Exp Astron
DOI 10.1007/s10686-011-9267-9

ORIGINAL ARTICLE

An array of lens-coupled antennas for cosmic microwave background measurements in the 30 Ghz band

Angel Colin · David Ortiz · Enrique Villa · Edurado Artal · Enrique Martínez-González

Received: 15 March 2011 / Accepted: 24 October 2011

Abstract An array of bow-tie slot antennas coupled through an extended hemispherical lens is proposed to operate in the 30 GHz frequency band. The design includes a combination of three microstrip Wilkinson power dividers (WPD) and transitions to coplanar wave guides (CPW) to form the feeding antenna network. This configuration is suitable for the integration with heterodyne imaging detectors commonly used in radioastronomy. Measurements and simulation results exhibit a frequency range of operation from 20 to 40 GHz with a bandwidth of 24% achieved for −10 dB return loss at the central frequency. The measured radiation patterns show a maximum peak gain of around 13 dB with HPBW of 10° for the E-plane, and whose first side lobes are lower than 13 dB below the main lobe in both angular shift sides. The presented results will be considered as preliminary feasibility studies in the 30 GHz QUIJOTE-CMB Instrument, which is designed to study the anisotropies of the Cosmic Microwave Background (CMB).

Keywords Bow-tie slot antenna · Antenna-coupled · Lens · Cosmic microwave background (CMB)

A. Colin (✉)
Instituto de Microelectrónica de Barcelona, IMB-CNM (CSIC), Campus UAB., 08193, Bellaterra, Barcelona, Spain
e-mail: angel.colin@imb-cnm.csic.es

D. Ortiz · E. Martínez-González
Instituto de Física de Cantabria (CSIC-UC), Av. Los Castros s/n., 39005, Santander, Spain

E. Villa · E. Artal
Dep. Ingeniería de Comunicaciones, Universidad de Cantabria, Plaza de la Ciencia s/n., 39005, Santander, Spain

1 Introduction

Cosmic Microwave Background (CMB) observations require multi-band measurements to compare the photon fluxes at different frequencies in order to separate the different astrophysical emissions in both the microwave and the mm-wave ranges.

Many of the instruments built for the CMB study utilize very big and heavy horn antennas placed into the focal plane to receive the incoming electromagnetic signal from the primary reflector aperture, such as: CBI [13], PLANCK [15], PIQUE and CAPMAP [2], QUIET [3], or the recently QUIJOTE-CMB experiment [14] developed to study the anisotropies of the CMB, are just some of which are currently operating. It is well known that horn antennas provide the most desirable characteristics such as high beam symmetry, low cross polarization, large bandwidth, low level of side lobes, good return loss, and low attenuation [12]. However, they consume a large area of the focal plane, and the mass of such structures can have adverse implications for the cooling system. As an example, the first multichannel instrument installed in QUIJOTE, has a focal plane area of around 30 cm in diameter and holds only five horn antennas with different sizes, since the required parameters depend on the associated frequency for each receiver, while the second instrument designed to operate at 30 GHz will hold nineteen horn antennas, each one with 7 cm in diameter and 30 cm in length approximately.

Most of the current CMB instruments tend to increase the number of receivers to improve the sensitivity of future observations, therefore new designs for both high and low frequencies are needed in order to optimize the surface of the available focal plane in both ground and space telescopes, and also to reduce cost and weight of the instruments designed for space missions. Nowadays, the combination of lenses with planar antennas is being proposed as a good solution to overcome this issue. Several applications have demonstrated that a dielectric lens in direct contact with the antenna provides circular polarization and good match to the f-number of a telescope [7, 8, 16], such is confirmed with the new CMB polarization experiment called POLARBEAR [10, 11].

We propose an array of planar antennas coupled through an extended hemispherical lens to operate in the 30 GHz frequency band, which includes a collimator to focus the incoming signal. The array consist of four elements of bow-tie slot antennas aligned to the *x*-axis and connected by a microstrip feed line (MFL) joined to a combination of three Wilkinson power dividers (WPD), which is followed by transitions to coplanar wave guides (CPW) to form the feeding antenna network. This facilitates its incorporation into systems composed of the emerging front-end monolithic microwave integrated circuits (MMIC).

