BRAIN/MBI: a bolometric interferometer dedicated to the CMB polarization

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A. Tartari(1), J.G. Bartlett(1) , E. Battistelli(2), A. Baù(3), D. Bennett(4), L. Bergé(5), J.-P. Bernard(6), A. Bounab(6), E. Bréelle(1), E. Bunn(7), R. Charlassier(1), A. Cruciani(2), S. Collin(5), G. Curran(4), P. De Bernardis(2), L. Dumoulin(5), A. Gault(8), M. Gervasi(3), A.Ghribi(1), M. Giard(6), C. Giordano(2), Y. Giraud-Héraud(1), M. Gradziel(4), L. Guglielmi(1), J.-C. Hamilton(1), V. Haynes(9), A. Iacoangeli(2), J. Kaplan(1), A. Korotkov(12), J. Lande(6), B. Maffei(9), M. Maiello(10), S.S. Malu(11), S. Marnieros(5), S. Masi(2), A. Murphy(4), C. O'Sullivan(4), F. Pajot(12), A. Passerini(3), S. S. Peterzen(2), F. Piacentini(2), L. Piccirillo(9), M. Piat(1), G. Pisano(9), G. Polenta(2,14), D. Prêle(1), C. Rosset(1), A. Schillaci(2), G. Sironi(3), S. Spinelli(3), G. Tucker(13), P. Timbie(8), F. Voisin(1), B. Watson(9), M. Zannoni(3)

(1) *Université Paris Diderot*
AstroParticule et Cosmologie (UMR7164)
10 Rue Alice Domon et Léonie Duquet
75205 Paris Cedex 13, France
Email: tartari@apc.univ-paris7.fr
(2) *Università di Roma – La Sapienza*
P.le Aldo Moro, 2 00185 Roma, Italy
(3) *Università di Milano-Bicocca*
piazza della Scienza,3 20126 Milano, Italy
(4) *NUI-Maynooth*
Maynooth, Co. Kildare, Ireland
(5) *CSNSM-Orsay*
91405 Orsay Campus, France
(6) *CESR-Toulouse*
9, Avenue Colonel Roche, 31028 Toulouse, France
(7) *University of Richmond*
28 Westhampton Way University of Richmond, VA 23173, USA
(8) *University of Wisconsin*
1150 University Avenue Madison, WI 53706-1390, USA
(9) *University of Manchester*
Oxford Road, Manchester, M13 9PL, United Kingdom
(10) *Università di Siena*
via Roma 56 - 53100 Siena, Italy
(11) *IUCAA-Pune*
Post Bag 4 Ganeshkhind Pune University Campus Pune 411 007, India
(12) *IAS-Orsay*
Centre universitaire d'Orsay Bât 120 – 121 91405 Orsay, France
(13) *Brown University-Providence*
Providence RI 02912 (401) 863-1000, USA
(14) *ASI Science Data Center, c/o ESRIN*
via G. Galilei, I-00044 Frascati, Italy

INTRODUCTION

In this paper we present a new experiment dedicated to the study of the Cosmic Microwave Background (CMB) polarization. BRAIN/MBI, the result of the merging of two formerly distinct experiments, MBI (see [1], and references therein) and BRAIN (see [2], and references therein), both based on a Bolometric Interferometry (BI in the following), will be called henceforth QUBIC (Q and U Bolometric Interferometer for Cosmology). This ground-based experiment will be one of the next-generation CMB polarimeters and will fill a technological gap, being the only adding interferometer proposed in the field of CMB research, and with a sensitivity needed to target B-modes. Among proposed and/or running experiments, there are fully integrated coherent polarimeters (QUIET [3]), imagers (ClOVER [4], BICEP [5], QUaD [6]) and broadband heterodyne interferometers (AMiBA [7]). QUBIC will explore a different experimental approach, allowing cross-checks with other experimental techniques, and the final validation of BI at mm-waves. This is of crucial importance, since the detection of B-modes (if any) will be achieved by an experiment reaching the best balance between sensitivity and accuracy (control of systematics). The structure of the paper is the following. We introduce in brief the science case driving this experiment; we outline the basic principles of BI, mostly developed by people within this collaboration; we present the architecture and some of the main characteristics foreseen for QUBIC. Then we concentrate on subsystems which have a unique role in BI: the phase shifter and the beam combiner. For these subsystems we present a variety of possible technological choices, some of them now under study.

