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Efficient Waveguide Feeds for Low-Profile Submm-wave Lens Antennas

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***Abstract*—A small volume and low-mass THz spectroscopy instrument, integrated in a CubeSat platform, enables an accessible and low-cost pathway to earth science. Low-profile lens antennas emerge as a suitable candidate to realize a high gain, 50 dB, over a wide bandwidth, from 450 GHz to 550 GHz. To achieve a high aperture efficiency with a large numerical aperture lens, an advanced waveguide feed is required. In this work a concentric corrugated waveguide feed and multi-layer leaky-wave feed are presented and benchmarked against an open-ended circular waveguide feed. All three feeds are fabricated and will be evaluated in combination with a 7.4 cm diameter silicon lens. It is shown that the two feeds result in a 65% aperture efficiency, i.e. a 13% improvement with respect to the open-ended waveguide.**

I. INTRODUCTION

TERAHERTZ spectroscopy instruments are capable of remotely studying the atmospheric composition of earth or other planetary bodies. The integration of such system on small spacecraft, such as CubeSat, would enable low-cost earth science, e.g. studying water vapor and pollutant transportation in the earths atmosphere. Heavy restrictions in terms of volume and mass make the design of the antenna front-end challenging. At mm-wave frequencies, a high gain can be efficiently achieved with deployable mesh reflectors [1]. This solution is not considered to be scalable to submm-wave frequencies, due to stricter surface roughness and -accuracy requirements. Planar array technologies are typically trading of bandwidth and efficiency when a high gain is required. A metallic reflector can be made low-profile but will suffer from blockage effects and is high in mass. Attempts have been made with deployable balloon reflectors [2]. State-of-the-art THz lens antennas, based on resonant leaky-wave feeds, are typically high in focal number and will thus result in a high profile and a large volume silicon when a large radiating aperture is required [3]. Instead, a free-standing silicon collimating lens would be a low-mass and low-loss solution, suitable to create a large numerical aperture and low-profile antenna. Such collimating lens is shown in Fig. 1(a) and (b), of which the dimensions are tailored to realistic requirements for CubeSat THz spectroscopy. A 74 mm diameter radiating aperture would result in a 50 dB gain at 500 GHz, when a 65% aperture efficiency is assumed. To achieve a 3 cm low antenna profile, a large feed truncation angle of $\theta_0 = 61°$ is required. Such large lens solid angle cannot be illuminated efficiently with a standard open-ended waveguide feed (OEWG). In this work we will present the design and performance of two waveguide (WG) feeds, i.e. a concentric corrugated WG (Fig. 1(d)) and a multi-layer leaky-wave (LW) feed (Fig. 1(e)), to couple efficiently to the low-profile lens and benchmark the results with a circular OEWG feed (Fig. 1(c)). All three feeds are fabricated and will be measured and evaluated in combination with the collimating lens in terms of patterns and lens aperture efficiency over the full bandwidth from 450 GHz to 550 GHz.

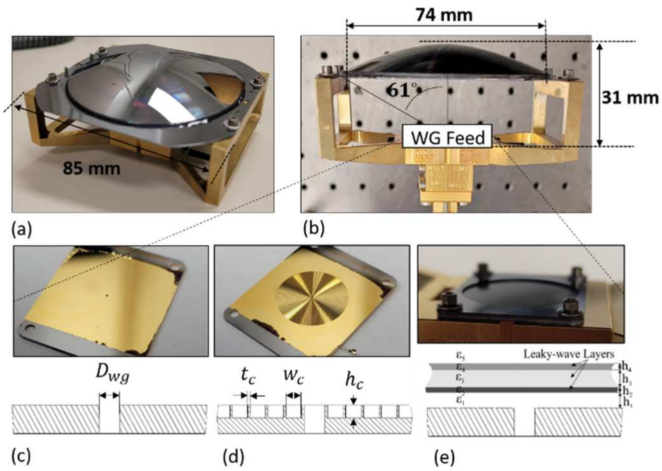

Fig. 1. Low profile lens antenna and WG feeds under investigation. (a) Bird's eye view of the assembled lens antenna. (b) Side-view of the assembled lens antenna; indicated is the position of the WG feed. (c) Benchmark OEWG. (d) Corrugated WG. (e) LW feed.

II. WAVEGUIDE FEEDS DESIGN

Circular OEWG antenna feeds that operate well above cut-off frequency (i.e. when $D_{WG} \approx \lambda_0$ with λ_0 being the wavelength in free-space, only exciting the fundamental TE_{11} mode) are characterized with a good impedance match with free-space and feature clean and symmetric radiation patterns. The amplitude tapering of this OEWG radiation pattern over a large feed truncation angle is however high and the lens will be non-uniformly illuminated, leading to a low lens aperture efficiency. The waveguide diameter can be decreased slightly to lower the feed directivity, at the expense of a higher return loss and increased pattern asymmetry. This OEWG feed, with $D_{WG} = 2\lambda_0/3 = 400$ μm at 500 GHz, forms the benchmark feed in this work and is shown in Fig. 1(c). The waveguide is silicon micromachined in a gold-plated silicon wafer and will be attached to a metal machined WG-block that is shared with all feeds under consideration, shown in Fig. 1(b). The feed pattern is shown in Fig. 2(a) at 500 GHz and the reflection coefficient is shown in Fig. 2(g) by the purple curve. Indeed, the pattern is asymmetric and the return loss is compromised. At lower microwave frequencies, corrugated waveguide feeds have been exploited to improve the axial symmetry of the radiation patterns [4]. Recently, concentric corrugations on the aperture ground-plane around an OEWG have been used in combination with a resonant leaky-wave (LW) dielectric lens at mm-wave frequencies, to reduce the radiation of the undesired TM_0 leaky-wave mode over a wide bandwidth, resulting in highly symmetric patterns [4]. Here, in the considered non-resonant case with a free-standing lens, such concentric corrugations will be used to improve the axial symmetry of the pattern and decrease the spillover losses in the E-plane. The optimized and silicon micromachined corrugated WG feed is shown in Fig.

