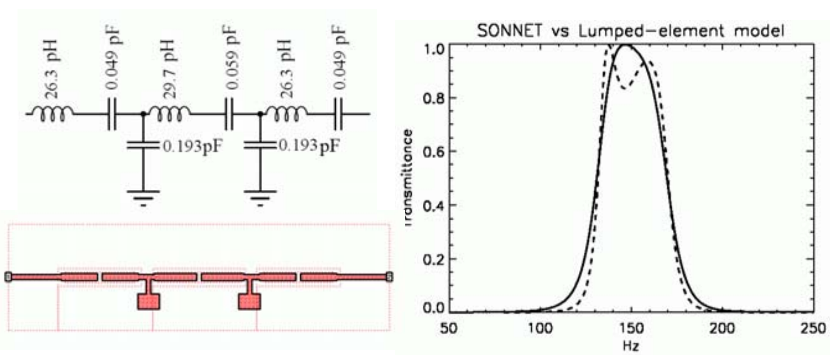
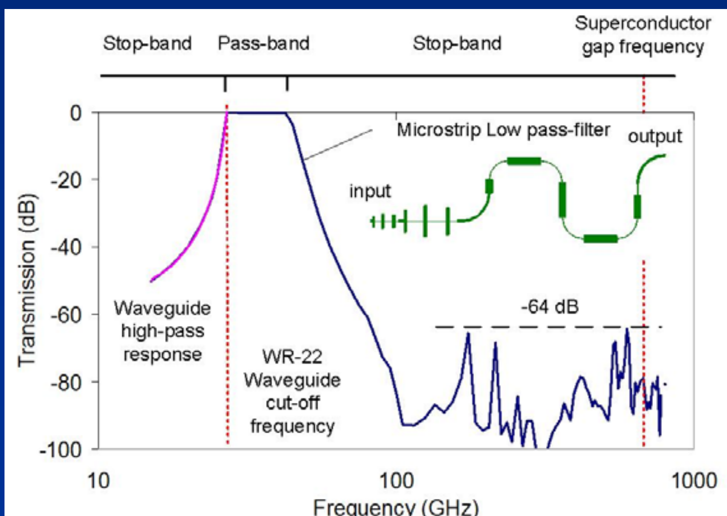


Figure 2. *Top left:* The lumped element model for a 3rd order *LC* bandpass filter [3,4]. *Lower left:* The layout for the corresponding SONNET model. *Right:* The transmittance for the lumped-element model (solid) and the full wave SONNET calculation (dashed).



References:

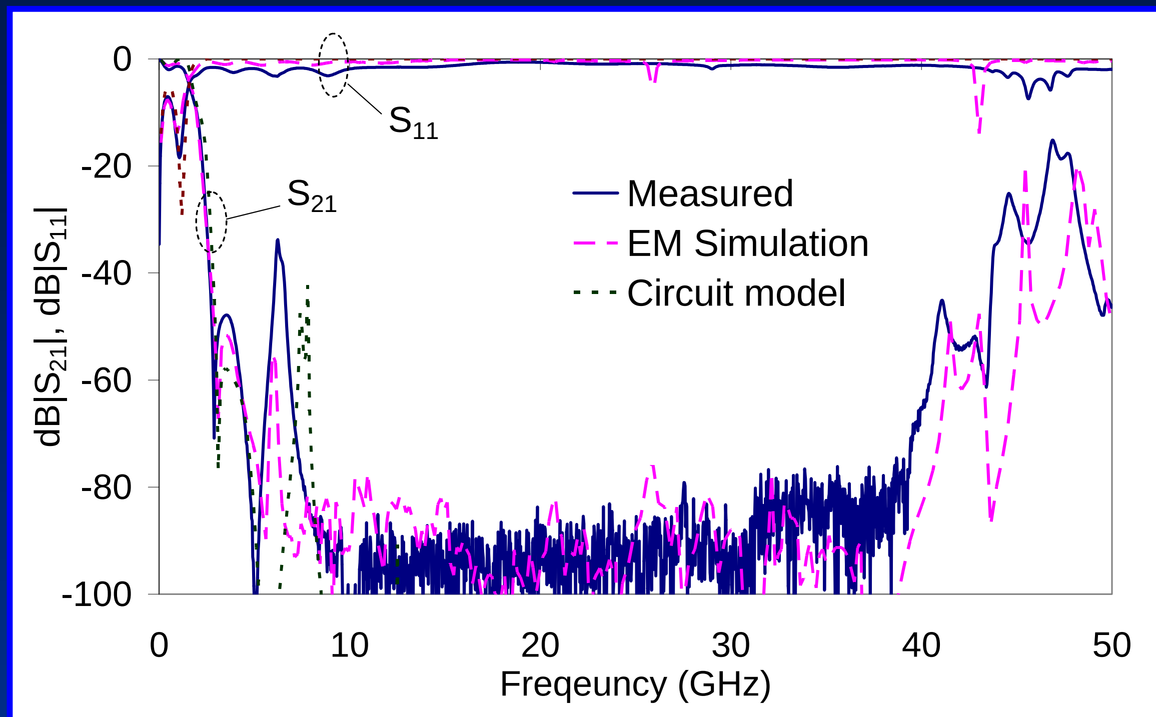
[1] O'Brient, R. et al., v151, p459, JLTP 2008

