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***Abstract*—Modern wireless systems, especially at millimeter-wave, place increasingly stringent requirements on size, weight, power and cost (SWaP-C). In this talk we present an overview of our recent work on active beamsteering array antennas for mm-wave sensing applications, highlighting an active transmitarray antenna for Ka-band (34-36 GHz) monopulse tracking radar with commercial SiGe-based beamforming chips developed for 5G. Moreover, an outlook is given towards higher levels of integration between electronics and array antennas, where co-design techniques such as direct matching and in-antenna combining may help optimizing output power and efficiency.**

I. Introduction

The ever-increasing demand for improved wireless communication and sensing performance within a densely allocated radio frequency (RF) spectrum is rapidly pushing developments to millimeter-wave (mm-wave) frequency bands beyond 30 GHz. The wider available bandwidths at higher frequencies can provide better range resolution and smaller device sizes, as demonstrated by the shift from 24 to 77 GHz in automotive radars [1].

Active electronically scanned phased arrays (AESAs) show promise for a wide range of (satellite)-communication and radar sensing applications at mm-wave, enabling efficient use of radiated power using a steerable beam to track individual mobile users, satellites, or radar targets to name a few examples. However, the half-wavelength element spacing for wide-scanning arrays combined with the degrading efficiency performance of active devices at mm-wave leads to tight area budgets and stringent thermal considerations. Moreover, the decreasing achievable power levels of power amplifiers (PAs) when going up in frequency can make long-range performance a challenging and costly affair.

The authors present an overview of their work on improving size, weight, power, and cost (SWaP-C) performance in demanding mm-wave antenna systems, with a focus on a scaleable active transmitarray for Ka-band monopulse radar with low-cost silicon germanium (SiGe)-based beamforming integrated circuits (BFICs). Moreover, an outlook is given towards higher levels of integration between electronics and array antennas. With increasing frequencies we expect increasing levels of integration within the same package or even on the same die, where co-design techniques such as direct matching and in-antenna power combining may help push performance beyond the capabilities of a modular approach.

II. SiGe-based Active transmitarray

Thanks to advances in the development of millimeter-wave electronics for the fifth generation mobile network (5G) and satellite communications, off-the-shelf BFICs operating at Ka-band are becoming more commonly available. These devices are silicon or SiGe-based, which limits their achievable power levels compared to III-V semiconductors such as gallium arsenide (GaAs) and gallium nitride (GaN) [3]. However, the benefits of vastly lower costs and the on-chip integration of digital control makes them attractive in AESAs for commercial satellite communication and mobile

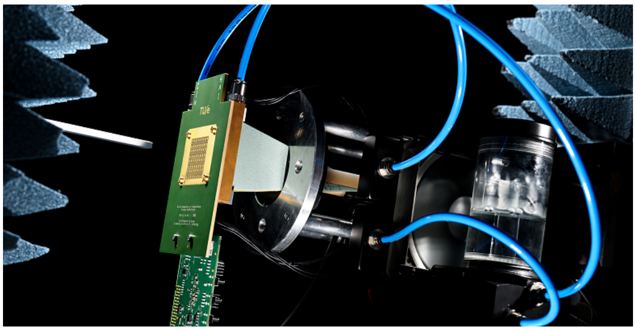

Fig. 1: The demonstrator array in the near-field measurement setup. Photo by Bart van Overbeeke photography, from [2].

networks [4], [5]. These developments can also benefit radar technology with reduced system complexity, time-to-market and development cost.

We demonstrate this potential for technological cross-pollination with the design of an active Ka-band transmitarray, proposing the use of SiGe-based 5G BFICs in a large-scale and high-power naval radar. The transmitarray design simplifies the distribution of power over a large number of elements, and provides lens-like gain enhancement for a monopulse system. The limited power per chip can be offset through sheer number of low-cost elements, adding both transmit power and antenna gain. The combination of per-element phase shifting and power amplification results in a rapidly steerable pencil beam to track fast-moving targets.

A small-scale 8×8 array has been realized and characterized in the anechoic chamber of Eindhoven University of Technology (TU/e) as shown in Fig. 1. The array achieves a peak EIRP of 56 dBm, a 12° HPBW and presents the first demonstration of beam-scanning with a BFIC-based reconfigurable transmitarray in published literature [2]. The small-scale array can scan up to ±60° in the H-plane with $\cos\theta$ scan loss and no grating lobes, as shown in Fig. 2. E-plane scanning is achieved up to ±45° with $\cos\theta^{1.1}$ scan loss. Integrated liquid cooling channels enable a high degree of thermal scalability.

