Hybrid Eigenmode Analysis of Dielectric Waveguides for the Design of Travelling Wave Endfire Antennas

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Introduction & Motivation

- **Monostatic radar level measurements** in the **industrial environment** under **harsh process conditions**
  - Antenna insertion through existing nozzles
  - Challenge: Small diameters ($d_{\text{max}} = 50 \text{ mm}$)

- **FMCW radar technique** (8.5 - 10.5 GHz)

- **Antenna requirements**
  - Highly directive
  - Extremely low „ringing“
  - Compact outer dimension

- **Conventional antenna classes**
  - **Conical** metallic horns (with or w/o encapsulation by lenses)
  - Dielectric rod antennas (made of chemically inert material, e.g. PTFE)
Previous designs – Multimode antennas

- Dielectric cylindrical inserts with tapered cavities [1]
- Excited by short flange-integrated metallic horns
  - Equivalent TE$_{11}$ horn diameter: $d_{eq} = 77$ mm (single cavity), 111 mm (dual cavity)
  - Length reduction compared to optimal rod: ~50 % (single cavity), 27 % (dual cavity)


- **Major drawback:** Distinct axial length
Tapered rod vs. tapered cavity

- Dielectric rod as a length-independent concept well-known (HE$_{11}$ mode excited)
- Comparison of directivity efficiency (Sweep, 50…200 mm)
  - No further optimization of the taper geometry

- Mode-controlled excitation of tubular eigenmode system
  - Tubes preferable for highly directive endfire radiation
Reference values by analytical approach

- Solving Maxwell’s equations in cylindrical coordinates
- Common approach for solid rod and tube
  - MATLAB based implementation
- Field continuity at domain boundaries
  - Implicit solution of characteristic equations
  - Eigenmodes are derived by finding the roots

- Type of eigensolutions (modes):
  - Radial symmetrical TE / TM modes ($H_{0p}$, $E_{0p}$)
  - Hybrid non-cylindrical symmetrical ($HE_{np}$, $EH_{np}$)
  - Special: Fundamental $HE_{11}$ w/o cut-off

- Major conclusions:
  - NF: Thin rods are single-moded
  - Tubes with small wall thickness are single-moded
  - FF: $HE_{1p}$ hybrid modes have single beam in endfire direction (thus applicable for monostatic radar)
CST Performance evaluation – Let’s start simple

- Simulation of a dielectric rod made of PTFE ($\varepsilon_r = 2.08$)
  - CST MICROWAVE STUDIO (Vers. 2009, SP0), Mesh density - at least 20 lin/λ
  - Evaluation of „default“ waveguide port & boundary condition settings
  - HE$_{11}$ fundamental mode excitation (TE$_{11}$ equivalent circular waveguide mode)
  - Symmetrical to xz- and yz-axis (E- and H-plane)
PTFE rod – Initial results

- Waveguide port: HE$_{11}$ mode field pattern
  - Frequency-dependent (as expected)
  - Decaying electric field magnitude over frequency

Remarks:
- Plausible port mode field distribution
- Ripples on initial S-Parameters in both cases
- Obviously $S_{11}$ too large (compared to $S_{11} < -100$ dB for circular metallic waveguide mode TE$_{11}$)
### Dialog „Special Solver Parameters“

- **Evaluation of special solver settings / options**
- **Two important settings identified for hybrid mode excitation**
  - “Broadband for inhomogenous waveguide ports” (abbr. Broadband…)
  - “Absorb unconsidered mode fields for inhomogenous ports” (abbr. Absorb…)

#### Default settings depicted
- Possible tuning options to improve port mismatch ($S_{11}$)
Results of a „One-Port-PML“ model

- **Scattering parameter $S_{11}$**
  - *Broadband*… Option: $S_{11}$ independent of frequency samples (3 or 21)
  - Considering large port area ($2p = 100$ mm)

Port Quantities

![Graph showing $S_{11}$ vs. Frequency](image)

- **Remarks:**
  - Both options cause inaccuracies (in port & field quantities)
  - Best broadband results obtained by switching both options OFF

Electric field distribution

![Electric field distribution](image)
Numerical hybrid eigenmode analysis

Electric field @ 9.5 GHz

- Best settings applied for a dielectric rod (radius 11 mm)
- Adequate port dimensions found by $S_{11}$ convergence study
  - Constant dip ($S_{11} < -80$ dB) at mode calculation freq. for $2p \geq 80$ mm
- Finite port dimension vs. infinite field hybrid extension
  - Analytical field magnitude independently scaled to incident peak power (1 W)

H-plane

```
CST: 2p = 25 mm, 2p = 80 mm
Analytical solution: ▲
```

E-plane

```
CST: 2p = 25 mm, 2p = 80 mm
Analytical solution: ●
```

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Waveguide Port - Mode unlatching

- Thin dielectric tube, \( R_{\text{out}} = 6 \text{ mm}, R_{\text{in}} = 4 \text{ mm} \) (Teflon, PTFE)
  - Weakly decaying outer fields
  - Large port area necessary, \( 2p > 300 \text{ mm} \) (!)

Observed effects:
- Port mode solver fails for thin tubes
- First port mode depends on the total number of calculated modes
Dielectric waveguide transition

- Applying derived settings: Accurate 2-Port modeling possible
- Transition between rod \((d = 22/0 \text{ mm})\) and tube \((d = 43/39 \text{ mm})\)
- Taper design and optimization
  - Evaluation of fundamental mode transmission \(S_{21}\) (Port1: **rod mode** \(\text{HE}_{11}\) → Port 2: **tube mode** \(\text{HE}_{11}\))

![Image of dielectric waveguide transition](image-url)
Numerical hybrid eigenmode analysis

Fundamental mode preservation @ 9.5 GHz

- Linearly tapered dielectric horn section
- Impact on radiated far-fields
  - Far-fields at PML boundary (neglecting field distortions at the tube’s end)

<table>
<thead>
<tr>
<th>Taper length / mm</th>
<th>Transmission (S_{21}, time-gated)</th>
<th>H-plane</th>
<th>E-plane</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>linear</td>
<td>Dir. / dBi</td>
<td>SLL / dB</td>
</tr>
<tr>
<td>150</td>
<td>0.883 -1.081</td>
<td>18.5</td>
<td>-27.5</td>
</tr>
<tr>
<td>350</td>
<td>0.936 -0.574</td>
<td>19.7</td>
<td>-30.4</td>
</tr>
<tr>
<td>550</td>
<td>0.957 -0.382</td>
<td>20.0</td>
<td>-30.4</td>
</tr>
<tr>
<td>HE_{11} tube</td>
<td>-- --</td>
<td>22.9</td>
<td>-32.5</td>
</tr>
</tbody>
</table>

- Observed effects:
  - Increasing HE_{11} mode preservation leads to higher directivity levels
  - Side lobe level (SSL) remains low, as desired
  - Approaching the theoretical limit of 22.9 dBi with increasing mode purity
Hybrid mode analysis is working fine!

except:
- Solver options (*Broadband*…, *Absorb*…)
- Port mode solver (Mode unlatching under special conditions: Small & thin tubes)
Thanks for your attention