A Metal Mesh Achromatic Half Wave Plate

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Abstract. Achromatic Half-Wave Plates can be realised using photolithographic techniques. Prototypes working at 150GHz have been designed, manufactured and tested and preliminary performance results are presented [1]. This type of device could replace the usual birefringent HWP used in mm/submm polarimetry experiments.

1. Introduction
Birefringent material based HWPs are used in many present experiments dedicated to the detection of the polarisation of the Cosmic Microwave Background radiation. Accurate models [2,3] have been developed which enable accurate prediction the HWP performances and enable through design modifications a minimization of systematic effects such as the inherent instrumental and the cross polarization levels. However, the demanding requirements for the next generation of CMB instruments, which aim to detect the very low level B-Mode signature, necessitates a new HWP concept which can be utilized with the very large arrays needed to achieve a meaningful sensitivity limit. The costs and the availability of birefringent materials of increasing size is a known problem (crystalline quartz available in ~ 110mm diameter boules and crystalline sapphire available in ~280 mm diameter boules) so alternative solutions must be sought. The type of HWP proposed here has a very good chance of replacing the crystalline technology with one constructed from metal mesh components. The manufacture of metal mesh components is a well established technology and will not be discussed in detail here (see filter review of these proceedings).

2. Concept
A Half Wave Plate introduces a phase shift of 180 degrees between two monochromatic electro-magnetic waves that have orthogonal polarizations and that are traveling through it. In an Achromatic HWP, this phase shift is maintained over a broader electromagnetic frequency band. When rotating, a HWP rotates any polarized incident vector at twice the angular velocity of the plate. Thus any linearly polarised incident radiation can be modulated and detected by using detectors sensitive to the polarisation (analyzers, OMTs, etc.) after the HWP. The phase shift between the orthogonal axes is normally achieved using the difference between the refractive indices of the ordinary and the extraordinary axes of a birefringent material. Hence , the plate thickness determines the frequency (or

multiples of it) at which the crystalline plate acts as a HWP and inherently it is only effective over a narrow frequency band. Since bolometric systems need broad photometric bands to achieve good sensitivity a single crystalline plate would prove very inefficient. A known solution to this was given by Pancharatnam [4], who demonstrated that a broader operational band can be achieved by stacking three or five plates together with appropriate rotation between their optical axes.

Here we propose an alternative solution that consists in using well know metal mesh technology to design and build submillimetre/millimetre HWP. Metal mesh grids with sub-wavelength geometries can be designed to manufacture filters for the FIR to submillimetre region. Here, the idea is to extend these studies and design grids which behaving differently for orthogonal polarised input and thus to artificially reproduce the behaviour of a birefringent material. Devices of this kind have been realised in the past using other technologies to make microwave retarders at low frequencies [5]. Here we have adopted a particular geometry used in these earlier designs to construct a device able to provide a phase-shift of 180 degrees over a 40% bandwidth around the central frequency of 150GHz. The concept of a HWP is readily visualised in metal mesh structures as the capacitive and inductive geometries [6] invoke opposite frequency dependent phase shifts. The mesh equivalent of the achromatic HWP thus requires special geometry meshes with delay lines to create a relatively flat phase of 180 degrees over the photometric bands with good in-band transmission of orthogonal polarised vectors. We have used HFSS electromagnetic modelling software and our own transmission line modelling to optimise the design of our prototype achromatic HWP using customized metal meshs. Here we describe the manufacture of a prototype device for use at frequencies near 150 GHz and compare its measured performance against the model expectations.

3. The 150 GHz prototype

The mesh HWP prototype is constructed from twelve meshes whose geometry was determined from the modelling. The device consists of two stacks of grids: one capacitive and the other inductive. The two stacks are built separately and mounted orthogonal to each other so that the axis of one stack is rotated with respect to that of the other stack. Each stack acts on one of the two polarisation directions leaving the transmission of the other one almost unperturbed. In addition to the phase effect, the capacitive stack behaves like a low-pass filter and the inductive one as a high-pass filter. There is a spectral region where both the filters have high transmission and their individual phase shifts have opposite signs. The combined difference between phase shifts gives the required 180 degrees delay. Pictures of the capacitive and inductive stacks are shown in Fig.1.

FIGURE 1

Pictures of the two stacks of inductive and capacitive grids of a 150 GHz Mesh-HWP.
The prototype had an internal diameter of ~35mm.

