Miniaturized Hard Waveguides For Use In Multi-Frequency Arrays

European School of Antennas (EuSA) Course on:
Artificial EBG Surfaces
and Metamaterials for Antennas

19 April 2005

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Motivation and Statement of Problem

Multi-Function Antenna Array
Miniaturized Waveguide Elements

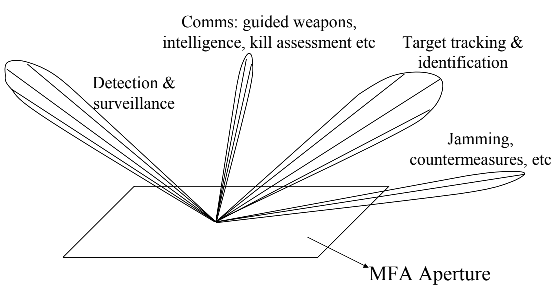
Motivation

- In the past: one antenna – one specific function
- Nowadays: desire to pack more functions into one single antenna – more the better
- Demands in mobile-phone industry
  - Triple-band
  - GPRS
  - Bluetooth
  - WLAN
- Requisites in aviation industry: aerodynamics

The challenge (in military)

- Modern warfare = Electronic warfare (EW): comms, intelligence, precision
- RF functions
  - radar, detection, tracking, surveillance, jamming, counter
- Presently: various functions performed by individual dedicated radars
- Problem with separate systems: higher radar signature (degrade stealth capability)
- Goal: Single RF front-end shared by all functions – to realize a Multi-Function Antenna (MFA) System

Multi-Function Antenna



Potential Advantages

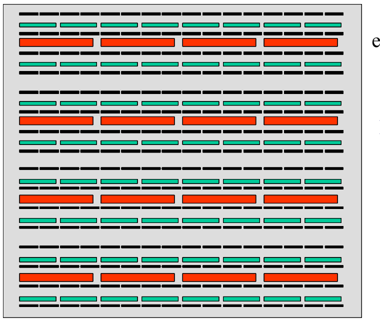
- Reduce platform radar signature (or RCS): enhance survivability
- Lower cost (less space, save on RCS reduction of many antennas)
- Reduced weight: vital for platforms with limited space & power (e.g. Unmanned aerial vehicles: UAV)
- Affords increase in number of functions

Potential Candidate: Phased Array

- Used in radar since WWII
- High scanning rate: operate simultaneously against several threats
- Versions: shipboard, land-based, airborne
- Aperture: shared-aperture or sub-aperture
- Option of study: Shared (aperture reuse)
  - Interlaced array
  - Open-waveguide as elements

2 approaches: (a) large broadband (b) compact narrowband elements

Example: Linearly polarized multi-band array of open-ended waveguide apertures (fractal geometry)



Full scan means element spacing < 0.5λ at all frequencies $f_1 < f_2 < f_3$

Highly miniaturized in *E*-plane: very small height (not reason for filling)

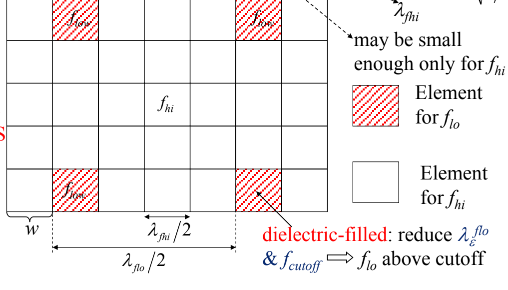
Slightly miniaturized in *H*-plane: width < 0.5λ (need some filling)

Interlaced dual-polarized dual-band array using open-ended waveguide elements

Miniaturization in both planes

Combined requirement on width *w*: $0.7\lambda_\varepsilon \le w \le \lambda_{min}/2$ (Above TE10 cutoff; Avoid grating lobes (full scan))

$\lambda_\varepsilon = \frac{\lambda_0}{\sqrt{\varepsilon_r}}$



NEED SMALL GUIDES

λ_{fhi} may be small enough only for f_{hi}

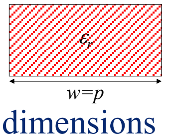
dielectric-filled: reduce $\lambda_\varepsilon^{flo}$ & f_{cutoff} $\Rightarrow$ f_{lo} above cutoff

Desire for: Compact Miniaturized Waveguides

To either leave space for other frequencies (fractal) or for low-frequency elements

Disadvantages of Full Dielectric Filling

- Attenuation
- High noise temperature
- Not flexible in choice of dimensions
- Heavy, higher cost?
- Cannot locate components within



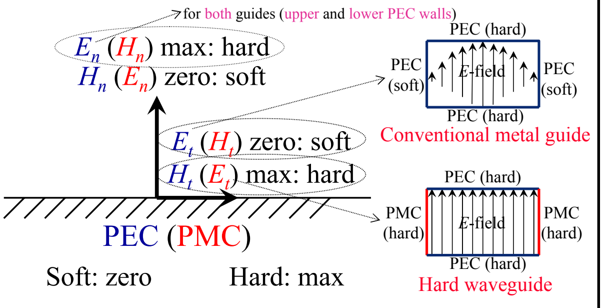
⟹ alternative small-guide that is still predominantly empty?

