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Citation for published version (APA):

Ederra, I., Gonzalo, R., Alderman, B. E. J., Huggard, P. G., Hon, de, B. P., Beurden, van, M. C., Murk, A., Marchand, L., & de Maagt, P. J. I. (2008). Sub-Millimeter-wave imagingarray at 500 GHz based on 3-D electromagnetic-bandgap Material. *IEEE Transactions on Microwave Theory and Techniques*, 56(11), 2556-2565. <https://doi.org/10.1109/TMTT.2008.2005926>

DOI:

[10.1109/TMTT.2008.2005926](https://doi.org/10.1109/TMTT.2008.2005926)

Document status and date:

Published: 01/01/2008

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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Sub-Millimeter-Wave Imaging Array at 500 GHz Based on 3-D Electromagnetic-Bandgap Material

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Abstract—The design, fabrication, and characterization of a 500-GHz electromagnetic bandgap (EBG) based heterodyne receiver array is presented. The array contained seven planar dipole antennas that were photolithographically defined on a common 20- μm -thick quartz substrate. Each antenna incorporated a Schottky diode and was connected to coplanar transmission lines that conveyed the down-converted 500-GHz signals to detectors. The quartz substrate was backed by a silicon EBG woodpile structure, which reduced antenna crosstalk and increased directivity. An off-axis parabolic mirror completed the beam-forming network.

Index Terms—Electromagnetic bandgap (EBG) technology, imaging array, millimeter-wave technology.

I. INTRODUCTION

THE challenge of realizing imaging arrays of heterodyne receivers for the sub-millimeter and terahertz spectral regions is a topic of current interest. Applications are multifold, ranging from security to astronomy and earth observation [1]. As the regions of interest in security and astronomy are usually distributed over many observing beams, the time needed to build an image can be reduced in approximately inverse proportion to the number of elements included in the array. Similarly, for air- and space-borne earth observation, a multiple beam observing system allows push-broom nadir or limb sounding, thereby simplifying the beam scanning requirements of the instrument.

Sub-millimeter imaging arrays have conventionally been based on feedhorns and waveguide technology and are usually assembled from discrete elements [2]. The costs, mass, and volume associated with this approach may limit the maximum

Manuscript received March 13, 2008; revised July 24, 2008. First published October 24, 2008; current version published November 07, 2008. This work was supported by the European Space Agency (ESA) under Project ITT AO/1-3760/01/NL/ND.

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Digital Object Identifier 10.1109/TMTT.2008.2005926

Fig. 1. Gold on quartz detector configuration, showing the dipole antenna (left) and first two sections of the RF choke (right). The grey rectangle represents the area of the Schottky diode chip. Numbers (bracketed) are the design (realized) dimensions (in micrometers).

Fig. 2. Imaging array. (a) Arrangement of the seven dipoles on the woodpile. The antenna arms lie along the bars of the top layer, whereas the RF chokes lie along the bars of the second layer. (b) Cross section through the z - y -plane showing mirror and the three dipoles located in this plane. The x - and y -direction corresponds to elevation and azimuth, or equivalently H - and E -planes, respectively.

practicable number of pixels. Being able to produce lithographically planar receivers with equivalent performance would permit the realization of much larger 2-D arrays [3], [4]. Such

TABLE I
MUTUAL COUPLING BETWEEN THE ARRAY OF DIPOLE ANTENNAS IN FIG. 2(a) FOR DIFFERENT CONFIGURATIONS

	Coupling from central element (dB)					
	C_{12}	C_{32}	C_{42}	C_{52}	C_{62}	C_{72}
Air	-24.51	-24.51	-38.81	-24.51	-24.50	-38.78
Air and ground plane	-25.21	-25.21	-38.95	-25.21	-25.21	-38.93
$\lambda/4$ Si and ground plane	-19.23	-19.21	-10.77	-19.45	-19.04	-10.67
Woodpile	-46.95	-48.27	-47.86	-41.73	-42.01	-47.25

an approach would also dramatically reduce cost and greatly simplify manufacture and assembly.

