IDENTITE DU PROJET :

**A3M**

Antennes large bande à Métamatériaux pour le MilliMétrique pour le spatial.
Metamaterial broadband Antennas for the Millimeter for spatial applications.

**Durée:** 42 mois  
**Aide demandée:** 540 000€

**Partenaires :**
- Centre de Nanosciences et de Nanotechnologies (Université Paris Sud)
- AstroParticule et Cosmologie (Université Paris Diderot)
- Galaxies, Etoiles, Physique et Instrumentation GEPI (Observatoire de Paris)

I. Contexte, positionnement et objectif(s) de la proposition

The Cosmic Microwave Background (CMB or 3K cosmological background), which is the first light emitted about 380000 years after the Big Bang, is an overwhelming source of information in Cosmology. A promising way to constrain inflation, an explosive period of expansion, is to measure and characterize precisely the so-called B-modes of the CMB polarization. This signal is however expected to be very tiny (of the order of a few nK over the 2.7K continuum) which needs a challenging instrumentation to detect it. For this objective, the CORE (Cosmic ORigins Explorer) satellite has been proposed to the M5 ESA call in October 2016. The detection chain is based on Kinetic Inductance Detectors (KIDs) which have made remarkable progresses in the last years. Arrays of thousands of KIDs detectors at 100mK are now produce routinely and are reaching more and more maturity especially with the NIKA and NIKA2 instruments (Néel IRAM KIDs Array). A major improvement of these detectors is nevertheless required in the way it is coupled to the incoming electromagnetic wave. Today, only simple absorbers are used in France, while antenna coupling is being developed in other countries (mainly in the USA). While simple, the use of an absorber has the disadvantages of being not intrinsically sensitive to polarisation and sensitive to a very large solid angle. This last point especially leads to the need of using heavy horns to couple detectors with the telescope in order to control sidelobes to very low level as required to detect the tiny B-mode signal on the sky. Even for the current developments of antenna-coupled detectors, sidelobes level are not controlled enough leading to the need of a complex optical architecture with a cold Lyot stop in order to decrease sidelobes on the sky. The aim of this project is therefore to go further to what is being developed for antenna-coupled detectors and replace heavy horns with planar structures able to get the same performances as horns: wide bandwidth (30% or more to produce multiband detectors but this is optional), low losses (>1dB), Gaussian beam of 10° to 20° FWHM down to -20dB, very low sidelobes (-30dB to -50dB), sensitive to polarisation with a low cross-polarisation (-30dB) and able to being efficiently coupled to the current detectors (TESs, KIDs). **Metamaterial antenna** appears to be a promising candidate to reach such performances.

The interest of metamaterials and the number of work undertaken on this subject has increased in the recent years due to their fantastic electromagnetic properties. Indeed, these metamaterials consisting of a periodic stack of metallic wires and split ring resonators (period \( \approx \lambda/10 \)) can exhibit permittivity and permeability simultaneously negative (D. Smith et al., 2000). The two frequency fields, optics and microwaves, are mainly different by the intrinsic properties of the materials used in these periodic structures, but also by the methods of realization and characterization. For example the use of metallic materials, which is relatively easy in microwave domain, becomes problematic in optics, even if recent developments open promising prospects. This explains why the study of metamaterial is mainly theoretical.
Many experimental works are made at low frequencies in the microwave domain (around 10 GHz) because the fabrication of such metamaterial-based devices uses the precept of printed board circuits. At higher frequencies (from mm/submm wavelengths up to the near infrared and visible), due to the small size of the elementary cell of the lattice, this technique is no longer feasible and the use of nano and micro technologies are required to realize prototypes. Furthermore, these frequency domains (from 100GHz to 1 THz) are not exploited because the lack of experimental set-up and applications in this frequency range. However more and more applications, in particular in radio-astronomy, appeal to this field of frequency which goes from 100GHz to a few THz, covering an intermediate band between traditional optics and microwaves. Within this framework, we propose to study the development of functions appealing to the particular physical properties of periodical structured materials. By using these news structures, we can realize broadband antennas, from 75GHz to 110GHz. Another objective will be the fabrication of multiband antennas. Recently, we have conduct research on the design and simulation of wide band planar antenna. The first conclusive results have led to an invited communication. This antenna is being fabricated to be tested. Our objective is now to associate metamaterial to improve their performances.