Soft and Hard Surfaces

Compact Quasi-TEM Hard Waveguides

Soft & Hard Surfaces (Kildal '88)

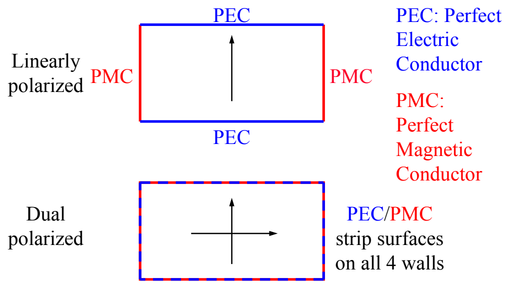
Terminology from acoustics



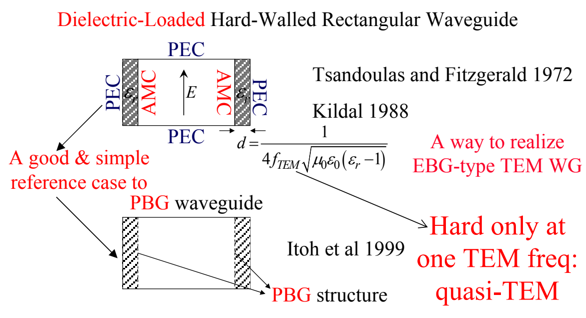
What is "Hard" Waveguide?

- Fields at all walls see them as "hard" (presented 'hard' boundary condition): Maximum on them
- Supports quasi-TEM waves: uniform aperture field distribution (plane wave)
- TEM waveguides (Itoh et al 1999)

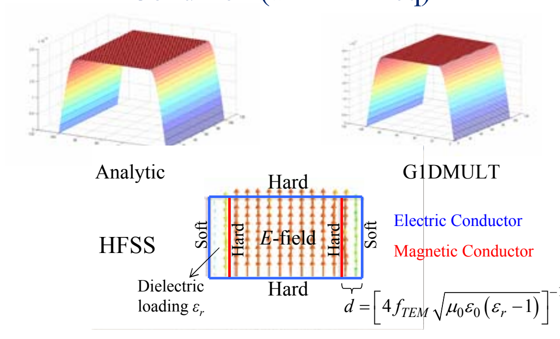
Examples of **ideal** "hard" rectangular waveguides supporting TEM



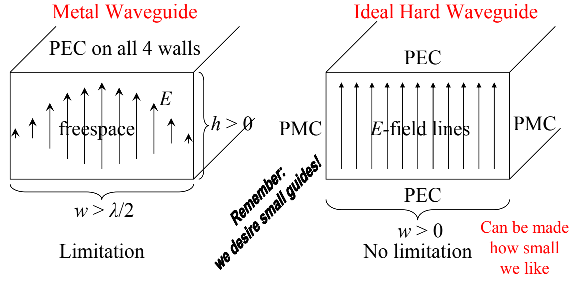
Examples of realized linearly-polarized hard quasi-TEM rect. waveguides



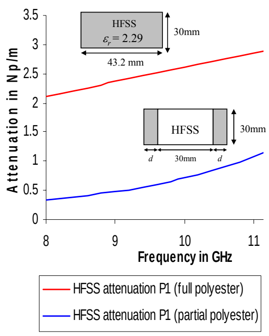
Uniform Aperture Field at Hard TEM Condition (at TEM freq)

