

A cryogenic waveplate rotator for polarimetry at mm and submm wavelengths

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ABSTRACT

Context. Polarimetry at mm and submm wavelengths is the new frontier of research in cosmic microwave background and interstellar dust studies. Polarimeters working in the IR to MM range need to be operated at cryogenic temperatures to limit the systematic effects related to the emission of the polarization analyzer.

Aims. We study the effect of the temperature of the different components of a waveplate polarimeter and describe a system able to rotate a birefringent crystal at 4 K in a completely automated way.

Methods. We simulate the main systematic effects related to the temperature and non-ideality of the optical components in a Stokes polarimeter. To limit these effects, a cryogenic implementation of the polarimeter is mandatory. In our system, the rotation produced by a step motor running at room temperature is transmitted down to cryogenic temperatures by means of a long shaft and gears running on custom cryogenic bearings.

Results. Our system is able to rotate a birefringent crystal at 4 K in a completely automated way and dissipates only a few mW in the cold environment. A readout system based on optical fibers allows us to control the rotation of the crystal to better than 0.1° .

Conclusions. This device fulfills the stringent requirements for operations in cryogenic space experiments, such as the forthcoming PILOT, BOOMERanG and LSPE.

Key words. instrumentation: polarimeters – techniques: polarimetric – dust, extinction

1. Introduction

Diffuse dust in our Galaxy is heated by the interstellar radiation field at temperatures ranging from 10 K to 100 K, depending on the dimensions of the grains and the radiative environment. Their emission is therefore in the submm/FIR range and is partially polarized owing to the alignment of grains in the Galactic magnetic field (see e.g. Draine 2003).

While FIR emission of interstellar dust has been mapped quite accurately even at high galactic latitudes by the IRAS, ISO and *Spitzer* surveys and is investigated in deep detail by the currently operating *Herschel* observatory, its polarization properties are almost unknown (see e.g. Hildebrand & Kirby 2004).

The interest in studying dust polarization is twofold. An accurate measurement of dust polarization at different wavelengths is important to better understand the nature and structure of dust grains and to probe the magnetic field of our Galaxy (see e.g. Vaillancourt 2008; Hildebrand et al. 2000).

Moreover, polarized dust emission is an important contaminating foreground in precision measurements of the polarization of the cosmic microwave background (CMB), the current ambitious target of CMB measurements. Measuring it at wavelengths where dust polarization is dominant is mandatory to correct the cosmological signal at the level required to measure B-modes (see e.g. Lazarian et al. 2009). Diffuse Galactic sources act as a foreground, mimicking the cosmological polarized signal (Hanany & Rosenkranz 2003; Ponthieu & Martin 2006): at frequencies above 100 GHz interstellar dust is the dominant foreground. Therefore, an accurate knowledge of the polarization

of these sources is necessary to perform a precise measurement of the polarized cosmological signal. This is made difficult by the small amplitude of the polarized signal of these sources and by its strong angular and wavelength dependence (Tucci et al. 2005).

Several experiments are planned to measure dust polarization at high galactic latitudes.

The *Planck* satellite (Tauber et al. 2010) and in particular the High Frequency Instrument (Lamarre et al. 2010) is performing a shallow whole-sky survey of dust polarization at frequencies up to 345 GHz. Here, the signal caused by interstellar dust at high galactic latitudes is roughly similar to the level of the CMB anisotropy (Masi et al. 2001, 2006; Ponthieu et al. 2005). Higher frequency surveys are more sensitive to the polarization signal of interstellar dust (see Fig. 1).

PILOT is a stratospheric balloon-borne experiment for the measurement of the polarization of the continuum emission in the diffuse interstellar medium at frequencies around 545 and 1250 GHz, with a resolution of $3.29'$ and $1.44'$, respectively (Bernard et al. 2007). The experiment is optimized to perform surveys of the polarized dust emission along the Galactic plane but also at high Galactic latitudes, where previous experiments have provided only upper limits (Benoit et al. 2004; Ponthieu et al. 2005). PILOT will probe the large-scale distribution of the Galactic magnetic field and the alignment properties of the dust grains, providing strong constraints for dust models, in particular via the dependence on frequency of the degree of polarization.

BLAST-pol, the polarization sensitive version of the very successful BLAST balloon telescope, will also search for

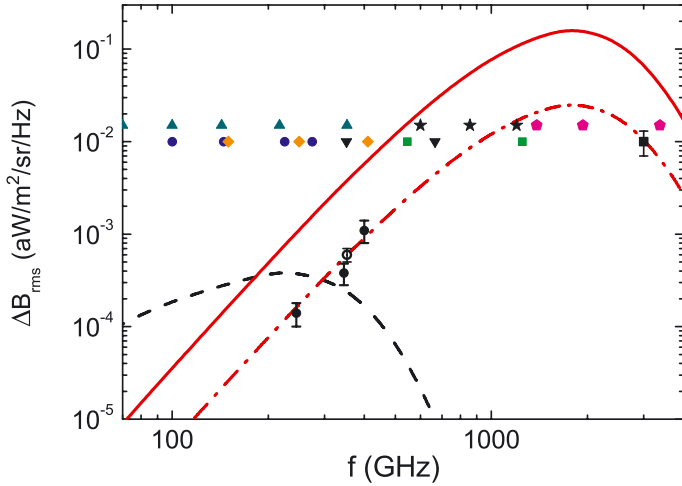


Fig. 1. Measurements of rms fluctuations in interstellar dust emission at Galactic latitudes above 20° (data points with error bars) from BOOMERanG (filled circles, Masi et al. 2001, 2006) and Archeops (empty circle, Ponthieu et al. 2005). The continuous line is a thermal spectrum with $T_d = 18$ K and ν^2 emissivity. The dashed line represents rms CMB anisotropy for $\Delta T/T = 10^{-5}$. The dash-dotted line represents the spectrum of the polarized signal from a dust cloud with brightness of 1 mK_{RJ} at 353 GHz and 10% polarization (see Benoit et al. 2004). The symbols mark the frequency bands explored by forthcoming polarization measurements from several experiments: *Planck* (up triangles), PILOT (squares), BLAST-Pol (stars), SPIDER (circles), EBEX (diamonds), SCUBA2 (down triangles), SOFIA (upgraded HAWC: pentagons).

polarized dust emission in the galactic plane in the southern hemisphere (Marsden et al. 2008; Fissel et al. 2010).

