A Study on the Performance of Half-wave Plates Designed for Sub-mm Studies

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

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Goal – Spectral characterisation of a metal mesh HWP designed for sub-mm, simulate the sky and study the effect of HWP systematics in CMB searches of *r* for mitigation strategies and compare to current HWPs used.

Introduction

To measure linearly polarised signals within the CMB sapphire HWPs have typically been used as polarisation modulators. However, more recently[4] embedded metal mesh (MM) based HWPs have shown good performance over a broad band in the sub-mm regime, presenting the possibility of replacing sapphire HWPs in CMB studies. This work presents the spectral characterisation of a MM HWP & bias on *r* caused by the HWPs systematics.

Method

Optical setup using an FTS to measure the spectral performance of a HWP shown in Fig 1, with the data extraction routine given below.

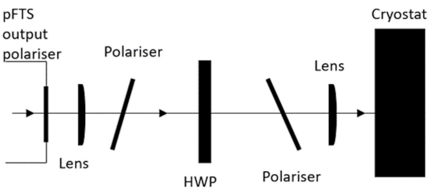

Fig 1: Schematic diagram of the optical test bench for transmission measurements of the NIKA2[4] HWP using a Fourier Transform Spectrometer[1] (FTS). Co-polarisation (co-pol) measurements obtained by orientating the polarisers parallel to one another. Cross-polarisation (cross-pol) measurements were obtained by rotating the polariser on the righthand side by 90°. HWP was held in a rotator and rotated through 360° to obtain full spectral data cubes.

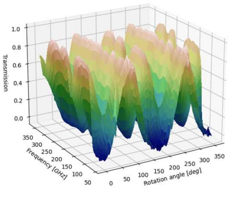

Fig 2: Measured co-pol data cube of the NIKA2 HWP using setup in Fig 1.

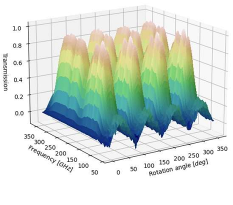

Fig 3: Measured cross-pol data cube of the NIKA2 HWP using setup in Fig 1.

Create a Markov Chain Monte Carlo (MCMC)[2] to generate best fit parameters for the HWPs Mueller matrix components over the frequency measured

Inject matrix parameters into timestream to simulate sky patches

Generate angular power spectra

Derive *r* constraints to see the impact of HWP systematics

Results

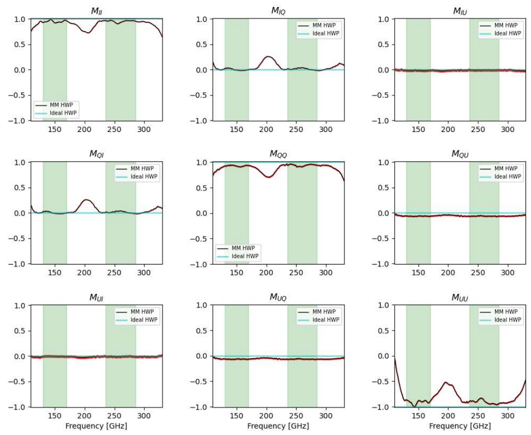

Fig 4: A "reduced" Mueller matrix of the NIKA2 HWP using the optical setup in Fig 1. Errors (1σ) are included in red and the green shaded regions represent the NIKA2 frequency bands, indicating the frequencies over which the HWP is performing over.

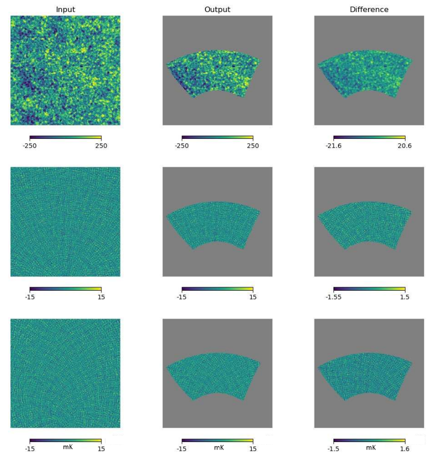

Fig 5: Sky patch maps generated by injecting the averaged components across the 150 GHz band in Fig 4 into the *s4cmb*[3] pipeline. Left column shows the I (top), Q (middle) and U (bottom) components of the input sky maps. The middle column shows the maps after demodulation and the right column shows the difference between the left and middle columns which is an order of magnitude smaller than the sky maps.