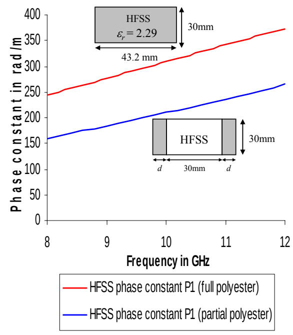


Conventional vs Ideal "Hard" Rectangular Waveguide

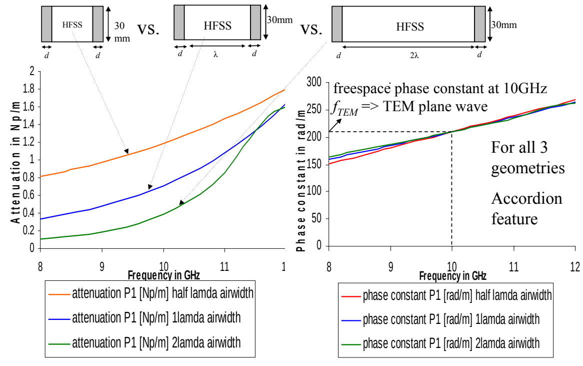


Propagation in full & partially-filled guides

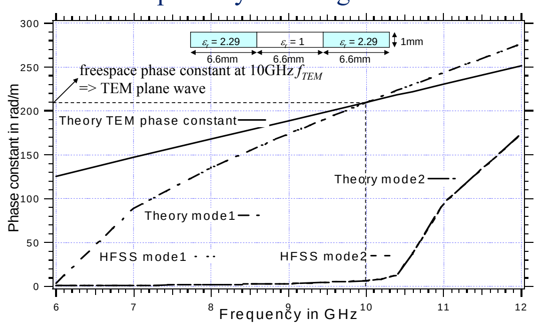




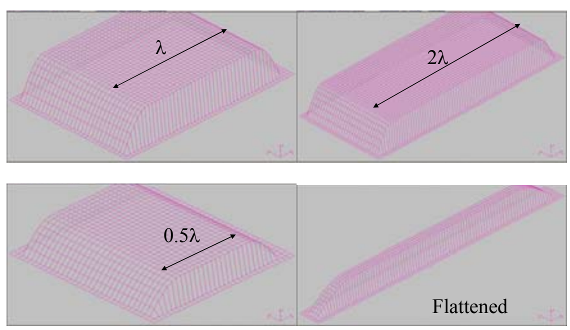
Vary central air width of partial guide



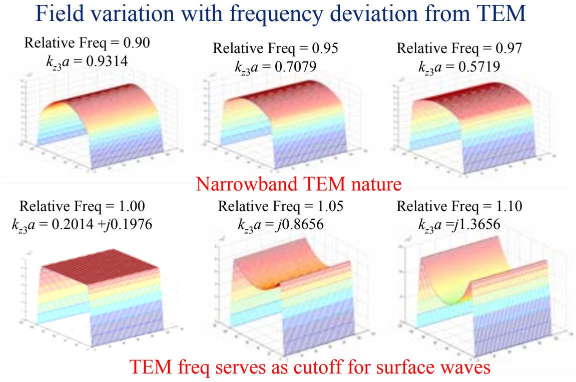
Analytical & HFSS Dispersion curves for partially-loaded guide