SPIDER (Crill et al. 2008) is an ambitious balloon-borne instrument aimed at the measurement of the polarization of the CMB by means of large arrays of polarization-sensitive detectors. Working in the stratosphere, SPIDER can cover high frequencies (in particular two bands at 225 GHz and 275 GHz) to monitor polarized emission from interstellar dust where it is not negligible with respect to the polarized component of the CMB.

EBEX is also a balloon-borne CMB polarimeter, aiming at smaller angular scales and with a dust monitor at 410 GHz (Oxley et al. 2004).

There are different instrumental techniques to detect faint polarized signals. Polarization-sensitive bolometers (PSB, Jones et al. 2003) have been used in B03 (Masi et al. 2006) & *Planck* (Delabrouille & Kaplan 2001).

Orthomode transducers have been used in WMAP (Jarosik et al. 2003) and other coherent systems.

A stack of a rotating birefringent crystals followed by a static polarizer implements a Stokes polarimeter, and has been used in the BRAIN-pathfinder experiment, where the waveplate operates at ambient temperature (Masi et al. 2005).

In MAXIPOL, instead, a DC motor outside the cryostat rotated a cryogenically cooled Half Wave Plate (HWP) by means of a fiberglass drive shaft crossing the cryostat shell and the tertiary mirror, mounted in the aperture stop of the optical system (Johnson et al. 2007).

EBEX will use a cold achromatic dielectric waveplate (Hanany et al. 2005) in the cold optics, rotated continuously by means of superconducting magnetic bearings (Hanany et al. 2003).

SPIDER will also use a large cold HWP as the very first optical component in the system (Bryan et al. 2010a).

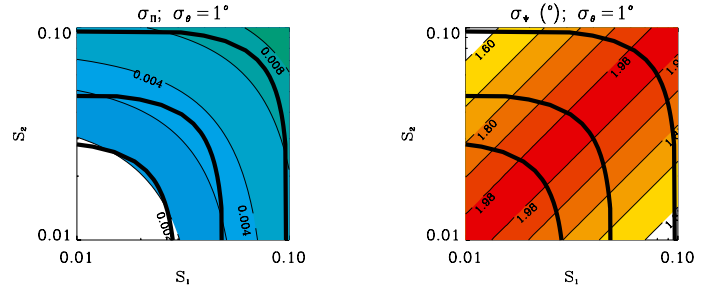


Fig. 2. Contour levels of the upper limits for the errors in the polarization degree σ_Π (left) and in the orientation angle σ_ψ (in degrees, right), caused by a positioning error σ_θ , versus the values of the Stokes parameters S_1 and S_2 normalized to S_0 . The figure refers to $N = 8$. The thick contours identify the normalized values of S_1 and S_2 for which Π is, from bottom left to top right, 3%, 5%, and 10%.

In PolKa a reflective system equivalent to a reflective waveplate is composed of a rotating polarizer close to a reflector at room temperature (Siringo et al. 2004). For a review of polarization modulation techniques see Ade et al. (2009).

In parallel to the development of techniques for polarization modulation, a vigorous theoretical effort attempts to describe the behavior of real dielectric HWPs (see e.g. Savini et al. 2009; Bryan et al. 2010a; Bryan et al. 2010b); moreover very promising metal-mesh waveplates have also been proposed (Pisano et al. 2008).

In this paper we describe the system we developed for PILOT, BOOMERanG, and LSPE (de Bernardis et al. 2009a), where the HWP will rotate in steps and will be kept at cryogenic temperatures. The paper is organized as follows: in Sect. 2 we briefly review the principle of operation of a HWP polarimeter and prove the necessity of cooling it down to cryogenic temperatures (Sect. 3). After listing (Sect. 4) the experimental requirements for the necessary cryogenic waveplate rotator (CWR), we present our implementation of the system; we describe the hardware structure (Sect. 5.1) and the tests we performed (Sect. 5.2). We conclude in Sect. 6 summarizing the main features of our system.

2. The HWP polarimeter

A polarimeter sensitive to linear polarization is composed of a HWP, rotating at frequency f_0 , followed by a stationary polarizer. Monochromatic linearly polarized light, passing through the waveplate, emerges still linearly polarized, but with its polarization vector revolving at $4f_0$. Unpolarized radiation is unaffected by the waveplate. If we place a polarizer between the waveplate and the detector, only the polarized component of the incoming radiation is modulated by the rotation of the waveplate. The amplitude of modulation depends on the polarization of the radiation: it is maximum (null) for radiation that is totally (not) polarized. The signal of interest is encoded at $4f_0$, far from the spectral region where $1/f$ noise is important. Any spurious signal or systematic effect is easily removable at a frequency different from $4f_0$. The rotating HWP polarimeter offers a substantial advantage with respect to a PSB: a single detector measures both the Stokes parameters of the linear polarization, so that the result is not affected by drift of uncertainties in the relative calibration of the different detectors of a PSB.

In some cases it is preferable to rotate the HWP in discrete steps. Our system follows this strategy. The power detected for

a HWP revolved through n discrete steps is (Collett 1993)

$$W(n\Delta\theta) = \frac{R}{2}(S_0 + S_1 \cos 4n\Delta\theta + S_2 \sin 4n\Delta\theta), \quad (1)$$

where R is the instrument responsivity, $\Delta\theta$ is the step size, and S_k are the Stokes parameters for the incoming radiation. Equation (1) is a truncated Fourier series from which we can recover, given the total number of steps N , the components S_k ($k = 0, 2$) of the Stokes vector as

$$\begin{aligned} S_0 &= \frac{2}{N} \sum_{n=1}^N W(n\Delta\theta), \\ S_1 &= \frac{4}{N} \sum_{n=1}^N W(n\Delta\theta) \cos 4n\Delta\theta, \\ S_2 &= \frac{4}{N} \sum_{n=1}^N W(n\Delta\theta) \sin 4n\Delta\theta. \end{aligned} \quad (2)$$

The drawback of the discrete rotation is enhanced sensitivity to $1/f$ -noise, because the polarized signal is modulated at a frequency on the order of $f_p = 1/T$, where T is the time required to cover the N steps; given the low value of f_p , the noise will be dominated by instrumental and atmospheric drifts.

