Hybrid Active-Passive Beamforming for Scalable sub-Terahertz Antenna Array

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***Abstract*—For massive multiple-input multiple-output applications in sub-terahertz band, both active and passive beamforming methods encounter challenges. This paper proposes a concept of hybrid active-passive beamforming using a combination of both to address the issues. We also introduce an implementation platform using glass interposer with patch antenna array on polymer build-up layers and integrated-circuit chips embedded in the glass core.**

Keywords—6G wireless communications; active beamforming; antenna array; passive beamforming; sub-terahertz

I. Introduction

Moving from 5G towards next-generation (6G) wireless communications, one of the key technologies for 6G to support >100Gbps data capacity is to expand new spectrum bands into sub-terahertz (sub-THz) frequencies above 100 GHz [1]. As the frequency increases into sub-THz, the path loss becomes much larger [2] and the atmospheric impact is also higher [3]. Therefore, communications in sub-THz is practical for short distance using massive multiple-input multiple-output communication with hundreds of antenna elements in an array that provides highly directional radiation beams.

To steer the antenna array beams, active beamforming is commonly utilised using active phase shifter, followed by power amplifier (PA) to drive each antenna element. This has challenges in sub-THz frequencies: on the one hand, the element spacing in an array is proportional to the wavelength, but the active chip sizes are not scaled down as much due to power requirements and therefore become larger than the array lattice [4]; on the other hand, active devices are less efficient at such high frequencies, resulting in a low effective isotropic radiated power (EIRP). One solution is to split the output from one RF channel to multiple antenna elements in a sub-array. However, this only improves the radiation towards the main direction as the sub-arrays are directional and the array gain is modulated by the sub-array pattern, resulting in a limited field of view (FoV).

An alternative option is passive beamforming. Passive beamformers, such as Butler matrix [5] and Rotman lens [6] selectively steer the array beam towards multiple directions without an active phase shifter. However, these implementations are practical for smaller arrays, but not scalable to a large array size. The complexity of these passive beamformers increases substantially for more elements, especially in a 2-D array.

In this paper, we propose a hybrid active-passive beamforming method using a combination of active and passive beamformers. This hybrid beamforming is scalable for large arrays, by accommodating active and passive circuits, without degrading EIRP or FoV.

II. Concept of Hybrid Active-Passive Beamfoming

A phased array steers the radiation beam by creating phase differences among antenna elements and thus aims the maximum array factor (AF) in a certain direction. The array pattern is given by AF multiplied by the element pattern. The phase shift can be achieved by either active or passive beamformers, but can also be executed in two stages, involving both types and beamformers.

We use an antenna sub-array with one RF channel as a unit, as illustrated in Fig 1, and feed it with a passive beamformer. For simplicity, we choose 2×2 elements as a sub-array, then the passive beamformer can be implemented using a 2-D Butler matrix which consists of four hybrid couplers. By selecting the input ports, The Butler matrix provides four beams aiming towards diagonal directions. Four additional beams are obtained by superposition of two equal inputs, which are given by two SP4T switches with power splitting and combining. The entire sub-array is driven by one PA along with an active beamformer (phase shifter), which can be integrated into a λ×λ area. A large-scale array with 2m × 2n elements is then formed using

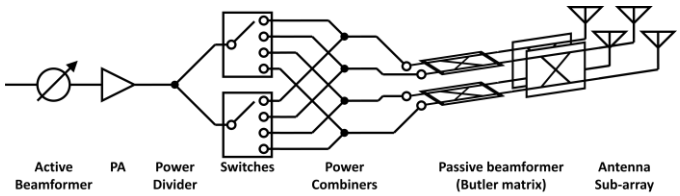

Fig. 1. Schematic of a 2-by-2 sub-array fed by hybrid active and passive beamformers. This is a basic unit for large scalable arrays.

