A 1-D Submm-wave Leaky-Wave Phased Array using MEMS Phase Shifters

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***Abstract*—Beam-scanning of submillimeter-wave spectrometers and radiometers have traditionally been implemented using mechanical scanning mechanisms due to the absence of low-loss electronic phase shifters. Recently developed waveguide-integrated MEMS phase shifters are paving the way to realize electronic beam-steering using submm-wave phased arrays. In this work, two phased array demonstrators are presented that operate from $500\,\mathrm{GHz}$ to $600\,\mathrm{GHz}$. A $20\,\mathrm{dB}$ directivity 8×1 leaky-wave antenna array will be demonstrated, using fixed waveguide feeding networks, to be capable of $\pm 20^\circ$ scanning with a scan loss less than $1.7\,\mathrm{dB}$. Secondly, an equivalent but smaller $17\,\mathrm{dB}$ directivity 4×1 array will be integrated with MEMS phase shifters to demonstrate a dynamic scanning capability over a $\pm 9.5^\circ$ range. The antenna array is based on closely sampled square waveguides, terminated with a double-iris, in close proximity of a low permittivity superstrate in order to reduce the grating lobes at larger scanning angles. Measurements are expected to be presented at the conference.**

I. INTRODUCTION AND BACKGROUND

Submillimeter-wave spectrometers and radiometers have shown to provide valuable information for various applications in astrophysics, earth- and planetary sciences due to the many interesting absorption and rotational lines that are present in this portion of the electromagnetic spectrum. In particular, the presence of numerous spectral lines in the $500\,\mathrm{GHz}$ to $600\,\mathrm{GHz}$ range that are associated to various water isotopes, allows for remotely studying atmospheric compositions and measuring the surface properties of cometary bodies. Up-to-date, beam-scanning of such submm-wave instrument is achieved by means of mechanical scanning of optical components or re-orientation of the instrument. An increase in imaging speed as well as a reduction in instrument mass, size and complexity can be expected when electronic beam-steering can be realized at those frequencies.

THz phased arrays have been demonstrated at frequencies between $340\,\mathrm{GHz}$ and $530\,\mathrm{GHz}$ using patch antennas, which limits the gain to 12 dB and bandwidth to 10% [1], [2]. Recently, a wideband leaky-wave lens antenna feed is presented that demonstrated $\pm 25^\circ$ of scanning with a $3\,\mathrm{dB}$ of scan loss [3]. This 1D scanning is achieved by mechanically translating the lens. If such feed is placed in a phased array configuration, a $48\,\mathrm{dB}$ gain can be achieved. Unfortunately, the large required phase shift for such sparsely sampled array is not yet demonstrated at THz frequencies. Up to $500\,\mathrm{GHz}$, a phase shift can be realized electronically with silicon integrated circuit technologies [1], [2], while at frequencies larger than $1\,\mathrm{THz}$ graphene technology have shown some promising results [4]. Recently, low-loss silicon MEMS phase shifters have been demonstrated in the $550\,\mathrm{GHz}$ frequency band [5], demonstrating a maximum measured phase shift of 145°. Such waveguide-integrated solution is a perfect candidate to realize a THz phased array.

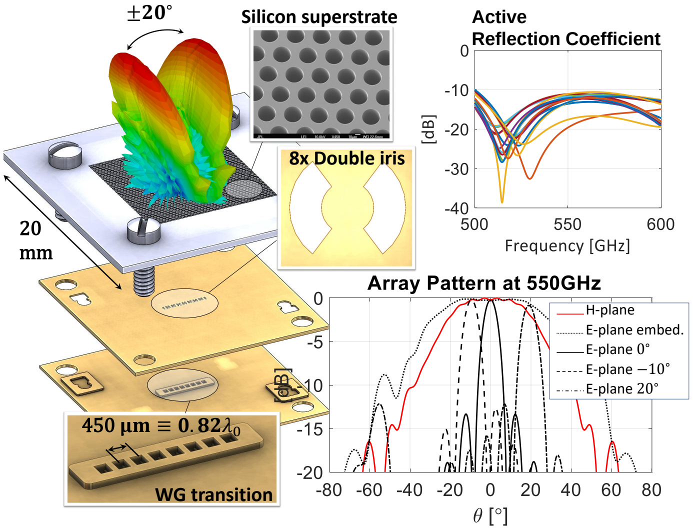

Fig. 1. The 8×1 antenna array demonstrator, fabricated in 3 silicon micro-machined wafers. In the top-right the simulated active reflection coefficient is shown. In the bottom right the simulated array pattern and E-plane embedded element pattern is shown.

In this work, a linear array of 8×1 leaky-wave (LW) antenna feeds is presented that is capable to cover a $\pm 20^\circ$ scanning range. By using a Fabry-Perot resonance cavity, the grating lobes of a sparsely sampled array can be suppressed as is demonstrated in [6], [7]. The scanning capability is planned to be measured by using a fixed waveguide feeding network. Subsequently, a reduced 4×1 array is presented that will be integrated together with MEMS phase shifters [5] to demonstrate dynamic scanning over a $\pm 9.5^\circ$ scanning range.

