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Integrated Silicon Lens-Antenna based on a Top-Hat Leaky-Wave feed for Quasi-Optical Power Distribution at THz Frequencies

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Abstract— **In this paper, we present a quasi-optical power distribution architecture based on the use of an integrated lens antenna that generates a uniform aperture field distribution. By using such distribution in combination with an integrated lens array, an efficient and scalable quasi-optical power distribution can be achieved at THz frequencies. The proposed architecture is based on a leaky-wave waveguide feed that illuminates an elliptical lens with a top-hat distribution. This method can distribute the power from one antenna to a 7-pixel lens array in a hexagonal configuration with a power coupling efficiency of nearly 60%. This scheme could be potentially used for the local oscillator power distribution in heterodyne THz arrays. A prototype at 450-615GHz has been developed and characterized, achieving an aperture efficiency higher than 80%.**

Keywords—**terahertz quasi-optical system, power distribution, terahertz antenna, multi-pixel heterodyne receiver.**

I. INTRODUCTION

Terahertz systems for space applications demand highly sensitive array of heterodyne receivers to achieve the wide-field mapping speed required for observing the continuous spectrum from interstellar dust to molecular clouds in galaxy formation [1]. Mixer technology used in space exploration, i.e., Hot Electron Bolometer (HEB) and Superconductor-Insulator-Superconductor (SIS) can achieve the wide bandwidth and sensitivity required for these observations [2] with very low Local Oscillator (LO) power consumption per mixer. However, one significant obstacle in realizing such multi-element arrays is to achieve a broadband efficient power distribution towards these mixers.

Currently, the power distribution is either done using waveguide-based distribution or phase gratings [3,4]. The use of waveguide splitters can be efficient for a small number of pixels physically close together. However, for higher frequencies, this solution becomes increasingly difficult, lossy, and costly. For example, losses of 13-20 dB were reported for a 2x2 divider at 1.37 THz [3]. Another approach has been the generation of multiple beams from a single source by using phase gratings [4]. These gratings are based on a $> \lambda_0/2$ periodic reflectarray and transform the incident wave into a series of diffraction orders that radiate in different directions. This solution is narrowband (<1%) and difficult to scale up in number of diffraction orders [4].

We propose a Quasi-Optical (QO) power distribution architecture for modular multi-element heterodyne arrays that provides efficient LO power coupling. In this architecture, the radiation is efficiently coupled from one port to an array via the use of high aperture efficiency and broadband silicon lens antennas. Moreover, the proposed architectures and technologies can be scaled up to at least 2 THz due to the tolerances and surface roughness achieved in a silicon micromachining fabrication process. We initially presented this novel architecture in [5, 6] without experimental results. In this contribution, the experimental results of the high aperture efficiency and broadband QO power distribution lens antenna, key for this architecture to work, will be presented in detail.

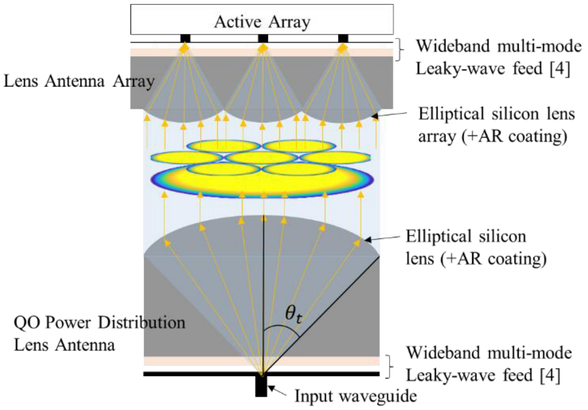


Fig. 1 Quasi-optical power distribution based on integrated silicon lens antennas with leaky wave feeds.

