Analysis of Absorbers under Quasi-Optical Systems: Distributed Incoherent Sources

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***Abstract*— This paper presents a spectral electromagnetic model for the analysis of absorber based detectors in the focal plane of quasi-optical systems. The methodology is particularly suited for the optimization of the resolution and the sensitivity of thermal imaging cameras at sub-mm wavelengths in terms.**

Keywords—Sub-mm absorbers, focal plane array, angular response, distributed source.

I. Introduction

Sub-millimeter imagers for stand-off security applications are widely used 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. images with over 100.000 pixels) and video rate speeds. 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 either using Kinetic inductance detectors (KIDs) [1] operating at around 8K or uncooled micro-bolometers that could be used for commercial systems.

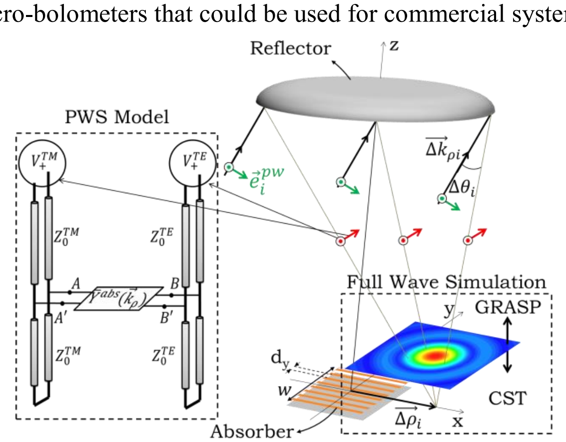

Fig. 1. The Fourier optics scenario coupled to the Floquet mode circuit for squared absorbers with side length w and period of d_y.

The 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 [2], a basic trade off oriented comparison between the performances of 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, and the optical efficiency for both point sources and distributed sources.

A schematic representation of the geometry considered is shown in Fig. 1. As shown in [3], the power received by a periodic absorber can be evaluated by using a Floquet mode born circuit model, whose generators are obtained by expanding in terms of plane waves, the direct fields, coming from the quasi-optical system. Here the methodology in [3] is extended to a more general type of periodic mesh absorbers and off-broadside incidence. Using this approach, we can derive the point source angular response of a bare absorber under a reflector, the optical 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 $\overrightarrow{\Delta k}_{\rho i} = k sin\theta_i cos\phi_i, k sin\theta_i sin\phi_i$, 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 (incident plus scattered):

$$P_{abs}(f, \overrightarrow{\Delta k}_{\rho i}) = \frac{1}{2} Re\left\{ \iint_{-w/2}^{w/2} e_{tx}(\vec{\rho}, \overrightarrow{\Delta k}_{\rho i}) h_{ty}^{*}(\vec{\rho}, \overrightarrow{\Delta k}_{\rho i})\, d\vec{\rho} \right\} \quad (1)$$

The optical efficiency, η_{opt}, can be defined for a plane wave arriving from broadside. Specifically it is the ratio between the power absorbed, (1), and the power incident to the reflector, $P_i = \frac{1}{2}\frac{|E_0|^2}{\zeta_0} A_{Ref}$, where A_{Ref} is the physical area of the reflector and E_0 the amplitude of the incident plane wave:

$$\eta_{opt} = \frac{P_{abs}(f, \overrightarrow{\Delta k}_{\rho i} = 0)}{\frac{1}{2}\frac{|E_0|^2}{\zeta_0} A_{Ref}} \quad (2)$$

Therefore, this optical efficiency constitutes the aperture efficiency of an absorber under a reflector, i.e. it relates the physical area of the reflector with the effective area. Resorting to (1) the normalized angular response, $F(f, \theta, \phi) = P_{abs}(f, \overrightarrow{\Delta k}_{\rho i})/P_{abs}$, of the imager can be assessed relating the power received for offside incidence, $\overrightarrow{\Delta k}_{\rho i}$, to η_{opt}. Fig. 2

shows the angular response of a linearly polarized absorber under a parabolic reflector with F over D ($f_{\#}$) ratio of 2 and 0.6, for different absorber sizes. As a validation of the proposed methodology, time consuming full wave CST simulations with an imported external source from GRASP reflector off-focus simulations (see Fig.1) are also provided. The agreement is excellent, even for very small $f_{\#}$ cases. The optical efficiency was also validated with these simulations.

