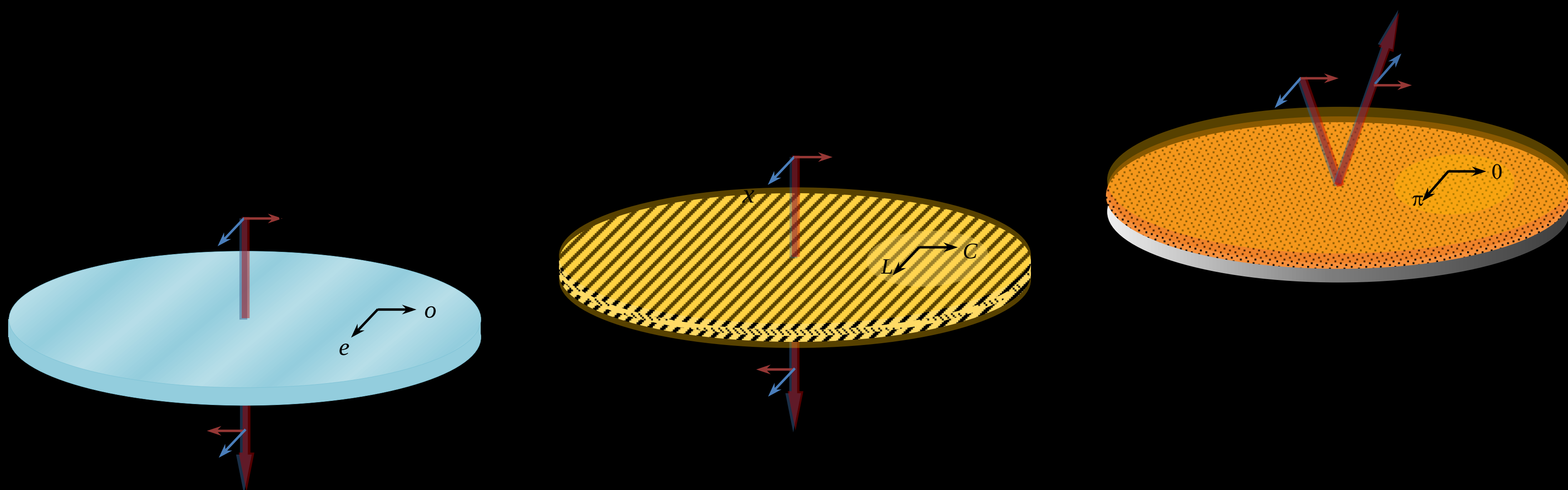
CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

Quasi-optical Components for Polarisation Modulation



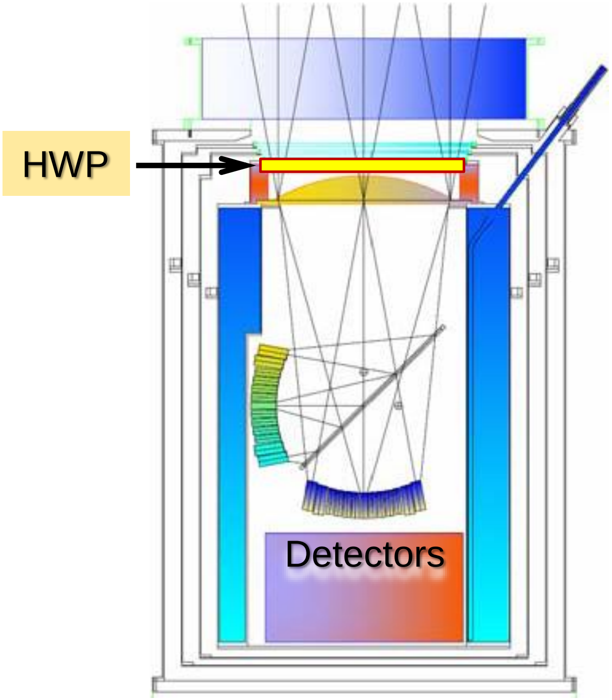
Giampaolo Pisano

Astronomy Instrumentation Group - Cardiff University

Towards the European Coordination of the CMB programme, Villa Finaly, Firenze, 9/9/2016

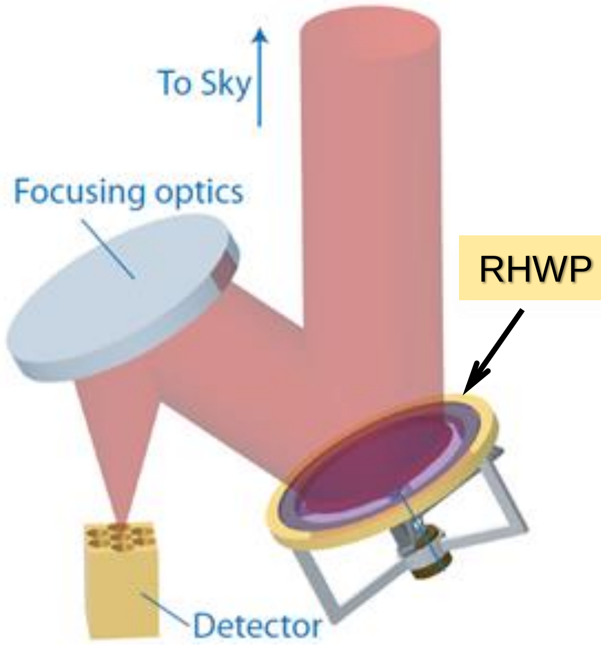
Polarisation modulation options

Transmissive Modulators



De Bernardis et al.

Reflective Modulators



Chuss et al.

Polarisation modulation options: Trade-Off studies

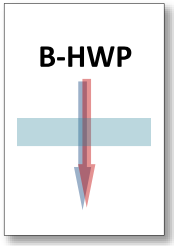
ESA-TRP collaboration
Cardiff Manchester
Rome RAL

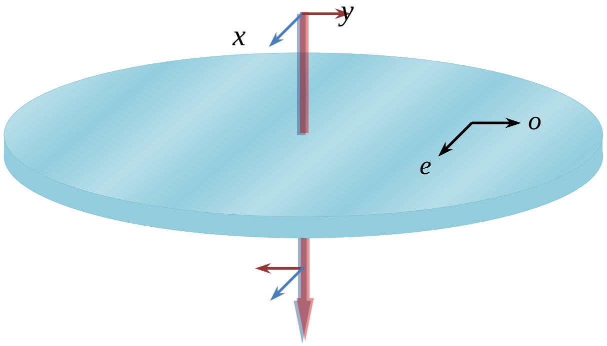
RF performance	Transmission modulators				Reflection modulators			
Mechanical modulation	Rotation				Rotation		Translation	
Material	Birefringent crystal		Metal grids		Metal grids + Flat mirror			
Modulator type	Single Plate	Multi-Plate Pancharatnam	Air-gap Mesh-HWP	Embedded Mesh-HWP	Air-gap Reflective HWP	Embedded Reflective HWP	Variab. delay Polarization Modulator (VPM)	Translational Polarization Rotator (TPR)
Modulator sketch	B-HWP	BP-HWP	M-HWP	EM-HWP	R-HWP	ER-HWP	VPM	TPR
Modulated Stokes parameters	Q & U	Q & U	Q & U	Q & U	Q & U	Q & U	Q or U	Q & U
Maximum bandwidth	Narrow	Very Broad ~110%	Broad ~80%	Broad ~100% T3.1	Narrow	Narrow T3.1	Narrow	Narrow
Multiple sub-bands	Need periodic ARC	Limited to max BW	Limited to max BW	Lim. to max BW T3.1	Periodic	Periodic T3.1	Periodic	Limited by QWP BW
Modulation efficiency	> 99%	> 99%	> 99%	> 99% T4.1a,b, 5.1,2	> 90%	> 90% T4.1a,b, 5.1,2	> 90%	> 90%
Transmission / Differential transmission	> 90 % < 1 %	> 90 % < 1 %	> 90 % < 1 %	> 90 % / < 1 % T4.1a,b, 5.1,2	Not applicable	Not applicable	Not applicable	Not applicable
Reflection/ Differential Reflection	3% 0.1%	3% 0.1%	4% 2%	< 4% / 2% T4.1a,b, 5.1,2	> 98 % < 1 %	> 98% / < 2% T4.1a,b & 5.1	> 98 % < 1 %	> 98% / < 2%
On-axis Average Cross-Polarisation	< -20 dB (6% BW)	< -20 dB (110% BW)	< -20dB (80%BW)	-35dB (25% BW) T4.1a,b, 5.1,2	< -30dB	Not available T4.1a,b & 5.1	Not Available	Not available
Co-Polar beam impact Ellipticity	Not available	Not available	Not available	~1% (25% BW) T4.1c & 5.1	<1%	Not available T4.1c & 5.1	Not available	Not available
Cross-Polar beams	Not available	~ -30dB	Not available	<-35dB (25%) T4.1c & 5.1	< -30dB	Not available T4.1c & 5.1	Not available	Not available
Flatness / Homogeneity	Very high	High	High	High T4.1d & 5.1	High	High T4.1d & 5.1	High	High

Legend: Advantage (green) | Disadvantage (grey) | Not usable (red) | Will be verified by Task # (blue)

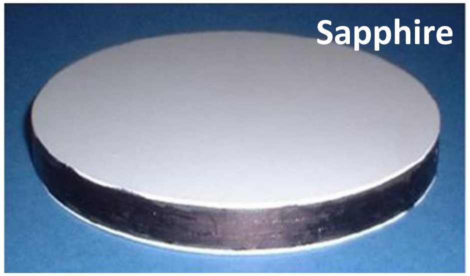
Transmissive HWPs: Options

Birefringent HPW

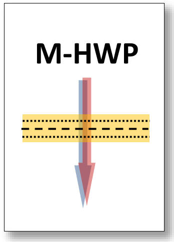


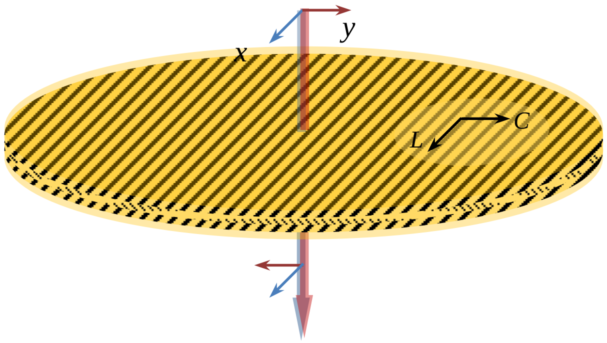


- **Pancharatnam HWP (BP-HWP)**:
  - Stack of rotated birefringent HWPs
  - Up to 50cm ∅
  - Heavy, need ARCs



Mesh HPW



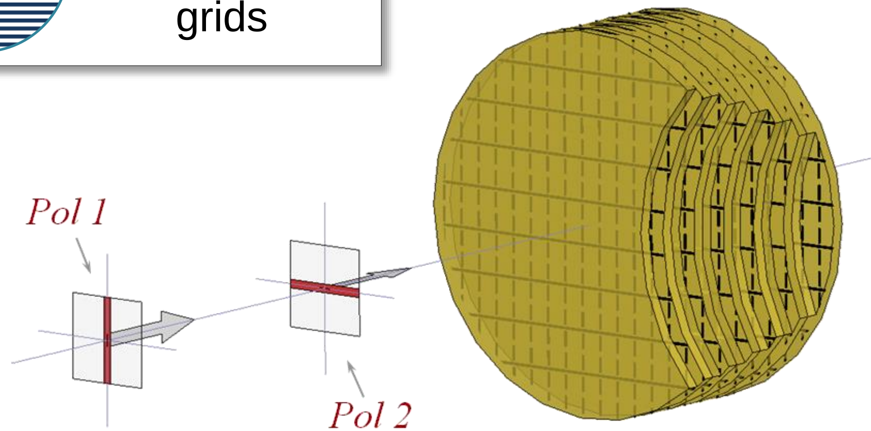


- **Mesh HWP (M-HWP)**:
  - Based on mesh filters technology
  - Large diameters achievable
  - Bandwidths ~100%

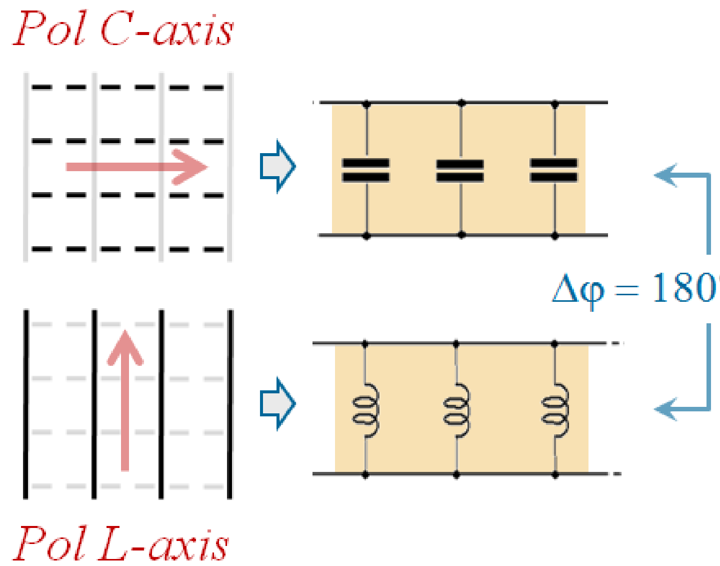
Mesh Half Wave Plates: Embedded design

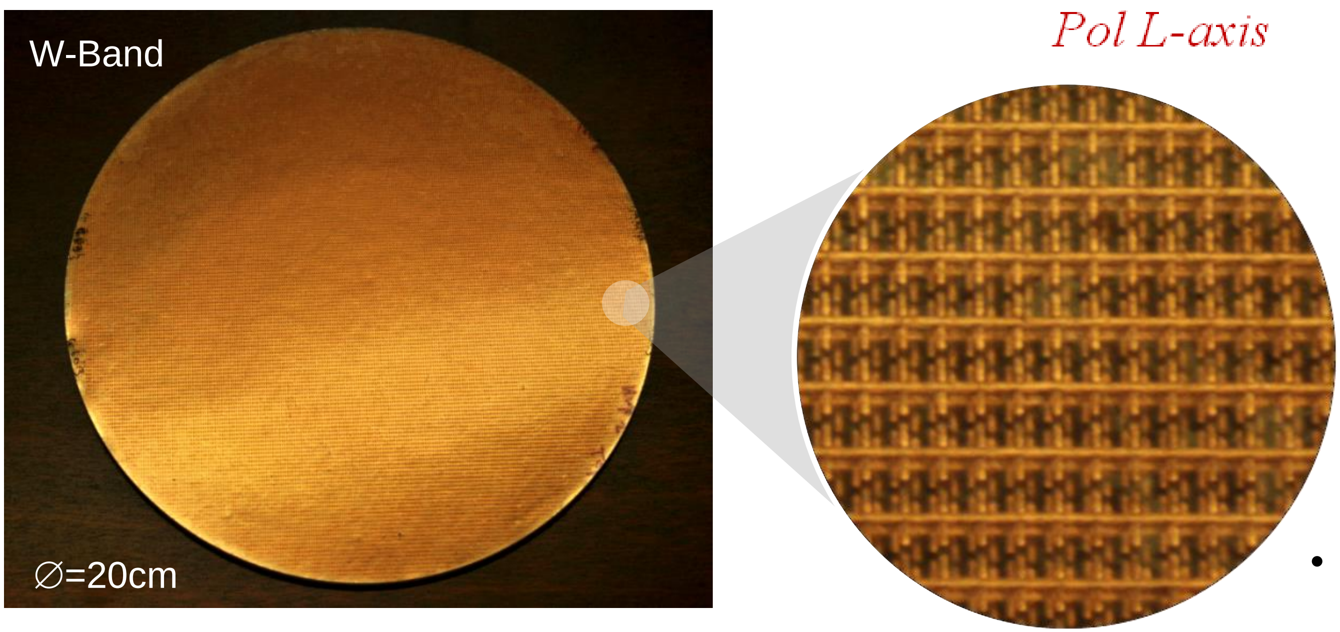
G. Pisano et al.
PIER M, **25**, p101 (2012)