II. QO POWER DISTRIBUTION LENS ANTENNA DESIGN AND OPTIMIZATION

The proposed QO power distribution network distributes the power form a single large lens antenna to an array of smaller lens antenna arrays, as schematically shown in Fig. 1. It relies on having all large and small lens antennas generate a very uniform aperture field, i.e. it requires antennas with maximum aperture efficiency. When these fields are maximally uniform, the only loss in the proposed network is related to how well the lens array can sample the QO power distributing antenna field, i.e., the fill-factor efficiency η_{Fill}. This fill factor efficiency will depend on the array grid, for example rectangular or triangular, number and size of the lens array elements.

Thus, designing a lens antenna that synthesizes of a uniform aperture distribution is essential to achieve a maximum coupling in this architecture. The proposed antenna is based on the leaky-wave feed presented in [7], where a top-hat pattern is synthesized inside the silicon medium using the multi-mode leaky-wave feed [7]. The array in [7] achieved an aperture efficiency above 80% over a bandwidth of 30% at 550GHz,

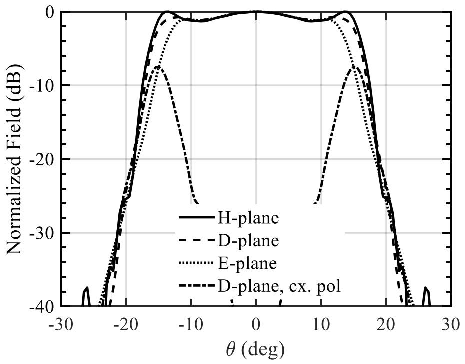


Fig. 2 Far-field radiation pattern (top-hat) of the leaky-wave feed on an infinite silicon medium.

which can be used to sample the uniform aperture field generated by the QO power distribution lens. As shown in Fig. 2, the radiation pattern of the top-hat field achieves very flat distribution when radiating on the silicon medium. To achieve highly uniform aperture field, a silicon elliptical lens, truncated at an angle θ_t is placed on top of this leaky-wave top-hat feed.

To optimize this truncation angle, the power coupling efficiency from a distributing antenna to the array has been calculated using a semi-analytical lens-to-lens near-field coupling analysis similar to [8] as follows:

$$\eta_c = \frac{1}{P_{in}} \sum_{i=1}^{N} \frac{\left| \frac{2}{\zeta_0} \iint_{S_i} \vec{E}_i^{array} \cdot \vec{E}^{QO\ ant} dS \right|^2}{16\, P_{rad}^i} \tag{1}$$

where $\vec{E}_i^{array}$ is the aperture fields of the antenna i of the array and and $\vec{E}^{QO\ ant}$ is the aperture field of the distributing antenna. P_{rad}^i is the power radiated by the antenna i of the array and P_{in} is the input power radiated by the distributing antenna.

The truncation angle has been optimized for a 7-element array of 10λ at 550GHz distributed hexagonally, making an equivalent aperture of 15.4 mm. The aperture fields are obtained by first calculating the field inside the lens using the Green's function for stratified media in the far-field (QO distributing lens antenna) or near-field (lens array) and then propagating this field out of the lens using geometrical optics [9]. Then, Eq. (1) has been employed to calculate the coupling efficiency. All the antennas have been assumed perfectly matched and at the lens-air interface, an anti-reflective (AR) coating layer of Parylene (εr = 2.62) at 550 GHz is considered. The coupling efficiency as a function of the truncation angle is shown in Fig. 3 at 550GHz . As it can be observed, a maximum coupling of almost 60% is achieved for a truncation angle of 18.5degrees. For smaller truncation angles, most power in the QO power distribution lens is lost to spill over. For larger truncation angles, the uniformity of the aperture field is too low to provide good coupling to all lenses. Note that the coupling efficiency can also be approximated as the product of the spill-over efficiency, the fill factor and the aperture efficiency of one element of the array. This approximation is in good agreement with the exact expression of Eq. (1) for small truncation angles, as shown by the dashed line in Fig. 3. For larger truncation angles, the assumption of uniform field distribution no longer holds and makes the approximation inaccurate.