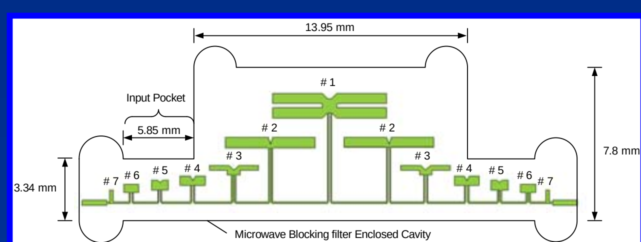
[2] U-yen K. et al., v54, i3, p1237, IEEE MTT, 2006.

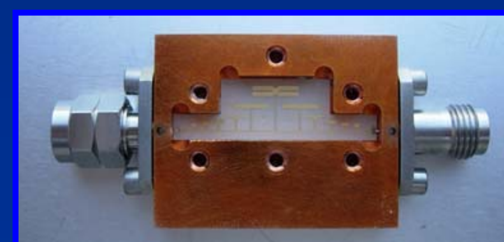
[3] Goldin, A. et al., v4855, p163, proc. SPIE, 2003

[4] Kuo, C. et al., to appear in proc. SPIE, 2008

Filter Design: Thermal Blocking

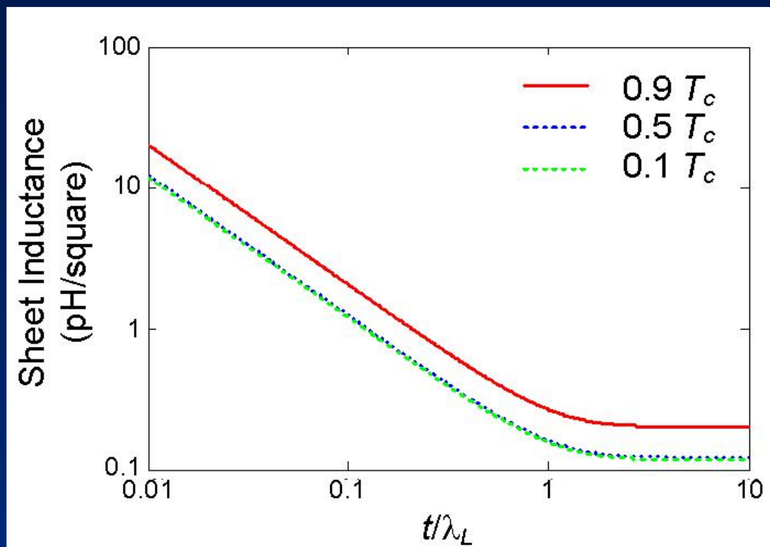


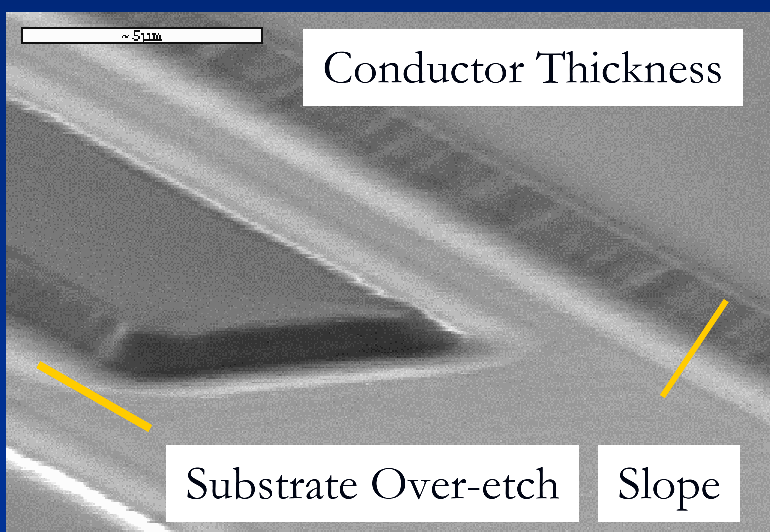




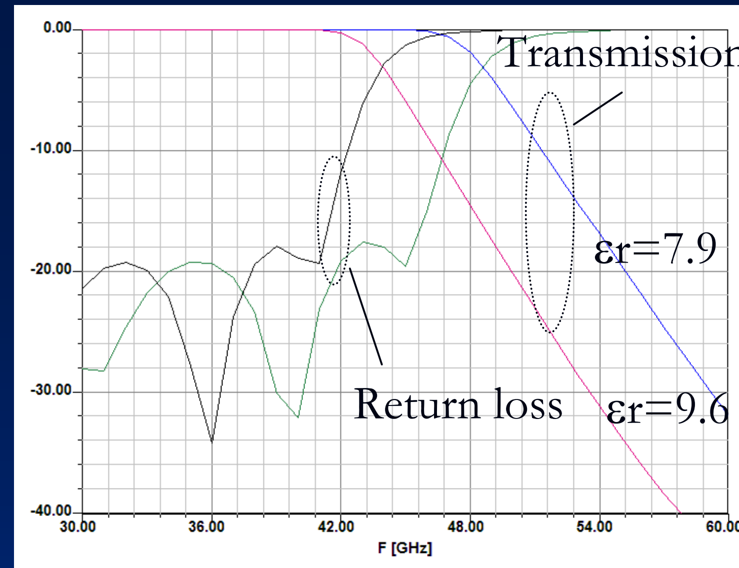
U-Yen, K. and Wollack, E.J., “Compact Planar Microwave Blocking Filter”, 2008, 38th European Microwave Conference, Amsterdam, Netherlands, accepted.

Process Repeatability





SEM image of a co-planar waveguide structure



- Process Variations:
  - Component Geometries
    - Conductor Thickness and Slope
    - Substrate Thickness and Etch
    - Packaging Effects and Variations
  - Material Effects
    - Critical Temperature, Complex Surface Impedance, Step Coverage…
    - Dielectric Constant…
    - → High Material Uniformity…
    - → Low Dimensional Variability…
- Modeling and Design:
  - Circuit Parameter Sensitivity…
  - Material Parameter Knowledge…

System Level Considerations

Advantages:

- Compatible with integration on a detector chip
- Can achieve high optical coupling efficiency
- Compact size
- Can lead to parts with high repeatability, yield and low process variation.
- Does not link frequency and angular band definition requirements
- Transmission line thermal requirements subdominant to detector requirements
- Transmission line loss above gap frequency limits out of band power
- Synthesis, modeling, and simulation design tools at relatively mature levels

Disadvantages:

- Geometries and materials can require tighter and greater control over process tolerances (relative to their quasi-optical counterparts) to insure desired operational performance
- Care must be taken in the overall design not to allow supporting circuitry to drive sensor fabrication and test complexity/risk
- Each single-mode transmission line channel experiences an independent filter which must be characterized in flight
- Polarimeter implementations which use different filters to form Stokes-Q need well-matched response to minimize relative calibration and foreground errors
- Cryogenic array characterization and screening capabilities presently at relatively low level of maturity

