Development of a transmit-array for heterodyne receiver

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***Abstract*—The development of large multipixel heterodyne imaging arrays is a challenge in modern THz spectroscopy. For large arrays (>100 pixels) the ease of fabrication and the reliability become an important factor. Stacking individual pixels next to each other, might not be the optimal solution for large arrays. There has already been lots of good progress by designing blocks for multiple mixers (e.g. for Supercam, JPL R&D work), which simplifies the task but still requires a lot of machining.**

Here we are exploring possibilities of further simplifying the design. One idea is to replace the horn or lens – that requires individual mechanical fabrication – with an array of planar lenses followed by or integrated in an array of mixers fabricated on a single silicon wafer. Here we are looking at transmit – arrays to take the role of focusing element. Each pixel will require one transmit-array, but an array of ~ 10X10 transmit-arrays for 10X10 pixels could be fabricated on a single wafer in a single process in the clean room. The idea is that this array of planar lenses as well as an array of mixers can be fabricated and aligned in one single process for large (~100) pixel arrays.

We have designed, fabricated and tested a prototype transmit-array for 600 GHz. First we calculated the phase shifts required of each cell of the transmit-array to focus the incoming planar wave front. In analogy to the classical bulky lens, the larger phase shift/delays are required in the center of each pixel to delay the incoming waves and allow constructive interference at the focal point. In order to obtain the necessary phase shift, we required that each transmit-array is composed of three layers of 2D metamaterials separated by two sapphire layers. We modelled the cell as a transmission line where each metamaterial layer is represented by a parallel impedance. Finally, the behavior of the cell is described by its reflection and transmission coefficients, which depends algebraically on the three parallel impedances. The phase of the transmission coefficient must be equal to the phase shift required by the cell. We performed numerical simulations in order to obtain the required phase shift, while keeping the reflection coefficient to -25 dB to maximize the efficiency. The prototype we designed so far allows the focusing of the light in one dimension.

We fabricated this prototype for a single pixel: this planar lens consists of a structure of metal cells we fabricate by depositing gold on three layers of 100 microns sapphire wafers, two layers of the golden cells will be recto/verso on the same wafer, the third layer on a second wafer. The dielectric plates will be aligned with a microscope to micron precision. We also measured the focusing capabilities of the planar lens.

I. Introduction

The heterodyne receiving pixels are made of very directive antennas. Normally the choice of the receiver is based on the beamwidth specification, which is approximatively 2,2°. Nowadays two solutions exist: the horn antenna, or the double slot integrated in a silicon lens. These solutions are good for single receiver, or in general for an array of few elements. When an attempt is made to increase the number of pixels it becomes difficult to realize them in a compact configuration. In this case a special attention must be given to flat elements, like the array of phased microstrip antennas. It consists of an array of superconducting patch elements drawn on a substrate which separates them by a ground plane. This configuration has the drawback of a too thin substrate which is difficult to realize. At this point the best solution seems to use the double slot antenna, where the bulk lens is replaced by a planar thin lens. A widespread literature exists about planar lens, also called transmit-arrays. The transmit-array consists in an array of single cells. Each cell provides the incoming wave with a phase shift to generate a constructive interference at the output, in the focal point. Many examples exist in literature of cells whose reflection coefficient and phase shifts are calculated numerically. Each cell is optimized to furnish a certain phase shift and a low reflection coefficient. They can be made of square rectangles, crosses or other metal motifs designed on a dielectric substrate, or dielectric cylinders on a different dielectric substrate, slots etc… In the totality of the cases, such shapes are too complicated to be rescaled for THz applications. In this work we are going to provide a transmit-array whose cells are made of simple structure which can be fabricated. Moreover we are going to provide a mathematical model which allows to calculate the phase shift and reflection coefficient of every cell, without resorting to numerical optimization in EM simulation softwares.

II. Objective

- The first objective of this work is to substitute the bulk lens of the double slot antenna, with a flat lens, which is easier to fabricate for large compact configurations. Such flat lens has the function of reducing the beamwidth of the double slot antenna, which must be less than 2,2°. The beamwidth is directly linked to the beam waist of the quasioptical equivalent Gaussian beam. The size of the beam waist decreases with the beamwidth. Since the beamwidth of the double slot is very large, the objective of the flat lens is to reduce the beam waist of the incoming light, to the beam waist of the double slot. Since the dimension of the transmit-array is quite small compared to the beam waist of the incoming light, and since the beam waist of the double slot is very small, we can assume that the transmit-array converts an incoming planar wave into a cylindrical wave, with the center on the double slot receiver.

