Leaky Lens Based UWB Focal Plane Arrays for Sub-mm Wave Imaging Based on Kinetic Inductance Detectors

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***Abstract*—A novel strategy for broad band focal plane array design is proposed. Its purpose is to couple the radiation from a Large F/D reflector system to an array of Kinetic Inductance detectors that are being investigated and realized at SRON. To maximize the benefits from using their BW properties the idea is to use Leaky Lens based array elements, as imaging pi**xels.

I. INTRODUCTION

ALL the existing quasi optical systems that are characterized by large F/D are designed to operate efficiently over narrow frequency bands. That is because in order for the entire system to be efficient, i.e. in terms of spill over, the final feeds should must be characterized by high directivities. While there are antennas that present large BW and high directivities, in most cases these properties are achieved at the cost of a poor phase center stability over the frequency, which eventually destroys the efficiency of the reflector system. As a consequence now days the most common trend, at least in the cm wave regimes, is to use complicated feeding networks, effectively realizing the narrow beams via phased array technology. The cost and complications associated to such technological solutions, im-portant also in the lower frequency regimes, appear formidable at THz regimes. Clearly it is in principle possible to oversize the optical system in such a way that spill over is not felt as a problem any more, by essentially accepting a very low aperture efficiency. However this comes at great costs and a solution that allows for a better aperture efficiency would be widely preferable.

Recently, UWB Leaky Lens antennas have been proposed [1]. These lenses are truly amazing instruments as they allow, at least on one plane, stable phase centers and directive patterns independently from the frequency, while maintaining low cross polarization levels. The reason for these properties is the particular type of radiation mechanism adopted. The leaky radiation occurring when a slot is etched at the interface be-tween two different dielectric media, discussed and described in [2] and [3], is effectively a broad band form of Cherenkov radiation. To the knowledge of these authors this radiation mechanisms even if known, at least by Cherenkov himself, was never used by E.M. engineers before. The performances of the non planar version of the Leaky Lenses have been demonstrated to be acceptable over a decade of BW and excellent over a 1:3 BW. Versions of these antennas that were compatible with printed circuit board (PCB) technology were also presented [4]. However their useful BW was in the order of an octave or less due to the feeding arrangements. In this paper, we will propose a focal plane architecture that is suited to host Leaky Lens antennas as imaging elements.

The feed arrangements are particularly suited to be used in conjunction with KID type resonators. In fact it allows for the use of a same CPW structure to host the low frequency resonator (GHz) read out signal, as to absorb the high frequency (THz) incoming radiation.

Hopefully, by the time of the conference, the measurements of the prototypes which are presently being manufactured at SRON to validate the conjunct use of the leaky lenses and the KID detectors at 670 GHz will be available.

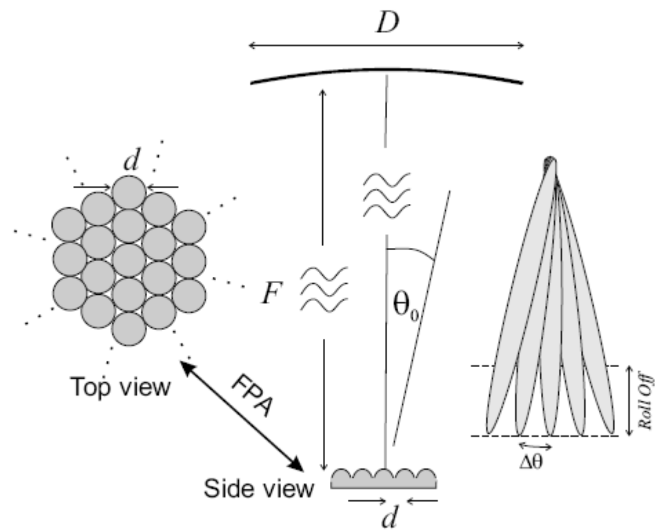

Fig. 1. Schematic view of Large F/D system and Focal plane array realized with circular symmetric lenses.

II. BACKGROUND

The purpose of this paper is general. Novel sub-mm wave receivers are all expected to need improved performances. However it is the Japanese SPICA [5] mission planned for 2017, that is now triggering the attention of many European and American Institutions. As a consequence since the role of TNO in sub-mm waves is mainly the cooperation with SRON, this contribution will focus a bit more on requirements which could be used for a mission like SPICA

A. Challenges from SPICA

Three main requirements have been proposed by the sci-entists for the SPICA mission instruments that, when realized, would constitute major breakthrough with respect to the essentially associated to the receiver technology, the other two major requirements are the number of pixels (in the order of the thousands) and the BW. Overall a decade BW is considered interesting for SPICA which at the present time is

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supposed to be divided in three separate bands and consequently investigated by three separate instruments. Given this scenario it is legitimate to imagine that if such targets will have to be achieved something new should arise. While SRON proposes KIDS for the sensitivity issue, TNO proposes Leaky lenses for the BW Kilo-elements focal plane array. In the rest of this paper we will imagine a focal characterized by F/D in order of 10, and accordingly d ~ $10\lambda_0$, with reference to Fig. 1, even if F/D ~ 2 would probably suffice for a thousand element array. Also a BW of operation in the order of 1:3 will be considered even if it will be clear that 1:10 BW are not out of the scope as there are no real limitations neither in the antennas or in the receivers.