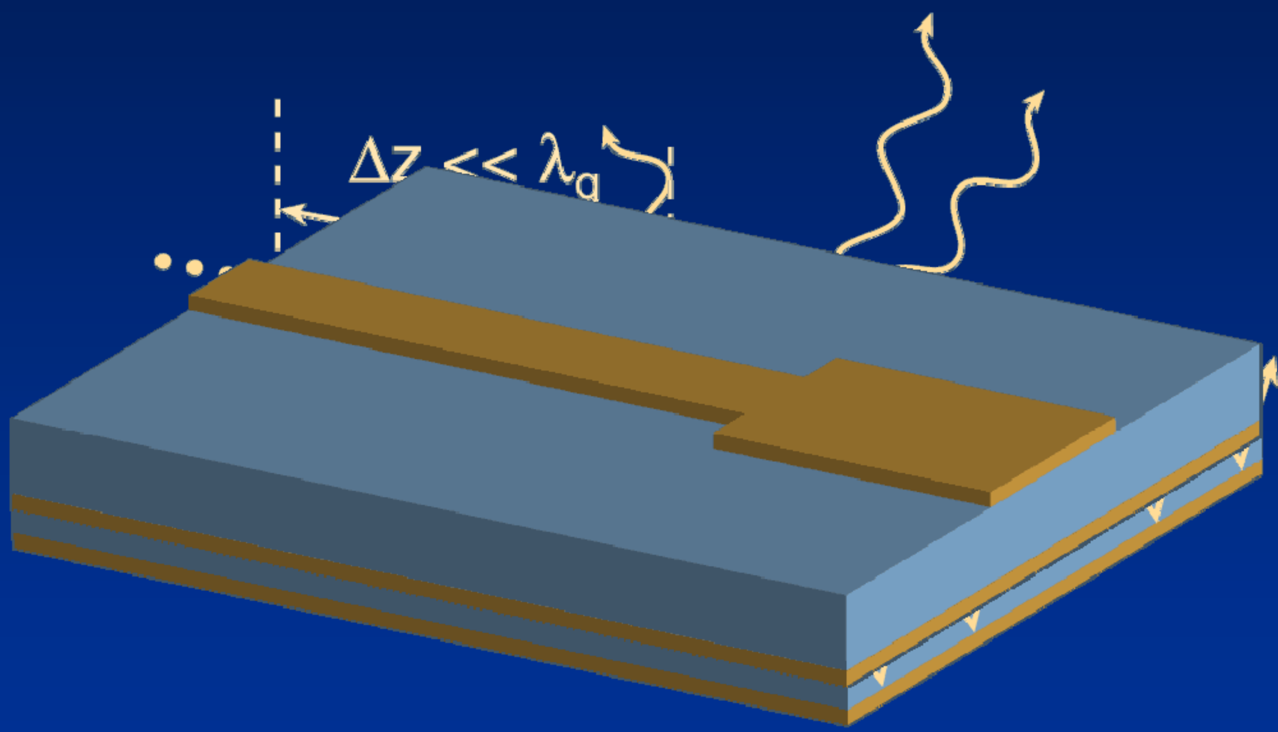
Technical Readiness Level

- Prototype variants on the required passive circuit elements to support CMB polarization science requirements have or will reach TRL ~ 5 under the on going funding cycle. Examples include:
  - Band-Pass Filters
  - Bolometer to Antenna Thermal Breaks
  - Superconducting Transmission Lines
  - Normal Metal Absorber Structures and Terminations
  - Power Combiners
  - Thermal Blocking Filters / Bias Chokes
  - Other…
- Continued support in this area will be required to produce high optical efficiency sensors and field representative devices in fully integrated systems.
- Further design and fabrication iterations will also be required to validate large numbers fully testable structures with acceptable levels of yield and reliability for spaceborne applications....

Future Development Milestones

- So are we ready? Is what we have built what we want?
  - Production of highest efficiency pixels possible is the key to controlling instrument cost and mission risk within allocated resources (e.g., design focal plane area, cooling power, mass…)
  - Demonstrated filter efficiencies for example are arguably an excellent start, however, from a systems perspective one might inquire…
    - Where did the remaining power go?
    - What is a reasonable target for the filter performance?
    - Given an acceptable target – what design margins are required to realistically meet the desired instrument sensitivity with this approach?

Planar Circuits: Loss Mechanisms



- Dielectric
- Conductor
- Reactive Mismatch
- Radiation
  - Freespace (3D)
  - Surface Wave (2D)

$$\alpha_d = k_0 \cdot \frac{\varepsilon_r}{2\sqrt{\varepsilon_{eff}}} \cdot \frac{(\varepsilon_{eff} - 1)}{(\varepsilon_r - 1)} \cdot \tan\delta$$

$$\alpha_c = \frac{R_s}{Z_0 W}$$

$$G_{rad} = \frac{1}{3\pi} \cdot \frac{\eta_0}{Z_0^{\,2}} \cdot \left(\frac{k_o h}{\sqrt{\varepsilon_{eff}}}\right)^2$$

$$f_c = \frac{1}{4} \cdot \frac{c}{h\sqrt{\varepsilon_r - 1}}$$

Planar Circuits: Design

Material Selection and Fabrication:

- Material parameters : ε_r μ_r σ
- Physical Dimensions and Tolerances
- Realizable Topologies
  - Number of layers
  - Apertures, Air Bridges, Vias, etc.
  - Dimensional Tolerances

