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Design Approach for Modular Millimeter Wave Beamforming Antenna Arrays for 5G Pico-Cells

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***Abstract*—In this paper, a concept for a modular 5G beamforming antenna array is introduced. The array consists of small tiles of planar 2x2 antenna sub-arrays. Each tile contains four patch antennas, a beamformer integrated circuit (BF-IC) and all other components needed to operate the BF-IC in a multilayer package. To build larger beamforming antenna arrays multiple tiles can be combined and placed on a control board. This modular concept leads to highly scalable solutions needed e.g. for various upcoming 5G pico-cell base stations.**

***Index Terms*—5G, antenna array, base station, beamforming, modular concept, pico-cell**

I. Introduction

The fifth generation (5G) of wireless communication systems is about to be introduced. The 5G goals are in summary enhanced mobile broadband (eMBB), ultra reliable low-latency communications (URLLC) and massive machine-type communications (mMTC) [1]. To cope with the demand for eMBB millimeter wave (mmW) bands, e.g. around 28 GHz and 39 GHz, will be used because of higher available bandwidths. Compensation of the high path losses at mmW requires high antenna gains and the introduction of small cells (pico-cells) with short-distance wireless links, which are part of a larger hierarchical cellular network consisting of macro-, micro- and pico-cells to handle URLLC and mMTC. A solution for increased interference in these cells is adaptive multi-user beamforming, which requires planar beamforming antenna arrays with high directivity steerable beams. The geometric size of the pico-cell base stations and the requirements on antenna gain and therefore the number of antenna elements vary greatly. Scenarios for pico-cell base stations may be consumer electronic devices inside buildings (e.g. TVs or ceiling lights) or outside (e.g. traffic lights). For use in pico-cell base stations the beamforming antenna arrays, together with networks for phase and amplitude control at each single antenna element and the entire RF chain, have to be integrated into these environments, which may be geometrically small. Due to highly variable requirements the arrays have to be scalable. Fabrication of the beamforming arrays may be done e.g. by consumer electronics companies, who are not necessarily experienced in the design and fabrication of mmW antennas compared to network providers building macro-cell base stations with less demands on high flexibility and scalability. With the 5G upcoming some chip manufacturers developed compact beamformer integrated circuits (BF-ICs) for bidirectional phase and amplitude control, as did Anokiwave [2] or IDT [3] for the 28-GHz-band. Integration of multiple of these four antenna BF-ICs together with the mmW antennas into small environments becomes a nearly impossible task for companies unexperienced in mmW integration aspects. The modular concept for mmW antenna arrays presented in this paper is intended to help these companies to build and integrate 5G pico-cell base stations.

II. Multilayer BF-IC integration concept

The halfduplex BF-ICs available on the market have one common RF port (RF common) and four antenna ports. In transmit direction (TX) the signal at RF common is split up to the antenna ports with controllable phase and amplitude with a maximum output power of about 10 dBm. In receive direction (RX) the incoming signals at the antenna ports are combined with controllable phase and gain at the RF common port. The phase can be controlled in discrete steps of usually about 5 degrees and also the gain for the amplitude is quantized (e.g. for the Anokiwave BF-IC there is also a 5 bit control for the amplitude). The geometric size of the

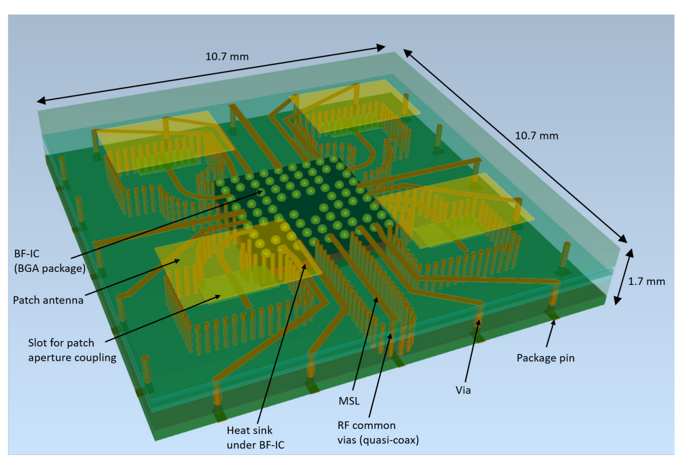

Fig. 1. Integrated multilayer structure for a BF-IC with four patch antennas. Inter-element distance is half a free-space wavelength