Waveguide and feedhorn technology provides a natural isolation between adjoining pixels. In contrast, the performance of planar antenna arrays can be severely limited by the parasitic cross coupling of the antennas via surface waves [5]. Electromagnetic bandgap (EBG) structures, working as surface wave suppressing substrates, have consequently attracted much interest [6]–[9]. EBG structures prevent the propagation of radiation, for frequencies within the bandgap, in one, two, or three spatial directions, the number usually corresponding to the number of dimensions in which the crystal is periodic [10]. While 2-D EBG materials have been proven to be a useful substrate for planar antennas [9], a 3-D EBG appears to be more desirable because any antenna fundamentally radiates in 3-D and an antenna array by definition extends over at least one dimension perpendicular to the boresight. A single dipole antenna backed by a 3-D silicon woodpile EBG [11], [12] has been previously studied [13], [14]. This combination exhibited low back radiation and a higher directivity when compared to the equivalent dipole in free space. Moreover, thanks to the suppression of surface modes achieved in these substrates, the coupling between array elements will be reduced with respect to the coupling in conventional substrates [15].

The enhanced performance of the single EBG backed element [16] encouraged us to develop a seven element Schottky-diode-based heterodyne array for 500 GHz, which is described in detail in this paper. This design represents a significant step towards the goal of an effective planar imaging array. The array was designed to match the typical optical system of a sub-millimeter wave astronomical instrument: $f/25$ with a far-field beam crossover level of -3 dB. In order to obtain these beam characteristics, a 90° paraboloidal mirror was used to modify the radiation pattern of the detectors. The design of the individual receivers was optimized for maximum sensitivity, i.e., for best impedance matching between the Schottky diodes and the planar dipole antenna.

The results presented in [17] are extended in this paper. In particular, the design process is detailed and the antenna patterns of all working receivers of the array are compared with physical optics simulations. In the remainder of this paper, the individual dipoles with their integrated Schottky diodes are first presented. A treatment of the limitations imposed by the EBG in terms of element spacings within the array follows. The design of the beam-forming optics is then discussed. Descriptions of the fabrication approach and beam measurement techniques are then given. Finally, the measured beam patterns are presented and are compared with the predictions.

TABLE II
DIRECTIVITY OF ONE OF THE DIPOLE ANTENNAS OF THE ARRAY IN FIG. 2(a) FOR DIFFERENT CONFIGURATIONS

	Directivity (dBi)
Air	1.67
Air and ground plane	7.59
$\lambda/4$ Si and ground plane	0.29
Woodpile	5.91

II. CONFIGURATION

A. Dipole and Array Design

Fig. 1 presents a schematic diagram of the optimized design [16] of the 500-GHz dipole antenna and first section of the associated RF choke/IF transmission line. The position of the Schottky diode chip is shown by the grey rectangle. Design dimensions of the gold areas are shown in Fig. 1, with associated realized values enclosed in brackets. The general level of agreement is within a few micrometers. Best RF performance is predicted for minimum substrate thickness, but manufacturing constraints led to the choice of a substrate thickness of $20\ \mu\text{m}$.

Limitations on the antenna separations arise from the 500-GHz silicon woodpile, which has a $72\text{-}\mu\text{m}$ bar width and $232\text{-}\mu\text{m}$ period in the substrate plane [18]. As the dipoles need to be placed above intersections of the bars in the top two layers [16], the separation between elements is consequently restricted to multiples of this period.

A previous study of the mutual coupling of dipole antennas on EBG substrates showed that a minimum separation of two periods is necessary to ensure coupling values below -20 dB in both E - and H -planes [15]. One compact configuration of seven antennas that meets this requirement is shown in Fig. 2(a). Although denser configurations are possible, the selected one offers the advantage that the six outer antennas lie between $3.6\text{--}4$ woodpile periods from the central element. It will be shown below that it is possible to design matching optics for this array that achieves the desired beam properties: the relatively narrow spread of radii assists in achieving a design that is compliant with the beam crossover point requirement.

