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Regular article

Ultra high molecular weight polyethylene: Optical features at millimeter wavelengths

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HIGHLIGHTS

- Ultra High Molecular Weight (UHMW) polyethylene (PE) features high resistance to traction and good transmissivity in the frequency range of interest. In this paper, we discuss the possibility of using UHMW PE for windows and lenses in experiments working at millimeter wavelengths, by measuring its optical properties: emissivity, transmission and refraction index. Our measurements show that the material is well suited to this purpose.
- We measured its emissivity at 90 GHz and 150 GHz obtaining few percent, this results are consistent with similar plastic polymer material as the HDPE. By using a MPI and a Golay Cell, as detector, we measured the transmissivity as a function of the thickness. We measure 90% from 150 GHz to 800 GHz for ten millimeter sheet. From these measure we derive the surface reflectivity, without coating, always less 20%. The results are very similar to HDPE. By using the same MPI as before we measured the refractive index, 1.537, and the absorption coefficient, 0.03 Np cm^{-1}, both obtained at 300 GHz.

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ABSTRACT

The next generation of experiments for the measurement of the Cosmic Microwave Background (CMB) requires more and more the use of advanced materials, with specific physical and structural properties. An example is the material used for receiver's cryostat windows and internal lenses. The large throughput of current CMB experiments requires a large diameter (of the order of 0.5 m) of these parts, resulting in heavy structural and optical requirements on the material to be used. Ultra High Molecular Weight (UHMW) polyethylene (PE) features high resistance to traction and good transmissivity in the frequency range of interest. In this paper, we discuss the possibility of using UHMW PE for windows and lenses in experiments working at millimeter wavelengths, by measuring its optical properties: emissivity, transmission and refraction index. Our measurements show that the material is well suited to this purpose.

1. Introduction

The survey sensitivity of CMB experiments is currently pursued increasing the number of radiation modes detected, either using large-format arrays of single-mode detectors or using arrays of multi-moded detectors. In both cases, the large optical throughput of the instrument requires large optical elements. The first element (skywise) of the receiver optical train is the cryostat window. Its optimization is crucial because it represents the first filter for the radiation, therefore must have a high transmission in the frequency bands of the experiment and, at the same time, must withstand without bending too much the large inwards force due to external pressure and internal vacuum.

Nowadays, High Density Polyethylene (HDPE) is widely used for cryostat windows [1–6] and lenses in the millimeter-waves frequency range of interest here [6–9]. UHMW PE is a kind of thermoplastic polyethylene. It has extremely long chains of polyethylene, all aligned in the same direction. The molecule forming UHMW chains is heavier than that of HDPE, and this makes the UHMW stronger and easier to be machined [10,11]. The tensile strength of UHMW PE is twice that of HDPE, therefore it represents a good candidate for replacing HDPE.

Although some experiments devoted to the measurements of the CMB, like the Atacama Cosmology Telescope, CLASS, and BRAIN pathfinder, already used this material for their optical components [9,12–15], direct measurements of its most important optical characteristics cannot be found in the literature yet. In this paper we

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report measurements of emissivity, transmission and refraction index for UHMW PE, providing useful data for the design of new CMB experiments and other optical instruments for mm-wave measurements.

2. Mechanical characteristics and simulations

The tensile strength of UHMW PE is ~40 MPa, while that of HDPE is ~20 MPa. In order to evaluate the impact of this characteristics on the mechanical performance of large windows, we performed a load simulation of a large diameter window, for both materials, using a finite element simulator.[2] The simulated window has a diameter of 50 cm, a thickness of 2.5 cm, and its temperature has been set at 300 K (room temperature). The pressure difference from top to bottom is 1000 mbar.[3] As expected, the simulations Fig. 1 confirm that the UHMW window deformates less. This means that it is possible to use less material in order to have the same mechanical performance of the HDPE, see Table 1. Less material means less weight, and better transmission. Thanks to this mechanical feature, each secondary machining on the surface, such as antireflection coating, is easier and the risk of damage to the material is reduced.

2.1. Deformation vs. thickness simulations

We use ANSYS software to show the deformation for three different cryostat windows, with diameter of 10 cm, 25 cm and 50 cm, as a function of thickness. We obtain results showed in Table 1.

The results in table shows how it is possible to reduce the thickness of windows from 25 mm to 20 mm, for each diameter, obtaining the same displacement and increasing the transmissivity, as it showed in Fig. 7.

3. Emissivity

The emissivity of the optical components is crucial because it represents part of the background power incident on the detectors and part of the optical load on the fridge of the cryogenic system.

The design of the detectors is strictly correlated with the background power, as well as the performance of the fridge depends on the optical load. A typical emissivity for the optical elements working at millimeter wavelengths is around few percent [16–18]. The direct measurement of the emissivity is not simple, since the quantity which we want to measure is small and it is easy that the experimental setup is dominated by systematics.