THE SCIENCE CASE

The fact that the degree of linear polarization of the CMB is nonzero, was recognized quite early [8]. More recently [9], it has been pointed out that the cosmological polarized signal can be decomposed into two topologically different components: the E- and the B-mode (respectively a gradient and a curl term). E- modes have been firmly detected by several experiments, the first one being DASI [10], an heterodyne interferometer, able to reach the sensitivity required to obtain a 6σ detection of a few μK signal (the expected level of polarized anisotropies), in the frequency band 26-36 GHz, on angular scales between 1.3^o and 0.2^o, after 3 years of operation. B-modes have not been detected until now and several experiments at different angular scales are aimed at their detection. Unlike the E-mode, whose amplitude can be estimated starting from temperature anisotropies, its amplitude is a priori unknown, since different inflationary scenarios foresee a range of allowed values which span orders of magnitude, while the debate on its lower limit is still open. We only know that, if there, it will be at least a factor 100 fainter than the E-mode signal. The search for B-modes is driven by the fact that their detection would mean an indirect detection of primordial gravitational waves [9] and a unique probe towards the physics at the energy scale of inflation.

BOLOMETRIC INTERFEROMETRY

The idea of using adding interferometers for CMB cosmology is quite recent [11], and the theoretical and experimental investigation of some issues concerning the sensitivity and the accuracy of this technique is still in progress. Nevertheless, [12], [13] and [14], a series of papers motivated by the simultaneous development of BRAIN and MBI, provide a clear direction for developing a practical and efficient bolometric interferometer, and show how to achieve the maximum sensitivity. This last point, in particular, is not obvious, and can be achieved satisfying a condition of coherent summation of *equivalent baselines* [12]. The introduction of this technique in the field of CMB cosmology is motivated by the fact that a B-mode experiment must be sensitive and not contaminated by instrumental effects. More precisely, the error budget has to be dominated by statistics, and not by spurious systematic effects. Interferometry allows to reach the desired angular resolution without using optics, but simply observing the sky using feed-horns, minimizing in such a way the effect of the cross-polarization; moreover it is intrinsically a coherent technique, allowing for such reason an easier rejection of contaminations. At the same time bolometers are the most sensitive detectors for the continuum broadband detection, and, at the state-of-the-art, they can be operated at the limit of CMB NEP. Therefore the ideal bolometric interferometer is expected to exploit the advantages of both interferometry (in terms of accuracy) and bolometric detection (in terms of sensitivity). We add that the output of an interferometer is the Fourier transform of the brightness distribution of the sky, which, in our case, is directly the angular power spectrum of CMB anisotropies. Here we just recall some basic facts concerning BI, all the details being extensively explained in the aforementioned papers.

In adding interferometry, EM fields are linearly combined and then detected by a bolometer. No correlation unit is needed, since correlation is obtained through detection. In a naïve picture, let's suppose that 2 antennas of an array (labelled j and k) give output signals E_j and E_k respectively. If these fields are then phase shifted by controllable devices, in a time-dependent way, and then phase shifted again, but this time simply because of different optical/electrical paths, then the resulting fields are $\bar{E}_j = E_j exp[i(\phi_j(t) + \phi_{g,j})]$ and $\bar{E}_k = E_k exp[i(\phi_k(t) + \phi_{g,k})]$. If a linear combination of these fields $E_m = \bar{E}_j + \bar{E}_k$ reaches a bolometer, then the output is proportional to