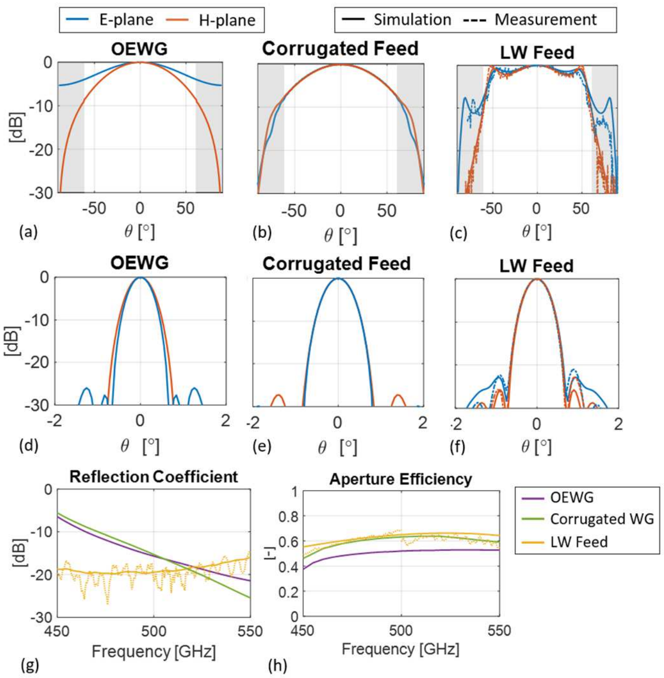

Fig. 2. Feed performance comparison. (a-c) Feed patterns at 500 GHz (E- and H-plane cuts) for, respectively, the OEWG, corrugated WG and LW feed. (d-f) Lens patterns at 500 GHz, (g) reflection coefficient and (h) aperture efficiency of the lens antenna.

1(d) and consists of 22 corrugations with $t_c = 35$ µm, $w_c = 273$ µm and $h_c = 230$ µm. The circular WG diameter is kept the same as for the OEWG. The corrugations are optimized with a BoR-MoM in Ticra GRASP to maximize the pattern symmetry, similar as in [4]. The feed pattern is shown in Fig. 2(b) and reflection coefficient in Fig. 2(g) by the green line. It is clear that the pattern is now highly symmetric with an acceptable amplitude tapering. Indicated by the grey areas is the angular region in spillover with respect to the lens. An ideal feed pattern would have a *top-hat* shape, i.e. a uniform field distribution within the lens solid angle (white area) and a sharp roll-off outside (grey area). Such feeds can be realized by exploiting leaky-wave beam-shaping properties as have been demonstrated in literature for efficient reflector illumination [6], grating lobe reduction in phased arrays or satellite coverage optimization [7]. A four-layer leaky-wave stratification is optimized quasi-analytically, similar as in [7], in terms of spillover and amplitude-/phase-tapering, using the asymptotic far-field approximation and dyadic spectral Green's functions representing the stratified media. The optimized feed is shown in Fig. 1(e) and consists of two micromachined SOI wafers. The desired relative permittivity of each layer is synthesized in the silicon with sub-wavelength perforations. The feed pattern is shown in Fig. 2(c) and shows the desired *top-hat* characteristic. The effect of the TM_0 leaky-wave mode can be identified in the E-plane but the impact on aperture efficiency is small. The antenna is well matched, as is shown by the yellow curve in Fig. 2(g). Currently, only the LW feed has been fully characterized and the measured E- and H-plane cuts and return loss are shown by the dashed lines. The patterns were measured on a rotational far-field stage with a calibrated diagonal horn antenna.

III. Lens Antenna Performance

The lens shape is optimized with standard ray-tracing and the lens antenna performance (and phase center optimization) can be efficiently analyzed using BoR-MoM in Ticra GRASP. Each feed can be assembled on the lens antenna fixture shown in Fig.1(b) and the lens height is adjusted to each feed's phase center appropriately. As shown in Fig. 1(a) and (b), the lens is adhered to a silicon lens support wafer. The bottom-side of this wafer contains a micromachined ideal anti-reflection (AR) coating whereas the top-side of the silicon lens is provided with a Parylene-C AR coating. The simulated far-field patterns and aperture efficiency of each lens antenna configuration are shown in Fig. 2(d-f) and (h) respectively. As expected, the benchmark OEWG has an asymmetric farfield pattern and a low 52% aperture efficiency at 500 GHz. The aperture efficiency includes the return loss, polarization purity, spillover and reflections on the lens, and amplitude- and phase-tapering efficiency of the lens. Both the corrugated WG and LW feed feature clean and symmetric patterns with low side-lobe level and an aperture efficiency of respectively 63% and 65% at 500 GHz. At lower frequencies, the aperture efficiency of the corrugated WG feed is compromised on return loss. The measured far-field pattern of the LW-feed (dashed lines in Fig. 2(f)) is the result of a standard near-to-farfield transformation of the measured complex near-field. A direct far-field measurement is impractical since the Fraunhofer distance is larger than 15 m. The aperture efficiency is extracted from the integration of the calibrated measured complex near-field and corresponds well with the simulations.

In this work we have presented WG feeds for efficient illumination of low-profile submm-wave lens antennas. The feeds, i.e. a corrugated feed and multi-layer LW-feed, are fabricated and measurements will be conducted and presented.

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