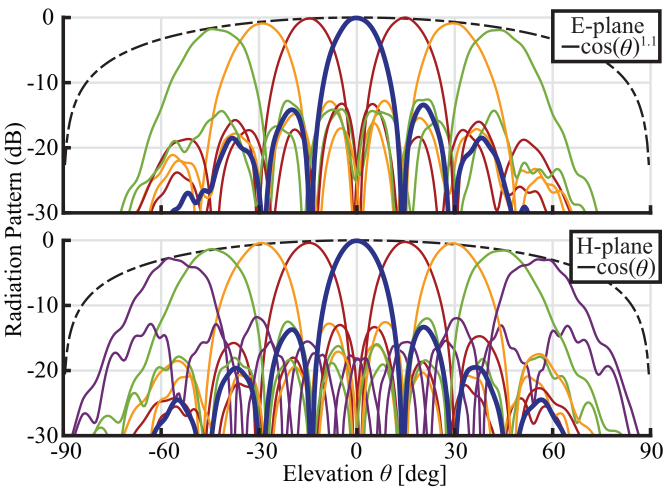

Fig. 2: Measured beamsteering performance of the Ka-band transmitarray in Tx mode, at 35 GHz with all BFICs operating in compression. Adapted from [2].

III. Amplifier-Integrated Array Antennas

In demanding applications such as long-range radars and high-volume wireless backhaul in 5G networks, high-power monolithic microwave integrated circuits (MMICs) in GaAs or GaN technology are widely used. Many of these MMICs are custom designs for specific applications, with relatively low production volumes and high unit costs. As a result, any power losses beyond the MMIC can be considered expensive.

The stringent SWaP-C requirements imposed by the small element spacing in scanning arrays can lead to highly integrated antenna systems within a package or chip [6]. This close integration limits the interconnect length, reducing the valuable power losses between amplifier and radiating element. This section highlights two potential PA-antenna co-design strategies to optimize output power, efficiency, and device size as described in [7]. The focus will be on scanning array implementations, as these were extremely limited in literature until recently [8].

A. Direct matching

The conventional 50 Ω interface as depicted in Fig. 3a may be a suboptimal solution terms of required area and power losses. Instead, a single matching network or a direct match between a co-designed PA and antenna as in Figs. 3b and 3c could help minimize size and losses which may outweigh the extra cost and effort of a custom co-design and the loss of modularity [9].

High-power transistors at Ka-band frequencies typically require a complex load to reach their optimum power and efficiency. The resistive part of this load tends to be low, as the output voltage is limited by the semiconductor material breakdown and peak output current must be increased.

From a circuit point of view, the antenna impedance Z_{ant} can be expressed as [10]

$$\begin{aligned} Z_{ant}(f) &= R_{ant}(f) + \mathrm{j}X_{ant}(f), \text{ where} \\ R_{ant}(f) &= R_{rad}(f) + R_{loss}(f). \end{aligned} \quad (1)$$

Both the resistive part R as well as the reactive part X are a function of frequency f. The antenna resistance R_{ant} describes both the desired 'loss' due to radiation R_{rad}, and the conventional losses in dielectrics and metals R_{loss}. As R_{loss} is generally undesired in each antenna design and should be

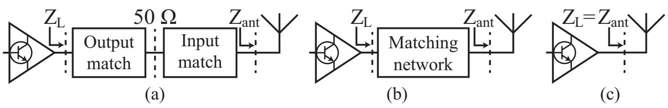

Fig. 3: (a) Conventional 50 Ω matching, (b) single matching network and (c) direct amplifier-antenna matching, from [9].