As for many other devices used for the detection of the CMB polarisation, one of the most important requirements of the HWP is to have a very low cross polarisation. The expected cross polarisation for the current device is at the -35dB level as predicted from the modelling. Measurements of the first prototype are shown in Fig.2 where the cross-polar response is observed to be about -25dB. The measurements were made using the same experimental setup adopted in [2]. The mesh HWP was held in a rotary stage between two aligned polarisers. Initially, one of the two axes of the HWP was aligned with the polarisers using a laser. The HWP was then rotated by 45 degrees to reach a minimum corresponding to the cross-polarisation signal. The discrepancy between model and data can be explained if the alignment between the grids during the assembly of the device was not perfect. However, the measured cross polarisation is already comparable to that measured for crystalline devices (for multiplate HWPs we mean the mimimum achievable signal integrated over the band obtained using the same experimental setup). The modulation efficiency of this prototype is greater than 99%.

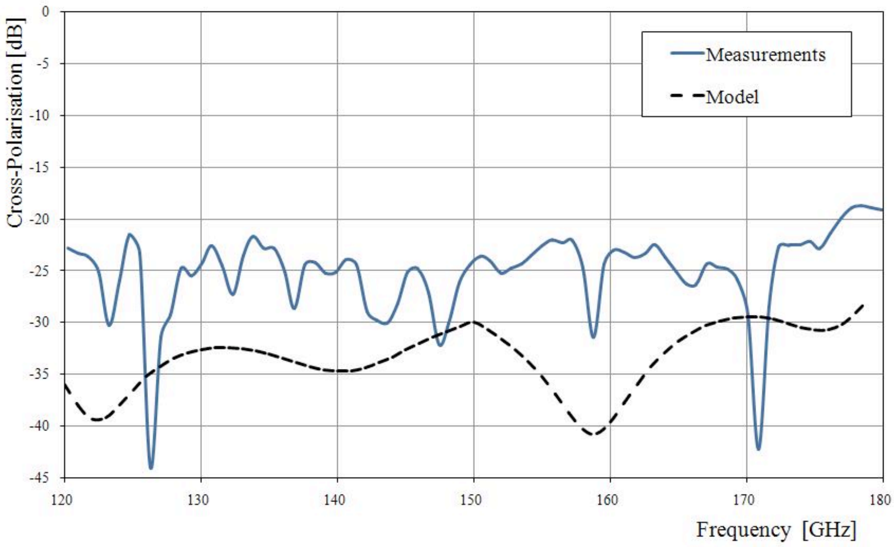

FIGURE 2

Predicted and measured cross-polarisation performance of a 150 GHz Mesh-HWP prototype.

4. Discussion

Mesh filter modelling and its manufacture technology are well understood and filter components made in this way are considered to be mature in terms of flight readiness from usage in a number of missions (ISOLWS, Spitzer, Mars missions, Herschel, Planck). The extension to 'anisotropic' grids to manufacture a HWP has been proved to work well. The designs are scalable to any frequency in the FIR to millimetre region. Conversely, there is not a wide range of birefringent materials available. Moreover, the dimensions of commercially available crystals are limited to ≤ 28cm diameter (sapphire only) and even then a complicated manufacture and anti-reflection coating for the three or five bonded plates need to be achieved for acceptable broadband performance.

On the other hand the mesh HWP design presented here is an air-gap filter type device. It relies on very thin (1.5 μm thick) copper coated mylar substrates on which the metal mesh geometries have been produced photolithographically. The grids are kept at specific distances by means of annular metallic spacers as used in the air-gap filters used in the cited space borne instruments. However, mesh filters can be also designed without air gaps being completely embedded into dielectric materials. These devices know as 'hot pressed' filters are very robust and like their air-gap counterparts can be cooled cryogenically. We are currently designing a modified 'hot pressed' version of the HWP presented here.

Another crucial difference between the technologies is the requirement to cool the devices. For the crystalline devices cooling is essential to remove absorption from phonon bands within the material and hence eliminate emission which could prove a serious sensitivity limitation in terms of the photon noise seen by the detectors. Metal mesh will have minimal absorption throughout the FIR to millimetre region as indeed the filter technology has demonstrated and thus offers the possibility of using the devices warm facilitating simpler rotation mechanism requirements.

From the systematics point of view one important aspect to be investigated is the effect of the mesh HWP on the optical beam. The effects due to normal mesh filters are known to be very low. Measurement of the mesh HWP cross polar beams are already planned.

5. TRL analysis

The device presented here was built using the air-gap mesh filters technology. The TRL of the present tested device is therefore rated as 9. Having proved the concept, the next prototypes of mesh HWPs will be made using 'hot pressed' recipes that we have in hand. The hot pressed mesh filter technology is also space qualified. Interestingly, the next devices will therefore only differ in the mesh geometries adopted and should otherwise be considered as a mature space-qualified technology.

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