Coated dielectric lenses for applications in high purity THz electromagnetic wave polarization detection

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Abstract: A comprehensive test programme has been implemented to enable the consideration of large refractive components with coating layers in the design of future satellite-based cosmic microwave background polarimetry missions. This requires understanding of systematic effects to an unprecedented level of precision, and validation of modelling tools and manufacturing techniques. We present the details of this study, and key results of the material and lens testing programme

Keywords: sub-mm; lens; anti-reflection; THz; polarization; dielectric; telescope; satellite

Introduction

The detection of the curl-like B-mode polarization of the cosmic microwave background (CMB) induced by a stochastic background of primordial gravitational waves is well recognized as a key test of cosmic inflation in the early universe. Future satellite instruments have been proposed [1, 2] to measure this signal down to the limit set by confusion from gravitational lensing. This requires the use of an optical system with exquisite control over polarization systematics [3]. In this paper we present the key findings of an ESA-funded study for an all-refractive telescope system to meet these very demanding scientific requirements.

The baseline design solution comprises three dielectric lenses per telescope barrel, with a separate telescope barrel for each of the five frequency bands (70, 100, 143, 217, 353 GHz). All lenses are anti-reflection coated, and are required to operate at around 4 Kelvin. There is a requirement for wide field of view, with extremely low beam distortion. The telescope is based around a modified Petzval camera, with a spherical focal surface [4]. The telescope feeds are ultra-Gaussian horns, as designed for the ClOVER experiment [5, 6]. The feed horns exhibit very low cross-polarization content and low beam pattern ellipticity (< 2 %) for the best possible match with the Airy disc produced by the optical system at the focal surface position.

Lens development and test programme

There has been much uncertainty in the use of dielectric lenses, particularly at low temperatures, and particularly in regard to polarization effects. The requirements for CMB-polarimetry experiments dictate that the maximum telescope aperture should be 445 mm diameter for the lowest frequencies, with a maximum component diameter of 585 mm. This severely limits the choice of lens material, as one cannot source single crystals of sapphire, quartz or silicon with such dimensions. Therefore, the lens/coating material combination developed was ultra-high molecular weight polyethylene (UHMW-PE), with a coating layer of porous PTFE (pPTFE).

There are many uncertainties over the use of refractive elements in this frequency range, such as;

- knowledge of the refractive index as a function of frequency and temperature,
- uniformity of the material,
- polarization effects in the material (e.g. stress-induced bi-refringence),
- uniformity and performance of any applied matching layer.

Modelling programme: A modelling a test program was implemented to address these uncertainties, and to validate software models for future instrument design.

The requirements on the accuracy of the analysis tools are very challenging. The lenses are electrically large and high accuracy is needed for the beam shapes and cross-polarization. The analysis must accurately take into account the effects of multiple reflections, coating layers and edge diffractions for both on-axis and off-axis feeds.

As no available tools were suitable for the task, new software development was necessary. The software package GRASP from TICRA was updated with BoR-MoM (Body of Revolution Method of Moments) and PO (Physical Optics) modules for analysis of dielectric lenses with coating. The BoR-MoM approach is in principle exact, but in the implementation of the method it is very important to represent the curved lens surface and equivalent electric and magnetic currents accurately. We have therefore used curved surface segments (instead of linear segments) and higher order polynomial basis functions for representing the currents. Also the coating layers are treated accurately with separate current sheets on each interface between layers. Although the BoR-MoM is an attractive approach, it requires much computation time, especially for coatings and off-axis sources. On the contrary the PO is very fast, but relies on certain high frequency approximations. It was found that if internal reflections inside the lens (and between lenses for multi-lens systems) are taken into account in the PO, very good agreement between PO and BoR-MoM is obtained. Also the coating layers can be treated accurately with PO by replacing the standard Fresnel refraction with plane wave refraction through multiple planar interfaces. As opposed to the BoR-MoM an off-axis source does not increase the computation time.

Material measurements: A significant component of this activity was a study of the materials involved in order to validate their optical performance to a high degree of accuracy [7]. For this reason UHMW-PE (lens material), and porous PTFE (anti-reflection coating material) were subject to rigorous optical analyses to determine their real and imaginary refractive index as a function of frequency and temperature. We show that accurate determination of these optical constants is paramount in order to predict the optical performance of the overall optical system. Additional tests for stress-induced bi-refringence were also performed in order to place an upper-limit on possible systematic effects which might occur due to un-planned stresses in the instrument cooldown.

Lens manufacturing: Two lens types (A and B) have been designed and built, using the measured refractive index for the same material batch for the lens design. A critical point here is to ensure that the lens material is fully annealed prior to manufacture, and that the optical constants are measured for the same annealed material from which lenses will be machined. They both have convex hyperbolic surfaces, but the first lens refocuses the incident field at the same distance (Fig. 2), whereas the other lens transforms rays from a point source into a planar wavefront (Fig. 3).

Anti-reflection coating: A reliable and repeatable process has been developed for anti-reflection coating of large plastic lenses [7].

Lens measurements: Lenses were tested in the frequency range 75 to 150 GHz, in their uncoated and coated states. A VNA with a high quality corrugated horn was used as a source, and a planar near-field x-y scanner probed the field at the opposite side of the lens. This was repeated for a number of de-focus positions. The same test was also performed off-axis with the source angled at 5-10°. The same test set was repeated after the lens was coated, to verify the success of the coating procedure, and how this affects the optical performance of the lens. The beam patterns of the source and probe horns were measured and characterized, and included in the analysis.

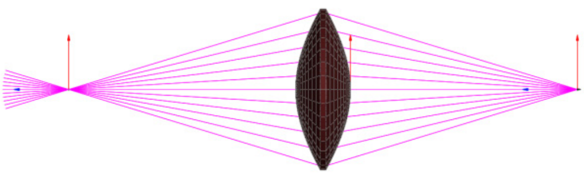

Figure 1. Schematic of Lens type-A

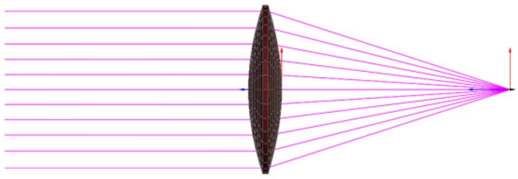

Figure 2. Schematic of Lens type-B

Results

We find excellent agreement (Fig. 3) between experiment and simulations in all cases. There is a small discrepancy in the measured focal position compared to model predictions that we ascribe to the residual uncertainty in measured refractive index.

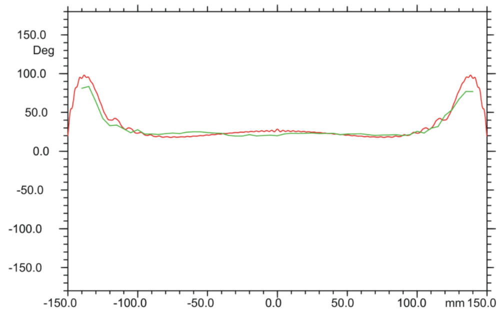

Figure 3. Phase of co-component at 100 GHz for annealed, coated lens. Red = simulation. Green = measured data.

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