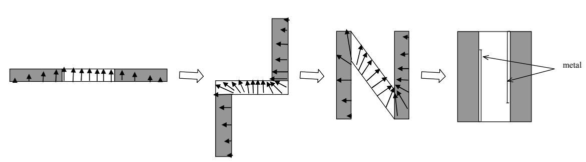
Flexible Dimensions



Field variation with frequency deviation from TEM



Novel Miniaturized Hard Quasi-TEM Waveguide: The Compact N-Guide



Size comparison with conventional empty guide operating at same frequency

Very small indeed

Transverse Field over Cross-Section of N-Guide

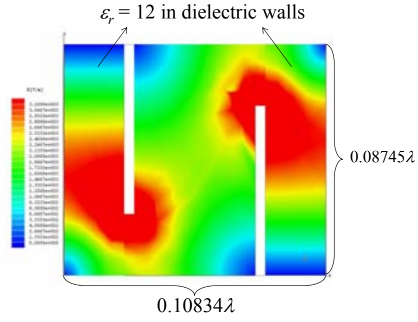
Relative permittivity = 12

TEM freq = 2.3GHz

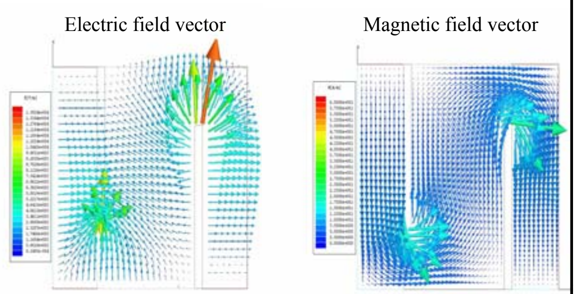
Dielectric dimension 11.3mm x 3mm

Freespace dimension: 11.3mm x 7mm

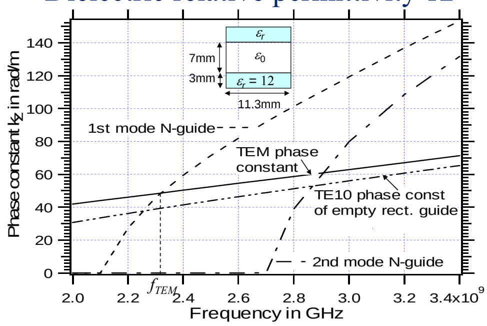
Metal fin thickness = 0.5mm



HFSS Vector Field Plots



HFSS Dispersion for N-Guide: Dielectric relative permittivity 12



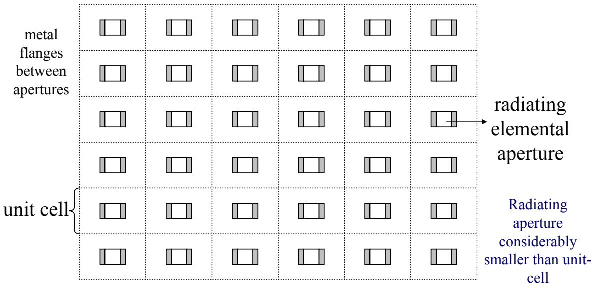
Summary of Modal Study

- Much lower loss than fully-filled (for same dielectric & cross-section): *TEM* vs TE_{10}
- Flexible cross-section
  - Preserve TEM behavior (uniform plane wave in freespace) for all cross-sections
  - Can make as small as desired
- Bandwidth Study
  - Narrowband TEM
  - TEM freq = cutoff for surface waves
- Ultra-Compact Quasi-TEM N-Guide (deformed)
  - Still predominantly empty
  - Defies conventional > 0.7λ width restriction
  - Opens new doors for research on miniaturized waveguides

Infinite Planar Array

Open-Ended Aperture Radiation

Infinite Planar Array of Miniaturized Dielectric-Loaded Rectangular Waveguide Apertures



Objective: Array performance of Miniaturized Hard Waveguides

- Recap (what we have thus far)
  - Multifunction Antenna: Small waveguides (allow space for other frequencies, low-freq elements)
  - Like full dielectric-filling: TEM hard waveguides can be made small (potential candidate)
  - Advantages: Lower dielectric loss, lighter, etc
- Purpose: Study array performance of miniaturized hard waveguides
  - Can they radiate well?
  - Anything special with TEM? → Presumably yes: to concretely find out

Can make small is one thing, but how it performs in array is another

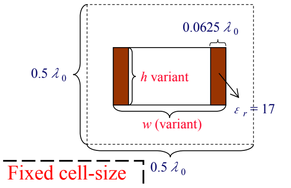
Parametric Studies

Effects of various attributes on array transmission

Reflection from aperture: Variation with width & height

Transmission increases with aperture size: works against us

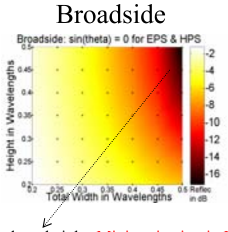
Geometry



Fixed cell-size

At TEM hard condition always

Broadside

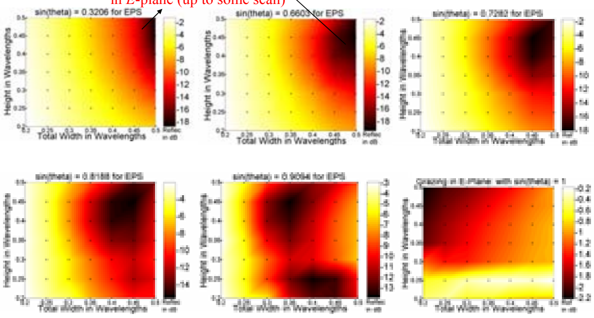


Elongated along height: Miniaturization in E-plane may still be possible (suits 1st diagram just now)

Various scan angles in *E*-plane

Still possible miniaturization in *E*-plane (up to some scan)

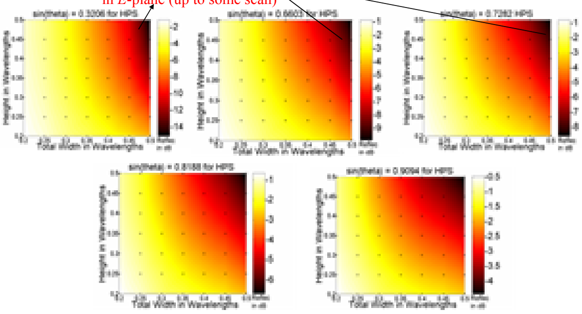
At TEM hard condition



Various scan angles in *H*-plane

Still possible miniaturization in *E*-plane (up to some scan)

