# Modeling of THz Focal Plane Array on Electrically Thick Substrate

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***Abstract*— Implications of printed antennas usage in focal plane arrays on thick substrates are investigated. Two different ways of obtaining a good antenna pattern on electrically thick substrate of finite dimensions are proposed, namely, substrate lenses placed on top of the antenna and holes going all the way through the substrate. Patterns of detector element with planar antenna in the focal plane of the focusing system are studied. It is shown that antennas with a slanted main lobe or with multiple main lobes are not usable for imaging purposes.**

***Keywords*— *THz imaging; FPA; planar antenna; antenna pattern; finite size substrate; substrate lens***

## I. INTRODUCTION

For the THz imaging, it is still a challenge to create multi-element focal plane array (FPA) detectors operating at ambient temperatures. New generation of multielement focal plane arrays is expected to enable real-time imaging, reduce the scanning time and increase the information capacity and reliability of the video system by eliminating mechanical scanning components. Currently, there are no large-format THz-range FPAs with good spatial resolution capable of real-time operation. Among various detectors recently proposed and realized for THz/sub-THz spectral region, two types of semiconductor detectors can be considered most promising for the ambient temperature operation: Schottky barrier diodes (SBDs) and field effect transistors (FETs). Both of them have shown the capability of achieving the noise equivalent temperature difference NETD~0.5 – 1 K [1], and have been used as direct detectors and as nonlinear elements in heterodyne mixers [2,3]. Further, narrow-gap mercury-cadmium-telluride (MCT) semiconductor thin layers with antennas were considered [5] both as sub-terahertz direct detection bolometers and infrared (IR) photoconductors. Estimated noise-equivalent power (NEP) for non-optimized MCT detectors studied at $\nu \approx 140$ GHz reaches $NEP_{300K} \approx 4.5x10^{-10}$ $W*Hz^{-1/2}$. Other types of broadband semiconductor detectors also show a good potential of operating in the THz/sub-THz range. E.g., an antenna-coupled AlGaN/GaN high-electron-mobility transistor (HEMT) has been mounted on an aplanatic hemispherical silicon substrate lens [6]. The transistors are used as direct power detectors [6] of radiation, achieving system values of NEP $=1.6x10^{-10}$W/√Hz at 590 GHz.

All those semiconductor detectors are promising for multielement array implementation by molecular beam epitaxy (MBE) or complementary metal-oxide semiconductor (CMOS) technology on thick dielectric substrates.

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In the THz range, for an efficient input of the signal power into the detector one requires a receiving antenna with the area much larger than the detector itself. Usually, in the THz range, horns or planar antennas are used. Planar antennas have lower gain and higher losses than horn antennas, but they can be implemented by CMOS technology. The homogeneity of the elements characteristics in matrix or linear arrays is desirable.

Low efficiency of planar antennas is usually associated with the excitation of substrate modes. Substrate modes and conductivity of the substrate contribute to energy losses and change of the antenna pattern, which has been theoretically analyzed [7] in the infinite substrate case. A possible way to decrease losses due to substrate modes is to use a high resistivity substrate or a thin substrate [8]. In spite of the Maxwell equations being linear, already existing antenna designs (e.g. mm-wave) cannot be scaled for operation in the THz region because of the impossibility to scale all parameters of the system due to technological limitations. Particularly, the substrate thickness in planar antennas cannot be scaled to a sufficient degree. It has been shown [9] that the presence of electrically thick (the substrate thickness $h>0.1\cdot\lambda_d$, where $\lambda_d$ is the wavelength inside the dielectric substrate) finite-size substrate is crucial for the antenna operation in the THz frequency range; the substrate electric thickness in THz FPAs plays a determinative role in the frequency characteristics of the system and should be much lower than the conventional one for CMOS technology. When the substrate is thick and its permittivity is high, many side lobes appear, and the antenna pattern as well as its frequency characteristics becomes different for different FPA elements. The gain dependence on the detector position on the finite substrate is the main factor of optical responsivity difference for the detectors in the array. We consider antenna pattern "good" if it has one main lobe normal to the surface and low intensity of side lobes, otherwise it is "bad".