Our investigation is aimed towards the preliminary feasibility studies for future developments in the second instrument of QUIJOTE. The characterization of this array was made by means of measuring some of the figures of merit such as the S-parameters, gain, and the radiation pattern diagrams. For our convenience, we analyzed the array performance in the unidirectional case by introducing a movable metallic reflector plane below the substrate and varying gradually its distance, thus providing the adjustment for the return losses. All these tests provide useful information to clarify the utility for this kind of antenna with respect to the typical horn antenna configurations commonly used in the current state-of-the-art. Moreover the proposed design is also of interest for similar designs required at higher frequencies, since it is more difficult to perform accurate measurements due to the small dimensions of the designs for those frequencies. Thus rescaling a high frequency design to lower frequencies such as the ones proposed in this paper will facilitate the characterization of the corresponding design.

2 Antenna array design

The geometry of the antenna array joined to the WPD is depicted in Fig. 1. The inset shows the parameters for a single element. The complete structure was done in one run by means of chemical etching on an Alumina substrate of 36 × 36 mm^2 with 3 μm-thick electroplated gold, 0.254 mm thickness, relative permittivity of 9.9, and loss tangent of 0.0001.

The substrate has a modified ground plane, since it has a centred square cavity of 22 × 22 mm^2 without backside metallization fitting it with the CPW line and bow-tie structure. The antenna array metallization has an area of

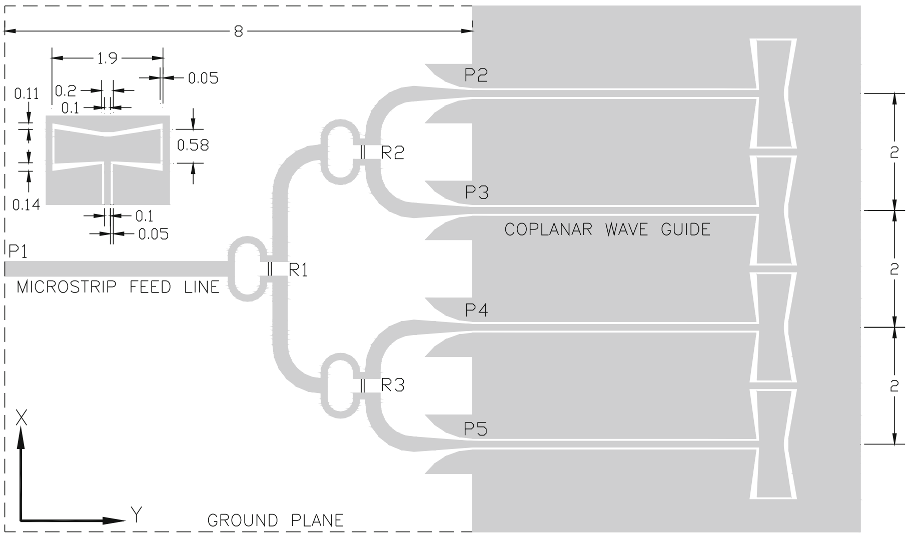

Fig. 1 Antenna array geometry (not to scale) and parameters, all dimensions are in mm

36×28 mm^2, while for the feeding section (MFL and WPD) is 8×36 mm^2. All these elements are shown in Fig. 2. The widths of the MFL and gaps of the CPW were calculated as in previous work [5] to provide characteristic impedances of around $Z_0 = 50$ Ohm respectively to reduce mismatch losses in the transition from MFL to a 50 Ohm 2.4 mm coaxial connector. The resistors R1, R2, and R3, must have 100 Ohm according to the WPD design. They were realized by means an additional Ni-Cr layer existing on the Alumina substrate. This layer has a surface resistivity of 20 Ohm/square so the resistor size determines its nominal value. A crucial aspect in the circuit design is to choose the appropriate dimensions of the resistors. With 100 Ohm each WPD has ideally perfect isolation between its two outputs. In this way a mismatch

