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On the Co-design of Lens-coupled Distributed Absorbers for Far Infrared Astronomy

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***Abstract*— Lens based Microwave Kinetic Inductance Detectors combined with distributed absorbers are one of the main candidates for large format, extremely sensitive detector systems for Far Infrared Astronomy. In this paper, the optimal design of integrated dielectric lenses, based on the response of the distributed absorber to incident plane waves, is studied. For the analysis, two efficiency terms are defined, namely spectral and spillover efficiencies, decomposing the effect of the absorber's response to incident plane waves from that of its physical dimensions, on the total power captured by the detector system. Linearly polarized absorbers, made of Aluminium strips are considered as an indicative absorber geometry, with or without a quarter-wavelength backing reflector.**

I. INTRODUCTION

ASTRONOMICAL observations at the far-infrared (FIR) band of the electromagnetic spectrum (30μm to 1mm) can provide critical information on cosmological processes, mostly invisible at other wavelength regimes. Although critical for the understanding of a variety of astronomical phenomena [1], the development of large format, background limited detector arrays at THz frequencies presents major challenges [2]. In addition, there are fundamental limitations arising from the high absorption in Earth's atmosphere above 1THz, dictating the need for actively cooled, space-based instruments to cover majority of the FIR band. Although the combination of the above has contributed to the currently limited availability of FIR astronomical instruments, technological advancements in the last decades have raised the interest in the development of observatories operating across the FIR regime [1].

To reach the required background limited sensitivity, detector technology candidates are Transition edge sensors (TESs), Quantum capacitance detectors (QCDs) and Microwave Kinetic Inductance detectors (MKIDs), with the latter offering the additional benefit of ease of multiplexing, enabling kilopixel arrays with a single readout line [2]. MKIDs are superconductive microwave resonators, in which their resonance frequency depends on the power incident on the detector. To couple the incident radiation to the detector, lens-based antennas or absorbers are commonly used. Antenna-coupled devices transform the incident field to a guided wave, which is then absorbed by the resonator of the MKID. In absorber-coupled devices, the absorber also acts as the inductive part of the resonator, limiting the design freedom of the radiation coupling mechanism. Although antenna based detectors feature better spatial selectivity [3], the use of absorbers simplifies the fabrication and assembly tolerances. This work will focus on the co-design of integrated dielectric lenses and distributed absorbers, in order to maximize the absorbed power, given the limitations in the response of a distributed absorber.

The analysis of lens-based distributed absorbers is based on

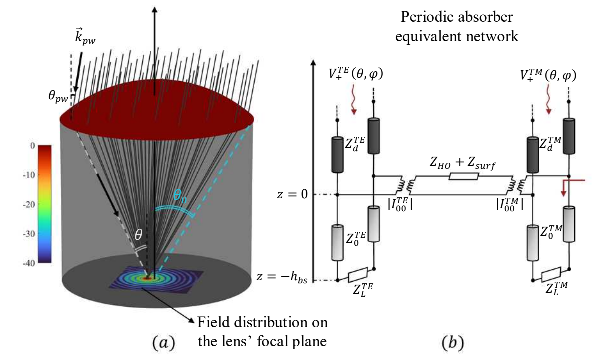

Fig. 1. (a) Integrated dielectric lens analysis under plane wave incidence. The total field distribution on the lens' focal plane is also plotted. (b) Equivalent network of periodic absorber under a plane wave incidence.

a Fourier-Optics methodology which allows the representation of the field in the focal plane of a focusing component, as a plane wave spectrum (PWS) [3]. Combined with an equivalent network of periodic absorbers to incident plane waves, it provides an analytical method for studying the spectral response of distributed absorbers under quasi-optical (QO) components. In this work, a combination of the above mentioned analysis tools is used to decompose the effect of the absorber's response to incident plane waves from that of its physical dimensions on the total power captured by the detector system. The objective is to provide better understanding of the absorbing mechanism as well as define guidelines for the design of lens-coupled distributed absorbers. Linearly polarized absorbers made of Aluminium (Al) strips, combined with high resistivity silicon lenses are used as a test case, similar to [4].

II. METHODOLOGY

The incident field on a lens' focal plane, in the absence of a scatterer (direct field), can be represented as a plane wave spectrum, limited within the lens' angular domain ($\pm\theta_0$). For the calculation of the field in the presence of a distributed absorber (total field), the spectral domain representation of the direct field is used as an excitation of the absorber's equivalent network per spectral direction (Fig. 1(b)). Upon coherent summation of the total plane wave spectrum, the field distribution on the focal plane can be derived (Fig. 1(a)). A figure of merit used to evaluate the percentage of the incident power captured by the absorber is the aperture efficiency

$$\eta_{ap}(f,\vec{k}_{pw}) = \frac{P_{abs}}{P_{inc}},$$

which is limited by: the geometry and dielectric material of the lens, the absorber's physical size and its spectral response within the lens angular domain. To explicitly study the latter, an efficiency term is derived in the spectral domain to express the impact of the distribution of the power in the PWS, in combination with the absorber's efficiency within this domain:

$$\eta_{spec}(f,\vec{k}_{pw}) = \frac{\iint_{-\infty}^{+\infty} \eta_{abs}(\vec{k}) \left|E_d^{\rho}(\vec{k},\vec{k}_{pw})\right|^2 dk_x dk_y}{\iint_{-\infty}^{+\infty} \left|E_d^{\rho}(\vec{k},\vec{k}_{pw})\right|^2 dk_x dk_y},$$

where $E_d^{\rho}(\vec{k},\vec{k}_{pw})$ is the ρ-component of the direct PWS, $\vec{k}_{pw}$ and $\vec{k} = k_x\hat{x} + k_y\hat{y} + k_z\hat{z}$ are the propagation vectors of the incident plane wave on the lens and the PWS, respectively, as shown in Fig. 1(a). The absorber's efficiency is defined as the percentage of power captured by a bare absorber, when illuminated by a uniform plane wave with incident direction $\vec{k}$.