In [9,10,11] it was proposed to use electrically thin substrates. However there are some technological constraints on the substrate thickness. The goal of the current study is to explore ways to improve antenna patterns on the thick substrate. The desired antenna pattern should be stable against small changes of frequency, substrate dimensions or substrate relative permittivity.

One more objective of this work is to investigate how a printed antenna on a thick substrate interacts with a focusing element. We investigate the influence of quasi optical focusing system on the sensitivity of linear array detecting elements. We compare the operation of antennas with "good" and "bad" patterns as an element of FPA.

## II. Ways to Improve Antenna Patterns on a Thick Substrate

Si substrate for CMOS detectors as well as GaAs substrate for MCT detectors has a large relative permittivity in the THz range. As we have shown in [9], for the conventional technology the substrate is thick enough to allow excitation of substrate modes, which in turn leads to the antenna pattern degradation. From the technological point of view, it is difficult to create thin substrate, so we investigate optional methods to obtain an antenna with "good" pattern on a thick substrate. For "bad" patterns, the frequency dependence stabilization and normalization are difficult, because the parameters are very sensible to the changes of frequency and substrate characteristics.

Here we propose three solutions for creating antennas on a thick substrate with the pattern stable against small changes of frequency, substrate dimensions and relative permittivity:

- Substrate microlens on top of the planar antenna.
- Holes in the substrate. Suppress the substrate modes by creating holes in places of substrates where electric field has maximum.
- Conductive layer. Adding conductive layer at the bottom of the substrate makes the substrate modes attenuate faster.

The latter solution is rather obvious and will not be discussed here. In the present work, we focus on the use of microlenses and on making holes in the substrate.

### *A. Real System with Microlenses*

Adding the substrate lens should make the antenna pattern better. To understand how a microlens on top of the planar antenna interacts with the antenna on dielectric substrate, we have modeled the system with the characteristics that are close to real setup, with a few lenses of different radius (Fig 1). We considered a rectangular substrate with length $a_{Sub}$, width $b_{Sub}$ and thickness $h_{Sub}$. There is a thin layer of conductive material (CdHgTe) which presents an active layer of THz detector with a certain thickness, relative permittivity and conductivity. On top of this layer there is a bowtie antenna with two additional contact pads as considered in [10]. Backside of the substrate is metalized. All metals are approximated as perfect conductors. The extended hemispherical lens of the radius *R* on a cylindrical basement of the height *h* is placed on top of the antenna. The height of the lens basement was half of the lens radius. The antenna pattern was calculated at the frequency of 140 GHz.