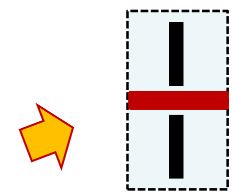
Homogeneous anisotropic grids



Lerner geometry





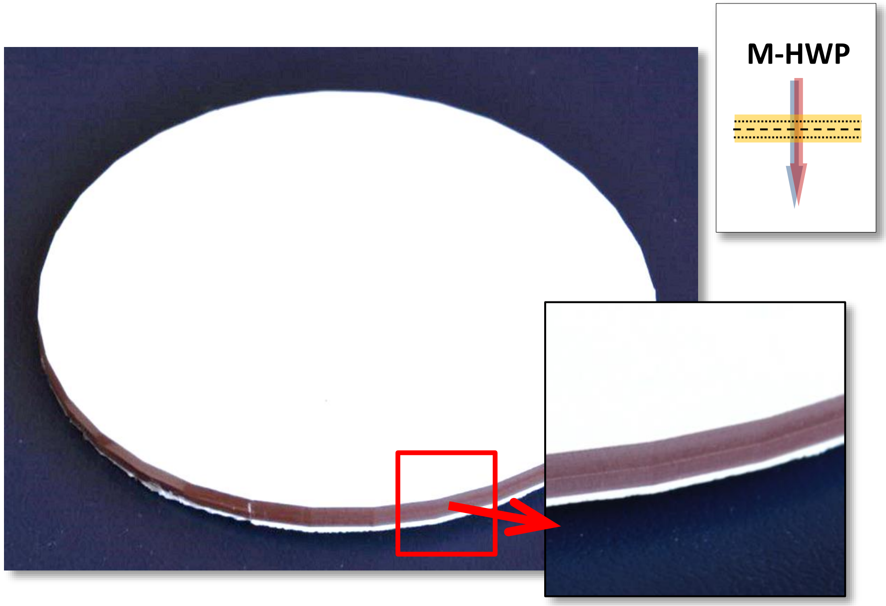


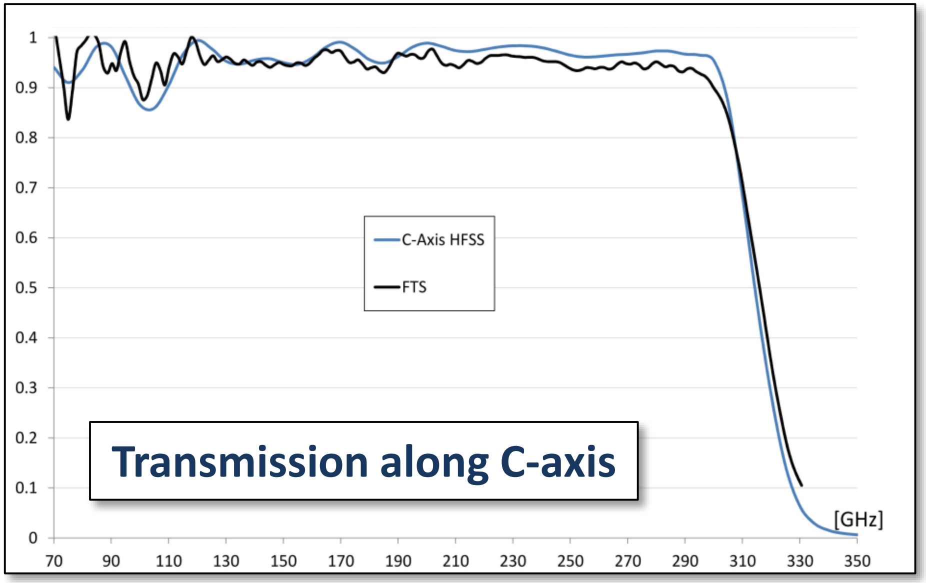
Unit cell

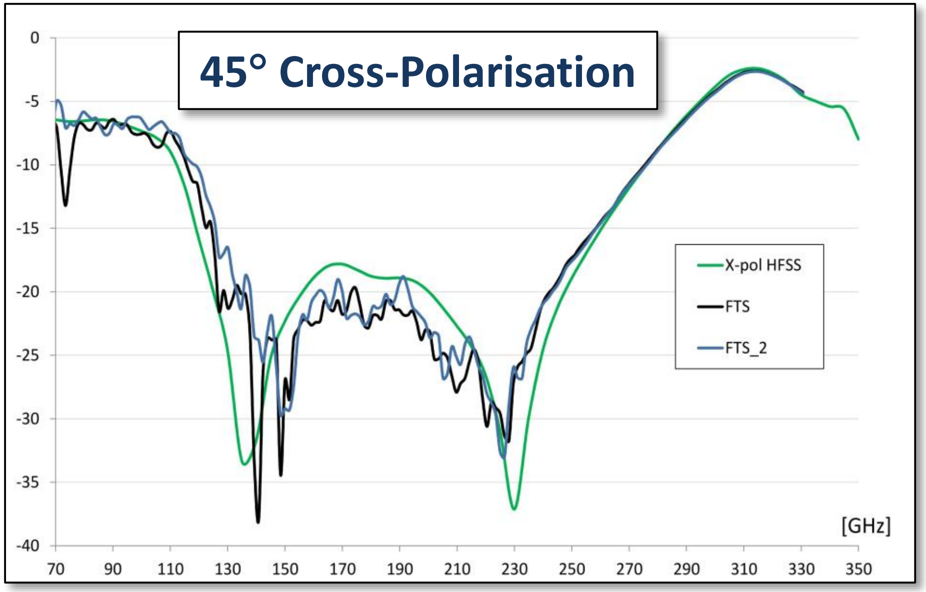
Other devices:

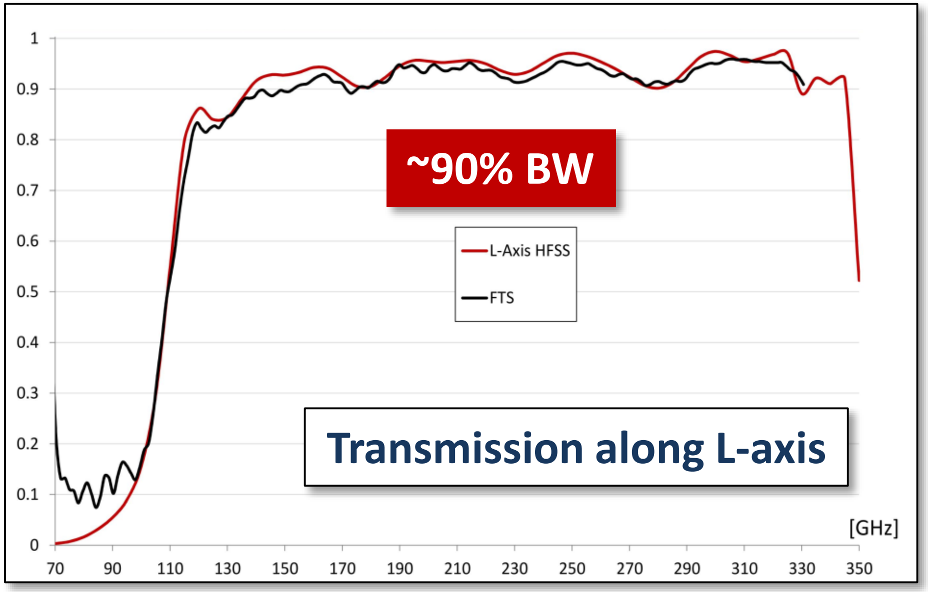
- QWPs (linear ↔ circular)

Embedded Mesh HWP: NIKA waveplate



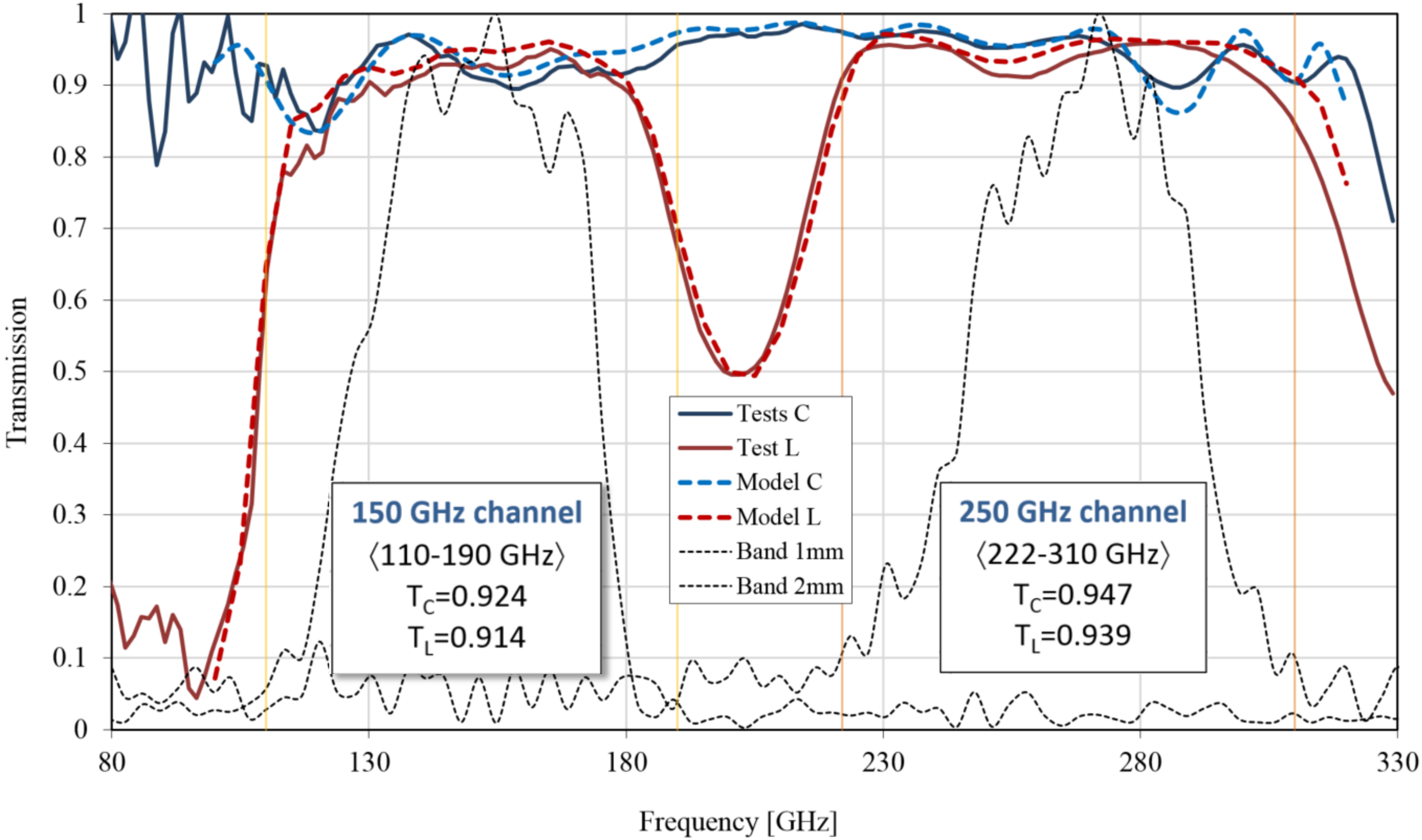






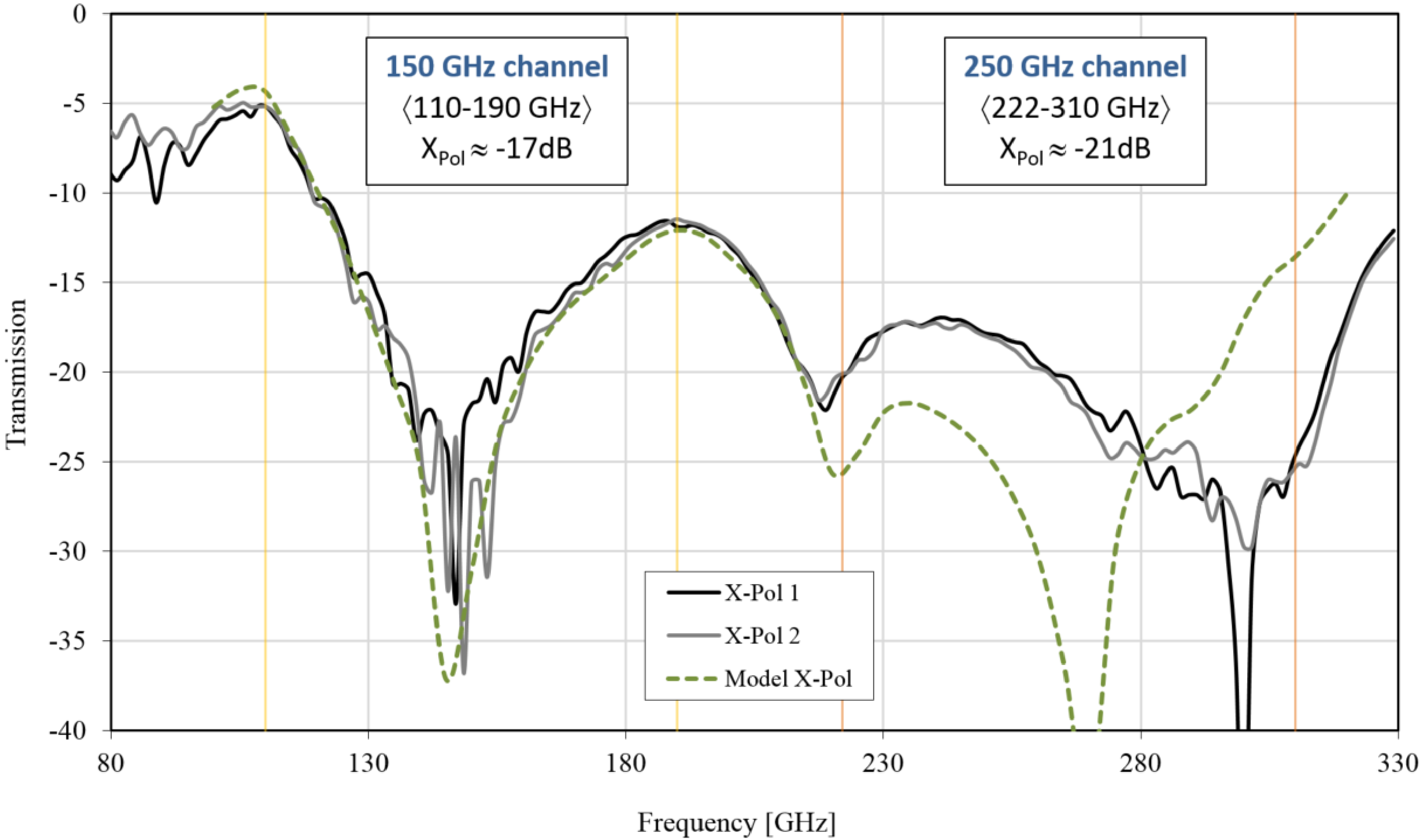
Embedded Mesh HWP: NIKA2 waveplate tests

Transmissions along the inductive and capacitive axes



Embedded Mesh HWP: NIKA2 waveplate tests

45 degrees cross-polarization leakage



Mesh HWPs: In the field..