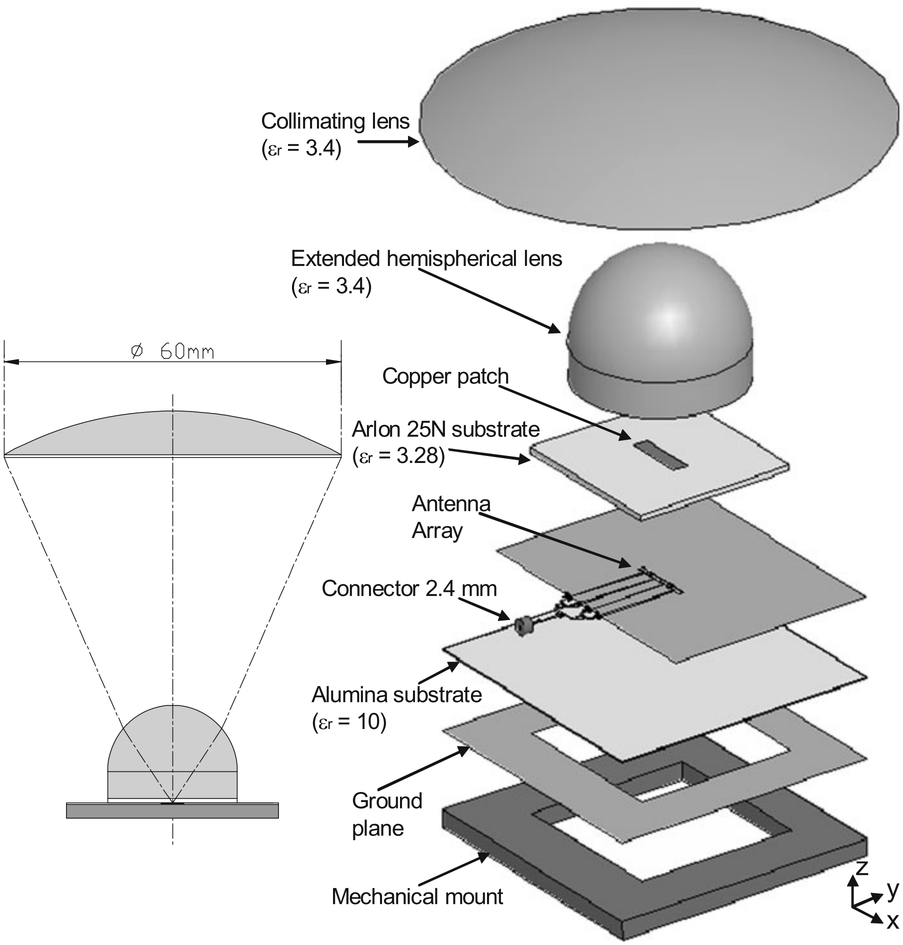

Fig. 2 Schematic arrangement (not to scale) of the setup

in an individual bow-tie element does not affect to the next element. In our case the width of the resistors is the minimum set out by the manufacturing process in the laboratory (50 μm). Following the (1), where L is the length of the resistor and W the width, the length of the resistors is determined by the resistor nominal value desired. Hence, the length must be 250 μm in order to get an equivalent resistor of 100 Ohm.

$$R = R_{square} \cdot \frac{L}{W} = 20\Omega \cdot \frac{250\mu m}{50\mu m} = 100\Omega \tag{1}$$

Once the structure was finished, it was assembled on a metallic mount made of brass material by attaching its ground plane with Epo-Tek H20E® (silver conductive epoxy).

Figure 2 shows the elements of the experimental setup, including the extended hemispherical lens fabricated as a single piece of Plexiglas® ($\varepsilon_r = 3.4$). It is composed by a cylinder of 22 mm of diameter, 4.5 mm height, and is joined to a hemisphere of 11 mm of radius. The lens is glued to a dielectric substrate, Arlon 25N® ($\varepsilon_r = 3.28$) of 22×22 mm^2 with an etched copper patch of 2×8 mm^2 on the top which in turn is glued to the antenna array structure. A concentric spherical lens of 60 mm of diameter made also of Plexiglas® is placed at the top of the hemispherical lens acting as collimator. The mechanical mount provides the basic mechanical principles to build antennas that require return losses adjustments since the movable reflector plane placed below the mount can vary vertically the reflection distance. In addition, the design can be used in direct contact with metallic surfaces, as well as with the cold plate of cryostats when low temperature experiments are required to facilitate the cooling process. Figure 3 shows two steps during the experimental setup, and the complete assembly on the structure mounted on a metal base can be seen in Fig. 4.