From Eqs. (1) and (2) we can set upper limits for the error in the polarization degree, $\Pi = (S_1^2 + S_2^2)^{1/2}/S_0$, and for the error in the orientation angle, $\psi = \frac{1}{2} \arctan(S_2/S_1)$, owing to inaccuracies in the position angles of the waveplate. We find

$$\begin{aligned} \sigma_\Pi &\leq \frac{4\sigma_\theta(|S_1| + |S_2|) \sqrt{4 + \Pi^2}}{S_0 \sqrt{N}}, \\ \sigma_\psi &\leq \frac{4\sigma_\theta(|S_1| + |S_2|)}{S_1 \sqrt{N} \sqrt{1 + S_2^2/S_1^2}}; \end{aligned} \quad (3)$$

where σ_θ is the uncertainty in the position angle θ of the waveplate.

To estimate the position accuracy required in a practical case, we model interstellar dust emission as linearly polarized radiation with a typical polarization degree $\Pi \sim 5\%$ and a typical specific brightness of about 6×10^{-16} W/m²/sr/Hz. Assuming $\sigma_\theta < 1^\circ$, and using Eq. (3) (i.e. neglecting other sources of error) with $N = 8$, we find an error in the polarization degree $\sigma_\Pi \lesssim 0.4\%$ (for any direction of the polarization vector), and an error in the orientation of the polarization vector $\sigma_\psi \lesssim 2^\circ$.

In Fig. 2 we plot the upper limits for the two errors versus the values of the two Stokes parameters of linear polarization. Increasing the error in the HWP position does not change the shape of the contour levels, given the linear dependence of the upper limits on this angle (see Eq. (3)).

Detector noise is an additional contribution to the error in the polarization degree and in the orientation of the polarization vector. This is quantified by the noise equivalent power (NEP) and by the integration time for each observed pixel (T): we have $\sigma_{\text{det}} = \text{NEP}/\sqrt{2T(s)}$, so that

$$\begin{aligned} \sigma_\Pi &= \frac{2 \sqrt{4 + \Pi^2}}{S_0 \sqrt{N}} \sqrt{4\sigma_\theta^2(|S_1| + |S_2|)^2 + \sigma_{\text{det}}^2}, \\ \sigma_\psi &= \frac{2}{S_1 \sqrt{N} \sqrt{1 + S_2^2/S_1^2}} \sqrt{4\sigma_\theta^2(|S_1| + |S_2|)^2 + \sigma_{\text{det}}^2}. \end{aligned} \quad (4)$$

The specifications for the PILOT experiment give a NEP of about 3×10^{-16} W/ $\sqrt{\text{Hz}}$ for the 545 GHz band. In Fig. 4 we plot

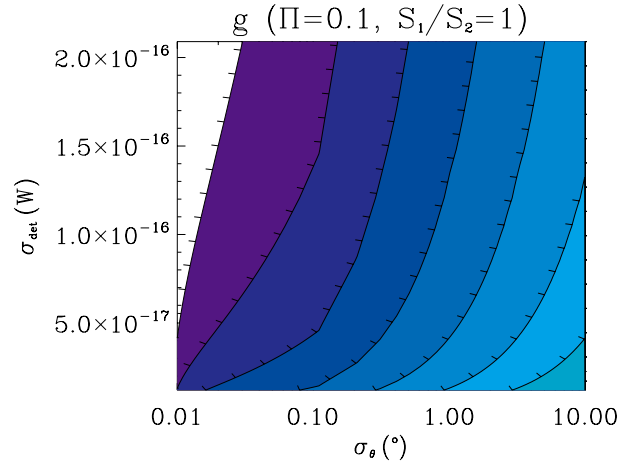


Fig. 3. Contour levels (from left to right: $1e-4$, $1e-3$, $1e-2$, $1e-1$, 1 , 10 and 100) for the g function defined in the text, Eq. (5), versus detector noise, σ_{det} , and inaccuracy in the position angle of the waveplate, σ_θ . For $g < 1$ the errors in the polarization parameters are dominated by detector noise.

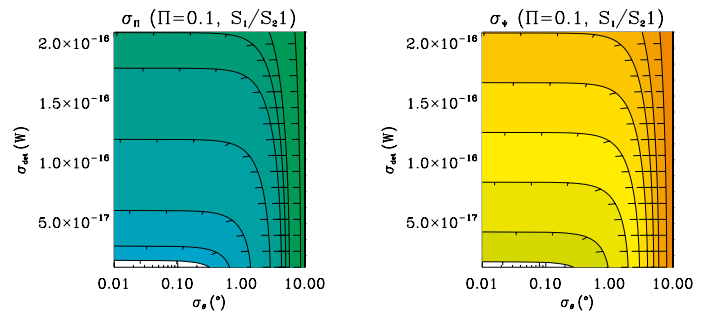


Fig. 4. Upper limits for the errors in the measurement of the polarization degree (left, from bottom left to top right: 0.003 , 0.005 , 0.01 , 0.02 , 0.03 , 0.035 , 0.04 , 0.06) and orientation angle (in degrees, right, from bottom left to top right: 0.8 , 2 , 4 , 6 , 8 , 10 , 12 , 16), versus detector noise (σ_{det}) and inaccuracy in the position angle of the waveplate (σ_θ).

the upper limits on the polarization degree and on the orientation angle in this case as a function of the two Stokes parameters of linear polarization, taking into account detector noise and integration time as specified above.