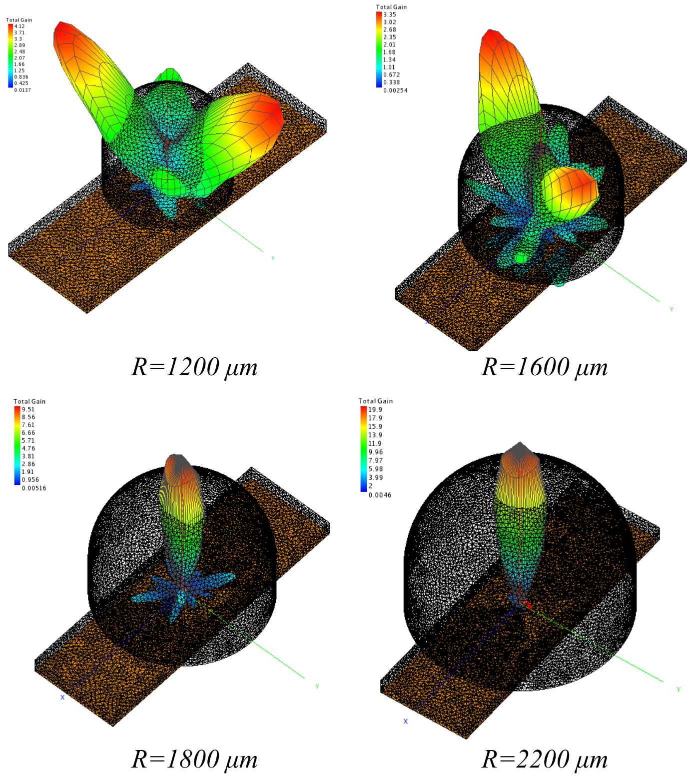


**Fig. 1.** Antenna patterns for different substrate lens radius. One can see that starting from *R=1800 µm,* the antenna pattern becomes "good".

Fig. 1 presents the dependence of antenna pattern on the lens radius. The lens begins to "work" starting from some "critical" radius. When the lens radius is above the critical value, the antenna gain grows with the lens radius increasing. We have also found that the addition of a microlens to a planar antenna on thick substrate makes it much more stable to the signal frequency change.

Since a larger microlens radius leads to larger gain, and a smaller lens radius leads to a more compact assembly of the multielement detector array, some compromise between the element gain and array dimension should be chosen.

### *B. Through-Holes in the Substrate*

Another way to obtain a "good" antenna pattern is to somehow suppress the substrate modes. To check this assumption, we modeled the dipole antenna on a finite substrate (Fig 2a) and found equivalent surface current distribution (Fig 2c). This antenna has two main lobes (Fig 2a). Then we modeled a system with substrate through-holes (Fig. 2b) where the surface electrical current has a maximum. The presence of holes changes the distribution of the equivalent surface current (Fig. 2d). As a result, the main lobe becomes single and normal to the surface (Fig 2f). Here we have shown that through-holes can prevent suppress the excitation of modes in finite size dielectric substrate.

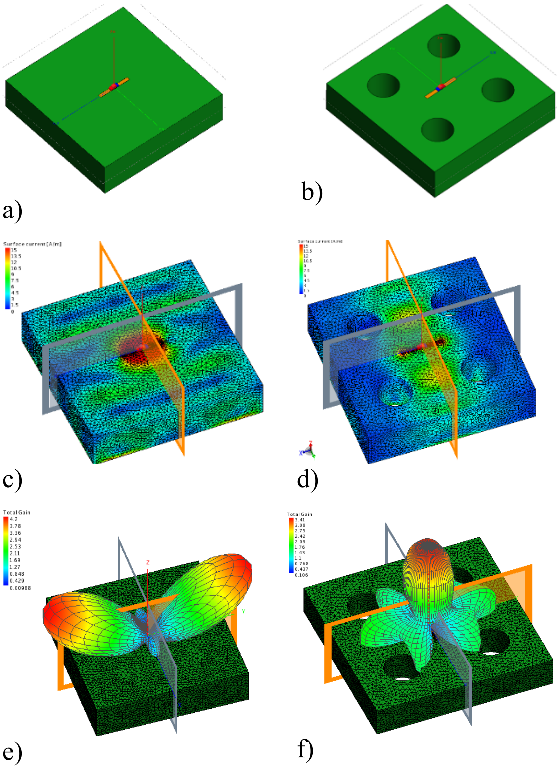

**Fig 2.** Changing the antenna pattern by modifying the substrate geometry (making holes) to suppress substrate modes. Substrate and antenna parameters are as in Fig 1. a) Printed dipole antenna on rectangular substrate; b) printed dipole antenna on rectangular substrate with holes; c) equivalent surface current distribution for system without holes; e) linear antenna pattern for system without holes; f) linear antenna pattern for system with holes.

## III. Printed Antenna Interaction With Focusing Element.

Focal plane array for the THz range consists of a focusing element (a lens or a parabolic mirror) and an array of detecting elements placed in its focal plane. We investigate the operation of an antenna placed in the focal plane of parabolic reflector. We aim to study the dependence of the antenna pattern on the distance *dx* of the antenna from the optical axis of the reflector, see Fig. 3. In this way, we simulate a multielement system, studying the inhomogeneity of the pattern for different array detector elements.