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m×n sub-arrays. The large array is an array of sub-arrays, whose array factor is determined by the phase difference among sub-arrays. The pattern of the entire array can be calculated as:

$$G_{array}(\phi,\theta) = AF_{m\times n}(\phi,\theta) \times G_{sub-array}(\phi,\theta)$$
$$= AF_{m\times n}(\phi,\theta) \times AF_{2\times 2,i}(\phi,\theta) \times G_{element}(\phi,\theta). \quad (1)$$

Since the sub-array has eight beams, there are eight options for $AF_{2\times 2,i}$ (i=1,2,..,8). Each beam covers 1/8 of the space or 45° azimuth angles, as shown in Fig. 2. To Steer the beam towards a certain direction within one of the eight regions, we first select the corresponding sub-array beams by switching the inputs of Butler matrix, then tune the active beamformers to aim the beam in the desired direction as in Fig. 2. We demonstrate the hybrid active-passive beamforming of a D-band 16-by-16 patch array (8×8 sub-arrays) with some examples of the simulated radiation beams in Fig. 2. With the sub-array gain of approximately 9 dBi for each beam, the simulated array gain is 25 – 28 dBi while steering the beam directions, giving a fairly uniform gain in a wide FoV.

III. Implementation Using Glass Interposer

Implementing 2D arrays at sub-THz frequencies is challenging due to the lack of space between antenna elements to route the feed network. We therefore propose a heterogeneous integration approach using glass-based packaging as shown in Fig 3 which connects the integrated circuits (IC) vertically to the antenna elements. D-band Patch antenna implementation is feasible on glass interposer [7], and IC chips can be embedded in the glass core beneath the antenna [8].

We create cavities on a glass substrate, where chips are placed, including beamformers, PA's, and switches. We then laminate polymer build-up films, on which Butler matrices and other passive circuits are fabricated. On the top most layer is the microstrip patch antenna array. An example of an antenna array

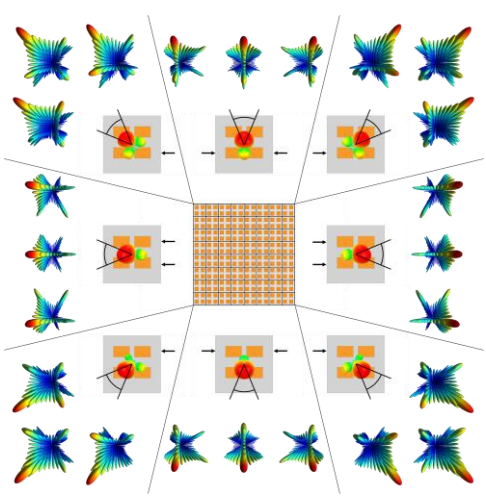

Fig. 2. Demonstration of the hybrid active-passive beamforming of a 16-by-16 array consisting of 8×8 sub-arrays. Each 2-by-2 sub-array has eight selectable beams depending on the inputs (indicated by arrows) of its Butler matrix feeding. The array beam is then steered by the active beamformer within each region.

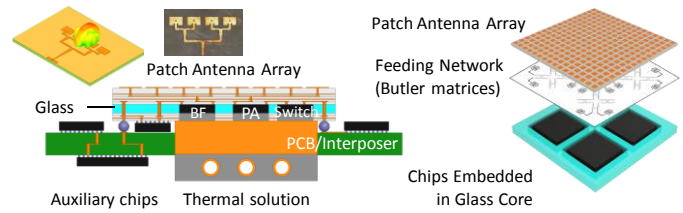

Fig. 3. Cross section and functional layers of a glass interposer. Polymer build-up layers are laminated on the glass core, with patch array on the top and passive feeding network beneath. Active chips, such as PA's and switches, are embedded in the glass with the sub-array areas. Other chips can be mounted on the back side or on the carrier board.

implemented on the glass interposer is shown in Fig. 3 with a gain of 10.6dBi, covering 133GHz – 143GHz. Heat generated by the active circuits can be removed from the back side. Auxiliary chips, such as power delivery, digital control, and IF/baseband chips, are mounted also on the back side or on a carrier board.

IV. Conclusions

We have proposed the hybrid active-passive beamforming for sub-THz antenna arrays. By two-stage phase shifting using a combination of active and passive beamformers, this method accommodates chips vertically connected to a scalable array. The operation of hybrid beamforming using sub-arrays with Butler matrix is demonstrated. We have also introduced its implementation on glass interposer with polymer build-up layers. Patch antenna arrays are on the top, with passive beamforming feeding network beneath. IC chips are integrated in the glass. This gives an opportunity to sub-THz applications for next-generation communications.

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