Delivered (data analysis phase):

- **CASPER** (110-300GHz, BW93%)
- **NIKA** (150+250GHz, BW98%)
- **NIKA2** (150+250GHz, BW98%)

Manufacture phase:

- **ASTE** (305GHz BW43%, 520GHz BW73%)
- **LSPE** (140+220+240GHz, BW70%, **500mm∅**)
- **BLAST-TNG** (600+857+1200GHz, BW92%)

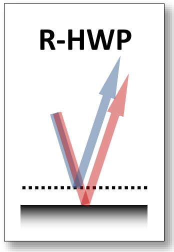
Design phase:

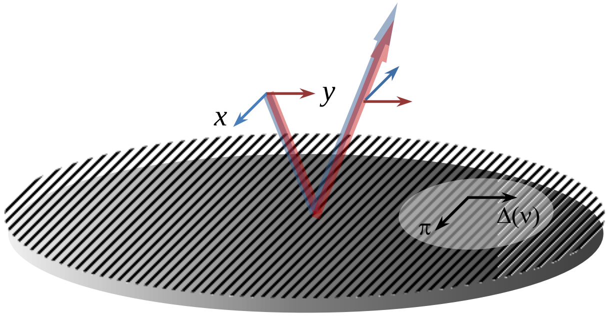
- **ACT-Pol** (HF) (150+230GHz, BW73%)
- **QUBIC** (150+220GHz, BW73%)

Under evaluation:

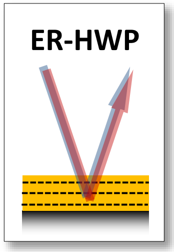
- **LiteBIRD**
- **GISMO2**
- **CLASS (MQWP)**

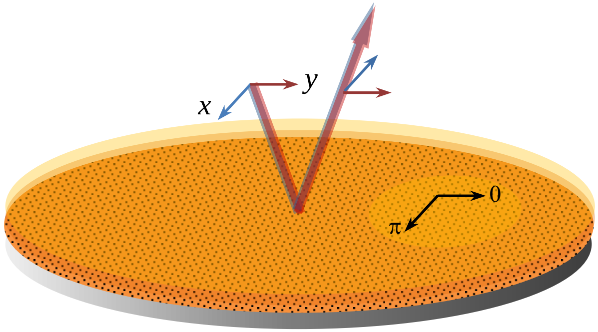
Reflective HWPs: Options





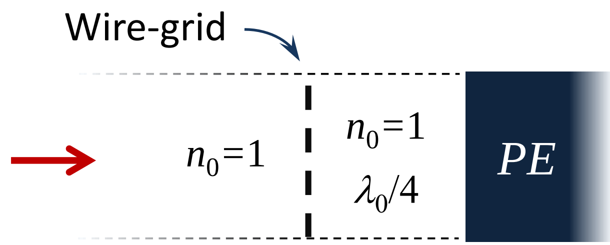
- **Reflective HWP (R-HWP)**
  - Based on fragile free-standing wire-grid parallel to a mirror
  - Periodic narrow bands

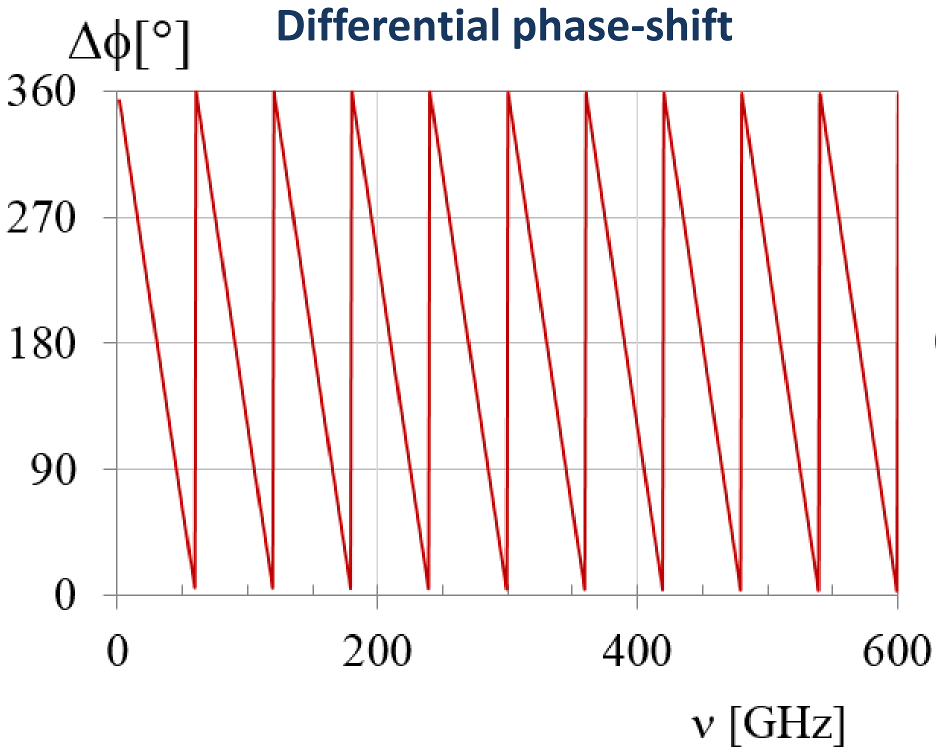


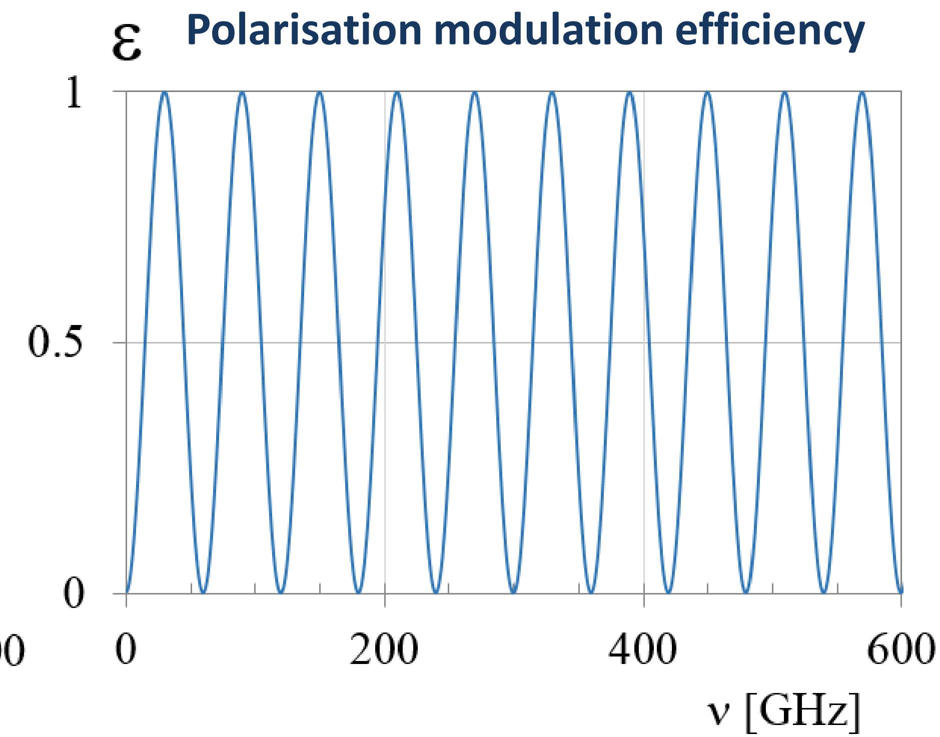


- **Embedded Reflective HWP (ER-HWP)**
  - Based on the more robust dielectrically embedded mesh filters technology
  - Large dimensions
  - Very large bandwidths

Reflective HWPs: Air-gap RHWP

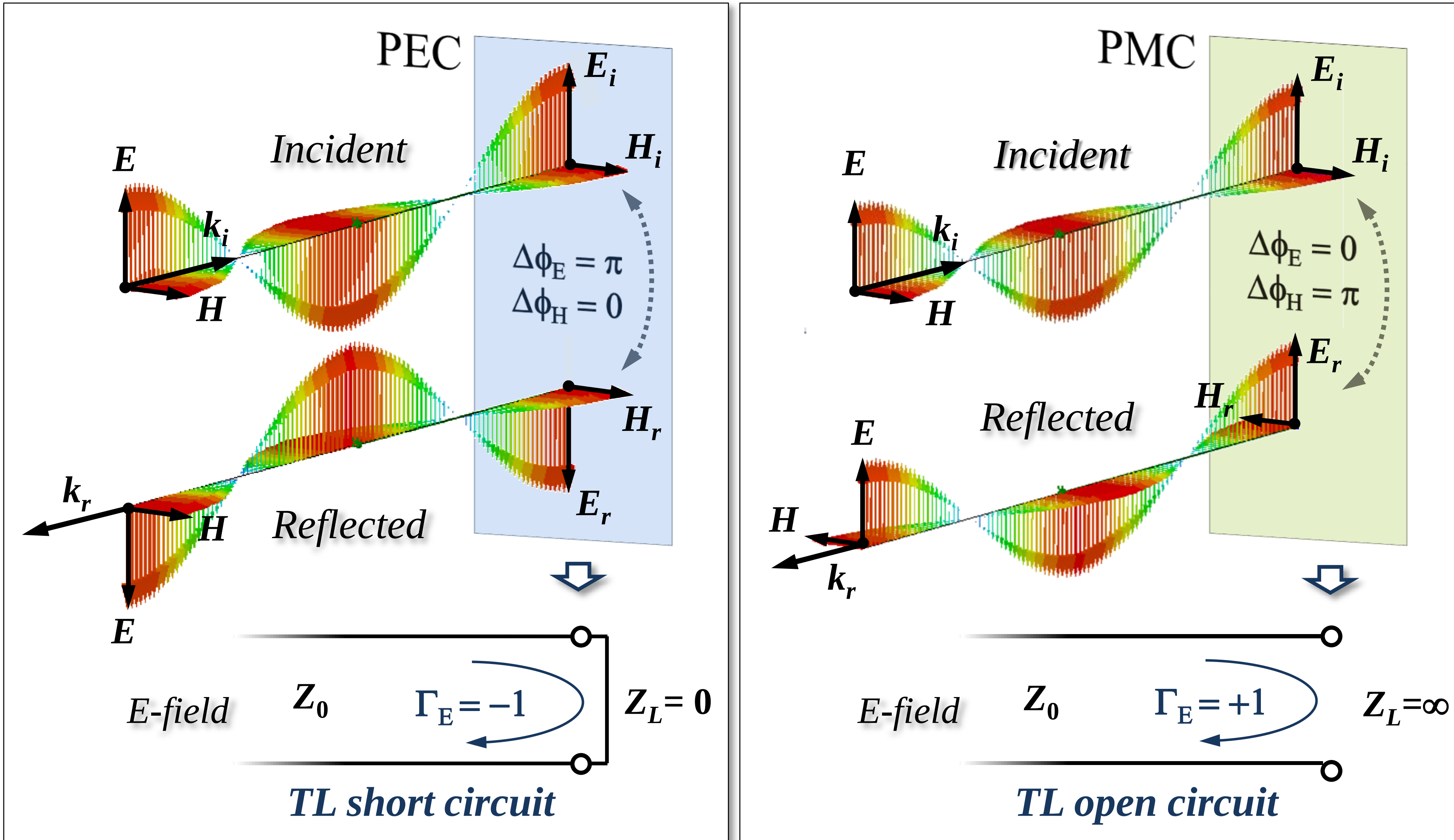






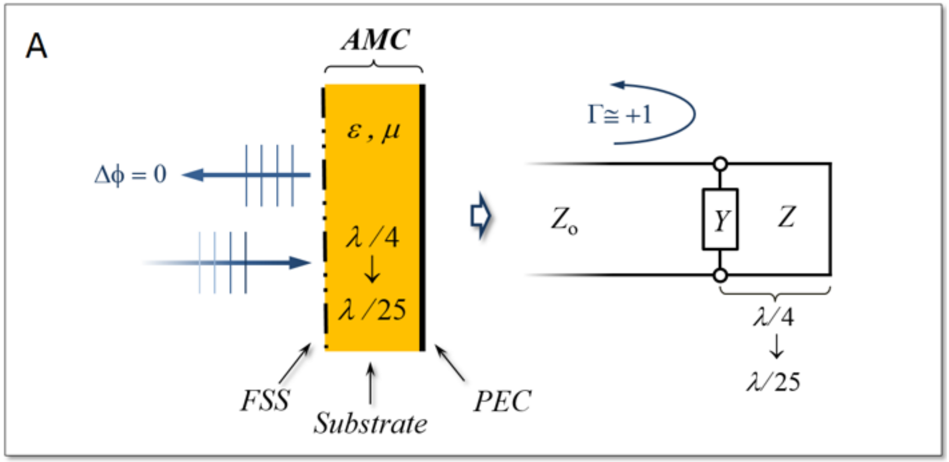
→ **Periodic narrow bands**

Electric and Magnetic Mirrors: Theory



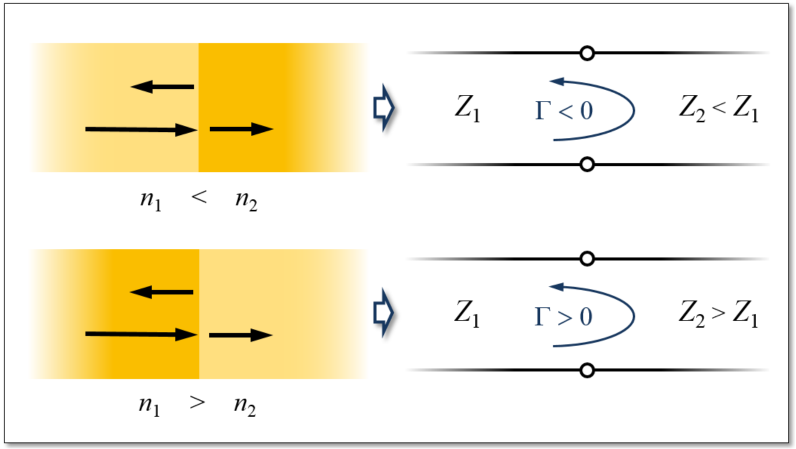
- Perfect Magnetic Conductors **do not exist** in nature

Magnetic Mirror (Artificial Magnetic Conductor): Concept 1/3



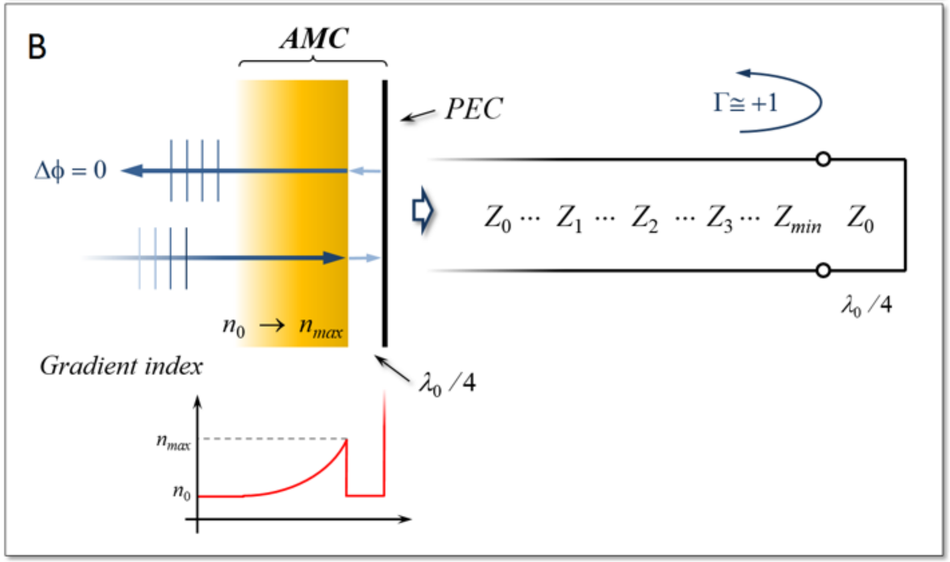
- Standard designs based on **resonant** structures
- In-phase reflection across **narrow** bandwidths
- These devices are **lossy**

- However, there is a simpler way..