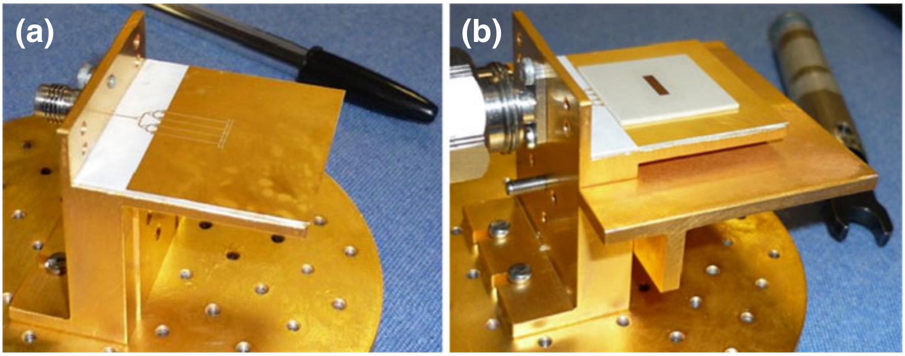

Fig. 3 Steps for the experimental setup. **a** Array of antennas mounted on the metal base. **b** Movable reflector plane placed below the metal mount after the Arlon® substrate was glued on the array

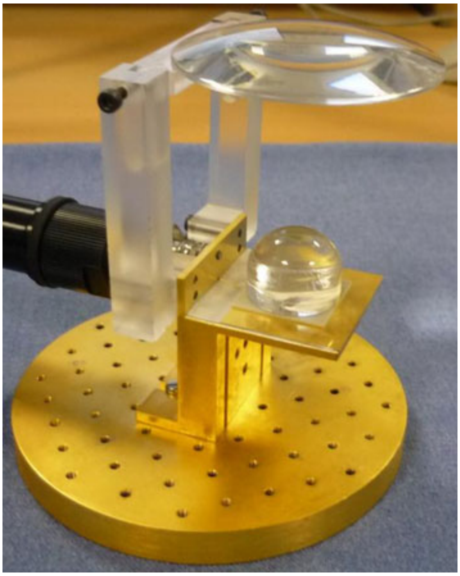

Fig. 4 Experimental setup mounted on a metal base with a spherical lens made of Plexiglas® acting as collimator

3 Measurements and simulation results

The experimental setup completely assembled was used during all sets of measurements that were made with a PNA-E8364A vector network analyzer, whereas the simulations were made using the commercial electromagnetic simulator package HFSS, which is based on the finite element method. The theoretical analysis for radiation patterns through the lens was followed using the geometrical-optics approach [8, 16]. In each set of measurements the reflector plane was placed at a distance of λ/4 below the metal base where the antenna array is glued. The gain G_A of the antenna array was measured using the comparison method with a standard horn as follow:

A bow-tie antenna unit was used as fixed antenna in the transmitter side, while in the receiver side a standard horn antenna was used as reference and then replaced by the antenna array under test. Special care was taken to place both, reference and antenna array under test, in the same position. Received power at the coaxial connector antenna array terminals was recorded, and antenna array gain obtained according to (2).

$$G_A = G_{REF} + \Delta P_R \quad (2)$$

with

$$\Delta P_R = P_A - P_{REF}$$

where G_{REF} is the standard horn antenna gain, from the manufacturer data, P_{REF} is the received power with the standard horn antenna and P_A is the received power with the antenna array under test. The results have shown that the antenna array gain achieves a maximum value of around 13 dB at the central frequency of 30 GHz.

The measurement of return loss is shown in Fig. 5. It exhibits a narrow bandwidth of 10% from 28.5 to 31.5 GHz achieved with a return loss of −10 dB. The appearance of the second resonance around 25 GHz could be caused by the finite size ground plane and the 2.4 mm connector, as well as the artifacts involved in the setup. On the other hand, the simulated results show two operating frequency bands at −10 dB, the first one from 23.5 to 31.5 GHz and the second one from 33 to 40 GHz, with bandwidths 26% and 21% respectively. It should be noted that the simulations do not take into account the real geometry of the setup, like the supporting and mechanical structures, the coaxial connectors, soldering and gluing, etc., thus given the differences between the simulations and measurements.