In order to estimate the UHMW emissivity, we build a setup like in [16]: a disk of UHMW, thickness of 10 mm, surrounded by a copper crown, which is, in turn, surrounded by an Aluminum ring, is suspended in air through some kevlar fibers, in order to thermally insulate the UHMW from its metal support. The aluminum ring is equipped with a number of evenly spaced heaters, which allow to control the temperature, while the disk of UHMW is equipped with two thermometers PT100: one at the center and one near the copper crown. Fig. 2 shows this setup. We verified, with dedicated tests, that the PT100 which is placed at the center of the UHMW disk, does not corrupt the measurement.

3.1. Instrumental setup

For this measurement, the instrumental setup is composed of low temperature detectors, in particular kinetic inductance detectors (KIDs) [19,20], and therefore of a cryogenic system, equipped with a dedicated optical system, and the readout electronics.

The sample is placed in such a way that the signal coming from it is chopped with a blackbody at 300K (Eccosorb sheet) before entering in the cryostat, the Eccosorb sheet is glued to Aluminum sheet and the temperature is controlled with a PID system by using a PT100 thermometer and resistor like heather. The bias and the readout signals of the detector are monitored through a dedicated electronics, which include a frequency synthesizer, a signal splitter, an IQ mixer demodulator, a low noise amplifier, a warm amplifier, and an ADC. Fig. 3 shows the scheme of this measurement setup.

3.1.1. Detectors

The detectors consist of two single pixel KIDs, built on 1 cm × 1 cm,300 μm thick, high-quality (FZ method), intrinsic Silicon wafer, with high resistivity ($\rho > 10\ \mathrm{k\Omega\,cm}$) and double side polished. The 90 GHz KID is a TiAl bilayer 10 nm thick Titanium +25 nm thick Aluminum, while the 150 GHz KID is in Aluminum 25 nm thick. For both the detectors, the feedline is a coplanar waveguide, matched to 50 Ω.

The absorber of the 90 GHz KID is a standard meandered line, while that of the 150 GHz KID is a III order Hilbert curve. For both the detectors, the capacitor has the interdigitated geometry, designed in order to guarantee the lumped condition, and to have a resonance frequency around 1 GHz for the 90 GHz KID, and 2 GHz for the 150 GHz KID. Fig. 4 shows the designs of the 90 GHz and 150 GHz KID.

The detectors are fabricated at the Istituto di Fotonica e Nanotecnologie (IFN) of the Consiglio Nazionale delle Ricerche (CNR), in Rome [21].

The 90 GHz KID has a critical temperature $T_c = (812 \pm 24)$ mK and the noise equivalent temperature on the detector is $\mathrm{NET} = (6.94 \pm 0.73)\ \mathrm{mK}/\sqrt{\mathrm{Hz}}$ [22]. The 150 GHz KID has a critical temperature $T_c = (1.32 \pm 0.04)$ K and the noise equivalent temperature on the detector is $\mathrm{NET} = (0.909 \pm 0.095)\ \mathrm{mK}/\sqrt{\mathrm{Hz}}$.

3.1.2. Cryogenic system

KIDs are low temperature detectors, they need to be cooled below the critical temperature of the superconducting film in order to work. The optimal choice is at least $T \lesssim T_c/6$.

The cryogenic system is a three-stage cryostat composed of a pulse tube cryocooler, a ^{3}He/^{4}He fridge, and a dilution refrigerator. This system is able to reach a base temperature of 136 mK, under an optical loading of about 14 μW, for about 7 h.

3.2. Measurements

For the setup described before, the signal is

$$S = \mathscr{R}\{\epsilon_{\mathrm{ecc}}[T_{\mathrm{amb}}(t_{\mathrm{UHMW}} + r_{\mathrm{UHMW}}) - T_{\mathrm{cho}}] + \epsilon_{\mathrm{UHMW}} T_{\mathrm{UHMW}}\} \quad (1)$$

were $\mathscr{R}$ is the system responsivity in V/K, while t_{UHMW} and r_{UHMW} are the UHMW transmissivity and reflectivity, respectively, ϵ_{ecc} is the Eccosorb emissivity. The product $\mathscr{R}\epsilon_{\mathrm{ecc}}$ is calibrated by removing the UHMW and placing an Eccosorb plate, cooled at $T_N = 77.8$ K, behind the chopper, in this case the signal is

$$S_{\mathrm{cal}} = \mathscr{R}[\epsilon_{\mathrm{ecc}}(T_N - T_{\mathrm{cho}})]. \quad (2)$$

The Eccosorb emissivity is estimated by measuring the transmissivity and the reflectivity of an Eccosorb slabs, using a high-power source: a 150 GHz Gunn oscillator. We obtained $\epsilon_{\mathrm{ecc}} = 0.972 \pm 0.002$. At this point, the UHMW emissivity, ϵ_{UHMW}, is measured by fitting the trend of $S/\mathscr{R}$ with the UHMW temperature, T_{UHMW}, Eq. (1), see Fig. 5. Table 2 collects the values of the responsivities and the results of the fits found for the two detectors

[2] Solidworks in this case, but other software, such as ANSYS and COMSOL MULTIPHYSICS give the same results.

[3] Usually the internal cryostat pressure is $\sim 10^{-6}$ mbar.