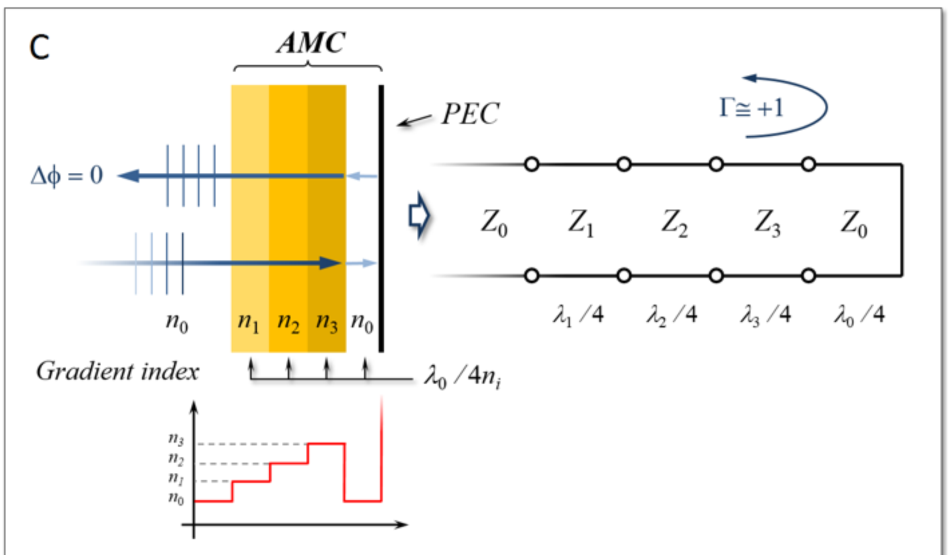


- We can get in-phase reflection at a **high-to-low** refractive index interface

Magnetic Mirror (Artificial Magnetic Conductor): Concept 2/3

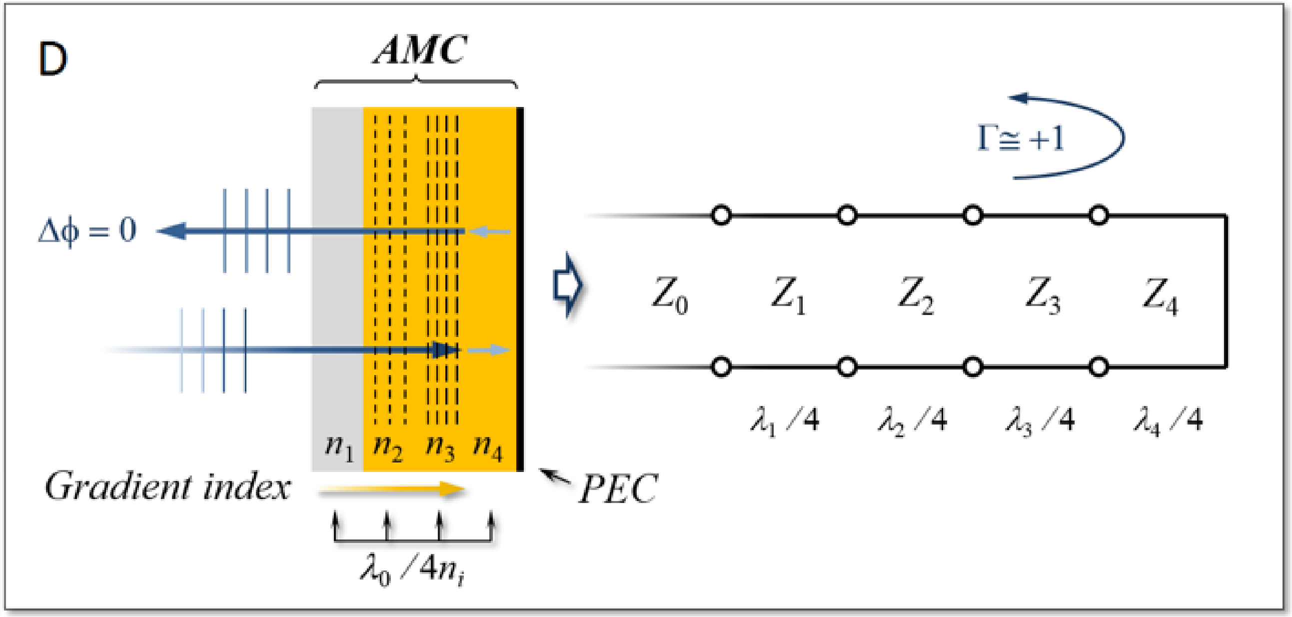


- Radiation needs to travel into a **high index** medium
- We need to **match the free space** with this medium
- We need to reach a **high refractive index**



- We can **discretise** the gradient into quarter-wavelength layers
- Unfortunately, there are not many **materials** available with the required refractive indices

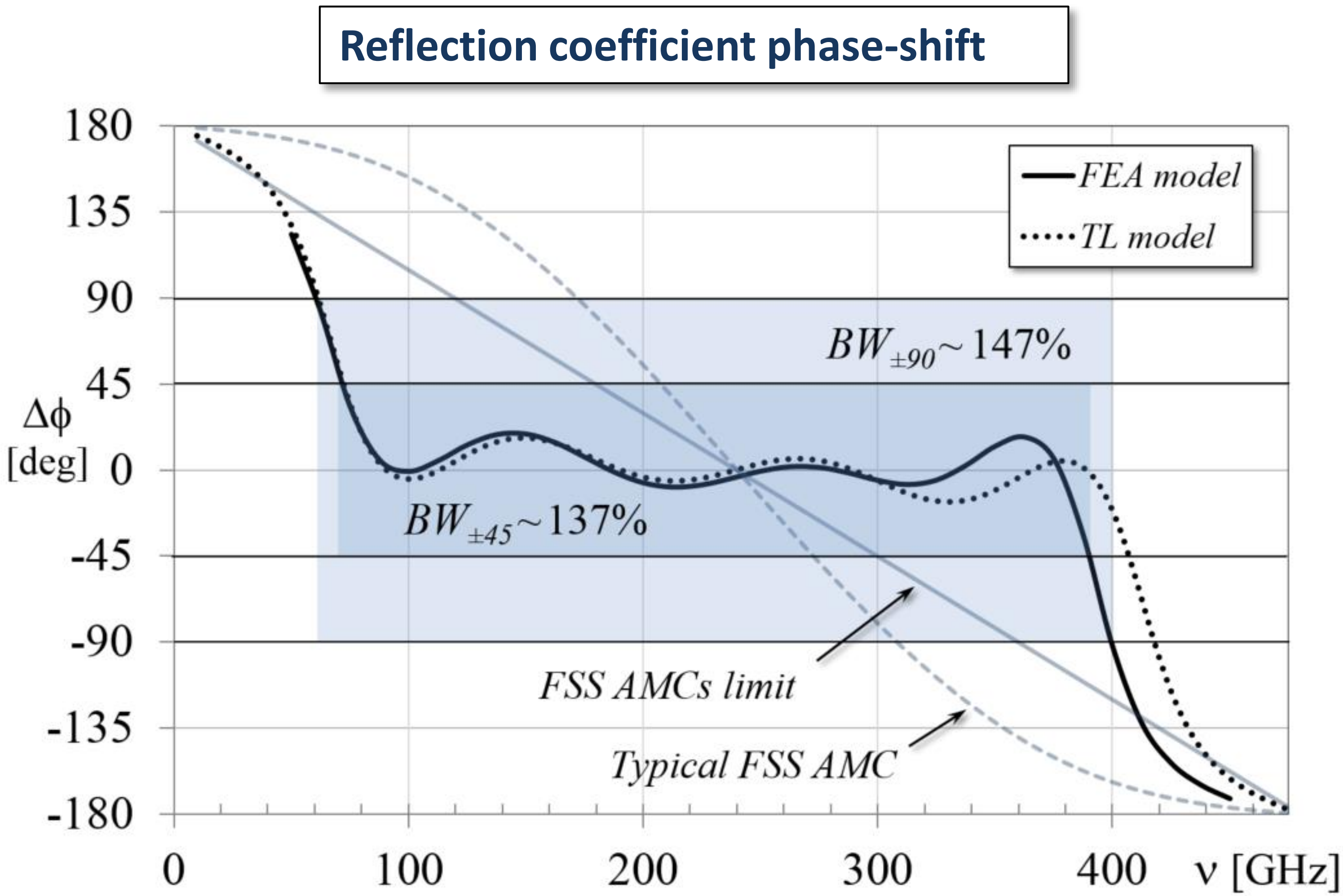
Magnetic Mirror (Artificial Magnetic Conductor): Concept 3/3



- We can design **metamaterials** to build up the gradient index
- We adopt the **mesh-technology**
- Most of the structure is **embedded in polypropylene**

Artificial Magnetic Conductor: Expected performance

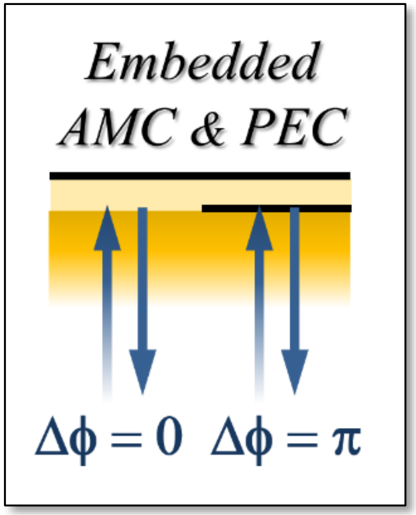
G. Pisano et al.
Applied Optics (2016)



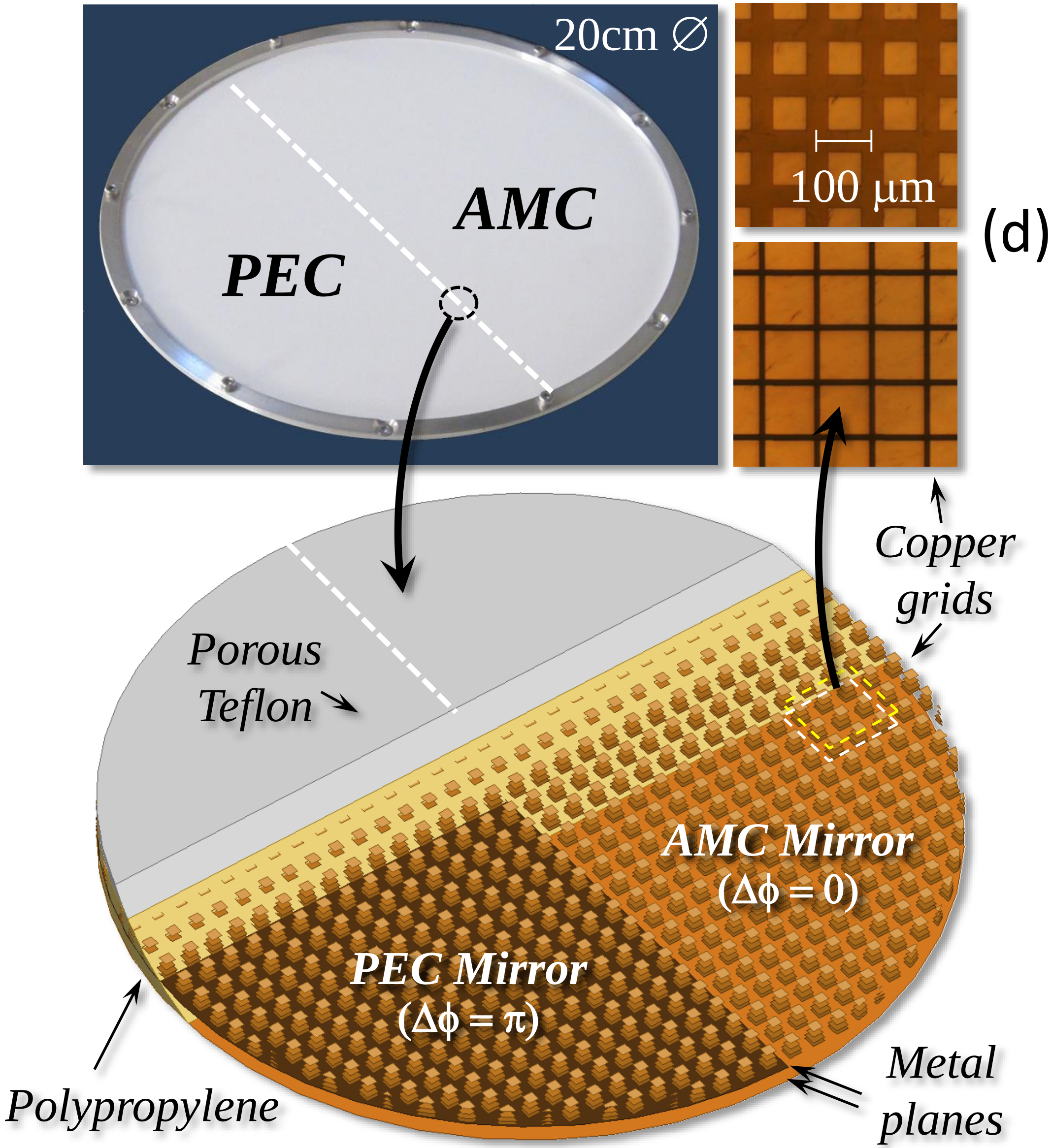
- Standard AMC realisations operate across narrow bandwidths
- Our design has performances superior to any device ever realised

Artificial Magnetic Conductor: Prototype realisation

G. Pisano et al.
Applied Optics (2016)

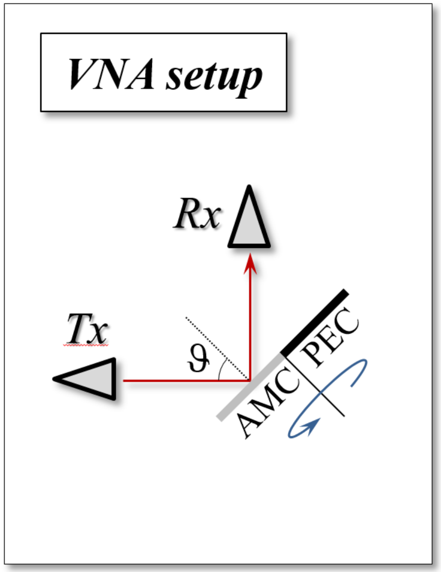


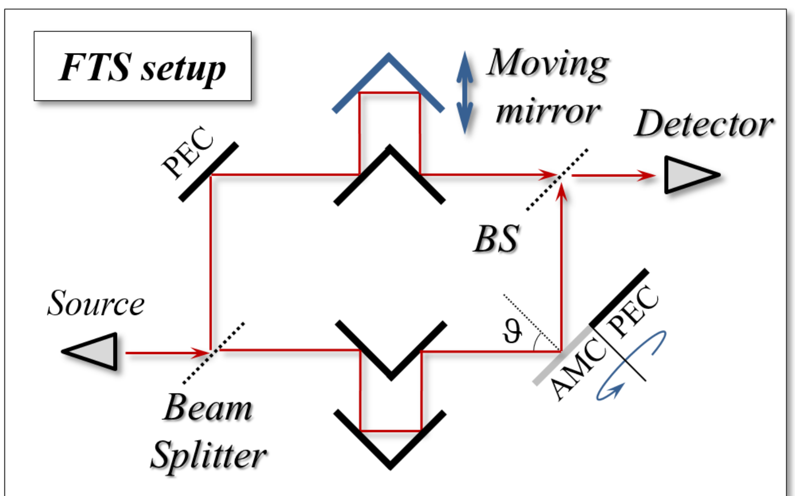
- We realised a prototype with both **PEC** and **AMC** surfaces