For a given degree of polarization, the measurement errors can be dominated either by detector noise or by positioning errors. We define the function

$$g = \frac{4\sigma_\theta^2(|S_1| + |S_2|)^2}{\sigma_{\text{det}}^2}. \quad (5)$$

When $g < 1$, the errors on the polarization degree and the orientation angles are dominated by detector noise and can be reduced by increasing the integration time. In the conditions described above for PILOT, this happens for $\sigma_\theta \lesssim 0.1^\circ$, as is evident from Fig. 3. If this positioning accuracy is achieved, one can fully exploit the sensitivity of the detectors (Fig. 4).

3. The necessity of cryogenic temperatures

Equation (1) is valid if the HWP acts as an ideal phase-shifter with negligible absorption and emission (ideal waveplate). The detected power is in general a sine wave with amplitude $A = \max(W(n\Delta\theta)) - \min(W(n\Delta\theta))$, and offset $O = \frac{1}{N} \sum_{n=1}^N W(n\Delta\theta)$. Non-ideal behavior of the HWP, the polarizer, and the detector change the amplitude and the offset of the detected power

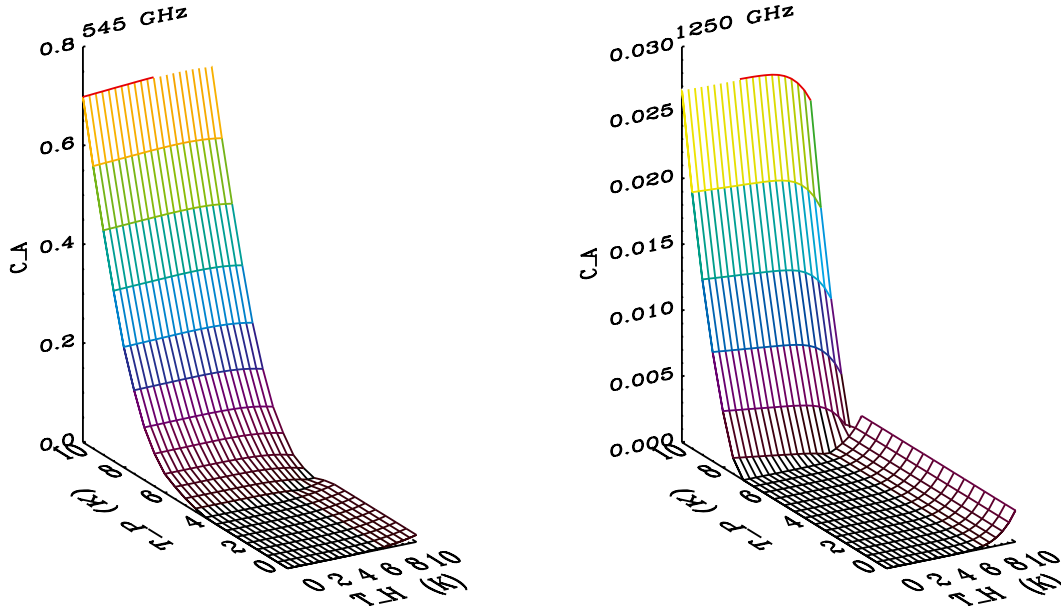


Fig. 5. Plot of the non-ideality parameter C_A defined in the text versus the temperature of the waveplate, T_H , and the temperature of the polarizer, T_P , and for two operation frequencies. The non-ideality parameter must be $\ll 1$ for a good performance of the polarimeter.

and can introduce spurious $\cos(2n\Delta\theta)$ and $\sin(2n\Delta\theta)$ components. The non-ideal behavior of the HWP alone is described by a Mueller matrix $M_{HT}(\theta)$, which is more complex than the standard phase-retarder matrix. Using the matrix form described e.g. in Bryan et al. (2010b), Salatino & de Bernardis (2010), we find that at temperature ~ 6 K the amplitude of the modulation changes by $\sim 2\%$ ($\sim 20\%$) at 545 (1250) GHz, while the offset can increase by as much as 40%.

In addition, the emission of the waveplate and of the other components of the polarimeter must also be taken into account. We studied how these non-idealities depend on the operating temperature of the polarimeter's components. We define two non-ideality parameters: $C_A = |\frac{A_{\text{real}}}{A_{\text{ideal}}} - 1|$ and $C_O = |\frac{O_{\text{real}}}{O_{\text{ideal}}} - 1|$, where $A_{\text{real(ideal)}}$ is the amplitude of the real (ideal) signal and $O_{\text{real(ideal)}}$ the offset. Here the word *ideal* means that only the signal *transmitted* by the HWP is considered. The word *real*, instead, means that the entire signals reaching the detector are considered (including HWP and polarizer *emission*), as well as the reflections among the different components. C_A is related to the modulation efficiency of the polarimeter and compares the actual excursion of the modulated signal to the excursion in the ideal case (the lossless and efficient polarimeter described by Eq. (1)). $C_A \ll 1$ indicates an instrument close to ideal, thus maximizing the S/N of the measurement.

C_O is related to the offset of the modulated signal, which should be minimized for an optimal use of the dynamic range of the instrument. A value of $C_O \ll 1$ indicates an offset close to half of the dynamic range, i.e. the ideal case.

For our simulation example we considered the measurement of polarization of diffuse interstellar dust, which we modeled with a temperature of 18 K and emissivity proportional to ν^2 , normalized to the Archeops data at 353 GHz (i.e. we used the spectrum plotted in Fig. 1); it is horizontally polarized, with a degree of polarization of 10%. We considered the two wavelengths $240 \mu\text{m}$ and $550 \mu\text{m}$, with finite bandwidths $\Delta\lambda/\lambda = 41\%$ and 33% , respectively. We considered only normal incidence on the HWP. The spectral dependence of the extraordinary and ordinary refraction indices of the HWP and of the corresponding absorption coefficients is given by Savini et al. (2006). We assumed a

linear decrease of the absorption coefficient with the temperature of the HWP. Small differences in the absorption coefficients of the HWP, at a level of about 10^{-3} , create a modulated polarized emission from the crystal itself. In a typical Stokes polarimeter (like e.g. MAXIPOL and PILOT) the HWP is followed by a polarizer, tilted of 45° with respect to the normal of the HWP surface. In this way two independent arrays, one detecting radiation transmitted by the polarizer, the other detecting reflected radiation, can use the same focal plane of the telescope, thus observing the same area of the sky. At these frequencies, metal wire grid polarizers are close to ideal. In our model we assume transmission coefficients $p_x = 0.99$, $p_y = 0.01$ and emissivity 0.01. The radiation is then detected by a bolometer, with emissivity 0.5, cooled at 0.3 K. Because of this very low temperature we neglected its emission.

