Analysis of Absorber Based Imaging Systems with Distributed Incoherent Sources

Dabironezare, S.O.; Neto, A.; Llombart, N.

DOI
10.1109/IRMMW-THz.2017.8067165

Publication date
2017

Document Version
Accepted author manuscript

Published in
42nd International Conference on Infrared, Millimeter, and Terahertz Waves, IRMMW-THz 2017

Analysis of Absorber Based Imaging Systems with Distributed Incoherent Sources

S. O. Dabironezare, A. Neto and N. Llombart [1]
[1] Delft University of Technology, The Netherlands

***Abstract*— Passive imaging cameras at sub-millimeter wavelengths are currently entering a new era with the development of large format arrays of direct detectors. Several of these arrays are being developed with bare absorbing meshes without any antenna coupling (lens or horn) structures. This paper uses a spectral electromagnetic model to analyze the performance of absorber based focal plane arrays in comparison to antenna based systems. The methodology is particularly suited to derive guidelines for optimizing the resolution and the sensitivity of thermal imaging cameras at sub-mm wavelengths. The proposed method is validated with full-wave simulations.**

I. INTRODUCTION

Sub-millimeter imagers are widely used for stand-off security applications to detect hazardous objects concealed under clothing [1]. Future security imagers will require Field of Views (FoVs) comparable to the size of a human body (i.e. >100.000 pixels) and video frame rates. Moreover, future generations of space imaging instruments require arrays of thousands of detectors to image a large portion of the sky in a reasonable image accusation time. The use of many detectors in the focal plane of an optical system, in a CCD like configuration, allows designing systems with such requirements. In the last years, there has been a significant effort in developing large format focal plane arrays (FPA) of bare absorbers using Kinetic Inductance Detectors (KIDs) [2].

The trade-offs that dominate the designs of focal planes based on antenna feeds are well known, especially when the systems are required to operate over narrow frequency bands. FPAs of bare absorbers are, however much less studied. In [3], a basic trade off oriented comparison between the performances of bare absorbers and antennas was presented within the scope of astronomical instruments. In this contribution, the analysis of bare absorbers based FPAs is performed resorting to an analytical spectral formulation. This analysis allows for an accurate evaluation of the imaging angular response, the optical efficiency for both point sources and distributed sources, and deriving guidelines for designing absorber based imaging systems.

A schematic representation of the geometry considered is shown in Fig. 1. As shown in [4], the power received by a periodic absorber can be evaluated by using a Floquet mode born circuit model, whose generators are obtained by expanding the direct fields in terms of plane waves coming from the quasi-optical system. Here the methodology in [4] is extended to a more general type of periodic mesh absorbers and squint incidences. Using this approach, we can derive the point source angular response of bare absorbers under a focusing system (i.e. reflector or lens), the aperture efficiency, and the power received from a distributed incoherent source.

II. POINT-SOURCE ANGULAR RESPONSE

The power absorbed by a resistive periodic absorber under a focusing system with an x-polarized plane wave of amplitude, E_0, and direction $\overrightarrow{\Delta k}_{\rho i} = k sin\Delta\theta_i cos\phi_i \hat{x} + k sin\Delta\theta_i sin\phi_i \hat{y}$ (see Fig.1), can be evaluated, assuming local periodicity, as the integral, over the absorber area, w, of the z-component of the Poynting's vector associated to the spatial total fields, $\vec{e}_t$ and $\vec{h}_t$, (incident plus scattered):

$$P_{abs}(f, \overrightarrow{\Delta k}_{\rho i}) = \frac{1}{2} Re\left\{\iint_{-w/2}^{w/2} \left[\vec{e}_t(\vec{\rho}, \overrightarrow{\Delta k}_{\rho i}) \times \vec{h}_t^*(\vec{\rho}, \overrightarrow{\Delta k}_{\rho i})\right] \cdot \hat{z} d\vec{\rho}\right\} \quad (1)$$

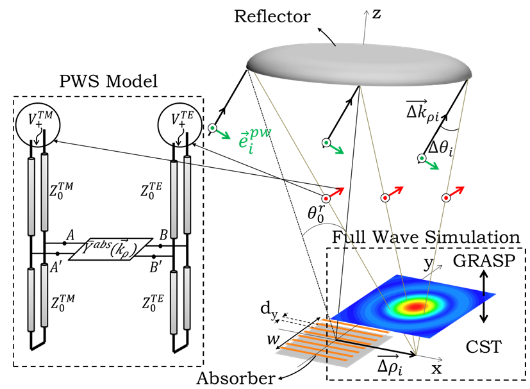

Fig. 1. The Fourier optics scenario coupled to the Floquet mode circuit for squared absorbers with side length w and period of d_y.