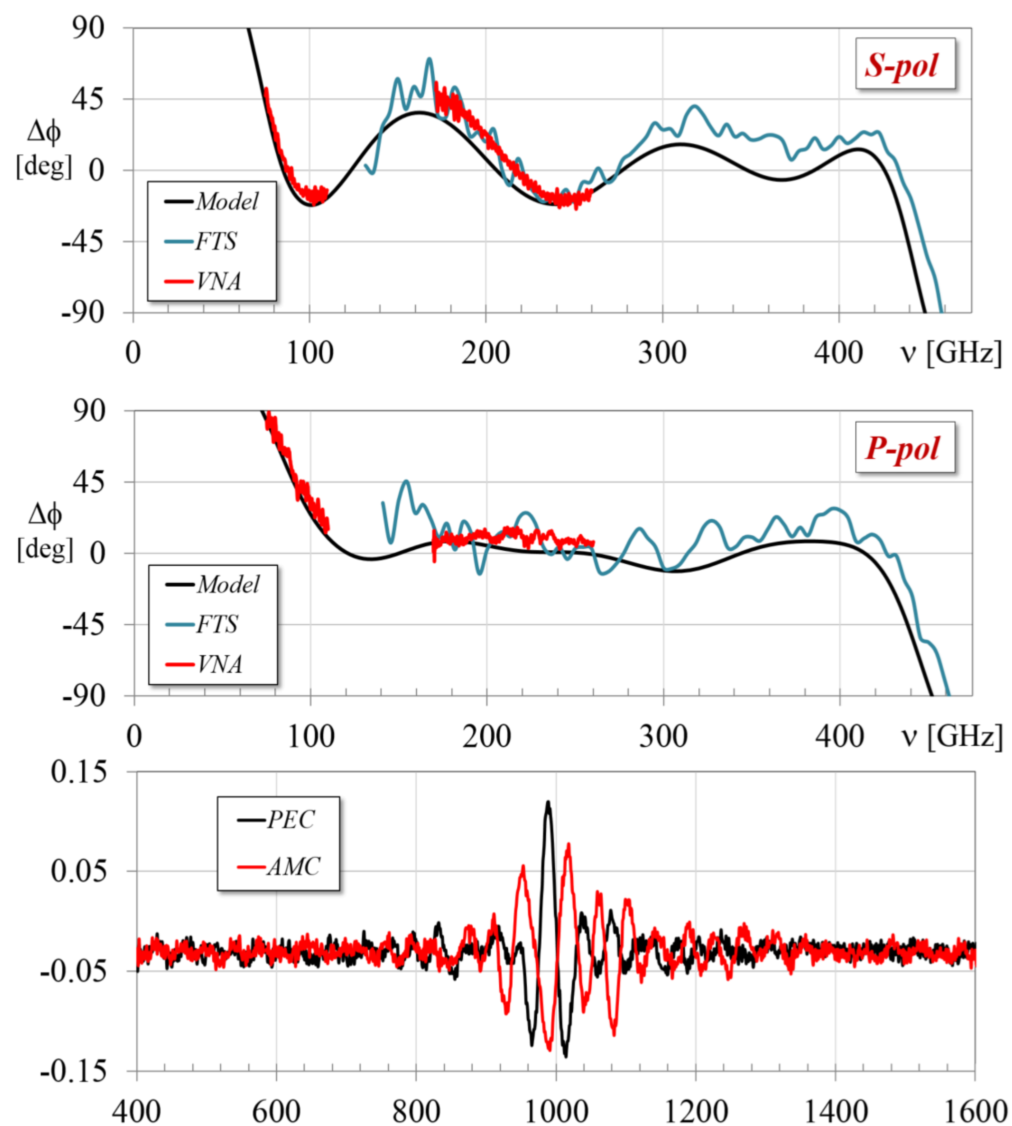


Artificial Magnetic Conductor: Experimental results

G. Pisano et al.
Applied Optics (2016)





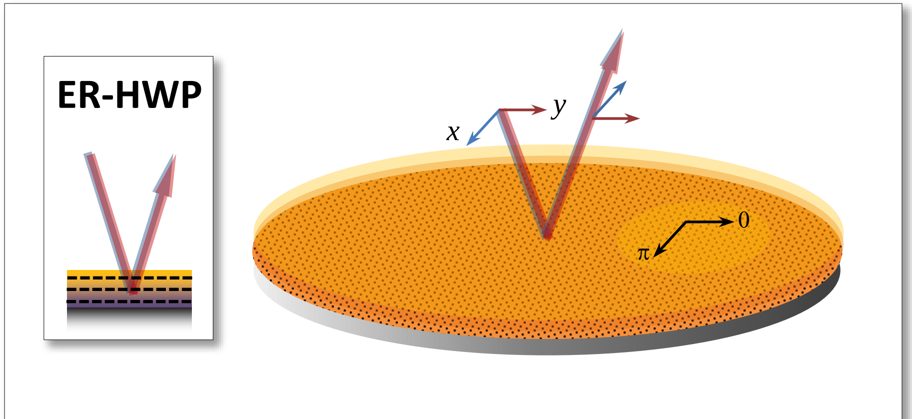


- The results are in **very good agreement** with the predictions

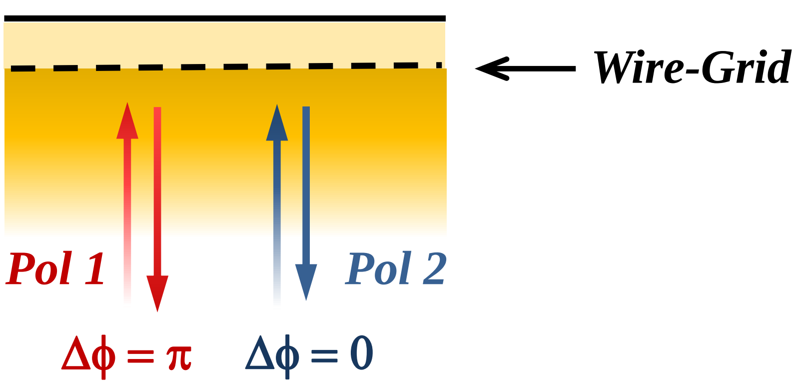
Embedded Reflective HWP: Concept

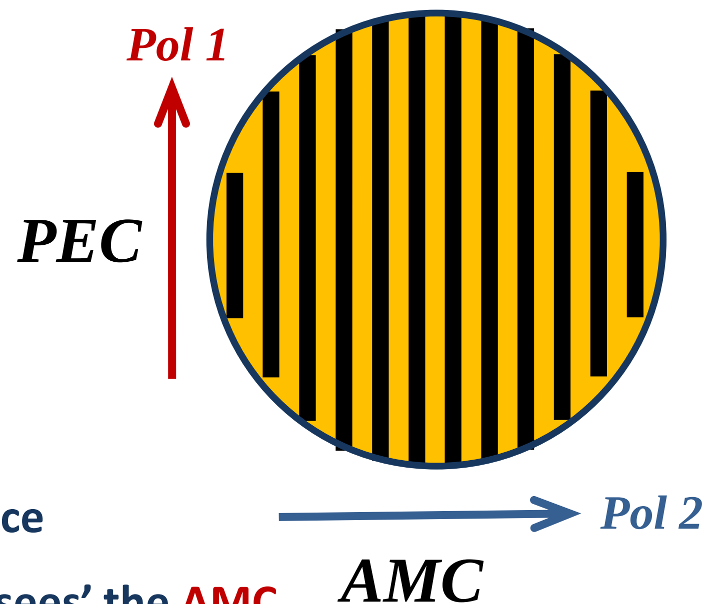
ESA-TRP collaboration

Cardiff, Manchester, Rome, RAL



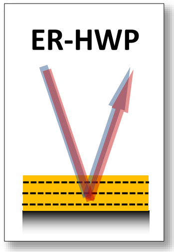
Embedded AMC & PEC

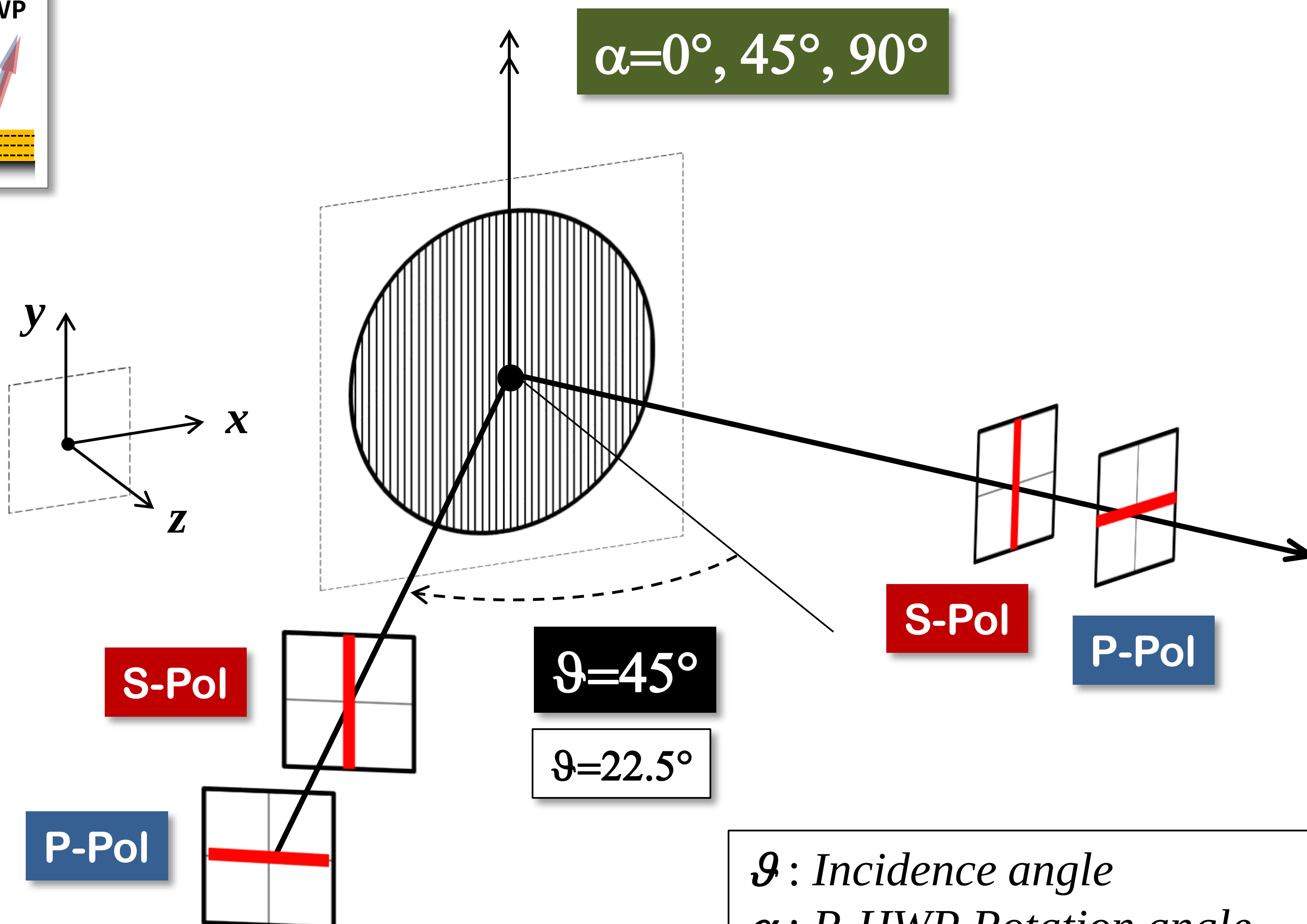




- We add a **wire-grid** into the high-to-low index interface
- One polarisation 'sees' the **PEC**, the orthogonal one 'sees' the **AMC**