The signal detected by the polarimeter, W_{det} , is given by the sum of the dust emission processed by the rotating HWP and the polarizer, the HWP emission processed by the polarizer and the polarizer emission reflected back by the HWP:

$$W_{\text{det}} = R(M_{PT}M_{HT}(\theta)S_d + M_{PT}S_{HE}(\theta) + M_{PT}M_{HR}(\theta)S_{PE}). \quad (6)$$

In Eq. (6) M_{PT} is the Mueller matrix for the transmission of a polarizer, $M_{HT(R)}(\theta)$ is for the transmission (reflection) of a HWP, $S_{P(H)E}$ is the Stokes vector for the emission of a polarizer (HWP), and S_d the Stokes vector for the emission of the dust.

With respect to the ideal case, in a real polarimeter the astrophysical polarized signal is modified with a reduction of the amplitude and an increase of the offset of the transmitted signal.

Our simulation for the amplitude of the signal (the offset is removed through a low pass filter) clearly shows that to increase the efficiency of the polarimeter it is necessary to cool down to cryogenic temperatures both the polarizer and the HWP (Fig. 5). From Eq. (6) the radiation emitted by the polarizer and reflected back by the HWP produces a $\cos 4n\Delta\theta$ -signal with the same phase as the astrophysical source, when the wires of the polarizer are aligned to the polarization vector of the signal (Salatino & de Bernardis 2010). Depending on the in-band spectrum of the incoming signal, this emission can add to the astrophysical

signal, mimicking a spurious increase of its amplitude. Rotating the polarizer by 35.26° , this emission becomes out of phase with respect to the astrophysical signal. Moreover, the polarized emission of the HWP, which directly crosses the polarizer, produces a signal modulated at $2n\Delta\theta$ in the detected signal.

The C_A parameter is dominated by the temperature of the polarizer. Only if the HWP is warmer than about 10 K the polarized emission from the crystal contaminates the $\cos 4n\Delta\theta$ signal. Given its definition, C_A includes all the terms contributing to the signal, including any $\cos 2n\Delta\theta$ term. Moreover, the C_A parameter also depends on the $\cos 2n\Delta\theta$ component because the nonlinear behavior of incoherent detectors produces a $\cos 4n\Delta\theta$ signal if the $\cos 2n\Delta\theta$ one is too strong. This additional signal can be several order of magnitudes stronger than the dust emission.

Given the higher emissivity of the HWP with respect to the one of the polarizer (by at least one order of magnitude) and the low reflectivity of the HWP itself, the C_O parameter is dominated by the HWP temperature.

We ran our model for a 300 K waveplate and found that the signal produced by the HWP is 10^4 times stronger than the dust signal. This poses extreme requirements for the stability of the polarimeter, which are completely relaxed for a cryogenic waveplate.

Both parameters decrease with frequency. This is because the refraction indices and the absorption coefficients increase with frequency, but the emission of interstellar dust at 18 K increases faster (at least for frequencies <1500 GHz): the net result is a decrease of the fractional disturbance.

The C_A parameter (Fig. 5) decreases quickly with the polarizer temperature and is <0.1 for both channels when the wire grid is cooled below 8 K.

The C_O parameter, instead, decreases quickly with the HWP temperature. It becomes 9.6×10^{-4} and 3.5×10^{-2} at 6 K, and 6.4×10^{-5} and 8.5×10^{-3} when cooling down the HWP to 4.5 K (higher and lower frequency respectively).

We also checked that our results are not very sensitive to reasonable changes in the parameters of the dust spectrum. For example, increasing the spectral index from 2 to 3 and reducing the temperature from 18 K to 15 K, the variations of the C_A and C_O parameters are less than 20%.

4. Experimental requirements

The rotation of the polarization plane is the same when the optical axis of the HWP is at 0° and at 45° . One can rotate more to achieve angle redundancy and check for systematic effects. For example one can check if the same signals seen in the 0° – 45° interval are seen again in the 45° – 90° interval. Moreover, a good sampling of the angles is found dividing the 0° – 45° interval in four parts. Therefore it is natural to observe eight positions $\theta_k = k \times \Delta\theta$ with $k = 0..7$ and $\Delta\theta = 11.25^\circ$, for a total angular coverage of 78.75° .

The aim of a polarimeter is to produce a map of the Stokes parameters over the sky area of interest. Accordingly the rotation of the waveplate has to be complemented by a scan of the sky. In a stepping polarimeter, the HWP angle is kept still during each scan of the sky, and stepped to the next angle at the end of the scan.

To maximize the overall observation efficiency, the time taken to rotate the HWP from any one position to any other should be much less than the duration of each scan. Typically one sky scan can be about one minute long, which means that the time required to step the waveplate angle by $\Delta\theta$ should be $\lesssim 10$ s: this requires a typical angular velocity of the waveplate of

about 0.19 rpm. The mechanism has to rotate the HWP from position number 1 to number 8, and then come back to position 1; moreover, this scan must be repeated for the entire duration of a typical experiment (a few days). This strategy minimizes microphonic signals (which are a concern for continuously rotating waveplates, unless they are levitating on superconducting bearings) and minimizes the power dissipated on the cryostat during the rotation.

The accuracy of the position of the HWP should be less than 1° to minimize the errors on the polarization degree and orientation angle (see Sect. 2). The HWP, placed in the aperture stop of the optical system, will operate at the temperature of liquid helium (Sect. 3). The mechanism has to ensure, by means of a good thermal contact between its mechanical structure and the phase shifter, a good thermalization of the birefringent crystal. Moreover, intercepting incoming and outgoing rays from the HWP itself (vignetting) have to be avoided.