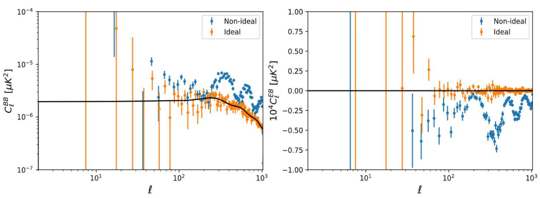

Fig 6: Left) BB power spectra and right) EB power spectra for an ideal HWP (orange) and the NIKA2 HWP (blue). Calculated using results in Fig 5 and maps generated by substituting ideal Mueller matrix components into *s4cmb*. The black curves represents the input C_ℓ^{BB} and C_ℓ^{EB} respectively. This assumes a CMB only case and does not include contributions from foregrounds.

- BB, EE and EB power spectra indicate an effective polarisation angle miscalibration
- Power spectra in Fig 6 calculate[5] a bias of $\delta r = 0.009 \pm 0.002$
- Further work required:
  - Cross check implementation of matrix components in *s4cmb*
  - Replicate calculation of δr using other pipelines[5,6]

Comparison

Sapphire HWPs (Pancharatnam designed)	Embedded metal mesh HWPs
• Good transmission across broad band[2] • Limitations on diameter size of sapphire plates, ~50 cm • ~20 kg (3 plate sapphire HWP) • Can be difficult to apply ARC[7] • Temperature dependence[2] • Frequency dependence[2] • Simulated performance[8] shows potential bias on *r* ~ 10^{-4}	• Good transmission across broad band[4] • Potential for HWPs to be made to diameters >50 cm (65cm mesh-reflective HWP built and tested) • ~1 kg – dependent on size • Easier to apply ARC • No temperature dependence • More work needs to be done to understand the effects of their non-idealities

Conclusions

The spectral characterisation of a metal mesh HWP produced Mueller matrix values close to the theoretically ideal values. Maps were produced with the injected 150 GHz band averaged matrix parameters and used to generate the angular power spectra for both the NIKA2 HWP and an ideal HWP. Subtracting $C_{\ell,ideal}^{BB}$ and $C_{\ell,NIKA2}^{BB}$ resulted in $\delta r = 0.009 \pm 0.002$. Further work is required to cross check method and ensure no miscalibration in the polarisation angle is occurring.

Literature Cited

[1]Savini et al. 'Recovering the frequency dependent modulation function of the achromatic half-wave plate for POL-2: the SCUBA-2 polarimeter', App. Opt. 48, 11 (2009).

[2] Moncelsi et al., 'Empirical Modelling of the BLASTPol Achromatic Half-Wave Plate for Precision Submillimetre Polarimetry', MNRAS (2014).

[3] Fabbian and Peloton, 'Simulating Instrumental Systematics of Cosmic Microwave Background Experiments with s4cmb', JOSS (2021).

[4] Pisano et al., 'Development and Application of Metamaterial-Based Half-Wave Plates for the NIKA and NIKA2 Polarimeters', A&A (2022).

[5] Giardiello et al., 'Detailed study of HWP non-idealities and their impact on future measurements of CMB polarisation anisotropies from space', A&A (2022).

[6] Azzoni, 'The early Universe from CMB *B*-modes: observational challenges', (2023).

[7] Hill., 'Sensitivity Simulations and Half-wave Plate Polarisation Modulators for Cosmic Microwave Background Observatories', (2020).

[8] Monelli, 'Impact of half-wave plate systematics on the measurement of CMB *B*-mode polarization', JCAP (2023).