The absorber's response to incident plane waves is derived using the equivalent network of Fig. 1(b), based on the Floquet modal expansion of the surface current distribution on the scatterer, similar to [5]. Therefore, it requires a good estimation of the surface current induced on a unit cell of the absorber. For a linear absorber made of metallic strips, the current distribution is considered uniform across the strip. Due to high losses, the response of the finite absorber can be considered the same as an infinitely extended periodic structure [4].

Since the spectral efficiency term corresponds to an infinitely extended case, to also describe the effect of its finite dimensions, a spillover efficiency term is defined as the percentage of the incident power captured by an ideal absorber:

$$\eta_{so}(f,\vec{k}_{pw}) = \frac{P_{abs}^{ideal}}{P_{inc}}.$$

The spillover efficiency provides an upper limit for the aperture efficiency, dictated by the lens geometry and material, as well as the absorber's physical dimensions.

III. Results

To examine the optimal lens design for a given absorber response, a study of the above defined efficiency terms is performed, as a function of an elliptical lens' focal distance to diameter ratio (F/D or f-number). Since the spillover efficiency mostly depends on the size of the absorber as a function of the wavelength in the dielectric (λ_d) and the lens f-number, for this study, the square absorber's physical side length is swept to always satisfy the condition $w_{abs} = 2\lambda_d F/D$. Two absorber geometries are examined, a linearly polarized absorber with a backing reflector and one without. The periodicity of the considered absorber is 4μm, the resistivity of the Al is 2 Ω/□, while the width of the strips is 100nm. The different stratifications used in the equivalent network, together with the absorber's efficiency, η_{abs}, as a function of the plane wave's incident angle at 1.5THz are showcased in Fig. 2(a).

For angles smaller than the critical angle (θ_{cr}), if the absorber is placed at the silicon-air interface, the absorption efficiency is limited due to loss of power in the transmitted wave. When a quarter-wavelength backing reflector is introduced, this power is recovered. After the critical angle, both geometries perform similarly. As a result, for absorbers with a backing reflector, the spectral efficiency increases with the focal distance to diameter ratio of an elliptical lens, as shown in Fig. 2(b). In this case, the power is distributed in a smaller angular domain, where the absorber's efficiency is high and the Poynting vector is primarily z-oriented, i.e. orthogonal to the absorber plane. On the contrary, without a backing reflector (Fig. 2(c)), the maximum of the spectral efficiency is found for $F/D = 0.8$. This is due to the fact that for large f-numbers (or small lens angular domains $\theta_0 < \sim\theta_{cr}$) the absorber's efficiency is lower and the power is not captured efficiently, while for small f-numbers, the tangential component of the Poynting vector becomes dominant, reducing the power captured, by a factor of $cos\theta$ compared to the broadside case.

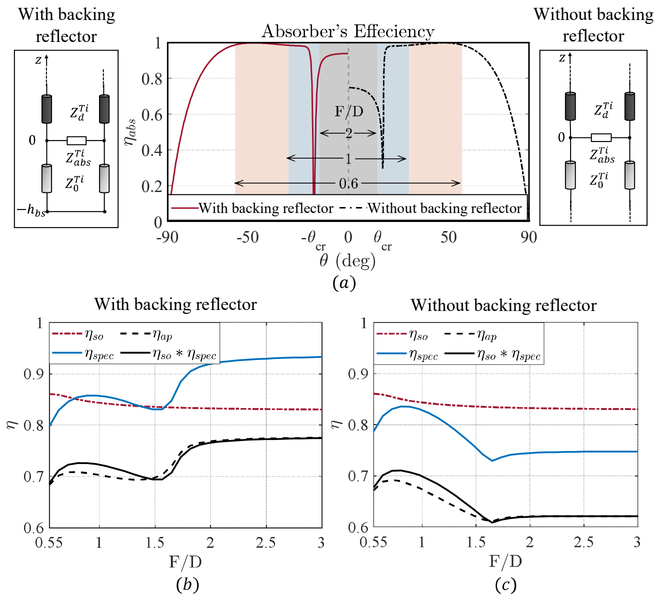

Fig. 2. (a) Absorber's efficiency as a function of the plane wave's incident angle, with and without a backing reflector. The insets showcase the modification of the transmission line model for the two cases. (b)-(c) Spillover, Spectral and aperture efficiency terms as a function of the lens' f-number with (b) and without (c) a backing reflector.

IV. Conclusion

This study showcases the potential of shaping the radiation coupling of integrated dielectric lenses to absorber-coupled MKID systems, to maximize the power captured, based on the spectral response of the distributed absorber. Due to the limitations in the design of an absorber, i.e. its dual purpose as radiation coupling mechanism and inductive part of the microwave resonator, as well as fabrication constrains potentially prohibiting the use of a backing reflector, optimizing the integrated lens to couple to a certain absorber's response becomes crucial for the design of lens-coupled distributed absorbers for FIR astronomy. The defined efficiency terms will also be used as objective functions to optimize the shape of integrated lenses when the incident field is not a uniform plane wave, as in the case of lens arrays placed below a QO system.

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