The modeled system (Fig. 3) consists of a parabolic reflector with the radius of 40 mm and the focal length of 80 mm. The antenna is positioned in focal plane at the distance *dx* from the optical axis. The reflector was modeled using the physical optics (PO) approximation, and antennas were modeled using method of moments (MoM). PO and MoM were decoupled to decrease required resources for the modeling. Dimensions of the reflector were chosen so as to strike a compromise between the required resources for modeling and the maximum gain.

We have studied antennas both with “good” and “bad” patterns. We have chosen printed dipole antenna on finite size dielectric substrate as having “bad” antenna pattern (see Fig 4a), while the same antenna with the substrate lens has “good” antenna pattern (see Fig 4b).

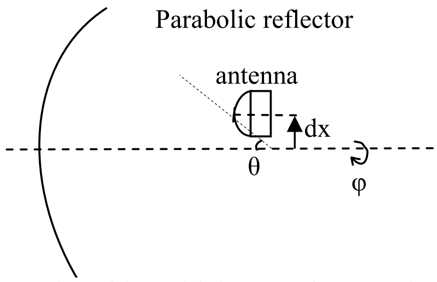


**Fig. 3**. Chart of the modeled system. The antenna is positioned in the focal plane of the parabolic reflector on the distance dx from the optical axis.

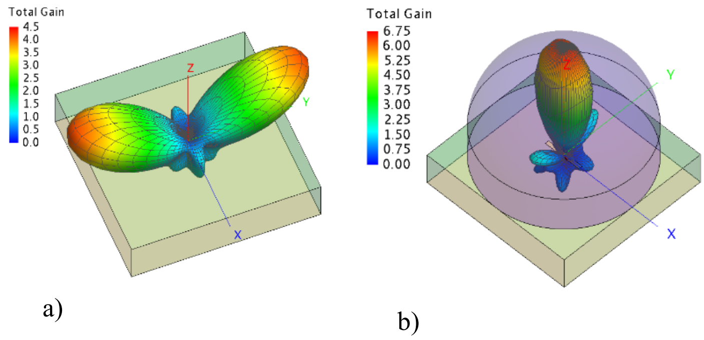


**Fig. 4**. Antenna patterns of printed dipole antenna on a finite dielectric substrate without (a) and with (b) a substrate lens. a) example of a “bad” antenna pattern b) example of a “good” antenna pattern. The antenna length is 600 µm, the substrate thickness is 460 µm, substrate relative permittivity is 9.36, the substrate width and length are 2000 µm each.

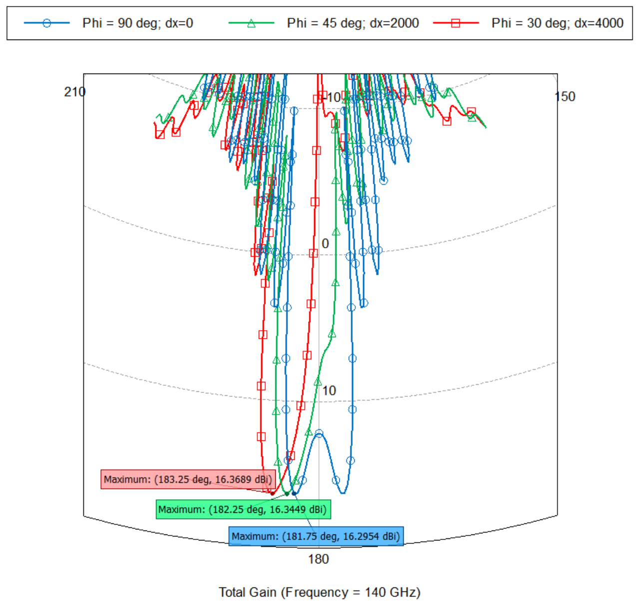


**Fig. 5** The antenna pattern as a function of angle θ (in the φ plane of maximum gain) for the “bad” antenna as shown in Fig.4a, depending on the distance *dx* (given in $\mu m$) from the parabolic reflector optical axis. The system is not suitable for imaging because of the double maximum for dx=0 and asymmetric θ dependence at *dx*>0.