The mutual coupling between the array elements was investigated. The results obtained with Ansoft Corporation's High Frequency Structure Simulator (HFSS) are presented in Table I. Ideal dipoles with dimensions as shown in Fig. 1, i.e., $255 \times 10\ \mu\text{m}$, were used in these computations. The coupling between the central element of the array shown in Fig. 2(a) and the other array elements is compared for the following four different configurations:

- array radiating in air;

Fig. 3. Predicted pattern of the seven beams of the imaging array. Solid and dashed lines show -3 - and -6 -dB contours, respectively. Dipole numbers correspond to those used in Fig. 2(a).

(a)

(b)

Fig. 4. (a) Close view of the dipole and Schottky diode array after fixing to the woodpile and attaching the IF leads and (b) complete assembly, with coaxial IF lines to SMA connectors, on the TPX plate. The three central holes at the top of the plate are used to attach the bracket for the parabolic mirror. The size of the woodpile is $40 \times 40 \times 5$ periods.

- array backed by a ground plane separated by $150 \mu\text{m}$ ($\lambda_0/4$ at 500 GHz);
- array placed on a $\lambda_g/4$ ($\lambda_g = \lambda_0/\sqrt{11.7}$)-thick silicon substrate and backed by a ground plane.

Fig. 5. Schematic of the VNA-based heterodyne measurement apparatus.

Fig. 6. Imaging array on the measurement apparatus showing the parabolic mirror and adjustments available for its alignment. The arrows show azimuth and elevation directions.

- proposed configuration, i.e., array printed on a $20\text{-}\mu\text{m}$ quartz substrate and placed on a woodpile.

To compute, the coupling has been obtained taking into account the mismatching in both dipoles following:

$$C_{i2} = \frac{S_{i2}}{(1 - |S_{ii}|)(1 - |S_{22}|)}.$$

As can be seen in Table I, the highest coupling corresponds to the array placed on a solid silicon substrate. The woodpile substrate improves the isolation between the array elements by approximately 20 dB in most cases. In the other two cases, in which the dipoles were in air, the coupling is also larger than when the woodpile substrate is used. Note that although the woodpile does not suppress the surface modes that could exist in the quartz substrate, this is so thin, $0.066\lambda_0$, that the surface wave effect is basically nonexistent.

The comparison of directivities computed using Ansoft Corporation's HFSS is shown in Table II. To facilitate the comparison, the metal ground plane, silicon substrate, and woodpile have the same size. The metal ground plane provides larger directivity than the woodpile substrate due to the fact that the selected dipole on the woodpile configuration ("perpendicular void-void") was optimized for good impedance matching and

Fig. 7. Measured radiation patterns for the array elements. The -15 -, -10 -, -6 -, and -3 -dB contours are shown in each false color plot.

not for highest directivity. In the silicon substrate case, the low directivity is caused by the interference between the main pattern and the radiation coming from the substrate modes, which for these particular dimensions create a minimum at bore sight.

B. Mirror Design

The design of the reflective optics, a 90° off-axis paraboloid that is placed above the array, will now be discussed. Although in principle a lens could have been used, reflective optics exhibit lower losses and standing waves. The $f\#$ requirement on the array imposes the far-field power half-angle, i.e., the directivity of the resulting antenna-reflector combination [19]. To meet the specification, the beamwidth of the output beams should be 2.2°

($f/25$). Therefore, the reflector must provide the required magnification, increasing the directivities of the radiating elements and simultaneously separating the beams. However, the further the antennas are from the optical axis of the system, the more degraded the directivity and beamwidths of their radiation patterns becomes. Thus, it is important to verify that any degradation exhibited by the selected design is not significant.

In Fig. 2(b), the top surface of the woodpile is designated as the x - z -plane. The central dipole is located at the optical focus of the mirror and the projection of the mirror on the x - z -plane is an ellipse with its major axis in the z -direction. To optimize the illumination of the mirror, the dipole array was also oriented with its major axis along the z -axis. From the perspective

of later measurements, elevation (azimuth) corresponds to the $H(E)$ -plane of the central beam, respectively.