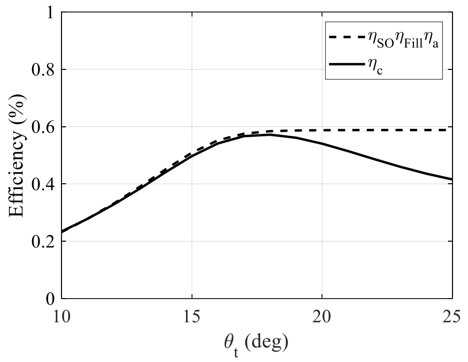


Fig. 3 Coupling efficiency of the proposed lens array coupling architecture as a function of the truncation angle.

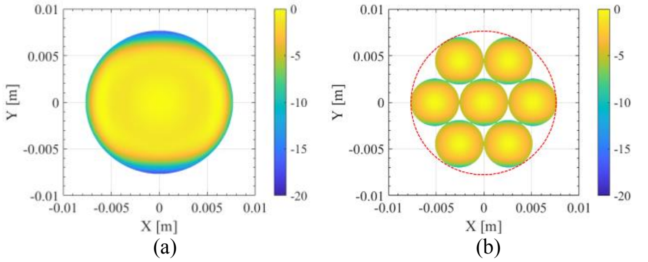


Fig. 4 Aperture field distribution of the (a) QO power distributing lens antenna and (b) the lens antenna array, for the optimized truncation angle at 550 GHz.

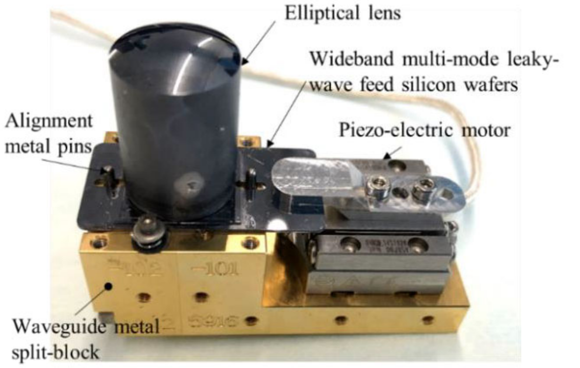


Fig. 5. QO power distribution silicon lens antenna prototype at 450-650 GHz

The aperture field distribution of the QO distribution antenna and the array for the optimized truncation angle is shown in Fig. 4 at 550GHz. As it is shown, the aperture field in both is nearly uniform with a sharp tapering around the edges. Note the amplitude tapering at the edge of each element of the array is different than for the large lens due to lens being in the near field of the feed. Overall, this aperture field of the QO distributing lens corresponds to an aperture efficiency of 85% at 550GHz. The variation in frequency will be discussed in the next section with the prototype measurements.

III. IMPLEMENTATION AT 450-650GHZ

We have developed a 450-650 GHz prototype of the quasi-optical power distribution lens antenna. The elliptical lens was fabricated by TYDEX and included a Parylene AR coating at the central frequency of 550GHz. The leaky-wave feed is synthesized using silicon micro-machined wafers, aligned using silicon pensile pins and glued together. The lens was glued to the silicon wafers containing the leaky wave feed and both were assembled using screws to a split-block metal fixture that contained the input waveguide and the transition to a WR1.5 waveguide flange. The leaky-wave feed and metal block were the same as the ones used in [7]. A piezo-electric motor aligned the lens and feed in one axis, while the other relied on a combination of optical and mechanical (metal pins) alignment. It was estimated that with the piezo-actuator, an alignment better than 10µm was achieved while the other alignment axis was around 100µm. The final assembled top-hat antenna is shown in Fig. 5.