$$Z_m = \mid E_m \mid^2 = \mid E_j \mid^2 + \mid E_k \mid^2 + \Re(E_j E_k^*) cos[\Delta\phi_{jk}(t) + \Delta\phi_{g,jk}] - \Im(E_j E_k^*) sin[\Delta\phi_{jk}(t) + \Delta\phi_{g,jk}] \quad (1)$$

where $\Delta\phi_{jk}(t)$ is the controlled phase difference and $\Delta\phi_{g,jk}$ is the constant geometrical one. In (1) we can distinguish a constant autocorrelation term, accompanied by phase-modulated cross-terms which corresponds to the visibilities of a radio interferometer. In fact, if the antennas are separated by the distance $\overrightarrow{d_{jk}}$, when they observe a signal coming from the direction $\vec{n}$, then the phase difference between these two branches of the interferometer is $\vec{u}_b \cdot \vec{n}$, where $\vec{u}_b = 2\pi\vec{d}_{jk}/\lambda$. If the antennas collect the field $\vec{E}$ with the same beam $\vec{B}(\vec{n})$, then $E_j = \vec{B} \cdot \vec{E}$ and $E_k^* = \vec{B} \cdot \vec{E} exp(-i\vec{u}_b \cdot \vec{n})$, so that, after integration on the angles, the third term in (1) gives the real part of the visibility

$$V(\vec{u}_b) = \int B^2(\vec{n}) I(\vec{n}) e^{-i\vec{u}_b \cdot \vec{n}} d\vec{n} \quad (2)$$

multiplied by a modulation function (the same considerations hold for the fourth term in (1)). Doing one step more, and assuming that each antenna is a dual polarization system, the cross-correlation terms will provide the visibilities of four Stokes parameters $\vec{S} = \{I, Q, U, V\}$, since one polarization of each antenna can be correlated with two polarizations of another antenna in the array. In particular, as shown in [12], at each time t, the output of the m-th detector will be a linear combination of the Stokes vector and of the b visibilities $\vec{V}_b = \{V_{b,I}, V_{b,Q}, V_{b,U}, V_{b,V}\}$, whose number is $b = N_h(N_h - 1)/2$, N_h being the number of horns looking at the sky. The crucial point, clarified for the first time in [12], is that there's a particularly useful way of representing a linear combination of baselines. Defining a family of equivalent baselines as the collection of baselines having the same length and direction, and labelling the families of equivalent baselines with β, the output terms of the m-th bolometer can be rearranged to obtain

$$Z_m = \vec{\Lambda}_m \cdot S + \sum_\beta \vec{\Gamma}_{m,\beta} \cdot \vec{V}_\beta \quad (3)$$

$\vec{\Gamma}_{m,\beta}$ and $\vec{\Lambda}_m$ being vectors whose elements are sines and cosines of the phase differences $\Delta\Phi$ of the signals reaching the m-th detector. What has been noticed by the authors of [12] is that, in order to be able to invert the complete linear problem and recover the sky signals (the visibilities), the equivalent baselines must share the same temporal sequence of phase shifts. In this way equivalent baselines are summed coherently on each detector, and the maximum theoretical sensitivity per each baseline can be achieved. Indeed this explains why the phase-shifter plays a peculiar role in BI: aside from signal modulation, needed to suppress the low frequency noise, it drives the process of equivalent baselines recovery, achieving higher signal-to-noise.

QUBIC

QUBIC will be a bolometric interferometer able to measure all the polarized visibilities.The basic architecture for QUBIC is shown in Fig.1. In this scheme the sky is observed directly with feed horns. Then, an Orthomode Transudcer (OMT) separates the two polarizations, labelled $\perp$ and $\|$. Therefore, if $N_h$horns are looking at the sky, $2N_h$branches of the interferometer have to be phase-shifted according to the coherent baselines summation scheme, and $2N_h$ identical phase-shifters (green, in Fig.1) have to be built. After each signal is phase-shifted in a proper way, at each time t, all the signals reach the input of the beam combiner, represented as light blue rectangle in the flow diagram in Fig.1. Here we do not add more on the combiner we will use for QUBIC, since this issue will be discussed in the following. Suffice it to say that it will be an all-to-one combiner, like a Fizeau interferometer. Its purpose is to produce linear combinations of all the input fields, as shown in Fig.1, in such a way that each detector can be reached by all the $2N_h$ input signals. As shown in the previuos paragraph, the correlation will be achieved after detection.