So the purposes of this project are the design, the fabrication and the characterization of a new family of superconductors broadband and directive antennas made with metamaterials working at 90, 150 and 220GHz. The performances of these antennas will be improved thanks to the electromagnetic properties of left handed materials and are dedicated to the radio astronomy applications.

In this project five steps are planned:

- The first step is dedicated to the numerical and experimental validation of our tools and methods for antennas working at 90GHz. In the same time, the experimental set-up will be to upgrade for higher frequencies (from 100GHz to 1THz).
- The second step concerns the design and the fabrication of these antennas. Then measurements will be done.
- The third step is devoted to the optimisation of the devices (new calculation, fabrication and measurements) and to the demonstration of the feasibility of the same at 90, 150 and 220GHz.
- The fourth step concerns the coupling of the microwave metamaterials antennas with classical detectors such as bolometers or KIDs. Indeed the development of bolometer arrays is very important for CMB experiments and the coupling with the microwave antennas appears to be unavoidable.
- The last step concerns the integration of these planar metamaterials antennas into the QUBIC instrument.

II. Organisation du projet et moyens mis en œuvre

The three partners in this project have worked together. This synergy and complementarity has already resulted in joint publications on previous projects. This project is based on the high complementarity of the different partners in the domain of the simulation, the design and the technological process as for the characterization tools. Actually, the multidisciplinary is illustrated by the know-how of each partner (developed in the Annex):

- U-PSUD/C2N provides simulations of metamaterial antenna and technological facilities.
- Université Paris Diderot/APC brings its knowledge of the experimental cryogenic measurements in the domain of the radio astronomy at low temperature (300mK).
- Observatoire de Paris/GEPI supplies its knowledge of antennas and associated test facilities.

Concerning the coordinator, Frédérique Gadot: Since 1996, she worked numerically and experimentally on photonic band gap materials and on metamaterials in the microwave and near IR domains (developed in the Annex)
Repartition of requested resources:

<table>
<thead>
<tr>
<th>Partners</th>
<th>Equipment</th>
<th>Personnel</th>
<th>Fonctionnement</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2N</td>
<td>10 k€ (computers)</td>
<td>120 k€ (PhD student)</td>
<td>100 k€ (30 k€ for the calculations and 70 k€ for the fabrication in clean rooms)</td>
</tr>
<tr>
<td>APC</td>
<td>40 k€ (experimental set-up)</td>
<td>100 k€ (Post-Doc)</td>
<td>30 k€ (modelisation)</td>
</tr>
<tr>
<td>LERMA</td>
<td></td>
<td>100 k€ (Post-Doc)</td>
<td>40 k€ (10 k€ for RF design and 30 k€ for realization)</td>
</tr>
</tbody>
</table>

TOTAL: 540 k€

III. Impact et retombées du projet

To summarize this innovative project, its main ambitions concern:

- The realization and the characterization of these metamaterial antennas at 90, 150 and 220 GHz at low temperature,
- The upgrade of the experimental set-up from 100 GHz to 1 THz at 300K or 4K (for vectorial measurements) and 300 mK (for coupling with the bolometers).

It may demonstrate the ability of our laboratories to transpose the physical properties of these periodical materials in usable highly integrated devices.

The synergy between the 3 associated laboratories and their respective know-how are a major asset in the success of this project. Furthermore, the launch of a space mission dedicated to CMB polarization under an M4 ESA mission is planned from 2026 if it is selected. This project could be included in this mission. Because research in observational cosmology is essentially made by academic laboratories, the financial help given by the ANR is fundamental to keep on the development on very high technological instrumentations dedicated to the precise observations of CMB polarization. This will allow us to constrain inflation which is one of the most complex phases of the young Universe. So, this project will have an impact on mm and sub-mm Astronomy and Cosmology. Another application could be the development of an heterodyne THz camera for the detection of atomic and molecular transitions which play a key role in the formation of stars, in the evolution of interstellar medium or in the physico-chemical process of planetary atmospheres including the earth.

Any development likely to be a patent will be safeguarding the interests of different partners. The joint publications will be encouraged. The project communication will be through the publication of key results in scientific journals with referees and acts of international conferences in which the four partners will be involved. An active communication at the national scale (GDRs, OMNT, JNOG, JNMO, etc.) will be also provided in respect of the scientific community to foster contacts favouring the prosecution beyond the project.

