Novel Technology for Ultra-Sensitive Cosmology Instruments

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Technology for Ultra-Sensitive Cosmology Instruments

- CMB B-mode science requirements.
- Instruments Design
- Telescope
  - Feed arrays
  - Phase modulation
  - Detectors
Why Phase Modulate?

- Reduce 1/f noise
- Measure Stokes parameters without moving correlation receiver components

\[ D1 = I - Q \cos \psi - U \sin \psi \]
\[ D2 = I + Q \cos \psi + U \sin \psi \]
Three flare-steps horn

Profiled Corrugated horn

Multi-flare (smooth-walled)
Generalize to a wideband horn
Hornsynth Software Package

- Written by P. Kittara, A. Jiralucksanawong (Mahidol University, Thailand) in collaboration with Ghassan Yassin (Oxford Physics)
- It consists of two software packages: (1) modal matching software (2) Optimization software
- The minimization package is a Genetic Algorithm routine and a Simplex routine
- The software searches for the global minima according to a “fitness” criteria. In our case it is the circularity and cross-polarization level.
Design using a Genetic Algorithm (GA)

1. Generate initial population of N sets of Potter Horn parameters.

2. Calculate beam patterns using the modal matching technique.

3. Evaluate quality function for each of the N individuals.

4. Reject poorest half of population.

5. Generate new generation using crossover and mutation.

6. Repeat for 500 to 1000 generations.

- We have successfully parallelized the code to run over the UK GRID computing system, in collaboration with Oxford eScience.

- Spread processor intensive modal matching and quality function evaluation over multiple processors.

- Currently optimizing designs with 4 flare angles.
Three angles horn design

Hornsynth output

<table>
<thead>
<tr>
<th>Results</th>
<th>Waveguide (mm)</th>
<th>Begin R</th>
<th>Length</th>
<th>End R</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section 1 (mm)</td>
<td>2.00000E-1</td>
<td>4.85800E-1</td>
<td>4.88400E-1</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td>Section 2 (mm)</td>
<td>4.88400E-1</td>
<td>3.98310E-1</td>
<td>5.95277E-1</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Section 3 (mm)</td>
<td>5.95277E-1</td>
<td>7.88560E+0</td>
<td>1.200</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>Error Function</td>
<td>3.99830E-5</td>
<td>3.99830E-5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Experimental Cosmology Group
Oxford Astrophysics
<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial waveguide radius,</td>
<td>1.24 (mm)</td>
</tr>
<tr>
<td>Length of the 1st conical section,</td>
<td>1.479</td>
</tr>
<tr>
<td>Radius of the 1st conical section,</td>
<td>1.486</td>
</tr>
<tr>
<td>Length of the 2nd conical section,</td>
<td>1.212</td>
</tr>
<tr>
<td>Radius of the 2st conical section,</td>
<td>1.812</td>
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<tr>
<td>Length of the 3nd conical section,</td>
<td>2.4</td>
</tr>
<tr>
<td>Aperture</td>
<td>3.652</td>
</tr>
</tbody>
</table>
First Three steps horn-220 GHz

Green: Theory

Red: Measured

H-plane

E-plane
First Three steps horn-250 GHz

Pattern at 250 GHz
Cross Polarization Measurement

Co and cross polar response

Response (dB)

Degrees

-40 -30 -20 -10 0 10 20 30 40

-70 -60 -50 -40 -30 -20 -10 0

Experimental Cosmology Group
Oxford Astrophysics
Drilling Technology

230 GHz H-plane Theory / Exp

250 GHz E-plane Theory and Experiment

Degrees

Response (dB)

Angle (degrees)
Four probe OMT

- Combine orthomode transducer and waveguide to transmission line coupling in single on-chip structure
- 4 rectangular probes in circular waveguide
- Probes sit in front of waveguide backshort
- Each pair of probes only respond to one polarization mode
- Signal is split equally between pair of probes

- Recombine signals in 180° hybrid, or send to separate detectors
- Hybrid improves cross-polar rejection - usually by > 20 dB
- Design is optimised in HFSS to give best return loss and cross-polar performance over desired band
Four probe OMTs in action

• 4 probe OMTs have been developed for C-BASS, a 5 GHz polarimeter, and the 150 and 225 GHz channels of Clover
• Now working on OMT for 350 GHz CEB
CBASS OMT at 5 GHz

Existing Methods of Modulation at Millimetre wavelengths

- Mechanical rotation: difficult and expensive to realise and mass produce in cryogenic environment and expensive
- Faraday Rotor Ferrite Rods: difficult to mass-produce and lossy.
- Rotating Wave-plate: Obstructs the array can suffer from anisotropy.
Planar Phase Modulation

• Collaboration between Oxford and Chalmers

• References:

\[ \omega L_c + \omega L_g \ll Z_0 \ll R \]

\[ I_c = j_c \times S, \quad L_c = \frac{\hbar}{2eI_c}, \quad R = \rho \frac{l}{S} \]
Devices fabricated at Chalmers
DC Tests

nanostrip 0.5x5.0 um

Experimental Cosmology Group
Oxford Astrophysics
Detector Block for Phase switch RF tests
RF Results see Kuzmin et al

Nanoswitch on quartz wafer NbN13 chip 43 0.8 µm

Current, µA

Voltage, µV

BWO V=1161

Current, µA

Voltage, µV
Preliminary Results at oxford
Phase Modulation work at Oxford…Cont

- Stage Three: Integrate nanostrip in microstrip:
  
  Designed

To detector

Power received from horn with antipodal finline

Nonostrip in microstrip

Hole in ground plane and dielectric layer

Transmission Line

Contact Pads

Nanostrip

Finline (not to scale)
• SIS
  – Very high dynamic range and saturation power
  – Very fast response
  – Cheap readout
  – Easy to integrate with planar circuits
  – Can be used as a direct detector and a Mixer
  – Problem:
    • Suppression of pair tunnelling
    • Shot noise
220-GHz Ultra-BroadBand Interferometer for S-Z – GUBBINS

- Single baseline interferometer at 190-260 GHz
- 0.5m baseline, 0.4m primary mirrors (11’ primary beam)
- 2x SIS mixers, designed for ultra-wide IF bandwidth
- Single closed cycle cryostat
- Single LO with phase switching in LO optical path
- Very wideband IF system:
  - Wideband, low noise IF amplifiers (initially 3-13 GHz, with upgrades intended)
  - 2-20 GHz analogue sideband separating complex correlator with 16 spectral channels
Ultra-wideband SIS mixer

IF bandwidth 2-15 then extend to 20 GHz
Band pass filter to isolate the high IF frequency
Complex mixer tuning circuits
RF transformer
Grimes \textit{et al}, STT, Groningen
New Finline Transition

Yassin, et al, Electron lett. (in press)
Mixer circuits
- Commercial bias tees
- 3-13 GHz cryogenic IF amps from CalTech (Sander Weinreb)

- 35 dB gain, 4-6 K noise
- Only need two for first version of GUBBINS, but later developments may need more (sideband separating mixers)