The mirror dimensions were optimized to match the array described above. Degrees of freedom available to comply with the system requirements are f , the focal distance, and D , the projected diameter. Directivity increases with D , whereas the effect of varying f (for a fixed D) is to alter the angular separations of the beams. Further, the larger the f/D ratio, the closer the beams are. Starting from a given D value, it was possible to determine an f value that yielded the required beam crossover points. The values $D = 17.3$ mm and $f = 25.4$ mm were selected and are indicated in Fig. 2(b).

Physical optics GRASP [20] software was used to calculate the far-field radiation patterns. As an input for this program, the radiation of an isolated dipole on a finite silicon woodpile, containing 11 periods, was computed with Ansoft Corporation's HFSS [21]. The -3 - and -6 -dB contour plots of the radiation patterns of the seven beams are presented in Fig. 3, which shows that crossover points of close to -3 dB are achieved. Due to the restrictions imposed by the woodpile on the possible antenna positions discussed above, which lead to different dipole separations in the z - and x -directions [see Fig. 2(a)], the -6 -dB-wide beam pattern extends from $\pm 3^\circ$ in azimuth and $\pm 3.5^\circ$ in elevation. Predicted individual beamwidths of $(2.1 \pm 0.1)^\circ$ were obtained, matching well the desired 2.2° value.

GRASP simulations also showed that there was negligible impact on the far-field radiation pattern from mounting the woodpile on either a dielectric, TPX, or a metal plate.

III. MANUFACTURING PROCESS FOR THE EBG ARRAY

A monolithic quartz substrate was used for the dipole array. Compared to producing several individual devices, this approach is aesthetically superior, and offers better coplanarity for the array with an inter-element separation tolerance limited only by the accuracy of the photolithographic process. Further, either alignment marks or judgment by the eye can be used to ensure accurate alignment of all dipoles on the EBG substrate.

Standard photolithographic techniques were used to pattern the array in a gold film that had been deposited on a fused quartz substrate. The quartz was then cut to size and lapped to a thickness of $20\text{ }\mu\text{m}$. During this processing, it was fixed to a silicon support wafer using commercial cyanoacrylate adhesive. After releasing the quartz, residual stress caused a slight curvature, but no cracking. Separated and substrate thinned Schottky diodes¹ were fixed in position on the metal using silver loaded epoxy (Epotek H20E). Care was taken to ensure that the polarities of all of the diodes were consistent. The adhesive was cured, in accordance with the manufacturer's instructions, by baking the assembly at 80°C for 90 min.

The silicon woodpile was placed on the TPX support plate and held using cyanoacrylate. The quartz substrate carrying the dipoles and diodes was then aligned and fixed using a small quantity of Araldite at its edges. This slow setting adhesive allowed positioning of the array and the application of localized pressure to remove the substrate curvature. Electrical connec-

¹Diode DBES105a, United Monolithic Semiconductors S.A.S., Orsay, France.

Fig. 8. Comparison of the -3 -dB contours of the measured (solid lines) after correcting for mirror misalignment and the predicted patterns (dashed lines).

tions were made from the ends of the choke filters to coaxial lines using gold ribbon and silver loaded epoxy (Fig. 4).

The characteristic curves of the Schottky diodes were monitored repeatedly during assembly. No deviation from the initial manufacturer's values was found apart from for one diode. Here, an increase in series resistance was localized to either the diode to substrate connection or to within the diode chip. Attempts at a repair were unsuccessful, and as further intervention was not possible without risking the array, the faulty device was left in place during the electromagnetic characterization. A second receiver failed unexpectedly prior to testing for an unknown reason.

Fig. 4 also shows the fixing holes used to attach the mirror bracket to the TPX plate. The mirror itself was made from a diamond-turned gold-coated parabolic reflector of 12.7 -mm focal length and a projected diameter of 17.3 mm (Fig. 2).