ER-HWP tests: Polarisation and rotation angles





ϑ : *Incidence angle*

α : *R-HWP Rotation angle*

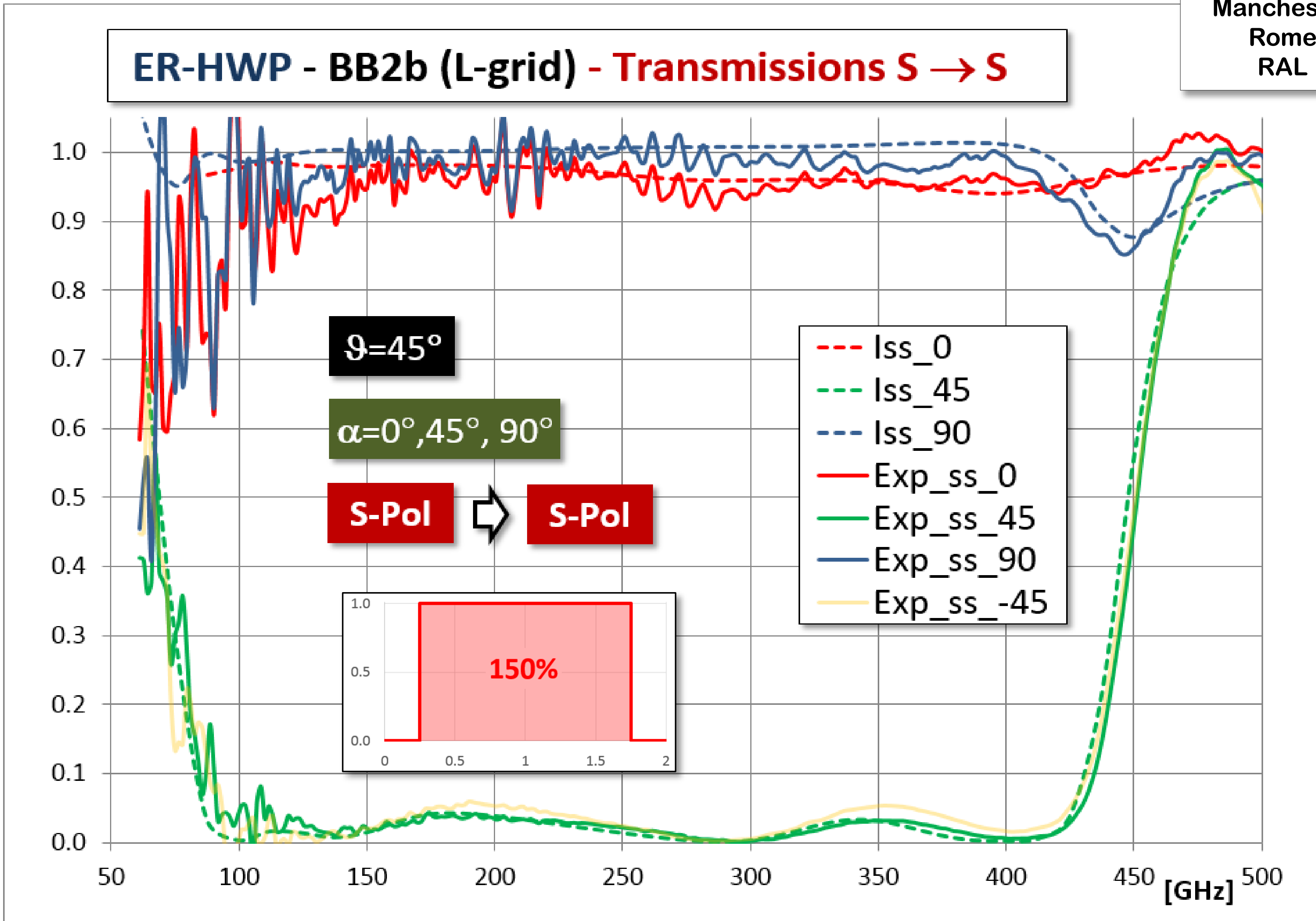
P-pol : *parallel to incidence plane*

S-pol : *perpendicular to incidence plane*

- More complex measurements

Embedded Reflective HWP: FTS measurements

ESA-TRP collaboration
Cardiff
Manchester
Rome
RAL



Embedded Reflective HWP: FTS measurements

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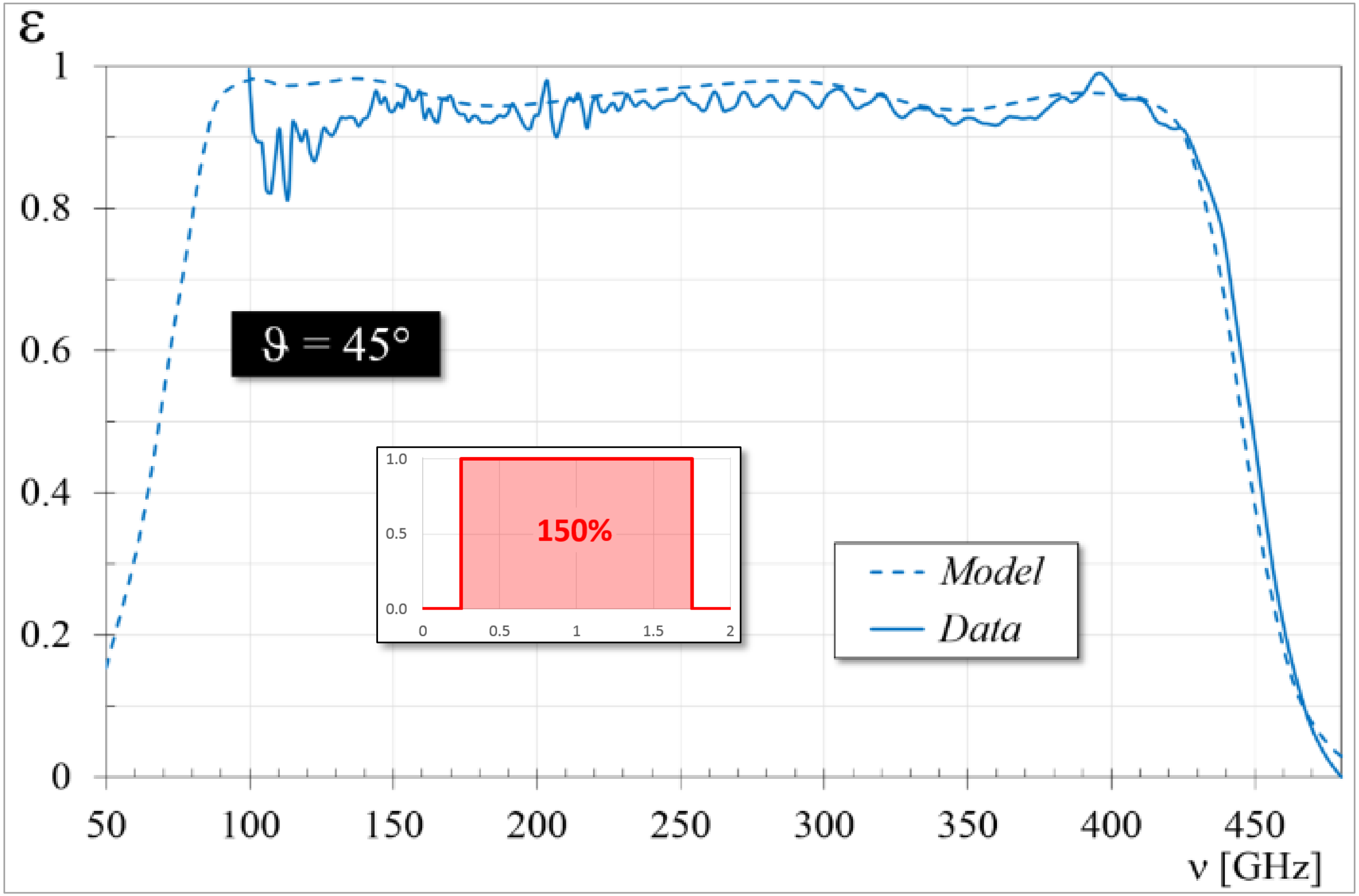
Manchester
Rome
RAL

Polarisation modulation efficiency



Embedded Reflective HWP: FTS measurements

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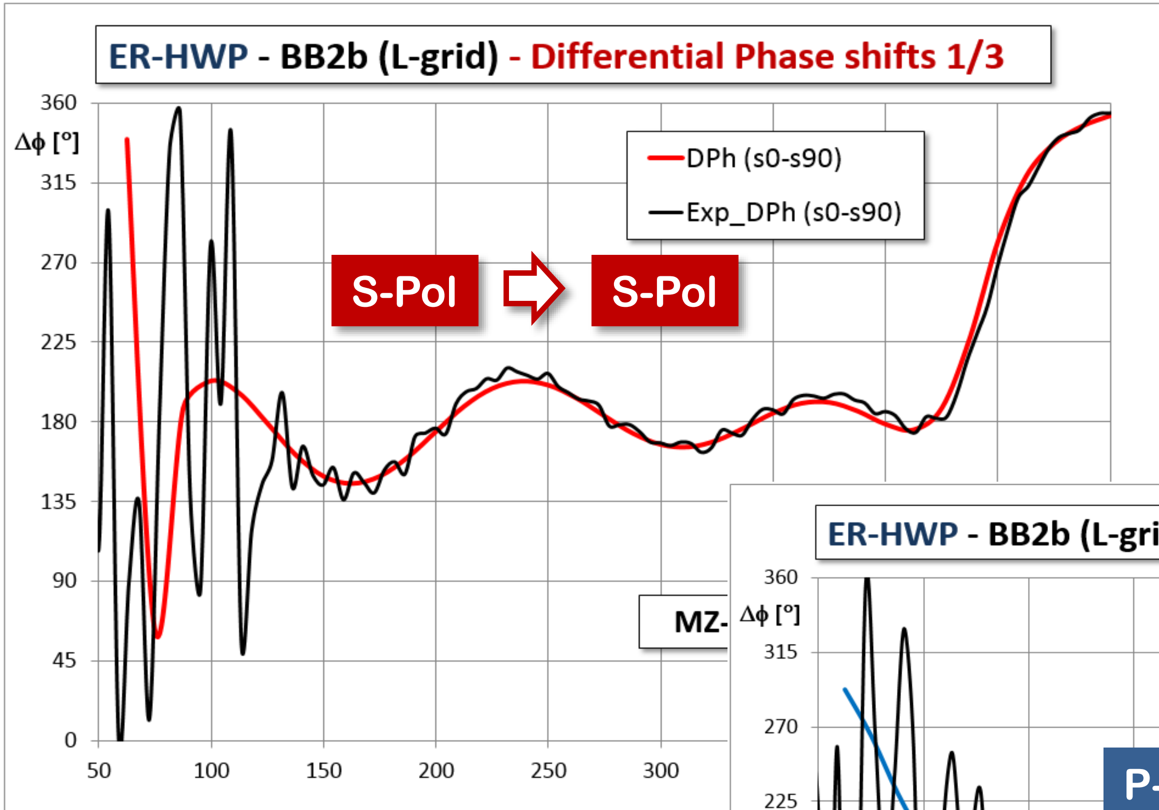
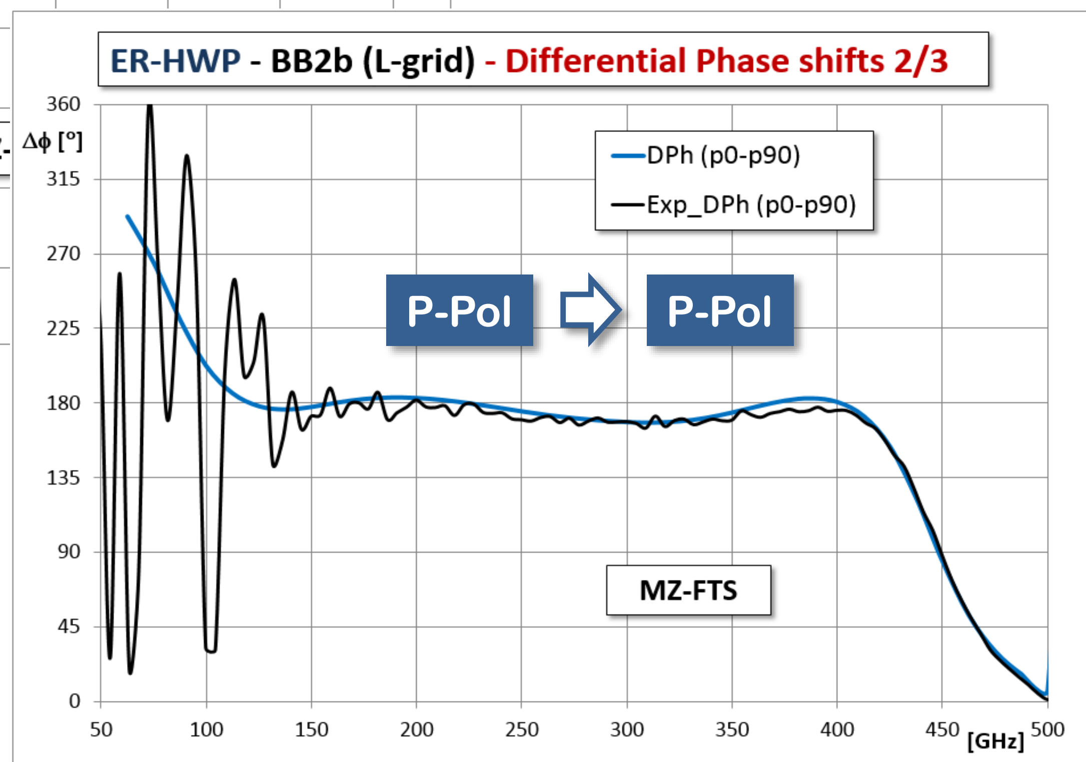
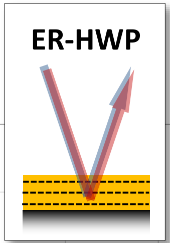


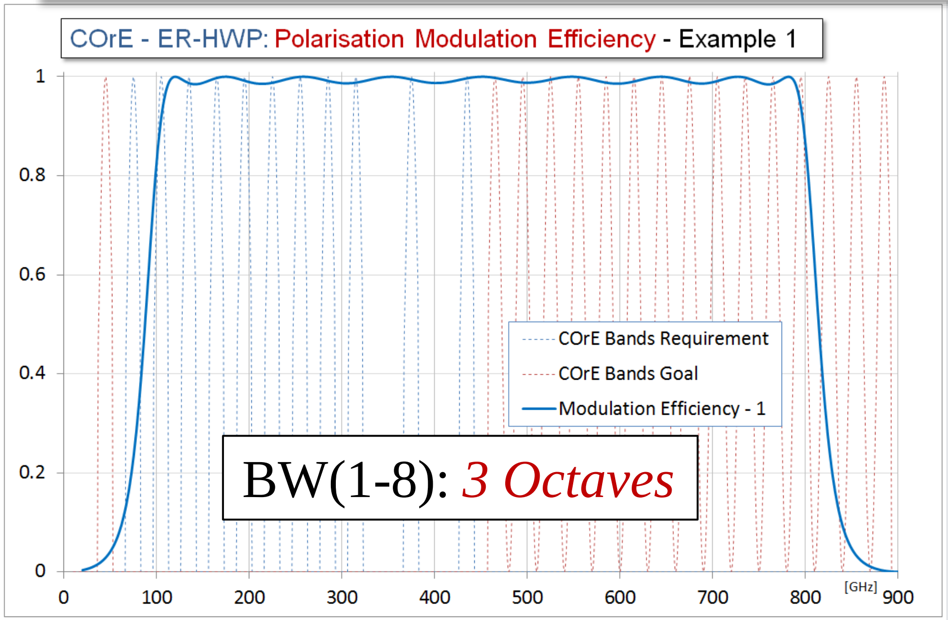
Differential Phase-Shifts

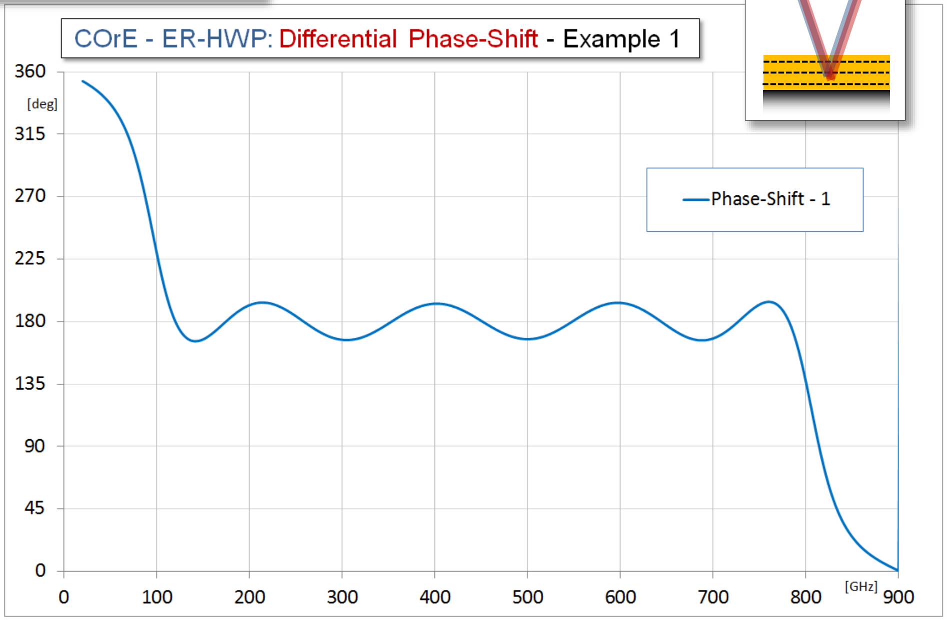


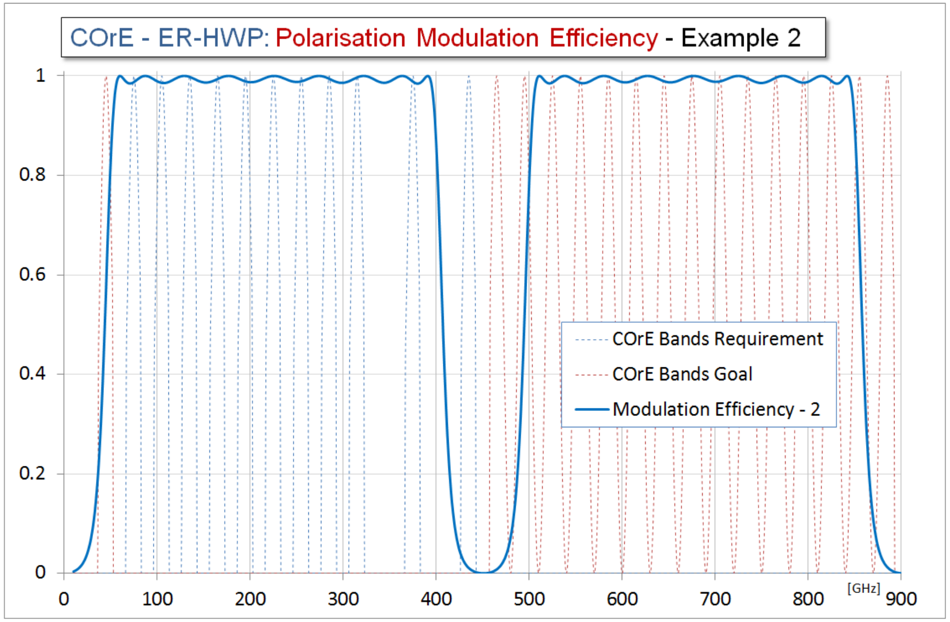
- Modified Mach-Zehnder FTS
- Very good agreement between model and data (FTS not sensitive at low frequency)