At TEM hard condition



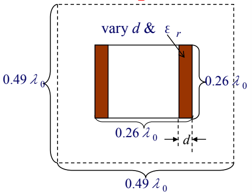
Findings

- Smaller the aperture relative to cell-size, poorer the array transmission
  - Against our interest
  - Impedance-matching to alleviate this
- Miniaturization may still be possible in *E*-plane (suits fractal example earlier on)

Reflection from aperture: Variation with dielectric depth and permittivity (Full-Scan)

Geometry:

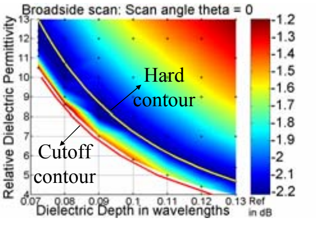
Mini aperture



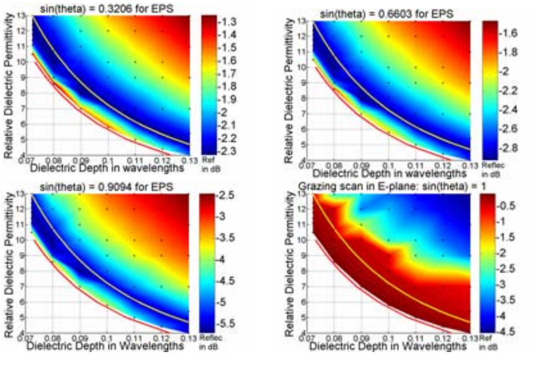
Fixed aperture & cell size

Vary depth & ε_r

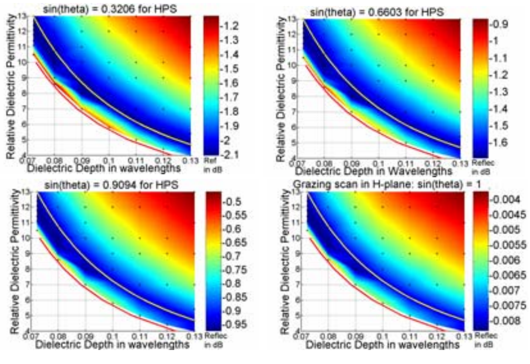
Broadside



Various scan angles in *E*-plane



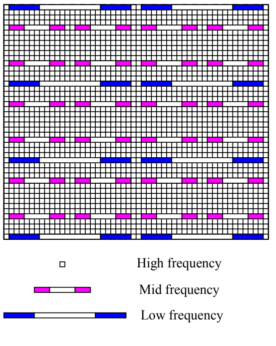
Various scan angles in *H*-plane



Findings

- Best transmission when operated around TEM condition
- Due to miniaturized aperture ($w < \lambda/2$): need loading – but just enough to attain TEM (not to underload or overload) : optimal loading
- As before: due to aperture smallness, poor transmission – impedance-matching can help

Multi-Frequency Interlaced Array

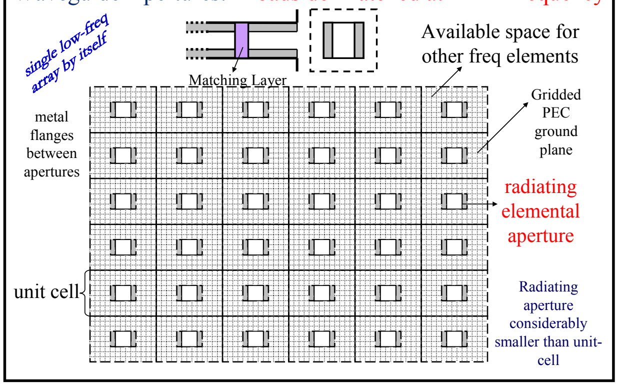


- Small higher-frequency apertures present gridded PEC plane to lower-frequency elements
- Thus higher-frequency elements covered with PEC in our analysis (neglect them) – study low freq array by itself
- But coupling of higher-freq into larger lower-freq elements not negligible – for future work