B. Leaky Lenses

The first Leaky Lens antenna was presented in [4]. Thanks to the type of radiation Leaky lenses are extremely efficient in concentrating the power in the denser medium. Moreover, even being leaky antennas, they do not suffer from the typical dispersion effects that typically characterize such antennas. These advantages have been recently exploited in [1] where an UWB version of this lens was presented. The measured results from the prototype demonstrated the following properties

- Good impedance matching over a decade bandwidth
- Directive radiation patterns that are frequency independent in the *H*-plane over two octaves.
- The most stable phase center for a directive antenna over two octaves.
- The smallest amplitude dispersivity for a directive an tenna.
- Negligible (with respect to other UWB non dispersive antennas) cross polarization levels.

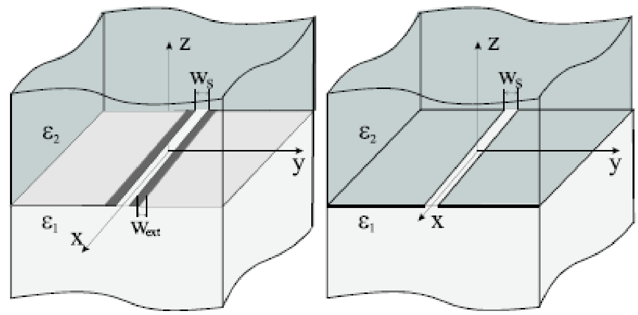
In particular, this antenna is probably the most suited to excite reflector antennas characterized by moderate to high F/D over and an ultra wide frequency band. To this regard it might be convenient to recall the flat measured directivity as function of the frequency which is reported in Fig. 18 of [1].

III. UWB Leaky with a Planar Feed

Realizing at sub-mm waves the fully 3D structure not easy. In [4] the radiating slot and pertinent circuitry was printed on a unique ground plane. However, due to the feeding via a narrow band balun, the overall operating bandwidth turned out to be limited (even if the structure could be operated at multiple central frequencies). Moreover the structure presented asymmetric patterns in the H plane. Finally as all the so far proposed leaky lenses, the overall efficiency was limited to about 60% due to spill over losses, see [1] sez.7.b. In this section we will improve the feeding arrangement of the mentioned fully planar leaky wave slots in order to have Ultra Wide Band, clean H plane radiation patterns and nearly fully efficient lenses thanks to reduced spill over. The key step is, as usual, theoretical. A leaky slot radiates two beams when it is center fed because it excites two leaky waves characterized in [2] by $\pm k_x^{LW}$. But if one manages to feed only one of these two modes a directive and nearly perfectly balanced pattern can be achieved also in the H plane, without the need of bending the ground plane that hosts the slots as in Fig. 1 of [1].

A. Characteristic Impedances of CPS and CPW lines

Since the slot propagation constant is very weakly dispersive the important step to obtain a single beam radiated in an almost frequency independent way is to achieve an appropriate feeding arrangement. A feeding arrangement that will excite only one, k_x^{LW} of the two possible leaky waves $\pm k_x^{LW}$. The solution appears clear when one considers two apparently very different transmission lines printed at the interface between two dielectrics, the Coplanar Strip-line (CPS) and the slot line, Fig. 2(a) and (b) respectively. Their characteristic impedances, when plotted as a function of the frequency present almost the same real part. Fig. 5 in [1] shows both real and imaginary part of the characteristic impedance of the slot for two different dielectric permittivities. The impedance of the CPS would in principle depend the width of the two metallic, w_{ext}, conductors to uniquely define it, see Fig.2 (a).



(a) (b)

Fig. 2. Geometry of transmission lines printed between two infinite dielectrics: a) propagating only CPS line; b) slot lines.

However it appears that also in the CPS as well as obviously in the slot case, only the separation, w, between the two metallic conductors is of some importance for the real part of the propagation constant and of the impedance. In [6] some parametric curves of the characteristic impedance as a function also of the width of the metallic conductors, w_{ext}, are indeed shown for a number of CPS lines printed on different dielectric stratifications. However the impact of w_{ext} is really minor and assuming w_{ext} as infinite still allows for a good approximation of the real part.

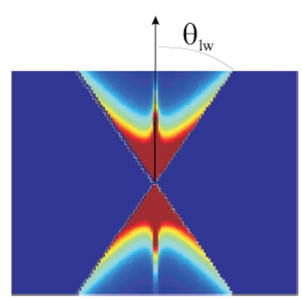


Fig. 3. Color map of the intensity of the electric current associated to the leaky wave mode excited by an electric source in parallel to a slot line.