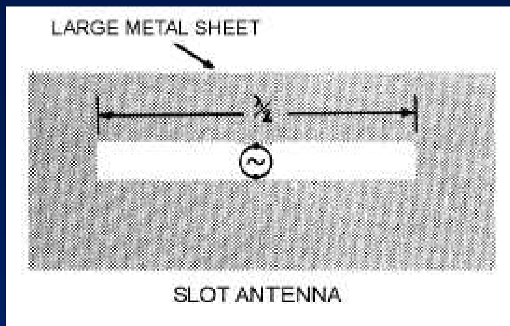
Design and Synthesis:

- Extract Circuit Elements
  - Impedance Contrast
  - Propagation Constant
- Transmission Line Model
- Full-wave Analysis

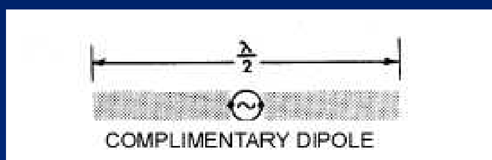
Circuit Validation:

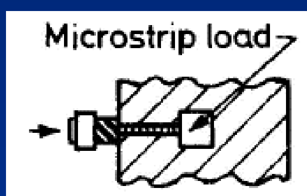
- Compare Models with Observation
- Reliability/Life Testing

Planar Circuits: Examples

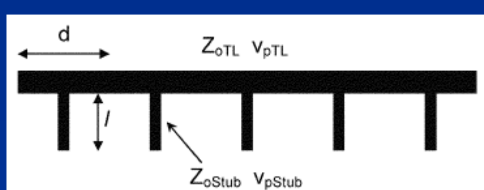


Antennas

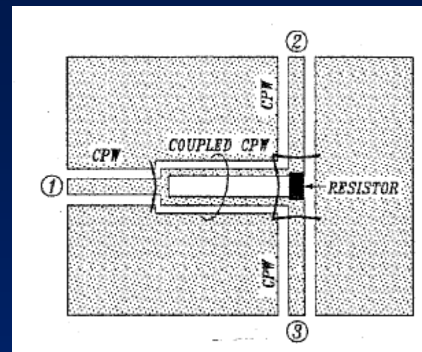




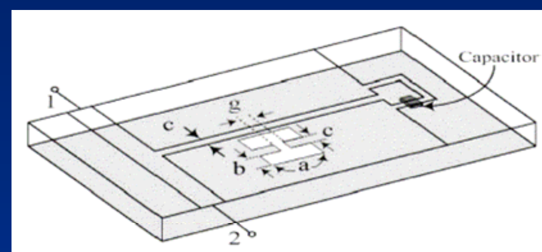
Terminations

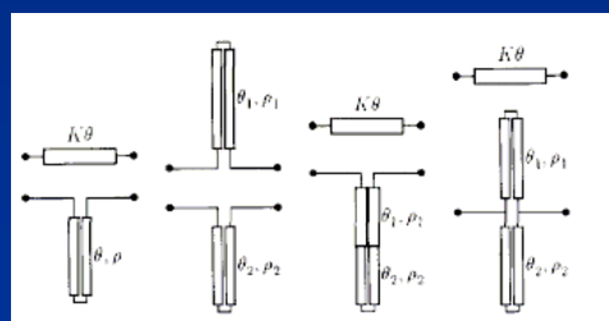


Artificial transmission line

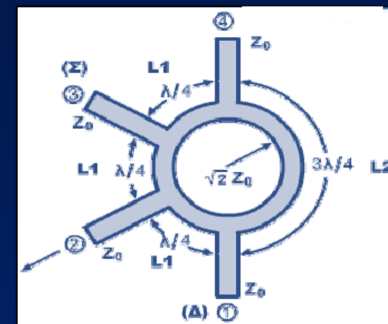


Power divider

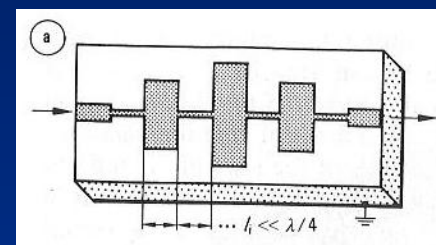




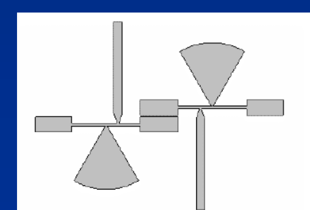
Phase Shifters



Hybrids



Filters



Bias Chokes