This architecture will be implemented for basic blocks whose size will be approximately around 10×10 horns. Several 100-horns modules, up to 6, will look at the sky through different vacuum windows, all the system being hosted in a cryostat (see Fig.2). The horns will be closely packaged, in such a way that the length of the shortest baseline will be approximately equal to the horn diameter. Considering realistic horns and vacuum windows diameters, the multipole range that can be sampled in the Fourier space will be $20 \lesssim l \lesssim 200$, corresponding to angular scales between 0.9^o and 9^o. In turn, this multi-module configuration will be replicated at two frequencies: 90 and 150 GHz. This is needed beacause foreground signals, mostly of galactic origin, have to be disentangled from the overall sky signal. This can be done recognizing their frequency spectrum, typically a power-law.

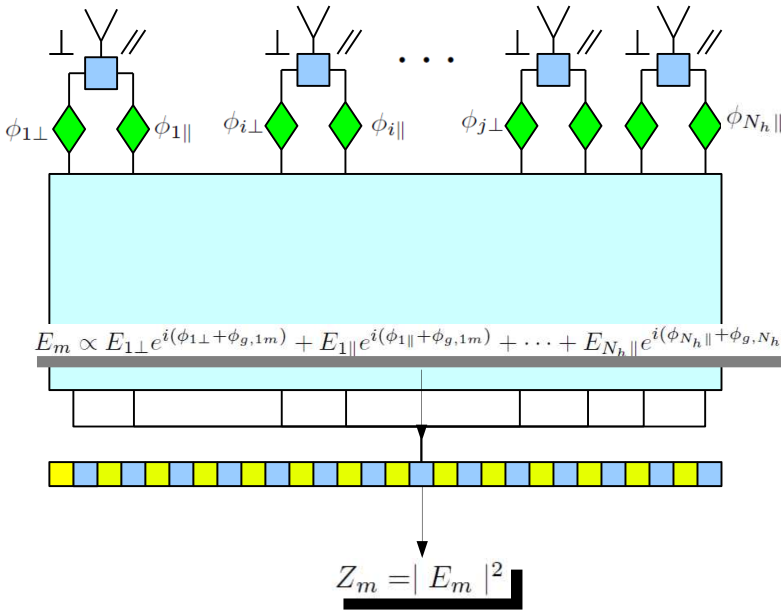

Figure 1: Here we represent the architecture of a QUBIC module. The feed-horns aim directly at the sky. The upper squares are the OMTs. Green: phase shifters. The light blue box represent the beam combination section, which may be both a quasi-optical combiner or a Butler matrix. Then, at the end, the row of detectors. Here we represent the m-th output of the system at a generic time t.

At present the definitive choice on the detectors for QUBIC has not yet been done, even if TES and KIDs may be the most important options.

More on the different subsystems will be added in the following paragraph. Here we just underline that with this kind of architecture, a number of phase-shifts of the order of 20 has to be foreseen for the equivalent baselines recovery.

SUBSYSTEMS

As pointed out in some of the early references on BI, the two technological challenges peculiar to this experimental technique are (1) the development of a multi-valued, low-loss, fast and broad-band phase modulator and (2) the design of a beam-combiner (optical or wave-guided) able to add each of the N_h signals to the remaining $N_h - 1$ on each detector. This can be done by means of a Fizeau optical combiner or, at least in principle, by means of a Butler matrix.