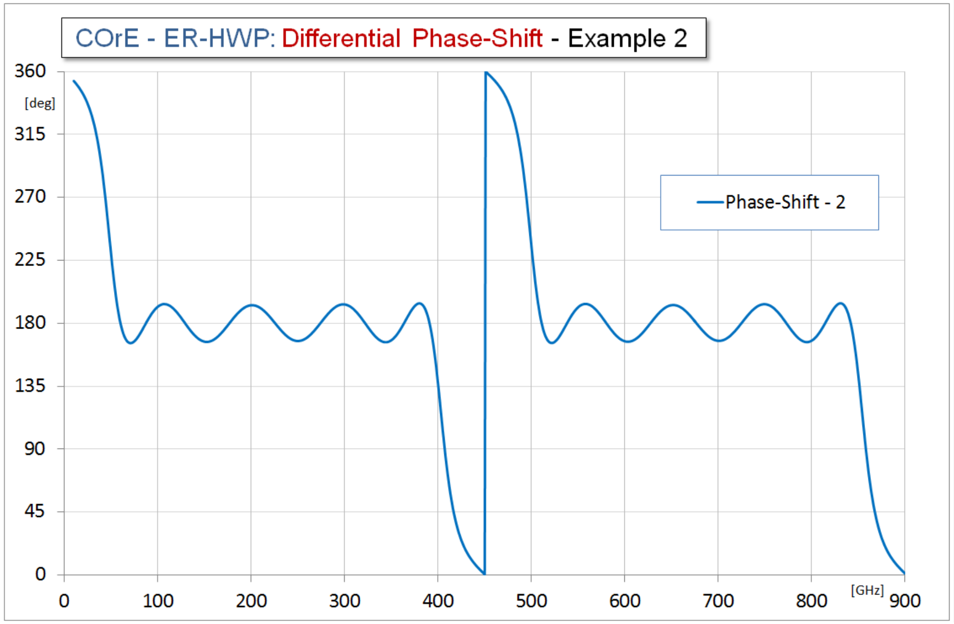
ER-HWPs: Larger and multiple bandwidths





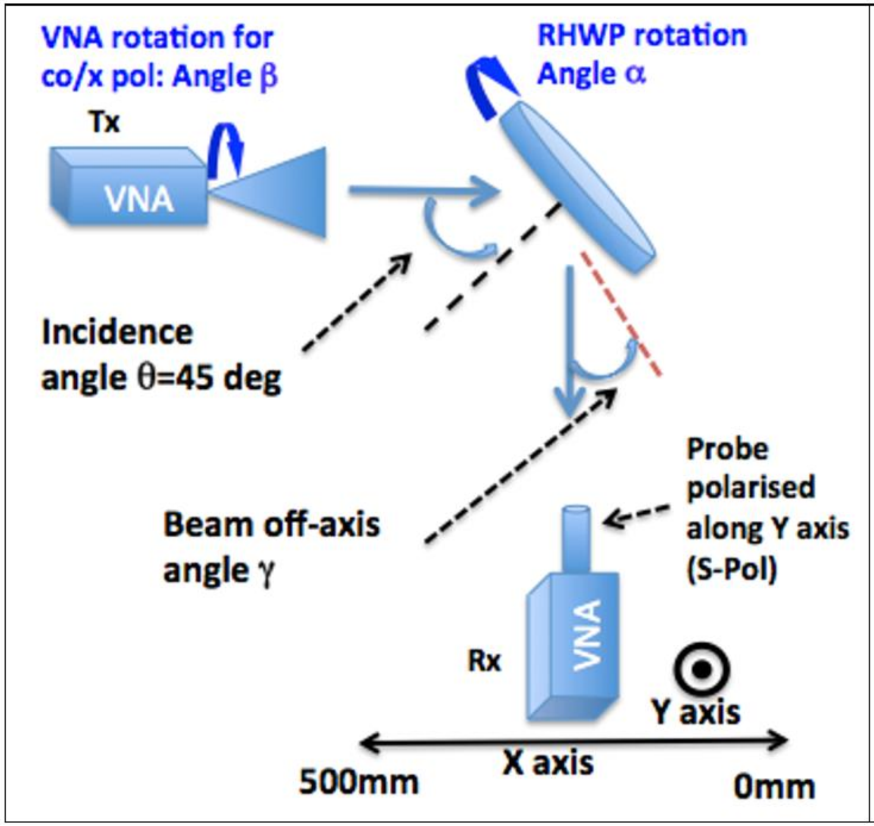


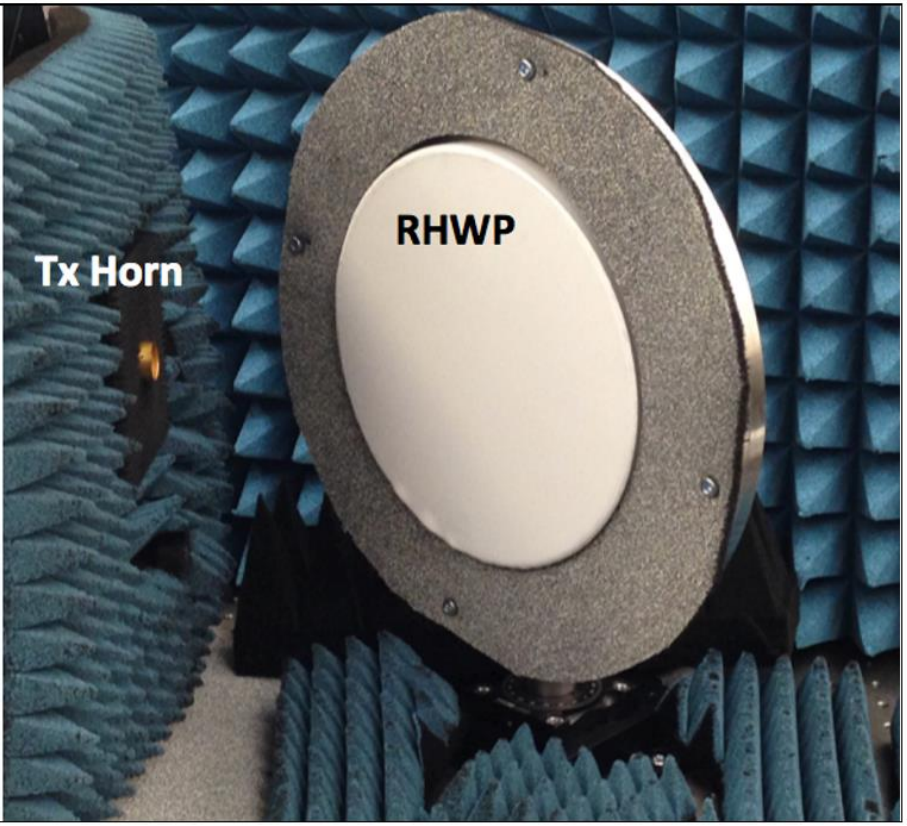




ER-HWP Beam Impact Tests: Experimental setup

B. Maffei



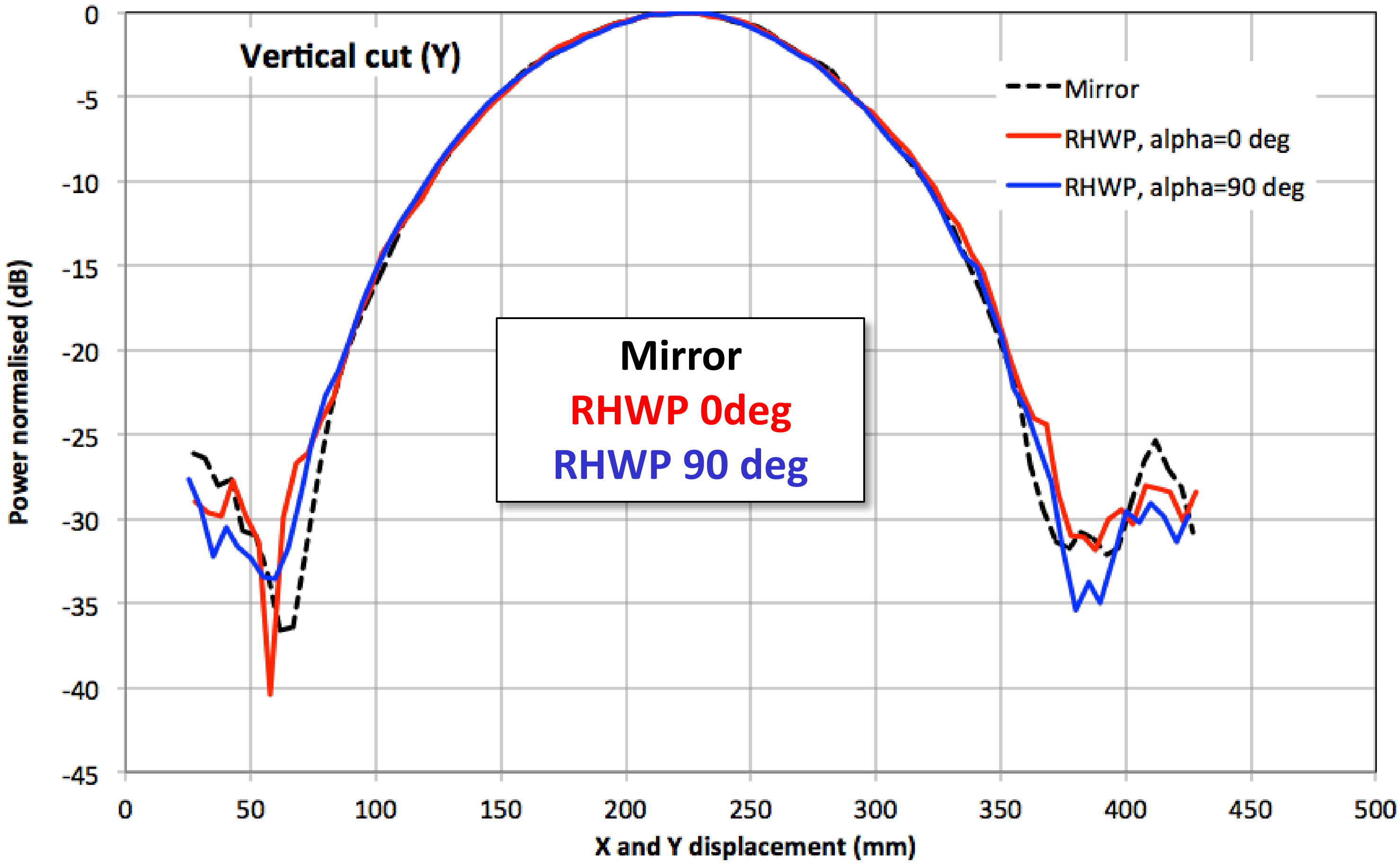


ER-HWP Beam Impact Tests: Beam ellipticity

B. Maffei

Beam cuts from measured 2D maps

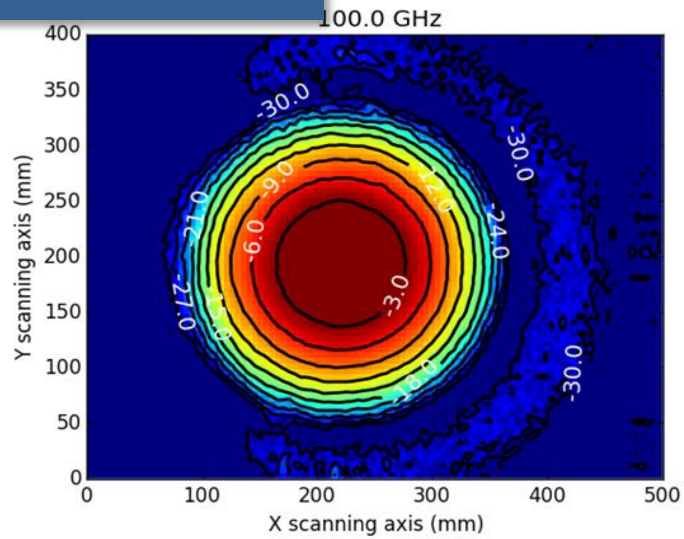
- 2D far-field map measurements
- Fitted with elleptical beam
- Ellipticity deduced