BF-ICs on the market [2] [3] is slightly below half a free-space wavelength λ_0, depending slightly on their package. Thus, when used together with four patch antennas, the size of the BF-IC is smaller than the size of the four antenna array. Antennas of an array are usually gridded in a rectangular fashion with an inter-element-distance of about half a free-space wavelength to have a good balance between high gain, low mutual coupling and to avoid grating lobes in the scanning range. Together with antenna sizes of slightly less than half a wavelength (e.g. patch antennas), this results in BF-IC and antennas being placed in different layers. Besides, there are layers for additional components required, such as heat sinks, feed lines and control signal lines (e.g. for SPI as used at the Anokiwave BF-ICs), always together with ground layers. In developing such multilayer structures as shown in Fig. 1, there are a number of aspects to be considered, espacially with regard to the lines carrying the mmW signals. From the RF engineering aspect a proper routing concept for the microstrip lines (MSL), which are required by the BF-IC footprints (e.g. ball-grid-array package, BGA, see Fig. 1), has to be created under the goals of low signal attenuation and reflections.

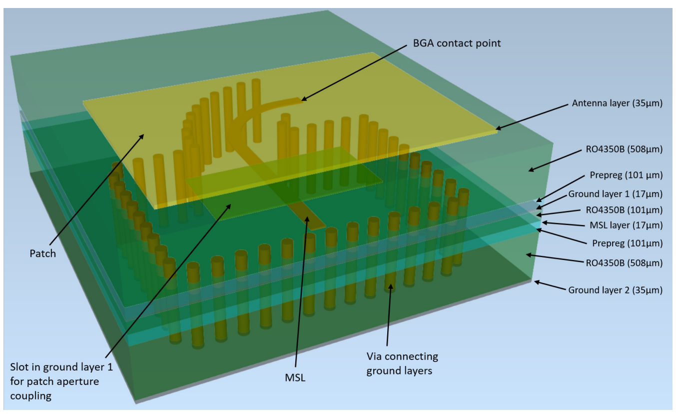

Fig. 2. Aperture coupled patch antenna in multilayer structure.

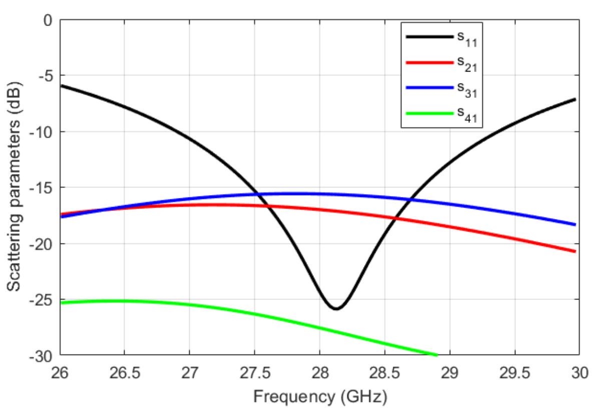

Fig. 3. Simulated scattering parameters (reference impedance 50Ω) for input at BGA contact point of antenna 1. Antennas 2 and 3 are neighboured to antenna 1.

Therefore the BF-IC was positioned with its footprint on the antenna side and turned against the antenna grid to get short lines (see Fig. 1). Routing over different layers for the mmW signals, e.g. RF common, has been done by quasi-coaxial via transitions as shown in Fig. 1 and as described in [4]. In the realization in Fig. 1 patch antennas are aperture coupled by the MSL and a slot in the antenna ground plane as can be seen from Fig. 2. The MSL lays between the ground layers which have to be connected by vias close to the MSL without influencing quasi-TEM mode. For good coupling the substrate between MSL and coupling slot has to be much thinner than the substrate between MSL and opposite ground layer (see Fig. 2). Rogers RO4350B was used as substrate together with Rogers 4450 prepreg with the thicknesses shown in Fig. 2. Performance of this kind of coupling is shown in Fig. 3. The input reflection coefficient s_{11} is lower than -10 dB over a bandwidth of 2.5 GHz with 28 GHz as center frequency. In Fig. 3 also the mutual coupling to the other three antennas on the tile is shown, which is lower than -15 dB. The simulated beamforming performance of a single four antenna tile as shown in Fig. 1 is shown in Fig. 4. Maximum directivity is more than 10.5 dBi at elevation angle $\theta = 0°$. The beam steering range is more than $80°$ with directivity higher than 8 dBi. Another important aspect especially when placing the

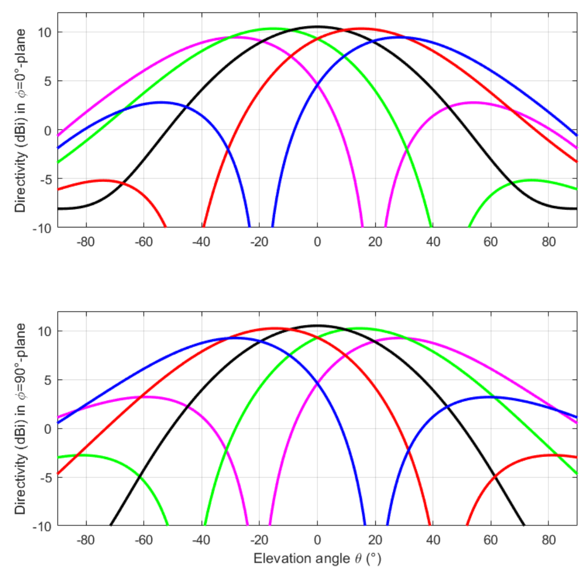

Fig. 4. Directivity of a single tile with beam steering over elevation angle in $\phi = 0°$-plane and in $\phi = 90°$-plane (azimuth angle).