Phase Modulator

The role played by phase modulation in a BI is twofold. On one hand, as in imaging experiments, it is a tool to keep under control the colored noise of the system ($1/f$, $1/f^2$...) and to operate it close to the white noise floor. On the other hand, it plays a peculiar role in BI: it is the process which allows a coherent summation, on a given detector, of all the equivalent baselines, that is, all the baselines corresponding to the same baseline vector $\vec{u}_b$. A phase modulation can be achieved modulating the electromagnetic dispersion properties in a waveguide device. This is the case of the rotary phase shifters, using a rotating half-wave plate [15] mounted in a circular waveguide between a couple of fixed parallel quarter-wave plates. The phase shift produced by this device is completely determined by the mechanical rotation (the phase shift is twice the mechanical rotation angle), and is flat in frequency. These properties have been demonstrated for example in [16], where results on a phase shifter operating in WR10 are presented. In particular, the authors find phase flatness within $0.7^o$and insertion loss <-0.3dB over the sub-band 80-95 GHz. A family of two-ports devices commonly used are the ferrite phase-modulators. They can be operated in a variety of ways, for example as Faraday rotation modulators, like

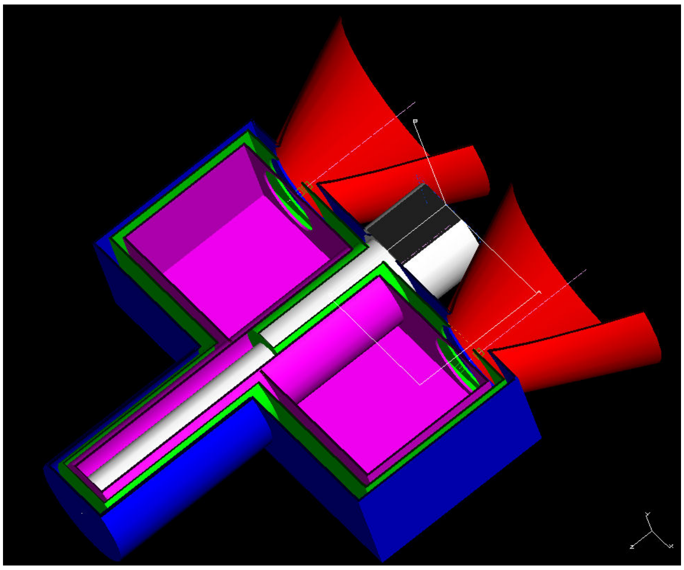

Figure 2: A possible cryostat for QUBIC. A single cryocooler head is used for a 4-modules configuration. Only two modules are represented in this projection.

those used for the ongoing BICEP CMB polarization experiment [17], where an insertion loss <-1dB has been achieved. Inside the QUBIC collaboration, ferrite phase shifters are currently used for MBI4, while rotary phase shifters have been used to build a single baseline demonstrator (DIBO). Both these technologies are intrinsically broadband, which is a stringent requirement for CMB instrumentation. Nevertheless, one is not suitable for applications at LHe temperatures, since it requires moving parts, while the other shows non negligible losses. Moreover, these kind of devices are mostly used in waveguide systems, whose scalability on arrays of hundreds of horns may be critical. For this purpose, planar technologies offer more attractive chances. We include in this family of phase-shifters also those based on ferroelectric (BST) thin films: in this case the phase velocity of the wave in a line section (a Coplanar Waveguide for example) is modulated tuning a distributed shunting capacitance.

A second way to build a phase modulator is to switch the incoming signal towards lines of different electrical length, in such a way that the phase difference $\Delta\phi$ between a reference and a delayed (Δl) path is simply $\Delta\phi = \beta_{nm}\Delta l$, where β_{nm} is the propagation constant of the wave propagating in the transmission line in the mode nm. In this case, the phase modulation is achieved (in discrete steps) combining mm-wave switches and delay lines, and the phase-shift varies linearly with frequency. In turn, this approach can be implemented according to different schemes, using PIN diodes or FETs as switching elements in single-pole/single-throw or single-pole/double-throw configurations [18]. Also MEMS [19] may be an important alternative to this purpose: extremely promising properties in terms of low-insertion loss ($\lesssim -0.4$ dB) and high isolation (from -30 to -40 dB) have been obtained [20] at 300 K on the full W band (75-110 GHz) using a CPW geometry with gold metallizations on a high resistivity silicon wafer. Best performances with insertion loss around -0.1dB till 100 GHz have now been achieved. Nevertheless the problem of long duration reliability for a device operating in a cryogenic environment, a key requirement for a CMB experiment, has still to be addressed.