Because the system is cooled by a liquid He bath, one has to limit the power dissipated by the rotation of the modulator to a maximum of few mW. Moreover, a reliable system working at cryogenic temperatures is required to control the HWP position in an accurate way.

5. The cryogenic waveplate rotator

In Sect. 5.1 we sketch the hardware concept of our cryogenic waveplate rotator (CWR hereafter); in Sect. 5.2 we present and discuss the tests we performed, with particular attention to the measurement of dissipated power produced when running the CWR at cryogenic temperatures (Sect. 5.3).

5.1. Mechanical structure

An achromatic HWP (Pisano et al. 2006), 50 mm in diameter, is mounted on a large hollow gearwheel¹, which rotates on a large thrust ball bearing. The HWP is surrounded by a 6061-aluminum alloy support and is thermally connected to the helium liquid temperature by means of a copper braid. The two halves of the bearing confine the balls in their grooves and are pressed against each other through Belleville washers, gently compensating any thermal shrinking and keeping the system on-axis. The rotation of the hollow gearwheel is obtained by means of a worm screw. A step motor running at room temperature outside the cryostat rotates the worm screw by means of a magnetic coupling to cross the cryostat shell, a long fiberglass tube shaft, and a flexible joint. The motor is mounted on the top flange of the cryostat to maximize the distance between the room temperature motor and the cold section of the cryostat, thus maximizing thermal insulation. A flexible metal joint connects the vertical shaft to the horizontal worm screw acting on the CWR gearwheel. A step motor was selected because without brushes can operate continuously in the stratospheric vacuum environment. The current in the step motor was limited to 0.1 A per phase to reduce the power dissipation in the motor coils and their self-heating in the absence of convective cooling. Tests under vacuum show that the motor does not heat up more than 2 K at a speed of 60 rpm with an operation duty cycle of 5%, while for a 100% duty cycle and with a speed of 90 rpm the temperature increase is less than 10 K. At this reduced current the torque from the motor is still more than enough to reliably rotate the cryogenic mechanism.

A careful choice of the materials and of the mechanical play of the parts, based on simulated thermal contractions at 4 K, is

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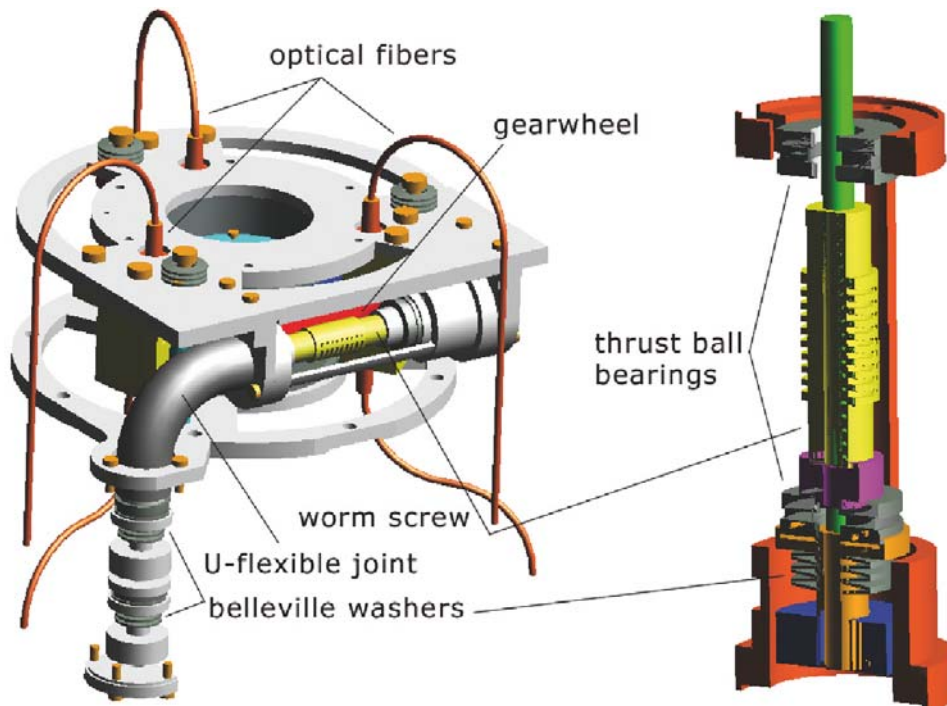


Fig. 6. CWR mechanical system (*left*), and a detail of the custom cryogenic bearings (*right*).

mandatory to avoid increased friction and eventually a stall of the system when cooled at cryogenic temperatures. Smooth rotation of the worm screw and of the drive shaft is obtained by means of a custom system which combines thrust ball bearings and belleville washers. The latter press the bearings that keep the gears on axis during the rotation and compensate the substantial shrinking of the system at cryogenic temperatures. The presence of a flexible U-joint, in place of commonly used conical gears, avoids thermal loads produced by the friction between rotating gears and mechanical play.

Three pairs of optical fibers sense the rotation angles of the system. Each pair consists of a fiber connected to an IR transmitter at room temperature (820 nm AlGaAs emitters Agilent Technologies model HFBR-1412), reaching the top surface of the gearwheel plate, and of a return fiber starting from the bottom surface of the gearwheel plate and reaching the IR detector at room temperature (silicon pin photodiodes OSRAM model BPX 61). In this way the gearwheel interrupts the three optical fiber pairs. Eight groups of 1 mm diameter holes are drilled through the gearwheel plate in eight positions, corresponding to the selected rotation angles of the waveplate. Each pattern reproduces in binary code the index k of the angle (Fig. 6). The operation of the system is similar to that of an absolute optical encoder: we detect and identify each integration position by analyzing the signals transmitted through (or blocked by) the gearwheel.

The gap (about 3 mm) in the optical fibers, owing to the thickness of the gearwheel, introduces a significant light loss. This is recovered by modulating at 1 kHz the IR emitters and recovering their signal by means of a synchronous demodulator. A block diagram of the readout electronics is reported in Fig. 7. For gaps smaller than 10 mm (which is our operating condition), the output signal is highly stable: global variations range from 0.5% to 2% depending on the amplification gain. A detection test, made with the insertion of a 1 mm diaphragm (the same diameter of the holes in the gearwheel) between the fibers, leaves the signal-to-noise ratio unchanged.