IV. CHARACTERIZATION OF THE EBG ARRAY

A. Experimental Approach

A vector network analyzer (VNA) based measurement technique and apparatus was used for the characterization of the beam pattern of the array at 500 GHz (Fig. 5). As a source, the 100 -GHz output of a phase-locked Gunn diode oscillator was quintupled in frequency and radiated by a corrugated horn antenna towards the EBG array. The Schottky diode detectors were sub-harmonically pumped at a local oscillator (LO) frequency of 16.66 GHz along the IF lines. The thirtieth harmonic of this signal mixed with the received 500 -GHz signal to produce an IF at 9 MHz. A stabilized dc-bias voltage was connected to the diodes through a bias-T in the IF transmission line in order to set the optimum operating point of the receiver. In each case, the LO power and applied dc bias were adjusted to maximize the signal-to-noise ratio of the IF signal. The optimum bias and LO settings and the maximum IF signal were different for each receiver.

The imaging array was mounted so that it could be rotated about azimuth and elevation axes through the optical center of the parabolic mirror (Fig. 6). A laser was used to align the mirror

Fig. 9. Comparison of the: (a) constant elevation and (b) azimuth cuts corresponding to D2. Angular scales have been translated in each case to be centred on 0° .

Fig. 10. Comparison of the: (a) constant elevation and (b) azimuth cuts corresponding to D4. Angular scales have been translated in each case to be centred on 0° .

to the array center with an estimated accuracy of $\pm 1^\circ$. Beam pattern measurements were made at a feed horn to array separation of 0.8 m. Although this is less than the ≈ 1 m calculated far-field distance, it was experimentally verified that beam patterns were not affected by the reduction, and a dynamic range above 25 dB was obtained for all the measurements.

B. Results and Comparison With Simulations

2-D beams scans are presented in Fig. 7 for the five working receivers over an angular range of $\pm 8^\circ$ with a step size of 0.5° . To improve the presentation quality, interpolation of the data has been performed and -3 -, -6 -, -10 -, and -15 -dB contour lines added.

Fig. 7 shows that far-field beam patterns are in reasonable qualitative agreement with predictions, but that sidelobe levels, up to -15 dB, are higher than expected. These unexpected sidelobes lie predominantly in the elevation direction. There is a hint that they are caused at the dipole and substrate level since the

sidelobes from D4 to D7 are generally higher at positive elevations, whereas that from the oppositely oriented D2 lies at negative elevations.

The patterns shown in Fig. 7 have been normalized to their maxima. Due to the subharmonic pumping of the detector diodes during the measurements, the levels of the maxima are highly dependent on the response of the diodes to the coupled LO power and on their dc bias. Both LO power and bias were optimized in order to maximize the IF signal in the first case by adjusting the dc source and the LO power by means of the step attenuator shown in Fig. 6. The optimum bias and LO settings and the maximum IF signal were different for the five receivers. The maximum IF levels of the different beams differed by less than 7 dB.

In order to make a more quantitative comparison with predictions, the angular positions and widths of the beams and higher resolution *E*- and *H*-plane beams scans are now dealt with separately.

Fig. 11. Comparison of the: (a) constant elevation and (b) azimuth cuts corresponding to D5. Angular scales have been translated in each case to be centred on 0° .

Fig. 12. Comparison of the: (a) constant elevation and (b) azimuth cuts corresponding to D6. Angular scales have been translated in each case to be centred on 0° .

To represent better the overall behavior of the array, a contour plot of the -3 -dB signal levels for all the beams is presented in Fig. 8. In the measurements, the absolute pointing of the array had an offset of 1° in elevation and 1° in azimuth from the nominal optical axis, which has been subtracted for this figure. The reason for this is probably a slight misalignment of the parabolic reflector and the test setup. This error is not surprising given the accuracy of the alignment and cumulative positioning tolerances. Good agreement between patterns is observed, although the individual measured beams are slightly narrower than predicted, which leads to crossover points of around -4 dB. The beam crossover point for some beams is very close to -3 dB, e.g., D4/D5 and D5/D6, whereas for others, the crossover is either higher (D6/D7) or lower (D4/D2) than the desired value. The predicted slightly compressed elevation plane characteristic is also exhibited by the measurements.