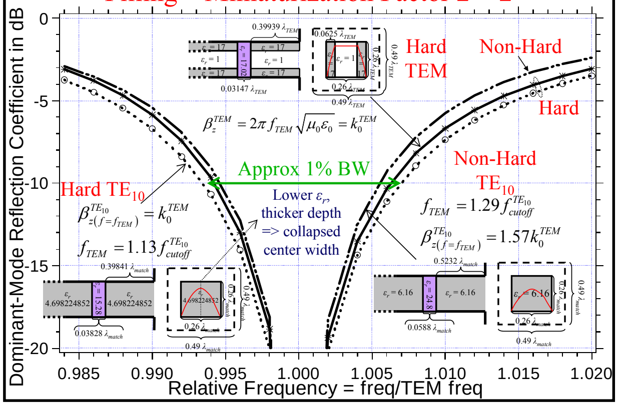
Matching Layer

Homogeneous Intermediate Section

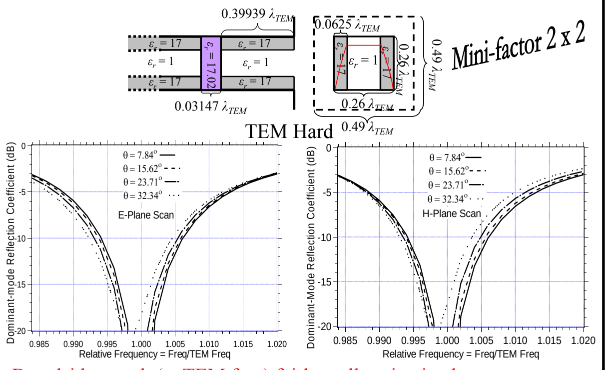
Infinite Array of Miniaturized Partially-Loaded Rectangular Waveguide Apertures: Broadside-Matched at TEM Frequency



Broadside-Matching at TEM Freq: Full & Partial Filling – Miniaturization Factor 2 × 2



Bandwidth: Few Different Beam Directions – Partial TEM Hard

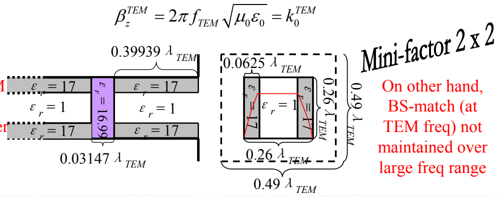


Broadside-match (at TEM freq) fairly well-maintained over some scan angle range: dip-frequency shifts left very slightly as scanned from BS

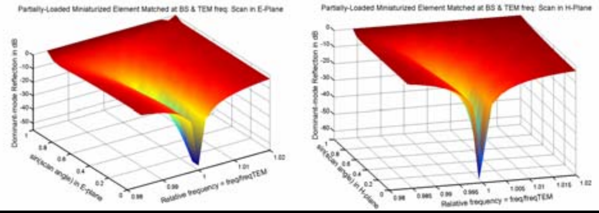
Bandwidth: All Beam Directions – Partial TEM Hard

$$\beta_z^{TEM} = 2\pi f_{TEM}\sqrt{\mu_0\varepsilon_0} = k_0^{TEM}$$

Broadside-match (at TEM freq) well-maintained over some scan angle range

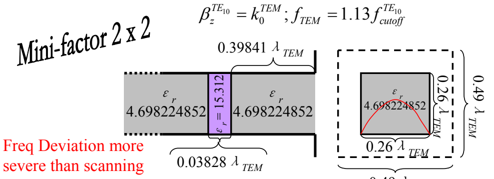


On other hand, BS-match (at TEM freq) not maintained over large freq range

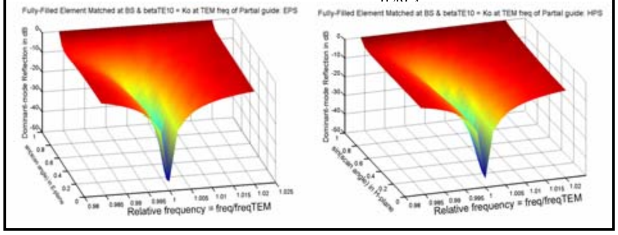


Bandwidth: All Beam Directions – Full TEM Hard

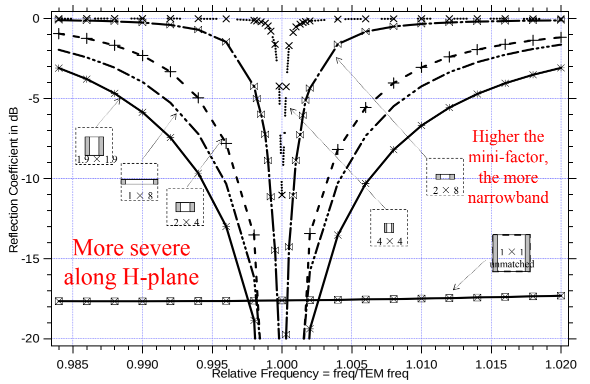
$$\beta_z^{TE_{10}} = k_0^{TEM}; f_{TEM} = 1.13 f_{cutoff}^{TE_{10}}$$