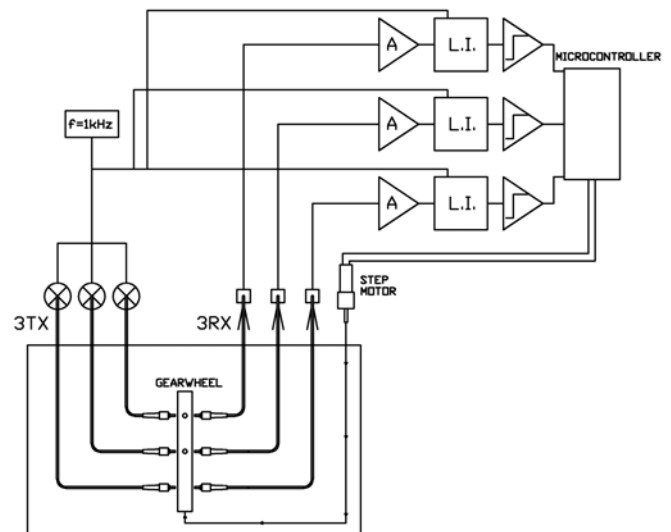


Fig. 7. Principle of operation of the CWR electronics. The modulated light of three IR emitters at room temperature (TX) is transferred via optical fibers to one side of the gearwheel, where a suitable pattern of holes identifies the eight integration positions. Through this pattern of holes three optical fibers, facing the opposite side of the gearwheel and aligned to the previous ones, receive the modulated light and transfer it back to three IR detectors (RX) at room temperature. The signals are amplified (A) and synchronously demodulated (L.I.), providing three bits that represent the current position angle.

5.2. Qualification tests

We carried out a number of qualification tests on the key components of this system.

The CWR, mounted on the cold stage of the photometer, will work with its axis approximately vertical. During its rotation we

Table 1. Repeatability of the eight HWP position angles.

Position	Nominal angle (°)	Measured standard deviation (°)
1	0.00	0.01
2	11.25	0.02
3	22.50	0.01
4	33.75	0.01
5	45.00	0.01
6	56.25	0.01
7	67.50	0.02
8	78.75	0.01

Notes. The first column labels the position number, the second is the mean position angle, the third the standard deviation of the position angle.

need to avoid shifts of the HWP. We verified that the shift of the rotation axis with respect to the aperture stop is limited to ≤ 0.13 mm when the CWR is rotated from a vertical axis configuration to an horizontal one. This shift is completely acceptable and was obtained by means of suitable Belleville washers pressing on the thrust bearing of the gearwheel.

The accuracy and repeatability of the rotation angles of the HWP was tested using a laser reflected on a small mirror mounted on the gearwheel. For all positions we find from the histogram of many measurements that the $1\text{-}\sigma$ dispersion of the position angle is always well below 1° (Table 1) which satisfies the experimental requirements (Sect. 4).

Optical fibers were tested sunk in liquid nitrogen; in this configuration, the transmitted signal shows an increase of about 38%. Tests with a He leak-detector excluded significant outgassing from the optical fibers and the flexible U-joint.

The thermal conductivity of the optical fibers was measured in the temperature range ($4 \div 300$) K. Fiber specimens, running between the base temperature and a controlled higher temperature, were mounted inside a test cryostat. We estimated the thermal conductivity from the power required to heat one side of the fibers, keeping the other side at 4 K. The conductivity of the support system and the radiative heat leak were properly taken into account. The estimated conductive thermal load from 4 K to the first thermal shield of the cryostat, where they will be placed, carried by three pairs of fibers, 30 cm long, is 0.1 mW.

The fiberglass driveshaft (length 710 mm, inner and outer diameter 2 mm and 3 mm, respectively), carries a conductive thermal load, from room temperature to liquid helium, of 1.0 mW. The total static heat load resulting from our system (driveshaft plus optical fibers) is accordingly about 1.1 mW, which is well within the experimental requirements (Sect. 4).

5.3. Power dissipation in dynamic conditions

The operation of the CWR at cryogenic temperatures was tested inside a laboratory cryostat cooled by a pulse tube cooler (PT). Key temperatures are read by four silicon diode thermometers mounted on the two stages of the PT, the CWR lid and the top of the CWR vertical cylinder. A data acquisition/switch unit reads the thermometers. The optical fibers, 2 m long, cross the coldest environment and reach the 300 K stage after thermalization on the intermediate PT stage. A mylar shield encloses them, avoiding conductive loads caused by the contact with the 300 K shield. A co-axial magnetic coupling transmits the motor torque through the vacuum shell of the cryostat; a stainless steel non-magnetic containment barrier allows complete insulation of the inner magnetic hub from the outer one without any contact.

The dissipated power is measured comparing the heating of the 4 K environment, induced by the CWR movement, to the ones produced by two power wirewound resistors, mounted on the CWR lid.

During this test the intermediate PT stage reached (68 ± 1) K; the low temperature one (4 ± 1) K, the CWR lid (6 ± 1) K and the CWR cylinder (6 ± 1) K. The torque required to rotate the system was lower than 0.08 N m.

With the CWR thermalized at cryogenic temperature, we performed a number of scans during which the electronic system read all the predetermined positions.

We performed a 50 min heat load test, rotating the waveplate and stopping in each integration position for 30 s. The residual friction generated during the rotation produced an increase of the temperature of the CWR lid ranging from 0.4 to 1.2 K, depending on the rotation speed.

The dissipated power produced by the rotation was estimated dissipating Joule power in a resistive heater mounted on the CWR, with the CWR steady. We had to dissipate from 4 to 15 mW, to produce the same temperature increases of the CWR movement.

A change of a fraction of a Kelvin of the HWP temperature from a base temperature lower than 6K results in a small change of the C_A and C_O parameters, which are already small (see Fig. 5). The net result is a negligible effect on the detected signal.