- The radiation which is incoming on the heterodyne is generated very far away from the observer. The resulting signal is very weak, therefore we don't want that it would be reflected away and lost. For this reason the transmit-array must be designed so that a very low reflection coefficient is achieved. In the analytical design the value of the reflection coefficient will be set to -25 dB.

III. METHOD

The transmit-array is composed by several cells stacked together into an array (fig 1)

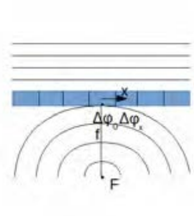

Fig. 1. Transmit-array scheme

In order to transform an incoming planar wave into a cylindrical wave, the single cell of the transmit-array, placed at a distance x from its center, must provide a phase shift given by eq. 1:

$$\Delta\varphi_x = \Delta\varphi_0 + \beta\left(\sqrt{f^2 + x^2} - f\right) \quad \text{(eq.1)}$$

Where $\Delta\varphi_0$ is the phase shift of the central cell, $\Delta\varphi_x$ is the phase shift of the cell a the distance x from the center, β is the wave number and f is the distance between the focal plane and the array. Eq. 1 represents the first condition that the cell must satisfy. The second condition consists in the minimization of the radiation reflected by the cell. Our objective is to determine the shape of the cell to achieve such requirements. Let's consider the generic cell made of three metal motifs separated by two dielectric substrates of the same material (fig. 2)

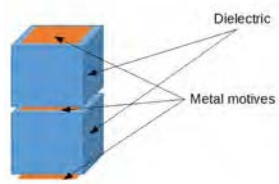

Fig. 2. Scheme of the three layers generic cell

Each layer (i.e. the metal motif) can be seen as an impedance in the equivalent circuit of the cell (fig.3):

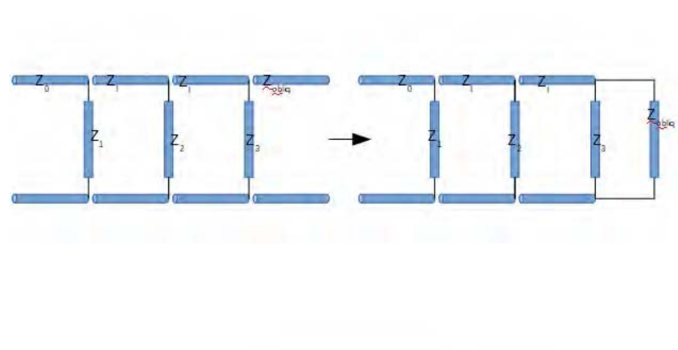

Fig. 3. Equivalent circuit of the cell

where Z_1, Z_2 and Z_3 represent the three values of the impedances; Z_l represents the impedance of the substrate, Z_0 is the impedance of the free space and $Z_{obliq} = Z_0/\cos(\theta_{TE})$ is the impedance of the free space which is seen by the outcoming beam, that is inclined by the TE angle θ_{TE} towards the focal line. The calculation of the equivalent impedance of the circuit allows to determine the reflection coefficient as:

$$\Gamma = \frac{Z_{eq} - Z_0}{Z_{eq} + Z_0} \quad \text{(eq.2)}$$

where Z_{eq} is the equivalent impedance. The forward part of the input and output signal with respect to the circuit is given by:

$$V_i^+ = \frac{V_i + Z_0 I_i}{2} \quad \text{(eq.3)}$$

and

$$V_o^+ = \frac{V_o + Z_{obliq} I_o}{2} \quad \text{(eq.4)}$$

respectively. So we have:

$$\Delta\varphi_x = \sphericalangle V_o^+ - \sphericalangle V_i^+ \quad \text{(eq.5)}$$

$$\Gamma = -25\ dB \quad \text{(eq.6)}$$

The value of the three impedance is varied until eq. 5 and eq. 6 are satisfied. It is possible to determine the shape of the motifs as a function of the impedances by means of the paper of O. Luukkonen (IEEE June 2008). They generally consist of an array of metal patches (or strips if the imaginary value of the calculated impedance is positive). Since only the dimension of the patch which is parallel to the electric field is important, the patches can be stacked together to form strips, as shown in figure 4 (the metal path is in blue);

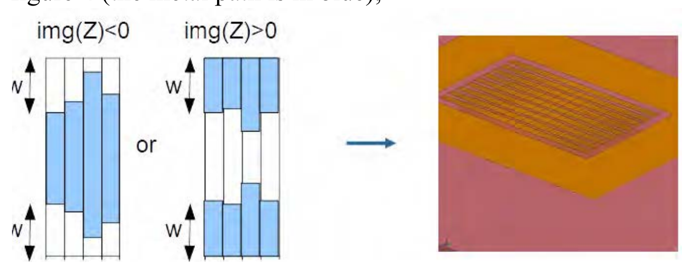

Fig. 4. Relation between the impedance and the metal motif

An array of metal strips orthogonal to the electric field will be created, so that the linearly polarized electric field will focus on a line which contains the HEB.