Freq Deviation more severe than scanning

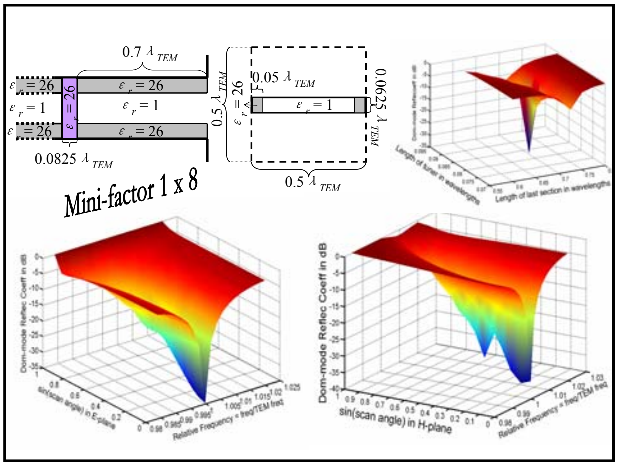


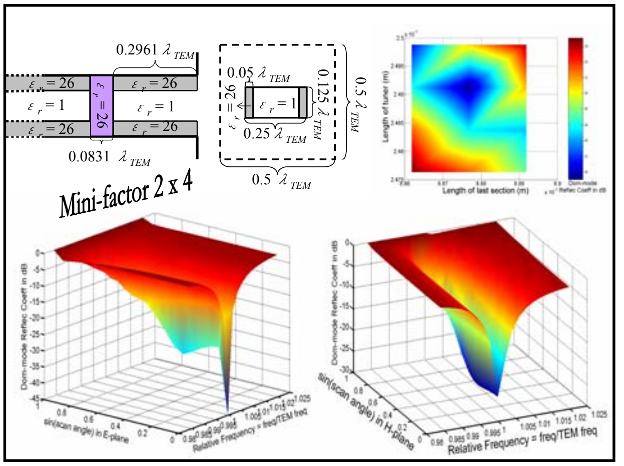
Bandwidth under Broadside Matched at TEM Frequency for Various Degrees of Miniaturization

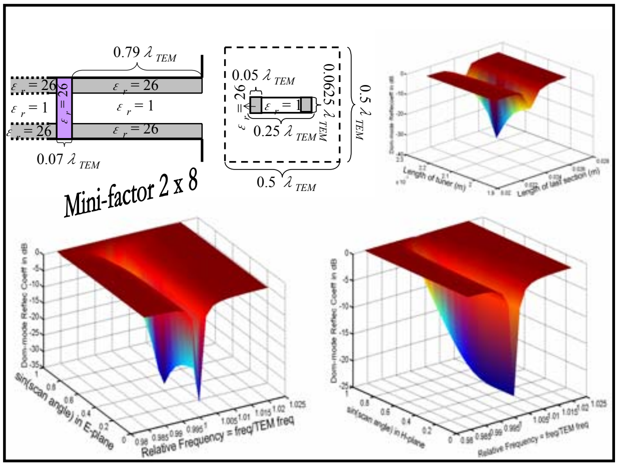


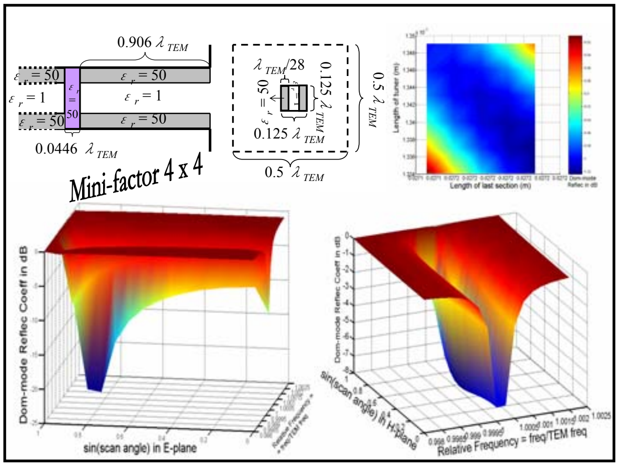
–10dB bandwidths for various miniaturization factors: $0.5\lambda_{TEM} \times 0.5\lambda_{TEM}$ unit cell

Miniaturization factor (along width & height)	$\varepsilon_{rd} = \varepsilon_{rm}$	l_m (λ_{TEM})	l_{out} (λ_{TEM})	–10dB bandwidth (broadside) in %
1.9 × 1.9	17	0.03147	0.39939	1.2
1 × 8	26	0.0825	0.7	0.75
2 × 4	26	0.0831	0.2961	0.65
2 × 8	26	0.07	0.79	0.18
4 × 4	50	0.0446	0.906	0.02