A possible choice for QUBIC could be based on superconducting delay lines, switched by a superconducting thermal switch. In fact we are interested in low loss applications. A natural choice, also considering that this is an important option for the OMT, is is to use superconducting (Nb, NbN) planar transmission lines (Coplanar Waveguides or Microstrips). Superconductors are the ideal candidates non only because of their intrinsically negligible ohmic losses (a residual resistivity is due to the quasi-particles population at T>0K), but also because of the sharp onset of the superconducting state: this fact suggest to exploit the transition from the superconducting state to the normal state to achieve the ON-OFF switching (see [21] and [22]). The transition can be obtained injecting current pulses or, as sometimes done in other domains of superconducting electronics, heating the electrons by means of optical pulses ([23] and [24]).

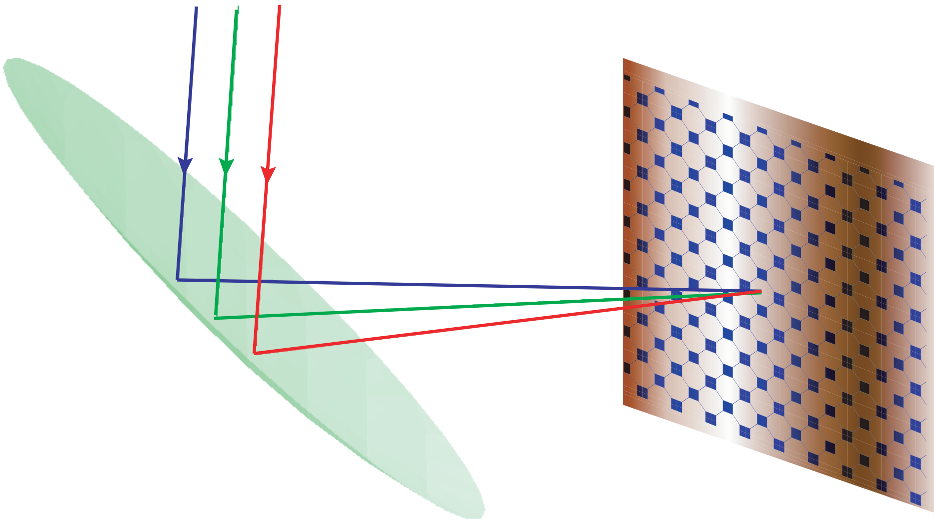

Figure 3: The principle of the optical combiner is schematized taking just three rays coming from different seconday horns. The parallel rays are focused on the same point on the detectors plane. In this configuration, the interference pattern is imaged by the detectors.

Combiners

There are two kinds of combiners that in principle can be suitable for use in a bolometric interferometer: an optical Fizeau beam combiner, and a Butler combiner. Both these devices map all the input signals on one detector. Stated otherwise, at each time t, each detector sees a linear combination of all the inputs of the combiner, the coefficients being phase factors in the ideal case. In fact the Fizeau combiner, unlike the Michelson interferometer in which the signals are combined pairwise, is an all-to-one system, satisfying the above condition.