The total time that the system was operated at low temperature is comparable to the duration of a balloon flight. No wear of the mechanism was observed yet. This was expected, because the mechanical stress on the different parts is very small.

6. Conclusions

We demonstrated the necessity of cooling down the optical components of a HWP polarimeter to cryogenic temperatures to improve its efficiency and reduce some systematic effects. We presented the mechanical design and practical implementation of a cryogenic rotator for a birefringent crystal. The system runs at cryogenic temperature, with an accuracy in the control of the rotation angle better than 0.1° . The total heat load on the cryogenic environment is about 1.1 mW (with motor off) and between 4 and 15 mW (when moving). This system meets the requirements of the PILOT stratospheric balloon experiment (Bernard et al. 2007), which will study the polarization of interstellar dust emission in the near future and is potentially useful for new CMB polarization missions, like LSPE (de Bernardis et al. 2009a) BOOMERanG and B-pol (de Bernardis et al. 2009b).

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References

- Ade, P. A. R., Ade, P., Amblard, A., et al. 2009, J. Phys. Conf. Ser., 155, 012006
- Benoit, A., et al. 2004, A&A, 424, 571
- Bernard, J. P., Ade, P., De Bernardis, P., et al. 2007, EAS Publication Series, 23, 189
- Bryan, S. A., Ade, P. A. R., Amiri, M., et al. 2010a, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy V, ed. W. Holland, J. Zmuidzinas, Proc. SPIE, 7741, 77412B
- Bryan, S. A., Montroy, T. E., & Ruhl, J. E. 2010b, ApOpt, 49, 3613
- Collett, E. 1993, Polarized light, Fundamental and Applications (Marcel Dekker, Inc.)
- Crill, B. P., Ade, P. A. R., Battistelli, E. S., et al. 2008, Proc. of SPIE, 7010, 70102P
- de Bernardis, P., Calvo, M., Giordano, C., et al. 2009a, Nuclear Physics B (Proc. Suppl.), 194, 350

- de Bernardis, P., Bucher, M., Burigana, C., & Piccirillo, L., 2009b, *Exp. Astron.*, 23, 5
- Delabrouille, J., & Kaplan, J. 2001, in *Proc. of the Pol2001 Astrophysical Polarized Backgrounds Conf.*, Bologna, Italy [arXiv:astro-ph/0112458]
- Draine, B. T. 2003, *ARA&A*, 41, 241
- Fissel, M. L., Ade, P. A. R., Angilè, F. E., et al. 2010, *SPIE*, 7741, 77410E
- Hanany, S., & Rosenkranz, P. 2003, *New Astron. Rev.*, 47, 1159
- Hanany, S., Matsumura, T., Johnson, B., et al. 2003, *IEEE Trans. Appl. Supercond.*, 13, 2128
- Hanany, S., Hubmayr, J., Johnson, B. R., et al. 2005, *Appl. Opt.*, 44, 4666
- Hildebrand, R., & Kirby, L. 2004, in *Astrophysics of Dust*, ed. A. N. Witt, G. C. Clayton, & B. T. Drain, *ASP Conf. Ser.*, 309, 515
- Hildebrand, R., Davidson, J. A., Dotson, J. L., et al. 2000, *PASP*, 112, 1215
- Jarosik, N., Bennett, C. L., Halpern, M., et al. 2003, *ApJS*, 145, 413
- Johnson, N. R., Collins, J., Abroe, M. E., et al. 2007, *ApJ*, 665, 42
- Jones, W., Bhatia, R., Bock, J. J., & Lange, A. E. 2003, *SPIE*, 4855, 227
- Lamarre, J. M., Puget, J.-L., Ade, P. A. R., et al. 2010, *A&A*, 520, A9
- Lazarian, A., Clemens, D., Adamson, A., et al. 2009, in *White Paper to the Cosmology and Fundamental Physics (GCT) Science Frontiers Panel of the Astro2010 Decadal Survey* [arXiv:0902.4226]
- Marsden, G., E. L. Chapin, M. Halpern, et al. 2008, *Proc. SPIE*, 7020, 702002
- Masi, S., Ade, P. A. R., Bock, J. J., et al. 2001, *ApJ*, 553, L93
- Masi, S., de Bernardis, P., Giordano, C., et al. 2005, *EAS Publication Series*, 14, 87
- Masi, S., Ade, P. A. R., Bock, J. J., et al. 2006, *A&A*, 458, 687
- Oxley P., Ade, P. A., Baccigalupi, C., et al. 2004, *Proc. SPIE*, 5543, 320
- Pisano, G., Savini, G., Ade, P. A. R., Haynes, V., & Gear, W. K. 2006, *Appl. Opt.*, 45, 6982
- Pisano, G., Savini, G., Ade, P. A. R., & Haynes, V. 2008, *Appl. Opt.*, 47, 6251
- Ponthieu, N., & Martin, P. G. 2006, *Proc. of CMB and Physics of the Early Universe*, Ischia, Italy, ed. G. De Zotti
- Ponthieu, N., Macías-Pérez, J. F., Tristram, M., et al. 2005, *A&A*, 444, 327
- Salatino, M., & de Bernardis, P. 2010, *Proc. of the 45th Rencontres de Moriond, La Thuile, Italy*, ed. R. Ansari et al. [arXiv:1006.3225]
- Savini, G., Pisano G., & Ade, P. A. R. 2006, *Appl. Opt.*, 45, 8907
- Savini, G., Ade, P. A. R., House, J., et al. 2009, *Appl. Opt.*, 48, 2006
- Siringo, G., Kreysa, E., Reichertz, L. A., & Menten, K. M. 2004, *A&A*, 422, 751
- Tauber, J. A., Mandolesi, N., Puget, J.-L., et al. 2010, *A&A*, 520, A1
- Tucci, M., Martínez-González, E., Vielva, P., & Delabrouille, J. 2005, *MNRAS*, 360, 935
- Vaillancourt, J. E. 2008, in *Astronomical Polarimetry*, ed. P. Bastien, & N. Manset, *ASP Conf. Ser.* [arXiv:0904.1979]