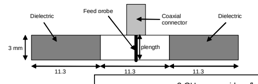




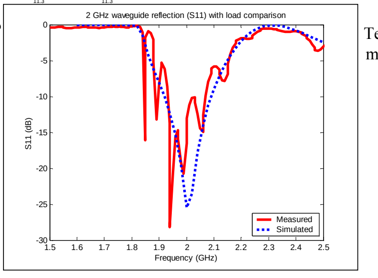
Physical Realization

Probe-Feeding of Miniaturized Dielectric-Loaded Quasi-TEM Hard Rectangular Waveguides

Feeding of Mini Guide: 2GHz TEM freq

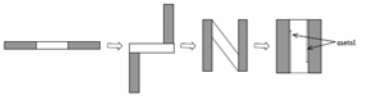


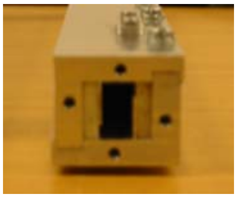
Possible to excite compact guide

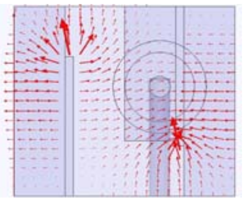


Terminated at matched load

N-Guide (cross-sectionally deformed version)







L-Feed: For miniaturized guides

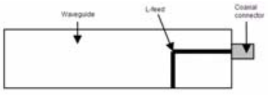
Common coax-waveguide transition (probe-feed)

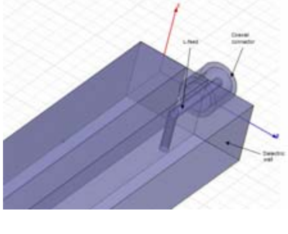
L-Feed

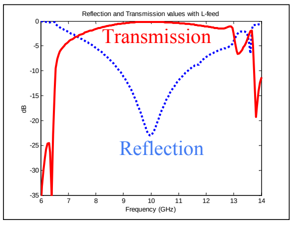
Fed from end-wall: compactness

L-Feed

L-feed simulated in a 10 GHz Teflon dielectric loaded waveguide.

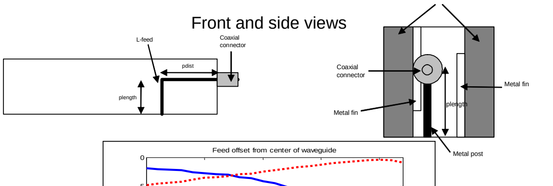




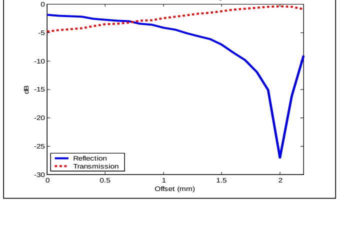


L-Feed in N-Guide

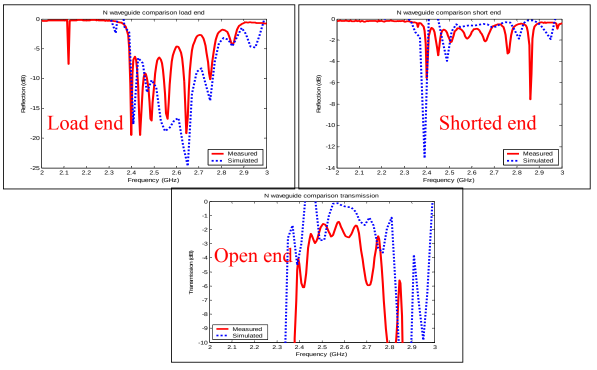
Front and side views



Parametric simulation to determine correct offset from the center of waveguide.



N-Guide Results: Load, Shorted, Open



Conclusions

- Difficult array transmission for highly-miniaturized (both planes) waveguide apertures
  - Can be improved with impedance-matching
  - BUT easier to miniaturize in *E*-plane within limited scan range (suits fractal example just now)
- Best performance within vicinity of TEM
  - Not to underload or overload
- Possible to excite miniaturized guide
- Miniaturized waveguide as a possible system component (especially in MFA systems)

Conclusions

- Matching layers overcome poor transmission from strong miniaturization
  - Narrowband though
    - Stronger mini-factor, more narrowband: More severe in H-plane
    - Nevertheless: good frequency isolation (simul ops of diff freqs)
  - Matching (under broadside at f_{TEM}) preserved over some scan-range
- For certain miniaturization factor, bandwidth about the same regardless
  - partially or fully loaded
  - hard or non-hard
- –10dB bandwidth of ≈ 1% possible for factors between 2×2 & 1×8: space for other freq elements