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Antenna-coupled MKIDs for an Integral Field Unit at 7.8 THz

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***Abstract*— A focal plane array of extended-hemispherical silicon lenses coupled to aluminum coplanar-waveguide (CPW) Microwave Kinetic Inductance Detectors (MKIDs) has been designed to operate at 7.8 THz. Low-dispersive leaky-wave radiation has been used to efficiently illuminate the antireflection-coated lenses. To minimize the radiation loss from the antenna feeding lines at these high frequencies, the CPWs have been miniaturized and placed on a dielectric membrane. A test device has been fabricated and its experimental characterization in terms of sensitivity, optical coupling, and beam patterns is ongoing.**

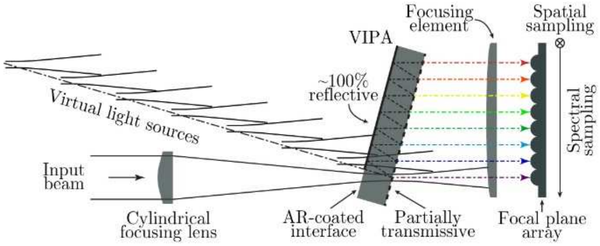

Fig. 1. Focal plane array of lenses capturing the output beams of a VIPA. This plane retrieves the spectral sampling and the perpendicular the spatial sampling.

I. INTRODUCTION

One of the key instruments for astronomy is the Integral Field Unit (IFU), a multi-pixel device combining imaging and spectroscopic capabilities. Although IFUs are wildly successful in optical astronomy [1], only a handful of small scale IFUs exist to date in the terahertz (THz) domain, either based on coherent receivers (e.g. [2]), typically providing very high spectral resolution of order $R = f/\delta f \approx 10^6 - 10^7$, or on direct detectors (e.g. [3]), which offer lower spectral resolution but do not suffer from quantum noise [4]. Among the different possible light-dispersion mechanisms for direct detection, the Virtually Imaged Phased Array (VIPA) [5] provides a high spectral resolution ($R \approx 10^4 - 10^5$) with a large angular dispersion of the monochromatic output beams impinging onto a focal plane array (FPA) of detectors as illustrated in Fig. 1.

In a multi-pixel instrument for astronomy, the detectors have two essential requirements: multiplexing capabilities and high sensitivity. Microwave Kinetic Inductance Detectors (MKIDs) [6] are superconducting pair-breaking detectors whose resonant nature makes them inherently easy to multiplex in the frequency domain and which have proven to be sufficiently sensitive to merit a space-borne mission [7]. Absorber-based MKID detectors have been extensively investigated [8], [9] but the lowest demonstrated Noise Equivalent Power (NEP) is of the order of $10^{-18}\,\mathrm{W \cdot Hz^{-0.5}}$ with disordered superconductors [10]. Instead, antenna-coupled detectors have better spatial resolution capabilities [8] and have been demonstrated to provide an NEP of the order of $10^{-19}\,\mathrm{W \cdot Hz^{-0.5}}$ with aluminum (Al) co-planar waveguide (CPW) MKIDs up to a kilo-pixel array configuration [7]. At THz frequencies, MKID-coupled leaky-wave lens antennas have been demonstrated over multi-octave relative bandwidths up to 1.5 THz [11]–[14]. The non-resonant nature of these antennas [15] makes them relatively large and thereby easier to fabricate at high frequencies. In this work, we propose a 7.8 THz multi-pixel lens-antenna array directly coupled to Al CPW MKIDs.

II. PIXEL DESIGN

The design of each of the focal plane array pixels is driven by the need to maximize the coupling to the detectors. This requires an adequate lens-antenna design to capture most of the power impinging on the lens surface, as well as the minimization of the loss mechanisms once the radiation is coupled to the transmission line on the chip.

A. Leaky-Wave Lens-Antenna

The antenna of each pixel consists of an extended hemispherical silicon (Si) lens coated with a $\lambda/4$ Parylene-C anti-reflection layer as illustrated in Fig. 2(a). The feeding point of each lens, illustrated in Fig. 2(b), is a tapered leaky-slot etched on the same Al film used for the detectors. As shown in Fig. 2(c), this metal plane is deposited on a sub-micron-thick silicon nitride (SiN) membrane opened on a Si wafer and separated from a Si lens by an electrically thin air-gap of 1.5 μm to excite low-dispersive leaky-wave radiation in the frontward direction while ensuring a high front-to-back ratio. These leaky-waves mainly illuminate the top part of the lens, which is its most efficient region [15]. The feed phase center is 22 μm behind the slot plane. The lens aperture efficiency (including spill-over and taper) and the front-to-back ratio have been calculated with the tool in [16] and the primary fields inside the lens simulated in CST Microwave Studio using a delta-gap-fed tapered leaky-slot embedded in the simplified stratification inside the yellow box of Fig. 2(c). A more realistic feeding structure based on CPW technology is discussed in the next section. The quasi-optical performance, the matching efficiency (normalized to 141 Ω) and their product are reported in Fig. 3. Illuminating the lens with the delta-gap-fed tapered leaky-slot provides a coupling efficiency to a plane-wave outside the lens in excess of 50% for more than an octave around 7.8 THz. The front-to-back, the taper and the spill-over efficiencies can all be improved by reducing the air-gap between the lens and the slot plane. The reason why this has not been done is twofold: firstly, to ease the already challenging fabrication and assembly process, and also to avoid the re-radiation from the CPW feed we discuss next.