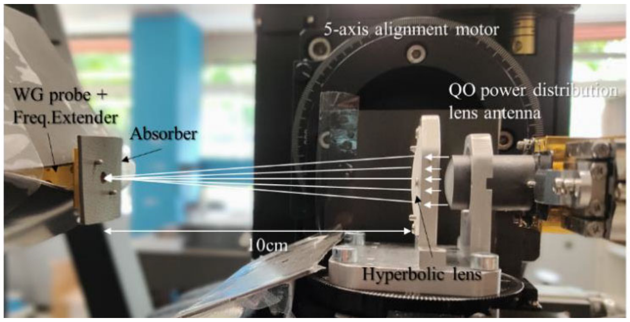


Fig. 6 Measurement setup of the QO lens antenna at 450-650GHz.

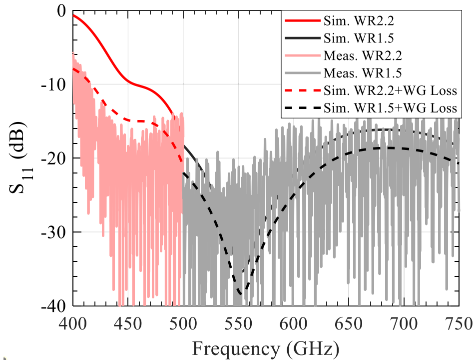


Fig. 7 Measured reflection coefficient as a function of the frequency from WR2.2 to WR1.5

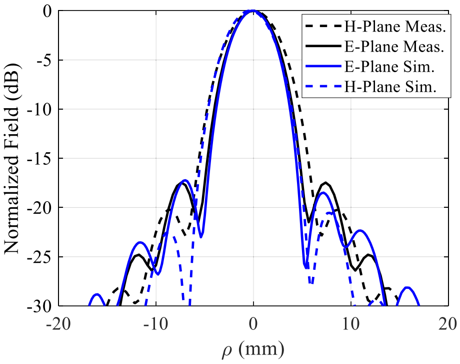
IV. EXPERIMENTAL SETUP AND RESULTS

The overall aperture diameter of the antenna is 15.4 mm, which denotes a far-field distance being over a meter. To facilitate the antenna characterization, a hyperbolic lens is used to focus the beam on a spot at 10 cm. With respect to near-field planar scanning, this solution provides a smaller scanning area to reduce the scanning time and an increase of the dynamic range [10].

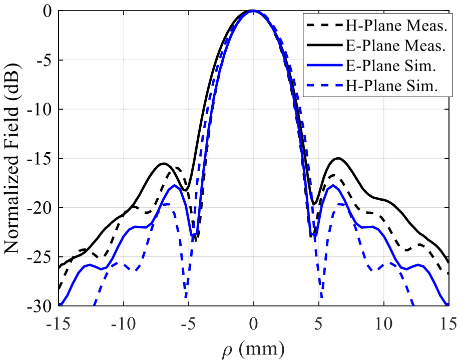
The measurement setup photograph is shown in Fig 6. A Vector Network Analyzer (VNA) and frequency extenders at WR2.2 and WR1.5 to obtain calibrated S-parameters. The waveguide flange of the frequency extender is placed at the focus of the hyperbolic lens (at 10 cm) on an x-y-z CNC scanner, and it is used to measure the radiation patterns in the spot plane. A thin sheet of Eccosorb is placed at the waveguide flange to mitigate the multiple scattering and reflections. Note that in order to filter out unwanted reflections from the setup, a time-gating was applied to the measurements. The hyperbolic lens is held by a 5-axis alignment motor to provide a precise alignment of <10um with the QO power distribution antenna, placed at a distance less than 1cm.

A. *Reflection Coefficient*

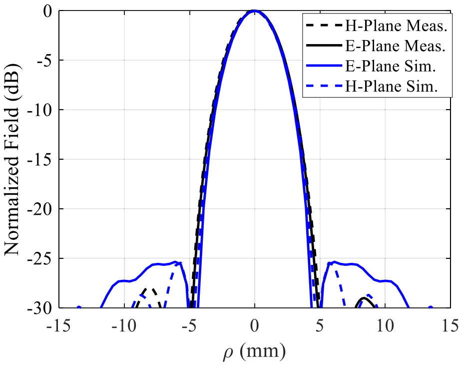
The reflection coefficient is shown in Fig. 7, measured at WR2.2 and WR1.5 frequency bands. Overall, we can see an excellent agreement with simulations over these large two bands. The simulation, including the waveguide loss of the metal fixture (around 3.2dB at 550 GHz), is added as a dashed line in the figure.