Far field radiation patterns were manually measured, taking values of the radiated power every three degrees in a scanned angle interval from −60° to 60° for the E-H planes. Our test results for E-plane pattern are compared with the simulation results (provided by Hoyland [9]) of one of those horn antennas at 30 GHz of QUIJOTE mentioned in Section 1, and are shown in Fig. 6.

With our planar array antenna observed that the beam pattern of the main lobe shows high degree of symmetry, achieving a maximum value of 13 dB with a HPBW of 10°. In contrast, the beam pattern of the horn antenna achieves its maximum at 18 dB, with HPBW of 20°. We also noted that with our design, the structure of the first side lobes is not symmetric, since it presents different levels between 13 dB and 20 dB below the main lobe. This asymmetry may be attributed to the field reflection produced by the top edge of the metal mount on which the 2.4 mm connector and the collimator support are screwed. It should be noted that the rough appearance of the radiation pattern is due to the manual measurement technique. On the other hand, the whole structure of the beam pattern generated by the horn antenna is entirely symmetric. Though

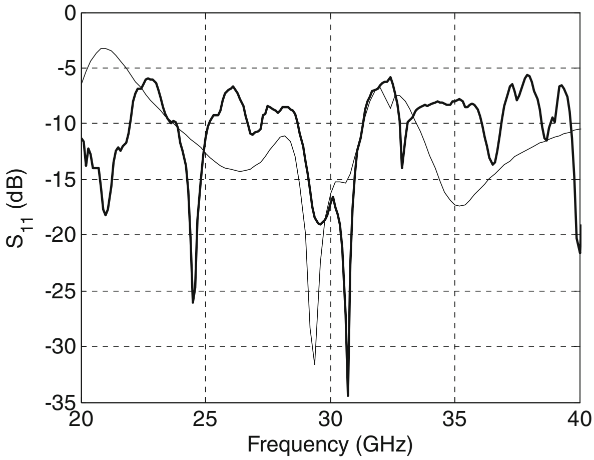

Fig. 5 Measured (*dark line*) and simulated (*thin line*) return losses

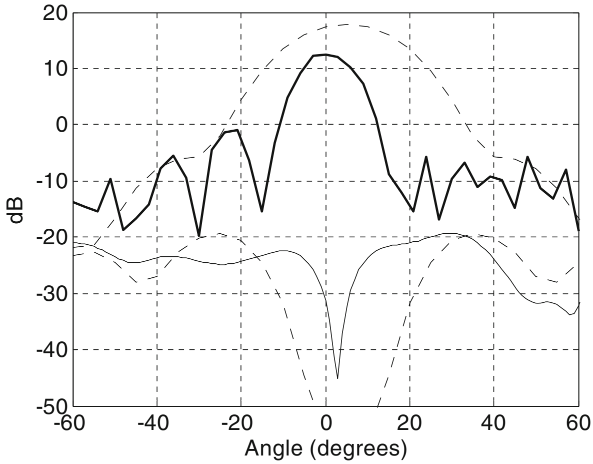

Fig. 6 Comparison of E-Plane radiation patterns at 30 GHz and cross polarization. *Dark line* and *thin line* correspond to measurements and simulation results of our planar array antenna respectively. *Dashed lines* are the simulated radiation patterns of a 30 GHz horn antenna generated with the electromagnetic simulator package GRASP®

in this plot we can only appreciate a prominent widening in the main lobe, the side lobe levels start decreasing at 40 dB below the main lobe according to the full provided data. It is evident that the horn antenna overcomes our planar array antenna in terms of gain and directivity by a factor of two approximately, but the beamwidth generated with our antenna is 0.5 times narrower than the horn antenna. It was also observed that our simulations of cross polarization present levels less than −20 dB, showing quite agreement with those of the horn antenna, thus giving us good expectations to further improve our future designs. Measurements of cross polarization were not included in this plot because of poor matching of the H-Plane measurements, in which we are working now to solve this mismatch and get the expected symmetric beam, and due to the horn antennas are still in the fabrication process.

In order to know the performance of our design with the collimator made of other materials, we realized separately a second set of measurements by replacing the collimator of Plexiglas® by one made of Teflon® ($\varepsilon_r = 2.1$), and we observed that the new results present very good similarity with the previous ones. This indicates that the measurements for both collimators are consistent to each other; hence these materials can be used for our purposes. These last results were not plotted for clarity in the graphics.