In order to investigate the sidelobe level further, angular scans with a 0.2° resolution were taken in azimuth and elevation planes through the maximum of each beam. The results are presented in Figs. 9–13, where for simplicity, the zero of the angular scales has been chosen as the beam center in each case.

The constant elevation cuts [see Figs. 9(a)–13(a)] show an acceptable agreement in the main beam and sidelobes. In the case of D2, D6, and D7, the predictions are close to the measured patterns. However, the sidelobes are higher than predicted for D4 and D5. In the worst case [see Fig. 11(a)], these sidelobes are 5 dB above the predictions.

In the constant azimuth cuts [see Figs. 9(b)–13(b)], the sidelobes show different distribution and reach higher values than in the theoretical analysis. At the same time, the main beam in this plane is slightly more directive than in the simulations. These sidelobes are not created by the mirror bracket since this bracket would mainly affect the constant elevation cuts. It is, therefore,

Fig. 13. Comparison of the: (a) constant elevation and (b) azimuth cuts corresponding to D7. Angular scales have been translated in each case to be centred on 0° .

thought that they are created by the difference between the radiation patterns of the individual dipoles and the dipole on top of the woodpile pattern used in the GRASP simulations. This pattern was obtained from HFSS simulations and, as was mentioned above, a limited volume HFSS model was used when these patterns were calculated and interactions with the neighboring dipoles were not included.

For the central beam, from dipole D2, the sidelobe distribution is different than in the prediction [see Fig. 9(b)]. For negative elevation angles, the second sidelobe is the largest one, more than 10 dB higher than the predicted levels at this point, and the first sidelobe is lower than the predicted one.

The dipole placed further away from the mirror bracket (D4) shows the best agreement between simulations and measurements (see Fig. 10). For the constant elevation cut [see Fig. 10(a)], the measured sidelobe pattern and levels are very similar to the predictions. In the constant azimuth cut [see Fig. 10(b)], the agreement is good for the first sidelobe, although the second one is 5–7 dB higher in the measurements.

For the other beams (Figs. 11–13), the azimuth cuts are in general good agreement. In the elevation cuts, the first sidelobe is the highest one. These sidelobes are significantly higher than predicted. In the worst case, i.e., D7 [see Fig. 13(b)], the difference is larger than 10 dB.

V. CONCLUSION

The design, assembly process, and characterization of the first sub-millimeter-wave heterodyne receiver array based on EBG technology have been presented. The 500-GHz planar array design consisted of seven detecting elements, each based on a dipole antenna with an integral Schottky diode, which were backed by a silicon woodpile. This array was planned to meet the requirements of a typical astronomical imaging instrument. The detector design, in terms of the element dimensions and position on the woodpile, was optimized for maximum sensitivity and beam quality. This optimization is subject to the limitation that antennas can only be placed at specific places of the silicon

woodpile, i.e., spaced by integral multiple periods of the structure.

The seven element array was assembled on a monolithic quartz membrane ($20\text{-}\mu\text{m}$ thick), which was placed on top of the woodpile. An off-axis parabolic mirror was supported above the array on an adjustable mount. Beam patterns were measured at 500 GHz with a dynamic range of more than 25 dB by using a VNA system and subharmonic pumping of the Schottky diodes. Acceptable agreement was obtained between the predicted and measured directions and angular sizes of the beams. However, measured sidelobe levels in the constant azimuth cuts tended to be significantly higher than the simulated values. The reason for this discrepancy may arise from the difference between the calculated dipole radiation pattern that was used in the simulation and the real one.

The demonstration of this array represents a significant step towards creating a useful heterodyne array-based imaging system for the sub-millimeter range. It is recognized that significant challenges in terms of introducing LO power, understanding and improving beam properties, and achieving IF access to large numbers of pixels still have to be overcome.

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