(a) 450 GHz

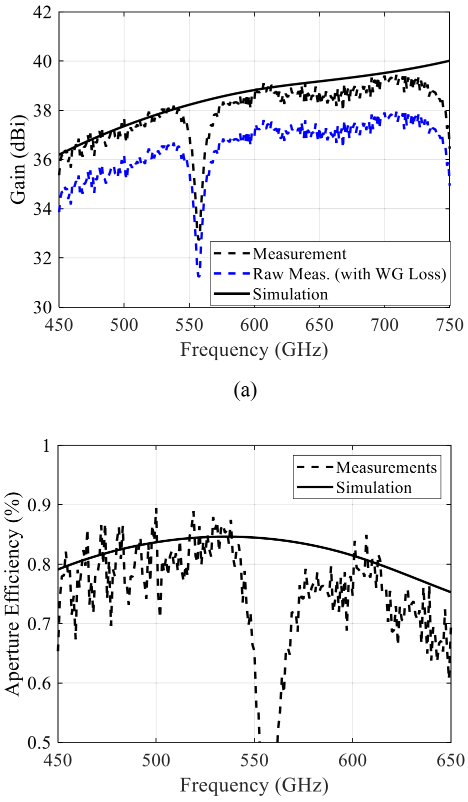


(b) 550 GHz



(c) 650 GHz

Fig. 8 Radiation patterns measured in the spot of the hyperbolic lens for 450 GHz (a), 550 GHz (b) and 650 GHz (c).



(a)

(b)

Fig. 9 Measured and simulated Gain (a) and aperture efficiency (b) as a function of the frequency

B. Radiation Patterns in the spot

The measured radiation patterns measured in the spot of the hyperbolic lens are shown in Fig. 8 in the WR 1.5 and WR 2.2 band. The simulated patterns are obtained by propagating the simulated lens-aperture fields shown in Fig. 4 to a focusing spot at 10 cm. The overall agreement with simulations is excellent, showing a highly symmetric pattern with side-lobes below 15dB at 550GHz.

C. Gain and Aperture Efficiency

The measured gain shown in Fig. 9a is obtained from the calibrated S21 measurement at broadside using a standard diagonal horn antenna and applying the Friis equation. To calculate the "raw gain," only the gain of the horn and the free-space path loss were considered. The measured gain represents the gain when the losses associated with the waveguide block (around 3.2 dB) and plastic hyperbolic lens (around 0.75 dB) are incorporated into the Friis equation. Overall, the agreement with the simulated gain simulations is fair (within 1 dB), although additional losses are probably present in the setup that have not been taken into account. The authors estimate that they belong to a combination of dielectric loss of the Parylene matching layer and a possible increase of the dielectric losses of the plastic hyperbolic lens. Note that the 557 GHz drop in gain corresponds to the absorption line of water.

The aperture efficiency as a function of the frequency is calculated from the measured gain without the embedded losses of the waveguide block. As it is shown in Fig 9, an aperture efficiency above 80% is achieved across the 450-615 GHz band which corresponds to a relative bandwidth of around 30%.

V. CONCLUSION

We have presented a design of a quasi-optical power distribution at THz frequencies based on top-hat lens antennas. It can achieve efficient and wide-band multi-pixel power distribution for heterodyne arrays in the order of 60% over 30% bandwidth. The high efficiency is achieved thanks to a top-hat lens feeding based on a multi-mode leaky-wave cavity.

The proposed QO power distribution antenna has been fabricated and characterized at the 450-650 GHz band achieving a good agreement with simulations.

ACKNOWLEDGMENT

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