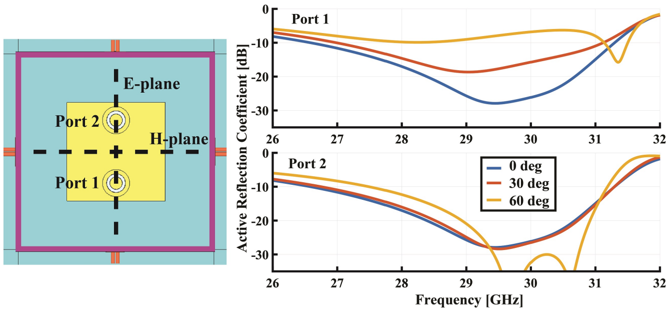

Fig. 4: Left: Unit cell model of a Ka-band multi-feed stacked patch antenna. Right: Simulated active-reflection coefficients for ports 1 and 2 when scanning in the E-plane.

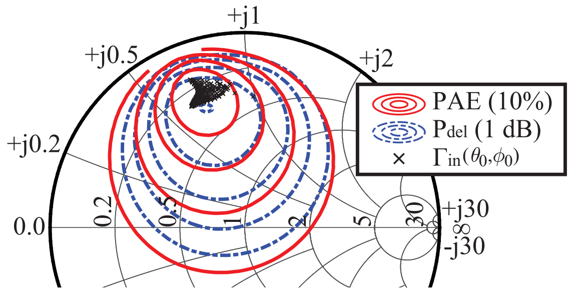

Fig. 5: Modeled example of varying load impedance of a beam-scanning single-feed stacked-patch antenna with matching network at 30 GHz, projected onto transistor load-pull data, from [9]. A power and efficiency operating point can be mapped to scan angles from broadside to 60°.

minimized regardless of interface impedance, a low R_{ant} for co-design will generally be achieved by reducing R_{rad}.

Whilst a low load resistance may benefit the PA, the antenna radiation efficiency η_{rad} may decrease according to

$$\eta_{rad}(f) = \frac{P_{rad}(f)}{P_{in}(f)} = \frac{R_{rad}(f)}{R_{rad}(f) + R_{loss}(f)}, \qquad (2)$$

where P_{in} and P_{rad} are the antenna input and radiated power.

Clearly, a trade-off between minimizing matching network losses and optimizing η_{rad} must be made. Moreover, Z_{ant} and the optimum load impedance may vary significantly over frequency, and the variations with scan angles make a direct match challenging to achieve in scanning arrays.

B. In-antenna power combining

Similarly to matching networks, the power combining network at the output of a high-power amplifier (HPA) will contribute to loss and reduce the overall achievable power efficiency. These combining losses can potentially be avoided by using a multi-feed antenna as power combiner [7].

Multi-feeds antenna generally offer little to no isolation between the feeds, which may lead to performance degradation in scanning arrays. As an illustrative example, a differential-fed stacked patch array element is depicted in Fig. 4. Scanning in the H-plane affects the active impedances at both ports equally due to the geometric symmetry. However, E-plane scanning results in different responses between the two ports: the reflection of port 1 deteriorates across the band, whereas an improvement can be seen around 30 GHz for port 2. The difference in active impedances will result in an asymmetric excitation, which will affect the element pattern and radiation efficiency. Whether this imbalance could be compensated for through the amplitude and phase at the ports, and whether antennas can be designed with better robustness against this effect, are both interesting topics for continued work.

C. PA-array antenna modeling

Aiming to derive generalized strategies for active-integrated array antennas (AIAAs) co-designed with amplifiers, we are presenting a model that combines antenna and transistor data for fast assessment of power and efficiency performance over a full scanning range as shown in Fig. 5. A more detailed description of this model is presented in [9].

IV. Conclusion & Outlook

As developments continue to push the boundaries of mm-wave system performance, two distinct design strategies are envisioned. On one hand, the commercialisation of mm-wave frequencies is expected to lead to wider availability of mass-produced, low-cost components operating at Ka-band and above. This in turn will make the development of mm-wave systems easier, faster and cheaper. Moreover, the availability of low-cost components will stimulate experimentation beyond their intended use, as has been demonstrated in Section II. A lower threshold for experimentation will potentially lead to new and innovative applications throughout the mm-wave bands.

On the other hand, in demanding AESA applications where every tenth of a dB is a valuable performance improvement, the level of system integration is expected to keep increasing. As circuits, antennas, interconnects and cooling need to be considered within millimeter-scale area budgets, it becomes increasingly difficult to tell where one discipline ends and where another begins. With co-design techniques becoming essential as a consequence, cross-disciplinary design flows and fast multi-physics simulation tools will be increasingly important assets in the mm-wave antenna engineer's toolbox.

Acknowledgment

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