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The same does not happen with a single slot line. Fig. 3 shows a view of the electric current amplitude on the dielectric side of the ground plane that hosts the slots, when only the leaky mode contribution to the total current is retained. The leaky mode can be easily viewed as the superposition of two mechanisms. A portion of the current is just propagating and flowing close to the slot edges, with cancelling radiating contributions, should they radiate. However another portion of the currents associated to the leaky wave propagate away or toward the slot at an angle θ_{LW} which is defined by radiation cone. Since these currents are not spatially localized in a zone of the ground plane which small in terms of the wavelength the two radiation contributions from these currents do not cancel out. These second currents give rise to an imaginary term in the characteristic impedances which is the only difference between the CPS and slot characteristic impedances.

Since the imaginary part of the characteristic impedances is always small with respect to the real part, a transition between a CPW line and a slot line is intrinsically characterized by broad band. An example of such transition, is shown in Fig.4. Assuming a dielectric contrast $\varepsilon r1=1$, $\varepsilon r2=11.9$ the reflection coefficient is always below -15 dB over a 1:3 BW.

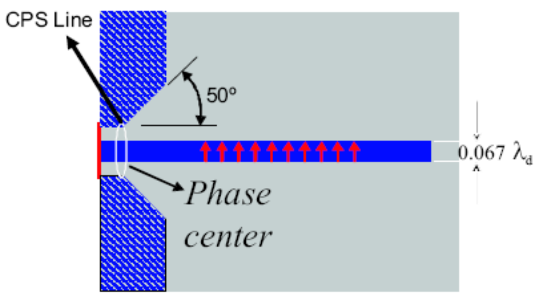

Fig. 4. Example of a transition between CPS line and slot line to achieve broad band matching and clear phase center.

This type of transition, not only is broad band but also introduces a clearly identified phase center. In fact it is exactly at the transition that the guided mode begins to radiate independently from frequency. The exact knowledge of the phase center is fundamental to design dielectric lenses with controlled radiation pattern.

B. Connection to the KIDS

In connection to the use of the Kinetic inductance detectors that is proposed by SRON, there are two advantages: 1) the feed is planar and 2) it is naturally integrated with Kinetic inductance detectors. These are GHz frequency resonators, typically realized, by SRON and others, in Coplanar Waveguide (CPW) Technology and kept at a temperature such that any E.M radiation entering in contact with them alters their intrinsic inductance. As a result the resonating frequency of such filters changes when they are excited by THz radiation. In order to realize the simplest wide band excitation of these resonators, here we propose to implement in the final part of the quarter wavelength resonator (at GHz frequencies) a small geometrical correction. The correction will be such that the portion of the resonator which is located under the dielectric lens will be realized with small external ground planes. The very final part of the CPW will support a radiating slot type mode and thus will act as a well matched receiving antenna as shown in Fig. 5. The transition guarantees that the radiating incoming from the lens is coupled to the leaky mode of the CPW in the wide ground plane zone with known phase center at the transition. Then this signal is slowly transformed into *losses* as it generates the cooper pairs. The radiation pattern for the double slot is essentially the same as that of a single slot twice as large in terms of the wavelength.

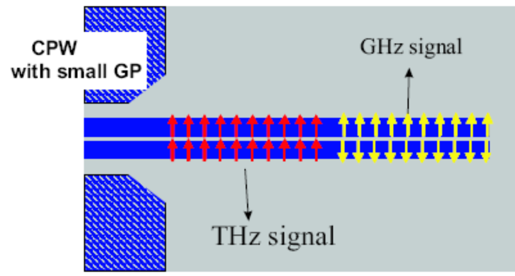

Fig. 5. Example of a transition between CPW and a twin slot line. The THz incoming radiation and the GHz read out signal are both supported by the same structure.

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REFERENCES

[1] S. Bruni, A. Neto and F. Marliani, “The UWB leaky Lens Antenna” *IEEE Transactions on Antennas and Propagation,* Vol. 57, no. 10, October 2007.

[2] A. Neto and S. Maci, “Green’s Function of an Infinite Slot Printed Between Two Homogeneous Dielectrics. Part I: Magnetic Currents”, IEEE Transactions on Antennas and Propagation, Vol. 51, no. 7, pp. 1572-1581 July 2003.

[3] S. Maci and A. Neto, “Green’s function of an infinite slot line printed between two homogeneous dielectrics. Part II: Uniform asymptotic fields”, *IEEE Transactions on Antennas and Propagation*, Vol. 52, no. 3, pp. 666-676, March 2004.

[4] A. Neto, S. Bruni, G. Gerini, M. Sabbadini, “The Leaky Lens: A Broad Band, Fixed Beam Leaky Wave Antenna”, *IEEE Transactions on Antennas and Propagation*, Vol. 53, no. 10, pp. 3240 -3246, October 2005.

[5] Core Science Requirements for the European SPICA Instrument, ESIRAL-REQ-0012, Iss. 0.1.

[6] Rainee N. Simons Coplanar Waveguide circuits, components and systems Wiley Interscience, 20