A website will be created to present the project and disseminate the main results to the general public. It will also trade online partner.
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i) UPS 11/C2N : Frédérique Gadot (Assistant Professor), Benoît Bélier (Research Engineer) and André de Lustrac (Full Professor).
   - Expertise in the research field:
     The photonic CRYstals and MEtamaterials (CRYME) team of the C2N has developed for several years studies around photonic and electromagnetic band gap (PBG and EBG) materials, and also around metamaterials. We designed and characterized passive and active PBG and EBG materials for many applications as substrate for antennas. Generally speaking, we develop simultaneously fundamental studies around these materials and applications in connection with industrial partners (France Telecom, EADS, THALES, ALCATEL) in the field of antennas, of the electromagnetic windows, and also in optics.
   - Technical facilities and know-how
     To carry through with these studies, the CRYME team has developed modelling tools, alongside of characterization and fabrication facilities.

ii) APC : Michel Piat (Full Professor), Damien Prêle (Research engineer), Andrea Tartari (Post-Doc), Alessandro Traini (PhD).
   - Expertise in the research field:
     The Observational Cosmology (OC) team at APC is involved in two instrumental projects related to CMB polarisation:
     (i) In the French R&D program BSD (B-mode Superconducting Detectors), APC is designing an original readout scheme for superconducting bolometer arrays. It is based on SiGe ASIC cool down to 4K to amplify and multiplex the signal from all detectors. The same team also contribute to the test of superconducting bolometers.
     (ii) QUBIC (Q and U Bolometric Interferometer for Cosmology) is an international project to realise a bolometric interferometer (BI) at Dôme C (Antarctica) to characterise the B-modes of the CMB. It is a collaboration between IRAP, CSNSM, LAL, IAS, University Sapienza (Roma), university of Milano Bicocca, Manchester University, Cardiff University, Brown University (Providence), University of Wisconsin (Madison), University of Richmond (Richmond), NUI (Maynooth) and APC. The APC team is involved in instrument design, BI demonstration in laboratory, detector readout electronics and Dôme C characterisation at 150GHz.
     The team has been also involved a feasibility study for a post-Planck satellite dedicated to the observation of the CMB polarisation (SAMPAN, BPol, PRISM, CORE, CORE+).
The OC team has a complete cryogenic instrumentation (100mK dilution fridge, a 300mK 3He fridge, deep stick to test microwave components at 4K), a millimetre wave network analyser that cover the frequency range from 70GHz up to 220GHz in the present configuration and the infrastructure for such instrumentation.

iii) GEPI : Faouzi Boussaha (Research engineer)
- Expertise in the research field:
  The expertise of the GEPI concerns the instrumentation, both hardware and software, as well as the satellite Earth and planet remote sensing studies that are closely linked to the instrumentation developments. GEPI is a key actor in Europe in the research activities on millimeter to THz components and instrumentation, with active participation in space borne missions within international collaborations. The modelling of the instrumentation, the processing of the data, and the development of Virtual Observation strategies are part of new research fields. The Earth and planet remote sensing activities of GEPI are internationally recognized.

Only a high synergy between the three partners allows the success of this project. In each step of the study the interdependency between the partners is important.

Concerning the coordinator, Frédérique Gadot, she graduated from the engineering school ESME Sudria in 1996 and obtained her PhD in 1999 on photonic band gap materials in microwaves. She joined the ‘CRIME’ group (CRiStaux photoniques et MEtamateriaux) at the end of her thesis at the IEF (Université Paris Sud 11) and works on photonic band gap materials and metamaterials in the microwave and near IR domains. She obtained her “Habilitation à Diriger les Recherches” in December 2010.

Studies on metamaterials have started for the first time in IEF (that becomes C2N) with Frédérique Gadot. This follows work undertaken on photonic band gap materials that had begun in 1996. Frédérique Gadot has fabricated and characterized for the first time in the laboratory a metamaterial operating in the near infrared. Frédérique Gadot has participated in numerous ANR and a European Network of Excellence on metamaterials called Metamorphose. She organised an international workshop in Paris in 2008. She is in the head of two projects concerning medical and astrophysical applications with metamaterials (ANR COSMOS – 2011).