II. 8×1 PHASED ARRAY DESIGN

An illustration of the antenna array is shown in Fig. 1, to be fabricated from three micro-machined silicon wafers. Each antenna element consists of a square waveguide ($400\,\mu\mathrm{m} \times 381\,\mu\mathrm{m}$ in dimension) that is terminated with a double iris for an impedance match and a slight suppression of the undesired TM_0 LW-mode. A square-to-rectangular waveguide transition forms the interface to standard WR1.5 waveguides. The array periodicity, in the E-plane of the antenna, is set to $450\,\mu$m, which was considered to be the minimal spacing feasible for fabrication. Since this periodicity is equivalent to $0.82\lambda_0$, grating lobes are expected. The grating lobes appears at $\theta_g = 60°$ for a scanning angle of $20°$. The effect of the grating lobe is minimized by introducing a directivity enhancement of the element pattern, which is achieved by using a Fabry-Perot resonance cavity and superstrate. The resonance frequency of the LW cavity is set at 550 GHz. The directivity enhancement is proportional to the permittivity of the $\lambda/4$ superstrate but is in trade-off with mutual coupling between elements, resulting in increased reflections or pattern degradation. The optimum permittivity of the superstrate, optimized using a full-wave simulator, is $\epsilon_r = 2.72$. The mutual coupling is in that case $-20\,$dB; which is also suggested by [7] to be an optimum in terms of directivity enhancement and impedance matching. The active reflection coefficient is shown in Fig. 1 for all 8 elements when scanning at $\theta = 0°, -10°, 20°$. The desired permittivity can be realized by perforating the silicon slab using silicon micro-machining to a porosity of 74% [8] (an example is shown in Fig. 1).

The simulated array pattern and E-plane embedded element pattern at 550 GHz are shown in the bottom right of Fig. 1. It can be seen that the directivity enhancement in the E-plane sufficiently suppresses the grating lobe when scanning to $\theta = 20°$. At 550 GHz, a simulated directivity of 20 dB is achieved with a scan loss of only 0.55 dB. The scan loss is lower than 1.7 dB over the full frequency band.

A total phase shift of $700°$ is required for the proposed 8×1 array. Since the current design of the MEMS phase shifters presented in [5] are designed for a $145°$ phase shift, the beam-steering performance of the proposed 8×1 array will instead be verified by means of a fixed waveguide network.

III. 4×1 ARRAY WITH MEMS PHASE SHIFTERS

As a second demonstrator towards the realization of submm-wave phased arrays, the design presented in the previous section is used in a 4×1 configuration and integrated with MEMS phase shifters [5]. A maximum phase shift of $145°$ implies a maximum scanning angle of approximately $9.5°$.

Since fewer antenna elements are being used, the directivity decreases to 17 dB at 550 GHz. In Fig. 2, the simulated array pattern and E-plane embedded element pattern are shown for the maximum frequency 600 GHz. At this highest frequency point, the distinctive LW radiation peaks can be identified. A consequence of those peaks, is that the directivity of the feed increases while scanning. This implies a negative scan loss as can been seen in the bottom-left of Fig. 2. The metal loss of the antenna array, without phase shifting network is lower than 0.2 dB. The envisioned phase shifting network, that contains the MEMS phase shifters from [5], can be seen in the right hand side of [5]. The phase shift network will be fabricated both using metal machining as well as silicon micro-machining. The expected transmission losses of the full network is simulated to be 1 dB.

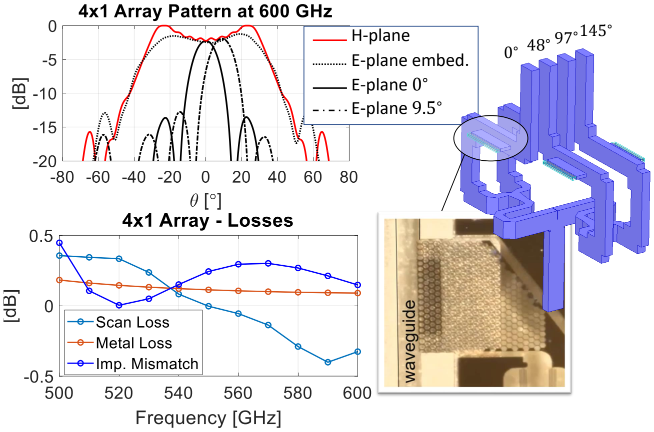

Fig. 2. Simulated performance for the 4×1 phased array demonstrator. Top-left: the simulated array pattern and E-plane embedded element pattern. Bottom-left: Simulated losses of the antenna array. Right: the envisioned 4×1 feeding network containing the MEMS waveguide phase shifters [5].

IV. CONCLUSIONS

This work presents a 8×1 phased array antenna architecture based on LW-feeds that can achieve ±20° scanning from 500 GHz to 600 GHz with high directivity. An equivalent but smaller 4×1 array is designed to demonstrate that recently developed MEMS phase shifters are the ideal candidate for future electronic beam-scanning at submm-wave frequencies. Both arrays are in their fabrication stage and measurements are expected to be presented at the conference.

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