The aperture efficiency of an absorber under a reflector relates the physical area of the reflector, A_{Ref}, (or considered quasi-optical system) with the effective area. We can calculate this efficiency, for broadside incidence, as the ratio between the power absorbed, (1), and the power incident to the reflector, $P_{in} = \frac{1}{2\zeta_0}|E_0|^2 A_{Ref}$:

$$\eta_{ap} = \frac{P_{abs}(f, \overrightarrow{\Delta k}_{\rho i} = 0)}{P_{in}} \quad (2)$$

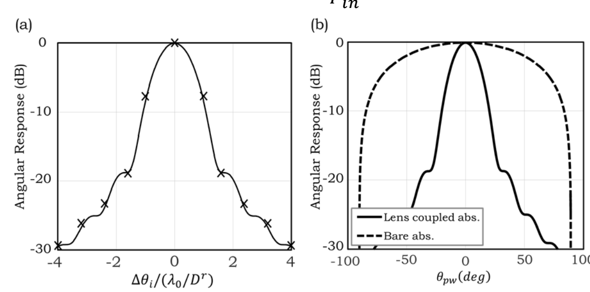

Fig. 2. The angular response of strip absorber to a point source coupled to: (a) a reflector with $f_\#^r = 2$ with side length of $w = \lambda_0 f_\#^r$, crosses represent the full wave simulation, (b) an elliptical lens with diameter $D^l = 0.75\lambda_0 f_\#^r$. Where $f_\#^r = 4$, the side length of the absorber is $w = \lambda_d f_\#^l$, and λ_d is the wavelength in the dielectric (silicon).

In Fig. 2(a) the angular response of a linearly polarized absorber under a parabolic reflector with F over D ($f_\#^r$) ratio of 2 is shown. As a validation of the proposed methodology, a time consuming full wave CST simulation (done using an external source linked to GRASP reflector simulation, see Fig. (1) is also provided. The agreement is excellent. The aperture efficiency was also validated using this simulation.

From the point source angular response, we can derive a *utilization efficiency* of the optical aperture, i.e. trade-off between aperture efficiency and *taper efficiency* (ratio between the achieved directivity, D_{ir}, in the angular response of the imager to the directivity of an uniformly illuminated optical system, D_{ir}^{max}: $\eta_t = \frac{D_{ir}}{D_{ir}^{max}} = \frac{D_{ir}}{4\pi A_{ref}/\lambda_0^2}$). The utilization efficiency is then expressed as $\eta_u = \eta_{ap}\eta_t$.

The taper and spill over efficiencies for an ideal absorber under a reflector are compared with those of an ideal antenna with a uniform square current distribution of side w. The spill over efficiency are comparable for both types of feeds, but the taper efficiency is significantly higher for the antenna feed, which leads to providing a much higher utilization factor. As the result, only for highly populated focal plane arrays with $w \leq 0.75\lambda_0 f_{\#}^r$, the utilization efficiency of bare absorbers is comparable to the one of antennas.

III. Distributed Incoherent Sources

The optimization of a densely populated FPA, requires finding a suitable trade-off between sensitivity and resolution. The sensitivity depends on power received from a distributed source, P_{abs}^{DS}, with an average temperature, T. In the Rayleigh limit, this power can be evaluated, for either antennas or absorbers, as:

$$P_{abs}^{DS} = \int_{f_1}^{f_2}\int_0^{2\pi}\int_{\theta_1}^{\theta_2} \frac{2k_B T}{\lambda^2} A_{eff}(f) F(f,\theta,\phi) sin\theta d\theta d\phi df \quad (3)$$

where $[\theta_1, \theta_2]$ represent the angular region of incoming THz radiations. This region is equal to $[0, \theta_0^r]$ and $[\theta_0^r, \frac{\pi}{2}]$ for the radiations coming from the source and the surroundings, respectively, where θ_0^r is the maximum rim angle of the reflector, see Fig. 1. $A_{eff}(f) = \eta_{ap}(f) A_{ref}$ is the effective area of the imager, k_B is the Boltzmann's constant, and $F(f,\theta,\phi)$ is the normalized angular response of the imager. By substituting the expression of taper efficiency, and approximating by a small bandwidth ($BW = f_2 - f_1$) using average efficiencies, the power received from a distributed source can be expressed as

$$P_{abs}^{DS} \simeq 2k_B T_s BW \frac{\eta_{ap}(f_0)}{\eta_t(f_0)} = 2k_B T_S BW \frac{A\Omega}{\lambda_0^2} \quad (4)$$

where T_s is the average temperature of the source.