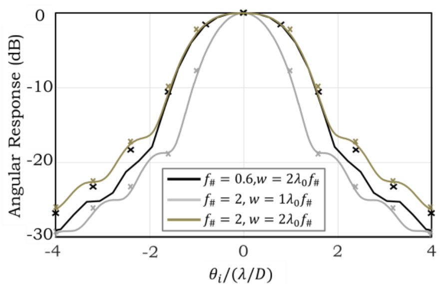

Fig. 2. The angular response of the an absorber coupled imager to a point source for different absorber sizes and $f_{\#}$. The crosses represent the full wave simulations.

From the point source angular response, we can derive a *utilization efficiency* of the optical aperture, i.e. trade-off between optical efficiency and *taper efficiency* (i.e. ratio between achieved directivity and theoretical maximum: $\eta_t = Dir/Dir^{max}$). In Fig. 3, the taper, η_t , and optical efficiencies, η_{opt}, for an absorber under a reflector are shown and compared to those of an antenna with a uniform square current distribution of side w. The optical efficiency (related basically to the spill over and impedance matching) are comparable for both types of feeds, but the taper efficiency is significantly different, with the antenna providing a much higher utilization factor. In the figure, we also report the aperture utilization efficiency: $\eta_u = \eta_o \eta_t$. The maximum of the utilization efficiency is obtained for an absorber dimension of $w = 1.2\lambda f_{\#}$, and it is only 37%. A significantly lower number compared to the maximum of 80% for Gaussian antennas with dimensions of $2\lambda f_{\#}$. Only for a highly populated focal plane arrays with $w \leq 0.75\lambda f_{\#}$, the utilization efficiency of bare absorbers is comparable to the one of antennas.

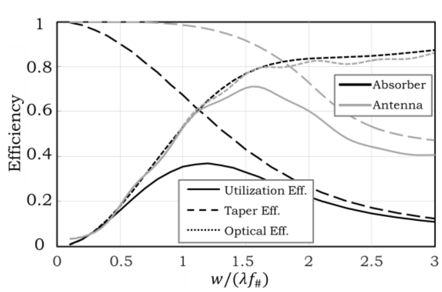

Fig. 3. The utility, taper, and spill over efficiencies for both antenna and bare absorbers, with a square dimension of side length w, for $f_{\#} = 2$.

III. Distributed Incoherent Sources

The optimization of a densely populated FPA, requires finding a suitable trade-off between sensitivity and resolution. The sensitivity in security application depends on power received from a distributed source with an average temperature, T. In the Rayleigh limit [1], this power can be evaluated, for either antennas or absorbers, as:

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

where $A_{eff}(f) = \eta_{ap}(f) A_{ref}$ is the effective area of the imager, η_{ap} is the aperture efficiency, k_B is the Boltzmann's constant, and $F(f,\theta,\phi)$ is the imager normalized angular response. Using the following relationship $\int_0^{2\pi} \int_0^{\frac{\pi}{2}} F(f,\theta,\phi) sin\theta d\theta d\phi = 4\pi/Dir$, we can expressed (3) as a function of the taper efficiency since $\eta_t = \frac{Dir}{4\pi A_{ref}} \lambda^2$. Approximating by a small bandwidth ($BW = f_2 - f_1$) using average efficiencies, we can then simplify (3) into

$$P_r \approx 2k_B TBW \frac{\eta_{ap}^{ave}}{\eta_t^{ave}} = 2k_B TBW \frac{A\Omega}{\lambda^2} \quad (4)$$

The ratio $\frac{\eta_{ap}^{ave}}{\eta_t^{ave}}$ is commonly evaluated in terms of throughput, $A\Omega$, of the system [2]. This throughput is different in case of antennas or absorbers:

$$\frac{A\Omega}{\lambda^2} = \begin{cases} \frac{\eta_o^{ave}}{\eta_t^{ave}} \; for \; absorbers \\ \eta_o^{ave} \; for \; singlemode \; antennas \end{cases} \quad (5)$$

For single-mode antennas, the aperture efficiency depends on both the optical efficiency and the directivity of the imager, therefore $\eta_{ap} = \eta_o \eta_t$ leading to the well-known single mode expression: $\frac{A\Omega}{\lambda^2} = \eta_o^{ave} \leq 1$. Whereas for bare absorber, the aperture efficiency basically is the optical efficiency, η_o, and therefore $\frac{A\Omega}{\lambda^2}$ could be any number.

The throughout is typically evaluated using geometrical consideration only in case of absorbers [2]. 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 $w = 2\lambda f_{\#}$ under $f_{\#} = 0.6$ parabolic reflector, the normalized throughput evaluated using the angular response in Fig. 2 will be $\left.\frac{A\Omega}{\lambda^2}\right|_{FO} = 2.19$, which is significantly different from the one derived in [2], $\left.\frac{A\Omega}{\lambda^2}\right|_{GO} = 3.14$, using geometrical considerations only.

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