IV. NUMERICAL SIMULATIONS

Figure 5 shows a qualitative study of the transmit-array in the transmitting mode. It consists of a FEKO simulation where a dipole is placed on the focal line of the transmit-array. It is clearly evident that the transmit-array transforms the cylindrical wave into a planar wave.

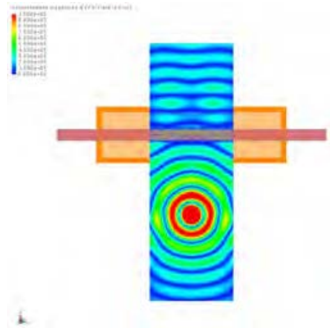

Fig. 5: Near field from a dipole through the transmit-array in the transmitting mode

A more quantitative study can be done in the receiving mode by assuming an incoming planar wave of 600 GHz. The transmit-array focal length is assumed to be 1,5 mm. A frame is placed around the transmit-array to block the interaction between the field downstream the array, and the external field. In this case an overall efficiency of 45% is achieved with a beam waist radius of 21% of the edge of the transmit-array. Such reduced efficiency is due to the blocking effect of the frame. Without the frame the transmitted power would be equal to the incoming power, but the focusing effect would be weakened. The 1,5mm focal length transmit-array is of great interest for a possible application for heterodyne receivers, however it is too difficult to test. For this reason a 20mm focal length transmit-array has been designed and simulated. In this case simulations show an efficiency of 53% within a beam radius of 42% of the transmit-array edge.

V. TEST

For the experimental setup we need a high frequency signal generator, which is the RPG chain, and a detector, which is the terahertz pyroelectric detector or QCM, from the QCM instrument Ltd. The experimental setup is shown in fig. 6.

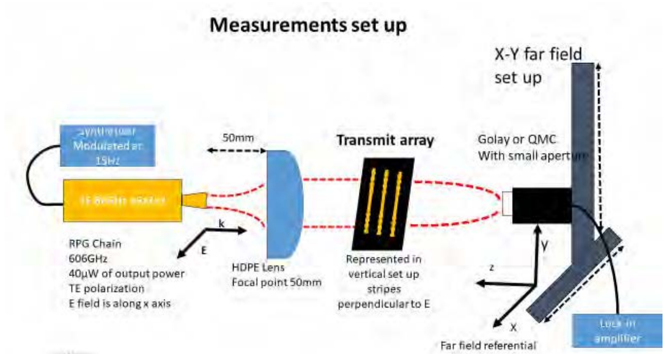

Fig. 6. Setup of the 20mm focal length transmit-array test

the signal generated by the RPG is collimated by a lens with a 50mm focal distance. The power collimation is necessary since the beam generated by the RPG is much diverging, and would lead to a too low signal to be detected by the QCM. The transmit-array is placed between the lens and the QCM. The distance between the array and the QCM is equal to the focal distance of the transmit-array, therefore it is 20mm. The resulting measured field is obtained by scanning the XY plane parallel to the transmit-array at the focal distance from it. A metallic disk with a hole of 1,5mm in the center is applied to the QCM to increase its resolution. Smaller the hole, higher the resolution, however the hole cannot be too small because the signal measured by the QCM would be too small.

We performed two main measurements: the first measurement is made with an empty frame on the sapphire dielectric substrate, while the second is made with the transmit-array and the frame together. We should see an increment of the collimation between the first and the second measurement, which can be quantified by the directivity. Figures 7 and 8 show the field measurement on the XY plane for the frame only and the frame with the transmit-array respectively:

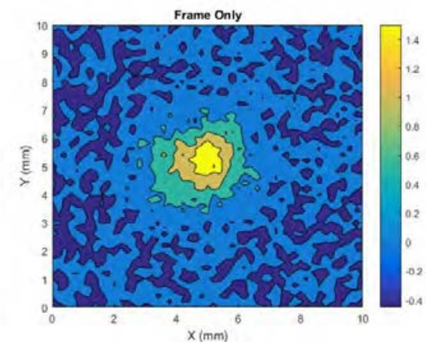

Fig. 7. Field measurement for the frame only

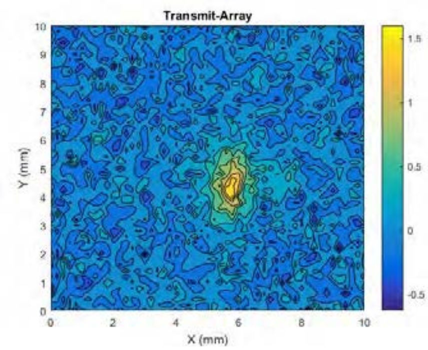

Fig. 8. Field measurement for the frame with the transmit-array

Let's now calculate the directivity. It is given by:

$$D = \frac{U_{max}}{(P_{tot}/4\pi)} \qquad \text{(eq. 7)}$$

where U_{max} is the maximum intensity of the power unit solid angle. Given $dy = 0{,}2mm$ the increment of the single element in the measurement plane, and given $r = 20mm$ the distance of the transmit-array from the measurement plane (which is equal to the focal distance of the transmit-array), it is possible to define the unit solid angle as:

$$d\Omega = \frac{dx\,dy}{r^2} \qquad \text{(eq. 8)}$$

Then the directivity can be expressed as:

$$D = 4\pi \frac{U_{max}}{\iint_{\Omega} U(x,y)d\Omega} \approx \frac{4\pi}{d\Omega} \frac{U_{max}}{\sum_{n,m} U(n,m)} \qquad \text{(eq.9)}$$

where $x = (n-1)dx$ and $y = (m-1)dy$. The results are shown in tab. 1

	linear	dB
Frame only	718	28,6
Transmit-array with frame	1258	31,0

Tab. 1. Directivity of the frame only and transmit-array with frame

The transmit-array shows a small increase in the directivity. This is the best result we can achieve with our instrumentation, where the standard deviation of the signal is 12% of the peak value.

Conclusions

A transmit-array design has been introduced which transforms an incoming planar wave into a cylindrical wave. Thus the signal is focused on a line parallel to the transmit-array plane and in the same direction of the electric field. Simulations show a good focusing effect for the 1,5mm focal length transmit-array, but the efficiency is reduced by the presence of the frame, which is necessary to avoid the interaction of the field downstream the transmit-array with the external field. Even if the converging of the 1,5mm transmit-array towards the focal line is good, it is difficult to test with the available instrumentation. For this reason a 20mm focal length prototype has been designed, simulated and tested. Simulations show a reduced focusing effect, due to the reduced curvature of the wave downstream the array, so that the beam waist is greater with respect to the 1,5mm case. The tests are performed with the QCM by measuring the far field in the focal plane of the transmit-array. Results show a very small increase of the directivity of the transmit-array, with respect to the case where the frame only is considered. This effect shows that the transmit-array is working, even if a more precise measurement is not possible with our instrumentation.

References

[1] L. Dussopt, H. Kaouach, J. Lanteri and R. Sauleau, "Circularly-Polarized Discrete Lens Antennas in the 60-GHz Band" *Radioengineering,* vol.20 no.4,.pp 733-738, December 2011

[2] H. A. Malhat, N. A. Eltresy, S. H. Zainud-Deel and K. H. Awadalla "Nano-Dielectric Resonator Antenna Reflectarray/Transmitarray for Terahertz Applications" *Advanced Electromagnetics,* vol.4 no.1,.pp 36-44, June 2015

[3] C. G. M. Ryan, J. R. Bray and Y. M. M. Antar "A Broadband Transmitarray Using Double Square Ring Elements" *13th International Symposium on Antenna Technology and Applied Electromagnetics and the Canadian Radio Sciences Meeting,* 2009

[4] C. G. M. Ryan, M. R. Caharmir, J. Shaker, J. R. Bray and Y. M. M. Antar "A Wideband Transmitarray Using Dual-Resonant Double Square Rings" *IEEE Transactions on antennas and propagation,* vol.58 no.5,.pp 1486-1493, May 2010

[5] A. Clemente, D. Laurent, R. Sauleau, P. Potier and P. Pouliguen "1-bit Reconfigurable Unit-Cell for Transmit-Array Applications in X-Band" *IEEE International Symposium on Antennas and Propagation (APSURSI)*,.pp 684-687, 3-8 July 2011

[6] J. Y. Lau and S. V. Hum "Reconfigurable Transmitarray Design Approaches for Beamforming Applications" *IEEE Transactions on Antennas and Propagation*,. vol 60, no. 12, pp 5679-5689, December 2012

[7] O. Luukkonen, C. Simovski, G. Granet, G. Goussetis, D. Lioubtchenko,A.V.Raisanen and S.A. Tretyakov "Simple and Accurate Analytical Model of Planar Grids and High-Impedance Surfaces Comprising Metal Strips or Patches" *IEEE Transactions on Antennas and Propagation*,. vol 56, no. 6, pp 1624-1632, June 2008