4 Outlook towards the 30 GHz QUIJOTE-CMB instrument

The presented array of planar antennas is the first step towards the possible developments of multiple arrays to study their feasibility and use in the focal plane of telescopes. The whole design provides a typical directional antenna to pointing its main lobe to a target or source, enabling its integration into an astrophysical instrument. With the geometry and structure of our design, we may propose a configuration of 19 collimating elements to cover a circular surface of 30 cm of diameter. Teflon®, Plexiglas®, and many other plastic materials, such as ultra-high molecular weight (UHMW) polyethylene, which is commonly used in cryogenic experiments, can be easily machined in a single plate to be used as a cryostat vacuum window at intermediate cooling stages or at room temperature, as is shown in Fig. 7. This proposal avoids the undesirable mechanical supports, providing free space and improving the coupling between the collimators and the hemispherical lenses coupled to the planar antennas.

We have studied and characterized previously a single element of bow-tie slot antenna at frequencies between 29 to 45 GHz, using the same Alumina® substrate and similar mechanical structure [6], but the results presented in this paper demonstrate that an array with four elements may improve the radiation patterns, increase the gain and directivity, and provide lower levels of side lobes. Each bow-tie antenna of this array is ten times smaller compared with the single one, and all of them are aligned to form a compact design, whose impedance of 50 Ohm provides a good match to microstrip transmission lines turning it suitable for integration with MMIC at these frequencies. Our mail goal is to achieve optimal structures that can be integrated with MMIC and included in low frequency coherent detection systems [1] compatibles with the 30 GHz QUIJOTE-CMB Instrument.

QUIJOTE has been conventionally designed to use horn antennas to couple the incident radiation into waveguides, mechanically connected to ortho mode transducers (OMT) to separate the signal in two orthogonal linear polar signals. With the preliminary results presented in this paper, we propose the use of our design for future experimental observations. We have taken in to account the significant advances in the technology of planar antennas. It is evident that they are promising large number of technical and physical advantages with respect to horn antennas, some of the most relevant are

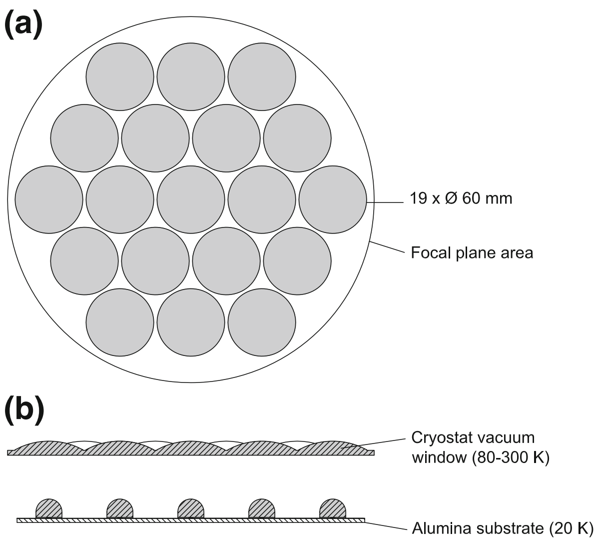

Fig. 7 Schematic arrangement (not to scale) for a configuration of 19 collimating elements machined on a single plate. It covers a circular surface of 30 cm of diameter. **a** *Top view*. **b** Section view, including hemispherical lens mounted on Alumina® substrate. See Fig. 2 for reference

for instance: (a) It has been demonstrated that slot antennas are sensitive to polarization, and can provide dual-polarized signals simultaneously [4]. (b) The combination of lens/antenna generates easily a circular and symmetric beam, and eliminates the need of expensive feed horns and quasi-optical filters. (c) A moderate bandwidths up to 15% can be easily achieved, and transmission line filters can be used in the same structure to define the operation frequency. (d) The flexibility to choice the substrate material to define the geometrical parameters, and (e) Structures at different frequency band can be constructed by simply geometrically scaling the previous design. Whether all of these advantages are taken into account together, we can offer a competitive alternative, since we are convinced that the planar antennas will be commonly used in astrophysical instruments in the nearly future.