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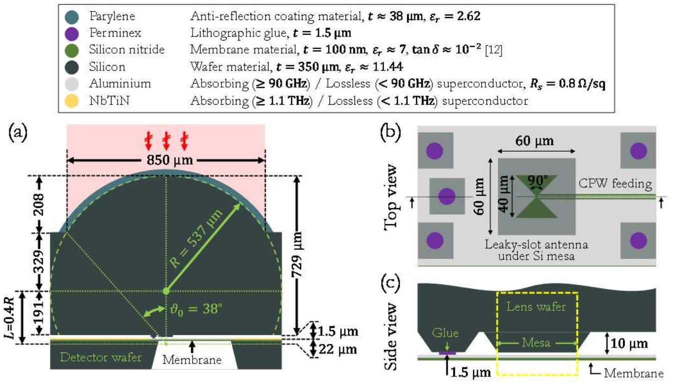

Fig. 2. Lens-antenna geometry and parameters: (a) cross-sectional view of a lens antenna, (b) top view of the feeding point, and (c) side view of the stratification around the antenna. The yellow box represents the simplified simulation stratification for the calculation of the primary fields in CST Microwave Studio.

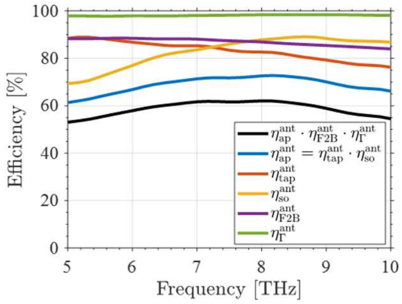

Fig. 3. Frequency dependence of the efficiency terms describing the coupling of a plane wave illumination of the lens-antenna to the power captured by the feeding point. The lens-antenna aperture efficiency ($\eta_{\mathrm{ap}}^{\mathrm{ant}}$) accounts for the taper efficiency ($\eta_{\mathrm{tap}}^{\mathrm{ant}}$) and the spill-over efficiency ($\eta_{\mathrm{so}}^{\mathrm{ant}}$). The product of the lens-antenna aperture efficiency with the front-to-back ratio (η_{F2B}) and the mismatch efficiency (η_{Γ}) is in excess of 50% over more than an octave around 7.8 THz.

B. Antenna Feed

The antennas designed in this work are directly coupled to Al CPW MKIDs, which respond in the microwave regime to the THz power absorbed in the central Al strip. One caveat of CPW technology at THz frequencies is its re-radiation loss. The use of narrow-featured CPW lines, and especially when placed in a dielectric membrane, strongly suppresses re-radiation [17]. To minimize re-radiation loss, the CPW lines used in the proximity of the antenna have 1.125 μm-wide gaps and a 0.5 μm-wide central conductor, and are laid on a sub-micron-thick dielectric membrane as illustrated in Fig. 2. The SiN of the membrane has a relative dielectric permittivity of $\varepsilon_r \approx 7$ and a loss tangent of $\tan\delta \approx 10^{-2}$ at THz frequencies [18]. Al absorbs radiation with a frequency higher than 90 GHz, which is its superconducting gap frequency. The Al central line of the CPW is the sensitive part of the KID, whereas the power absorbed in the ground plane is lost. An estimation of the different loss contributions of the CPW line has been carried out using Sonnet. After 400 μm, 54.5% of the THz power is absorbed in the central Al strip of the CPW, which is sensed in the microwave readout of the MKID. The rest of the THz power is in part re-radiated in the Si (12%) and in part dissipated in the SiN membrane (23%) and in the Al ground plane (10.5%). As a result, the coupling efficiency of the antenna-coupled MKID to a plane-wave illumination of the lens is estimated to be in excess of 27% (50% aperture efficiency multiplied with a 54.5% absorption in the Al strip of the CPW) around 7.8 THz.

III. CONCLUSIONS AND OUTLOOK.

A 7.8 THz 15x15-pixel focal plane array test chip based on antenna-coupled MKIDs has been designed and fabricated. The characterization of the sensitivity and the optical efficiency of the pixels [19], as well as the measurement of their complex beam patterns [20], is ongoing. Furthermore, we are currently evaluating the performance with an equivalent reflector quasi-optical system using the formalism described in [21].

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