At present the most attractive architecture for QUBIC is that one already proposed and built for MBI4 [1]. In this experiment, after the phase shifting, all the signals are launched by re-emitting (secondary) back horns towards an optical sytem (like that one represented in Fig.3) focusing the rays on the detectors plane. In this way, the detectors sample the interference fringes. The main requirement to be fulfilled by the optical combiner is that a family of parallel rays emerging from different secondary horns have to be focused on the same detector, as we can see in Fig.3, where a parabolidal mirror focuses three rays (red, green and blue) on the same bolometer. This system, despite its conceptual simplicity, is not easly designed. Despite the cross-polarization not being an issue (since polarizations are separated at the OMT level) other problems arise. In fact, in order to minimize aberrations, which could hamper the efficiency of the system, an on-axis large f/# combiner should be designed. The problem is that an on-axis two-mirrors system the primary is partially obscured, while increasing f/# means increasing the number of detectors needed to sample adequately the interference pattern. Moreover, in order to minimize the radiative load on the detectors, this optical system must be compact, suitable to be fit into a cryostat. Several solutions are now under study, preferably off-axis systems satisfying aberrations compensation conditions: among them gregorians and CATR. Three mirrors wide-field Fizeau combiners corrected for spherical aberration, coma, astigmatism and field curvature are also studied in literature, even if at optical wavelenghts and for completely different astronomical applications [25] .

As we have seen in the section dedicated to BI, there's a linear system that has to be inverted to retrieve the sky visibility functions. The elements of the matrix representing the transfer function of our instrument are essentially sines and cosines of phase differences. Considering two horns j and k aiming at the sky, the phase difference among them is $\Delta\Phi_{jk}(t) = \Delta\phi_{jk}(t) + \Delta\phi_{g,jk}$, so that the elements of the transfer functions will be in the form $sin[\Delta\Phi_{jk}(t)]$ or $sin[\Delta\Phi_{jk}(t)]$.

The term $\Delta\phi_{g,jk}$ in this relation is time-independent and purely geometrical (mostly due to the beam combiner), and it may introduce a constant unknown phase offset in correspondence of different baselines. Despite the study of the systematics in BI is in progress [26], preliminary results suggest that the most stringent requirements on phase errors have to be considered for the design of the phase-shifters, controlling the time-dependent term.

Another solution to achieve a suitable beam combination is the use of a Butler combiner. This device, commonly used for beam steering applications, has $2N_h$ inputs and the same number of outputs. It combines the beams exactly in the same way of the optical combiner, that is, it produces at each output a linear combination of all the input fields, the coefficients being phase factors.

The Butler can be realized in planar superconducting transmission lines, a technology that it may share with the OMT (A.Ghribi, this Conference) and the phase-shifter, which is an evident advantage. No doubt it would contribute also to an extremely compact design of the interferometer. Nevertheless the techincal feasibility of such a device for $N_h > 10^2$, resulting in microwave network with thousands of nodes, has never been assessed. On the other side, the problem of losses (radiative and dielectric) will be more relevant than in a properly designed optical system. Therefore, at present, the degree of technological readiness and efficiency considerations suggest to develop a Fizeau scheme for the QUBIC's combiner.

Orthomode Transducer

For completeness, we add that an OMT, which is a critical device meant to split the two polarizations with an extreme purity, will be developed for QUBIC. We do not add more on it, since a possible design of this device will be discussed thoroughly by A.Ghribi in this Conference.

FUTURE PROSPECTS

An important effort has been done in the recent years to understand BI from a theoretical point of view. Some experimental demonstrators have been built and tested.

We have tools to evaluate the tolerances on the different stages of a realistic BI architecture, given a scientific target. For each subsystem of QUBIC there are technological options already studied for other experiments or applications, but some peculiarities of BI will require this collaboration to make an all-out effort to develop state-of-the-art technologies. This is the case for the mm-wave phase-shifters and the multi-beam combiner. We believe that these efforts deserve to be undertaken since at present there are no experiments reaching a sensitivity close to the B-modes threshold. Some experiments that could reach the desired accuracy are planned, but there are different issues related to contamination from systematic effects that have to be addressed experimentally. BI could be an important alternative to imagers and heterodyne interferometers. A bolometeric interferometer can approach the sensitivity of an imager (though it will be slightly less than that of the imager [13]), but with all the advantages of traditional radio interferometers in terms of systematics control. In view of a post-Planck CMB space mission, we believe that an experiment like QUBIC will be useful to demonstrate all the potentialities of an elegant and conceptually simple technique like bolometric interferometery, and to allow a direct comparison of BI with other more consolidated experimental approaches.

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