The ratio $\eta_{ap}(f_0)/\eta_t(f_0)$ is commonly evaluated in terms of throughput, $A\Omega$, of the system [3]. This throughput is different in case of antennas or absorbers since the aperture efficiency of antennas is proportional to the taper efficiency and the radiation efficiency: $\eta_{ap}^{ant} = \eta_{rad}\eta_t$. Therefore the normalized throughput becomes:

$$\frac{A\Omega}{\lambda_0^2} = \begin{cases} \frac{\eta_{ap}(f_0)}{\eta_t(f_0)} & for\ absorbers \\ \eta_{rad}(f_0) & for\ singlemode\ antennas \end{cases} \quad (5)$$

For single-mode antennas, $A\Omega/\lambda_0^2 = \eta_{rad} \leq 1$. Whereas for bare absorber, $A\Omega/\lambda_0^2$ could be any real number.

In case of absorbers, the throughout is typically evaluated only using geometrical considerations [3]. Here instead the proposed formulation provides an accurate and fast EM methodology to account for non-geometrical behaviors (e.g. diffraction, polarization, optics with small $f_{\#}$, frequency selective behaviours, etc.). As an example, for an absorber with side length $w = 2\lambda_0 f_{\#}^r$ under $f_{\#}^r = 0.6$ parabolic reflector, the normalized throughput evaluated derived using the EM methodology is $A\Omega/\lambda_0^2|_{FO} = 2.19$, which is significantly different from the one derived in [2], $A\Omega/\lambda_0^2|_{GO} = 3.14$, using geometrical considerations only.

IV. Lens Coupled Absorbers

The angular response of a bare absorber follows the *Lambert's cosine law*, i.e. its' response is flat for a large angular region. Therefore, as (3) indicates, the bare absorbers placed under a reflector system with a large f-number, (i.e. small θ_0^r), receive a considerable amount of power coming from outside the reflector's rim angle, i.e. stray lights noise, which degrades the sensitivity of the imager. As for antenna based systems, stray light radiations are received less due to the directive response of the antenna.

By placing the absorber under a lens as shown in Fig. 3, the angular response of the detector becomes more directive compared to the one of the bare absorber. This is shown in Fig. 2(b), where the angular response of an ideal linearly polarized absorber under an elliptical lens with $f_{\#}^l = 2$ is compared to the one of the bare absorber. As it can be seen, the lens coupled absorber has significantly narrower angular response, comparable to an antenna feed. Therefore, FPA of absorbers are only comparable in terms of overall imaging system performance to antennas when coupled to lenses and used for sampling smaller than $\lambda f_{\#}^r$.

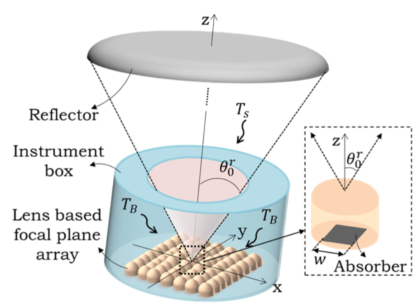

Fig. 3. The geometry of a lens coupled absorber focal plane array placed under a reflector system. The imaging system is confined within an instrument box. T_s and T_B represent the average temperature of the source and the stray light radiations coming from the instrument box, respectively.

Acknowledgment

This work was supported by ERC Starting Grant (ERC-2014-StG LAA-THz-CC), No. 639749 and FP7-Security project CONSORTIS.

References

[1] A. Timofeev et al, "Optical and Electrical Characterization of a Large Kinetic Inductance Bolometer Focal Plane Array," *IEEE TTST*, 2017.

[2] J. J. A Baselmans, et al, "A kilo-pixel imaging system for future space based far-infrared observatories using microwave kinetic inductance detectors", ArXiv e-prints, Sep. 2016.

[3] M. J. Griffin, et al, "Relative performance of filled and feedhorn-coupled focal-plane architectures," *Appl. Opt.*, Nov 2002.

[4] N. Llombart, et al, "Fourier optics for the analysis of distributed absorbers under THz focusing systems, " *IEEE TTST*, July 2015.