5 Conclusion

In this paper a compact design of an array of bow-tie slot antenna-coupled lens is presented. The antenna array exhibits a maximum gain of 13 dB in the centre frequency band measured in a frequency range from 20 to 40 GHz. It shows measurements of the return losses at −10 dB with 10% bandwidth centred around 30 GHz and HPBW of 10° in the main lobe. The measured results provide relevant information to be considered in the preliminary feasibility studies applied to the 30 GHz QUIJOTE-CMB Instrument. Although the measurements were performed only at room temperature, we do not expect major changes whether the performance is realized at low temperature, because the materials that we used, e.g. Alumina®, is well characterized and is very often used under cryogenic environments. The design offers feasible solutions for integration with MMIC, with planar detectors, and with optical systems. The mechanical mount provides the basic principles to build antenna systems operating under cryogenic environments in which adjustments for the return losses are required. The present design can be considered as a typical directional antenna system to pointing the main lobe to a target or source. Hence, it can be useful not only for astrophysical purposes, but also for some communication applications.

Acknowledgements The author is grateful to the technicians: Eva Cuerno, Ana Rosa Pérez, Santiago Cembellín, and Fernando Gómez for their contributions during the fabrication process. This work was supported by the Spanish "Ministerio de Ciencia e Innovacion" through the projects ESP2004-07067-C03-01 and AYA2007-68058-C03-02.

References

1. Aja, B., Artal, E., de la Fuente, L., et al.: Very low-noise differential radiometer at 30 GHz for the PLANCK LFI. IEEE Trans. Microwave Theor. Tech. **53**, 2050–2062 (2005)

2. Barkats, D., Bischoff, C., et al.: Cosmic microwave background polarimetry using correlation receivers with the PIQUE and CAPMAP experiments. Astrophys. J. Suppl. Ser. **159**, 1–26 (2005)
3. Buder I.: Q/U Imaging Experiment (QUIET): a ground-based probe of cosmic microwave background polarization. Proc. SPIE. **7741**, 77411D (2010)
4. Chattopadhyay, G., Zmuidzinas, J.: A dual-polarized slot antennas for millimeter waves. IEEE Trans. Antennas Propag. **46**, 736–737 (1998)
5. Colin, A., Febvre, P.: Design of a wideband slot bow-tie antenna excited by a microstrip to CPW transition for application in the millimetre wave band, pp. 1421–1425. PIERS Proc. Moscow, Russia (2009)
6. Colin, A., Artal, E., Villa, E., et al.: Bow-tie slot antenna for 29 to 45 GHz band. Far East J. Electron. Commun. **4**, 69–76 (2010)
7. Eleftheriades, G.V., Brand, Y., et al.: ALPSS: a millimetre-wave aperture-couple patch antenna on a substrate lens. Electron. Lett. **33**, 169–170 (1997)
8. Filipovic, D., Gearhart, S., Rebeiz, G.: Double-slot antennas on extended hemispherical and elliptical silicon dielectric lenses. IEEE Trans. Microwave. Theor. Tech. **41**, 1738–1749 (1993)
9. Hoyland, R.: Private communication
10. Kam, A., Ade, P.A.R., et al.: The POLARBEAR CMB polarization experiment. Proc. SPIE **7741**, 77411E (2010)
11. Myers, M.J., Arnold, K., Ade, P., et al.: Antenna-coupled bolometer arrays for measurement of the cosmic microwave background polarization. J. Low Temp. Phys. **151**, 464–470 (2008)
12. Olver, A.D.: Corrugated horns. Electron. Commun. Eng. J. **4**, 4–10 (1992)
13. Padin, S., Shepherd, M.C., et al.: The cosmic background imager. Publ. Astron. Soc. Pac. **114**, 83–97 (2002)
14. Rubiño-Martin, J.A., Rebolo, R., Tucci, M., et al.: The QUIJOTE CMB Experiment, Highlights of Spanish Astrophysics V, Astrophysics and Space Science Proceedings, pp. 127–135. Springer, Berlin Heidelberg (2010)
15. Villa, F., Sandri, M., Mandolesi, N., et al.: High performance corrugated feed horns for space applications at millimetre wavelengths. Exp. Astron. **14**, 1–15 (2002)
16. Wu, X., Eleftheriades, G.V., et al.: Design and characterization of single and multiple beam mm-wave circularly polarized substrate lens antennas for wireless communications. IEEE Trans. Microwave Theor. Tech. **49**, 431–441 (2001)