Ideally, to obtain a THz image without distortion, each element of the focal plane array should have a single narrow main lobe and low level of side lobes. Further, the angle of this main lobe should depend linearly on the distance between antenna and optical axis.

Our modeling of the system shows that the antenna with the “bad” pattern from Fig. 4a cannot be used as an FPA element. The essential reason is that the whole system has two main lobes for $dx$=0 (see Fig. 5) which is extremely undesired for vision systems. The direction of maximum sensitivity changes with both θ (polar) and φ (azimuthal) angles. The maximal gain (16 dBi) is much less than the maximal theoretically possible gain estimated from considering the reflector area as the antenna effective area: $G_{\max} = 4\pi^2 r^2 / \lambda^2 \approx 1.5 \cdot 10^4 = 42\text{dBi}$, where $r$ is the reflector radius (40mm) and $\lambda$ is the wavelength (2.1mm).

Fig. 6 shows that the antenna with the “good” pattern (see Fig. 4b) is suitable as the FPA element, owing to a single narrow main lobe in the resulting system, maximal gain comparable to $G_{\max}$ and linear dependence of main lobe direction from antenna displacement $dx$.

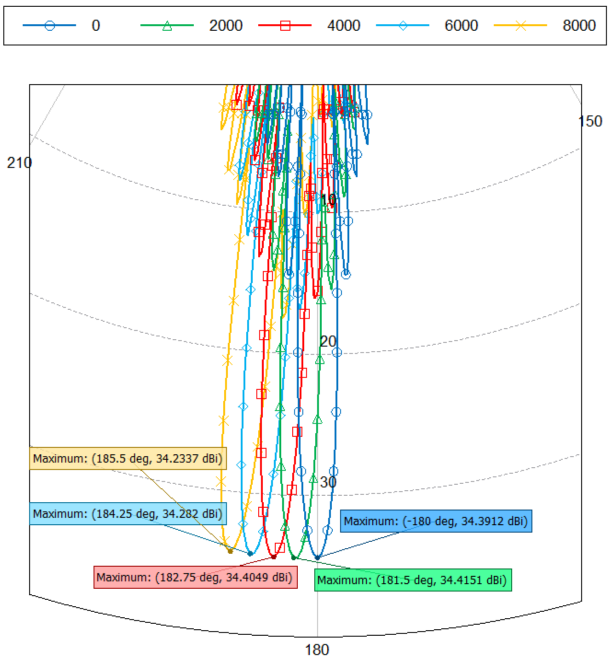


**Fig. 6**. The antenna pattern as a function of angle θ for the “good” antenna with the substrate lens as shown in Fig.4b, depending on the antenna distance $dx$ (given in $\mu m$) from the parabolic reflector optical axis. This system is suitable for imaging due to the linear dependence of the angle of maximum gain on $dx$>0.

## CONCLUSIONS

We have analyzed the implications of printed antennas usage on thick substrates in a focal plane array. We have shown that:

- The substrate microlens design allows the use of thick substrates for detector operation and negates strict requirements on the substrate thickness;
- The optimal radius of an extended hemispherical substrate lens should be slightly larger than the largest linear dimension of the antenna.
- Modifying the substrate geometry by making through-holes can suppress the substrate modes and thus enhance the antenna pattern.
- Antennas with a slanted main lobe or with multiple main lobes are not usable in FPA;
- Antennas with “good” pattern have a single narrow main lobe with an angle of slope that depends linearly on the detector distance from the optical axis. Such antennas can be used as elements in integrated FPAs with a focusing system. The gain of the system is comparable to theoretical maximal gain.

## ACKNOWLEDGMENT

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