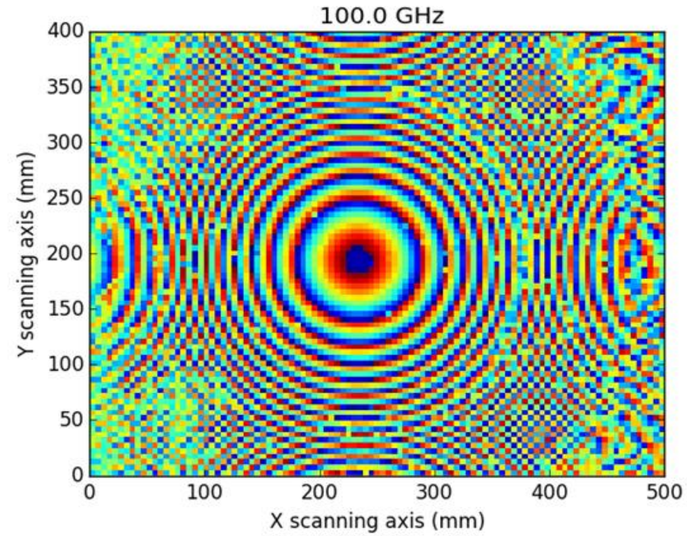


ER-HWP Beam Impact Tests: Beam maps

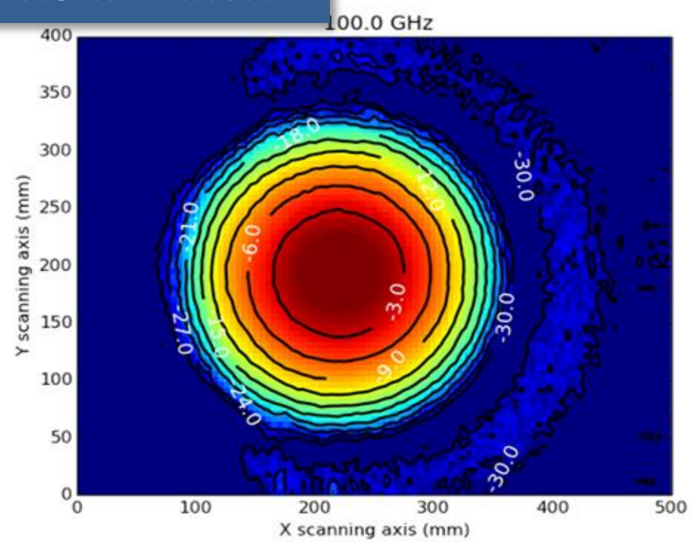
B. Maffei

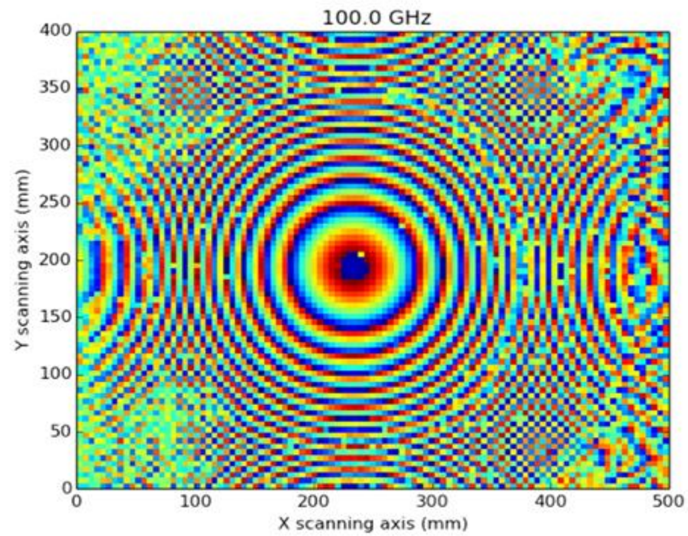
Map Horn + Mirror





Map Horn + RHWP

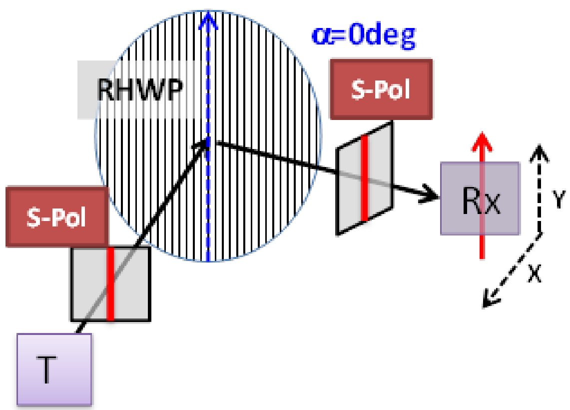


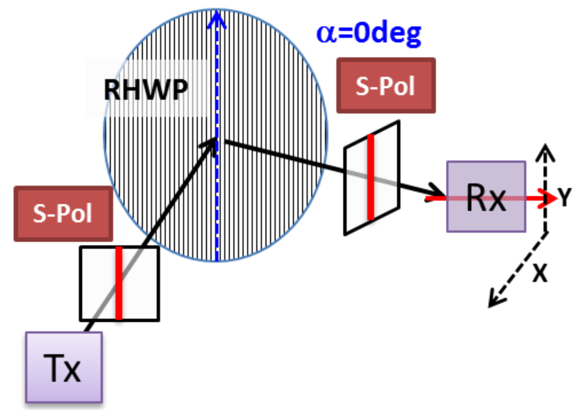


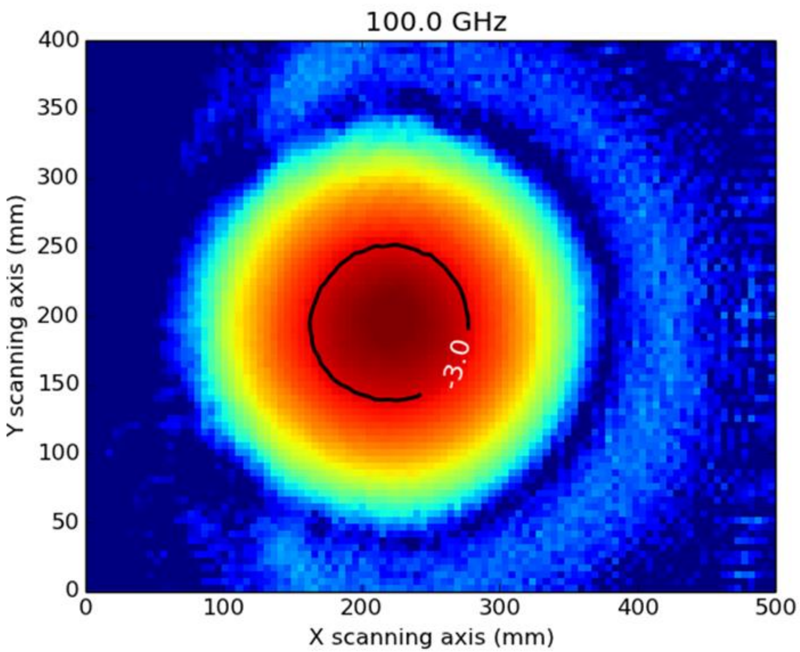
→ Increase of ellipticity ~ 1%

ER-HWP Beam Impact Tests: Cross-polar beam maps

B. Maffei

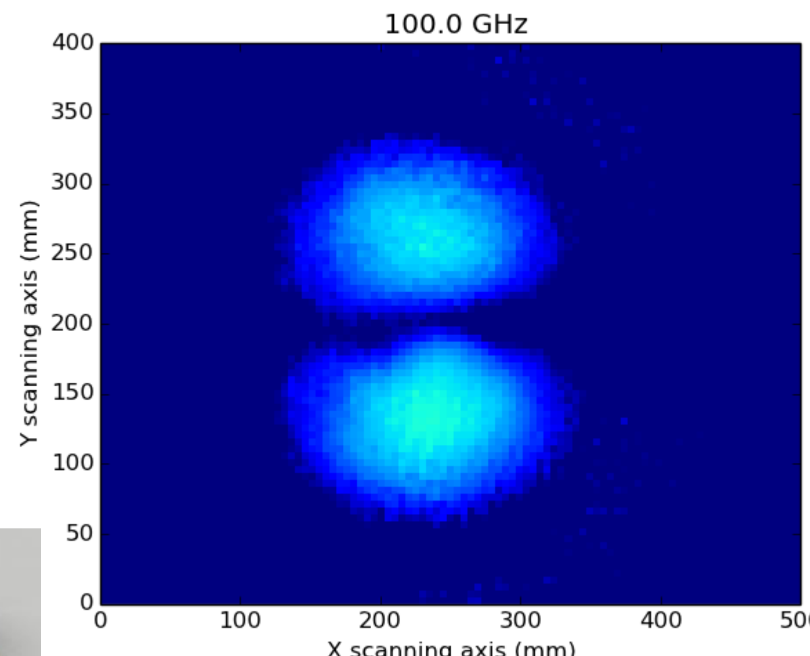






Co-polar beam

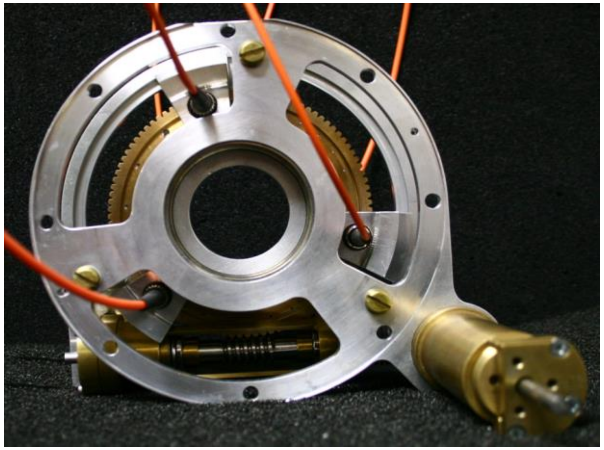
Measurements limited by probe's cross-pol

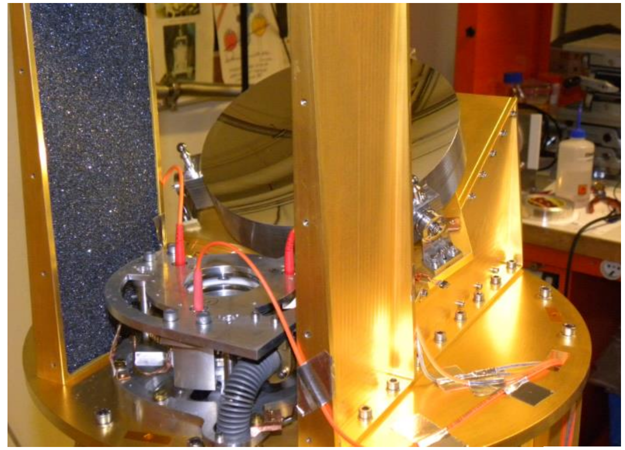


Cross-polar beam

Large HWP cryogenic rotation mechanism

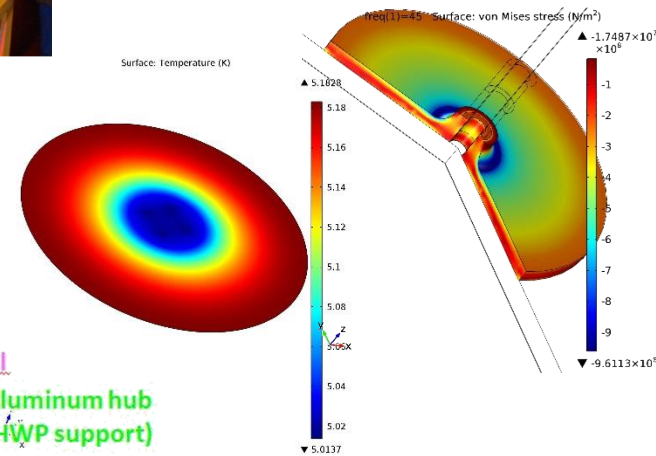
Rome



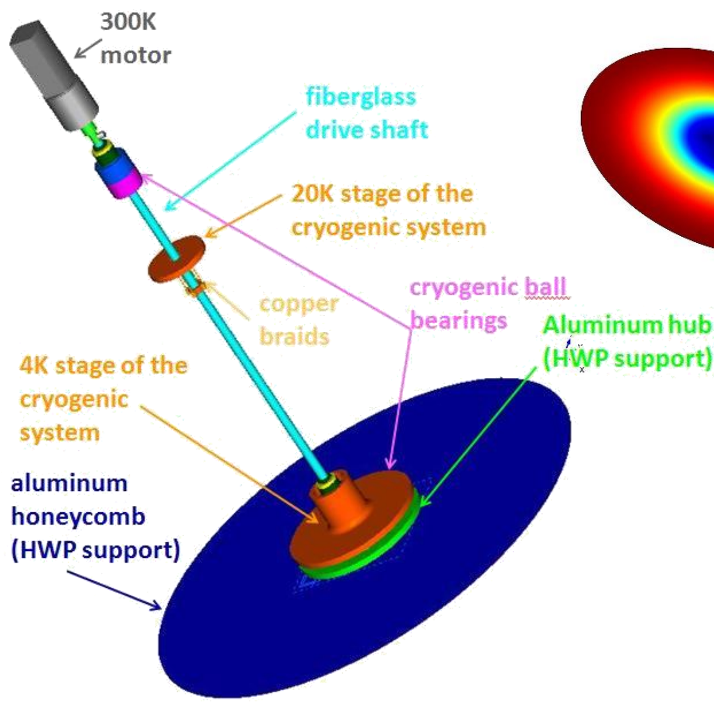


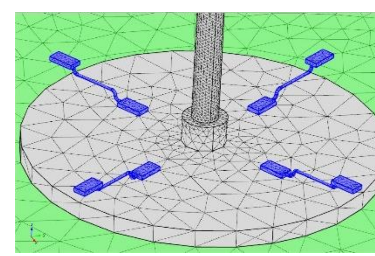
Cryogenic rotator (step) for the PILOT experiment (Salatino et al. A&A 2011)

Worked flawlessly in flight, sept. 20, 2015



- In COrE, the polarization modulator was large and was the first optical element.
- A smaller polarization modulator (reflective or refractive) can be placed between the telescope and the focal plane.
- Option under study.



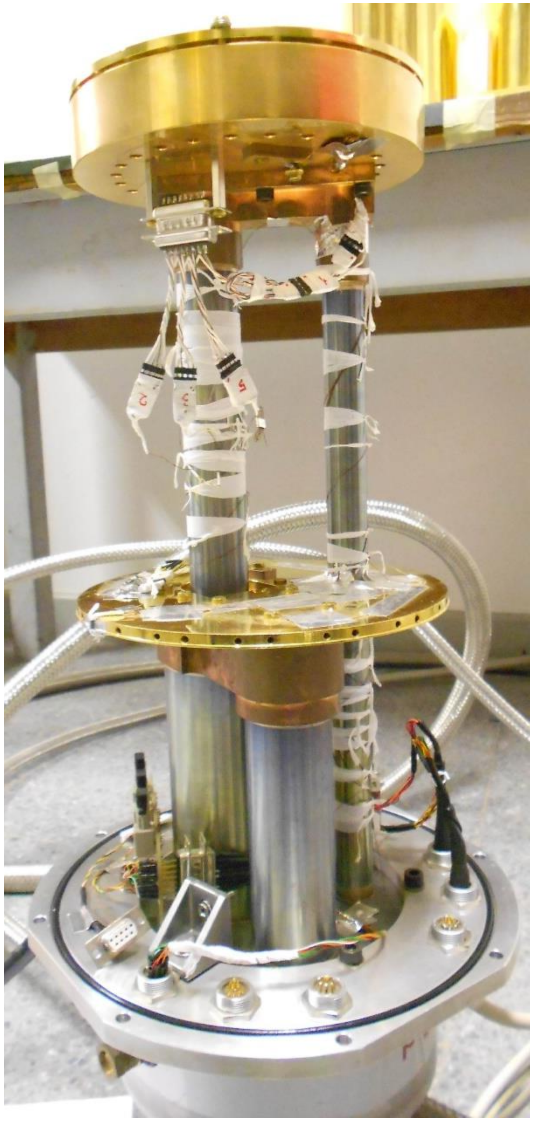


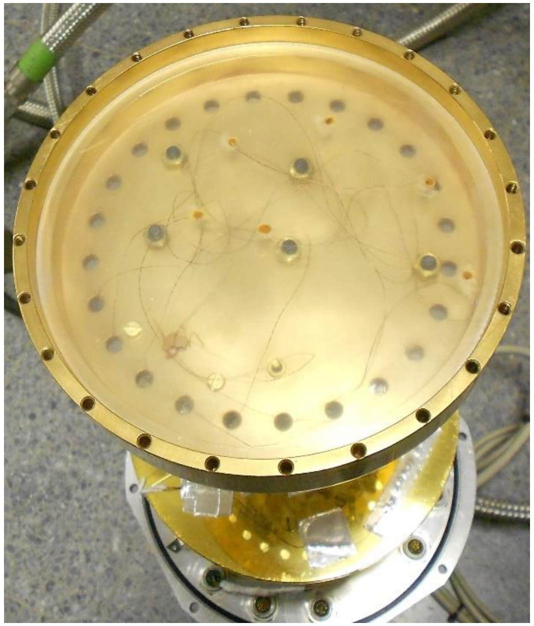
Similar design for COrE, thoroughly studied by the Rome group

ER-HWP cryogenic tests: Thermal gradients

Rome

- Measurement of thermal gradients on 160mm diameter, 0.5mm thick samples, under representative radiative background.
- Custom setup in *Rome Sapienza*:
  PT refrigerator and diffuse BB source with reduced emissivity.
- Polyethylene alone:
  $\Delta T = 4K$
- ER-HWP (similar thickness):
  $\Delta T < 0.3K$





Conclusions

- We have studied in details two polarisation modulation solutions

- **Transmissive Mesh-HWP**
  - Proved to work across **~90% BWs**
  - ~100% BWs achievable
  - ~150% BWs would require a different working principle

- **Embedded Reflective HWP**
  - Proved to work across **~150% BWs**
  - 160-170% BWs achievable
  - Periodic bands can also be used

- Ongoing **RF tests**
  - Characterisation/understanding of the HWP systematics of both solutions

- Ongoing **thermo-mechanical tests**
  - Rotation mechanism
  - Quantification of the HWPs gradient temperatures and emissivities