BF-IC inside the multilayer structure is thermal management. To dissipate the heat of the BF-IC, heat sinks may be placed directly on the BF-IC as can be seen in Fig. 1 and there should be additional heat sinks outside the multilayer structure. The large ground layers in the shown structure together with many additional vias between these layers can be used for proper thermal dissipation.

III. Modular array concept

As it was discussed in the introduction various pico-cell applications require different antenna array sizes. Building larger arrays than the 2x2 antenna array shown in Fig. 1 to get higher array gain requires combination of multiple of these structures. Combination can be done on a single large multilayer PCB as it is usually done for macro-cell base station antennas. This large multilayer PCB is difficult to manufacture for companies who want to integrate a pico-cell base station in one of their products but have not specialized in building this kind of large mmW multilayer structures. Besides, the array size would not be scalable as needed for different variants of the pico-cell application. A much more easy and flexible fabrication process for scalable antenna arrays is to package 2x2 antenna array structure shown in Fig. 1. Then multiple of these packaged tiles can be placed on a common control board as shown in Fig. 5. The control board PCB would not even have to be multilayered, which simplifies the design. Considerations have to be made on contacting control board and tile, wherein special attention should be paid to the mmW transitions for the RF common signals. Expensive external connectors should be avoided for these transitions due to high attenuation. One possible way is to have the already mentioned quasi-coaxial via transitions on both PCBs with contacting the outer PCB layers (see Fig. 5). Due to easier manufacturing a possibility to investigate is to let the vias protrude from the PCB at the tiles side to plug them into the control board PCB having holes instead of filled vias. All other lines can be routed by conventional via transitions as shown in Fig. 1 and for the transitions between the PCBs conventional packaging concepts (e.g. QFN-packages) and contacting (e.g. reflow soldering) can be used. Packages may be fabricated by using e.g. Laser Direct Structuring (LDS) [5] on plastic tile frames. To position the tiles correctly in the array grid with proper inter-element-distances for the antennas the packaged tiles may have the form of jigsaw puzzle pieces, which then can be plugged on the control board as shown in Fig. 5. The packaging frames can also be used as heat sinks to be included in the thermal management concept. Additional heat sinks may be placed on the control board. Besides, transceiver integrated circuits (TRX-ICs) and the entire RF chain may be placed on the control board as well. Splitting signals to multiple tiles (for TX) respectively combining signals (for RX) can be done by e.g. branch line couplers placed on the control board. There is no need for considering the phase relations between the output signals of all couplers, because phase can be controlled by the BF-ICs. The simulated beam steering performance of a four tile array as shown in Fig. 5 is shown in Fig. 6. The maximum directivity is approximately 17 dBi on elevation angle $\theta = 0°$ and the beam steering range is more than $100°$ with directivity higher than 14 dBi. With larger arrays tapering should be considered to suppress side-lobes, which has not been implemented for the shown simulation results. Tapering (e.g. Chebyshev distributed amplitudes) can be easily realized with the BF-IC based tiles due to their amplitude control.

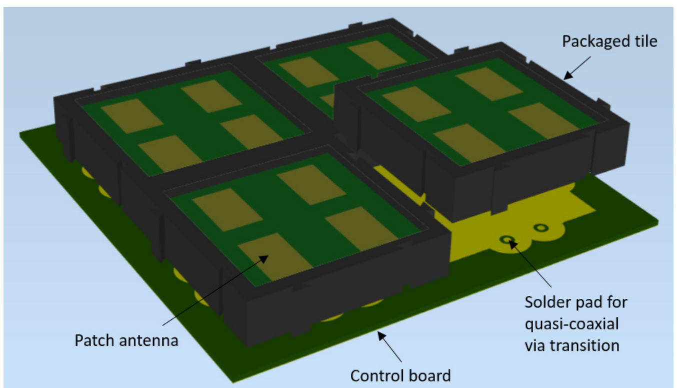

Fig. 5. Four packaged 2x2-antenna modules (tiles) placed on control board to get a 4x4 antenna array.

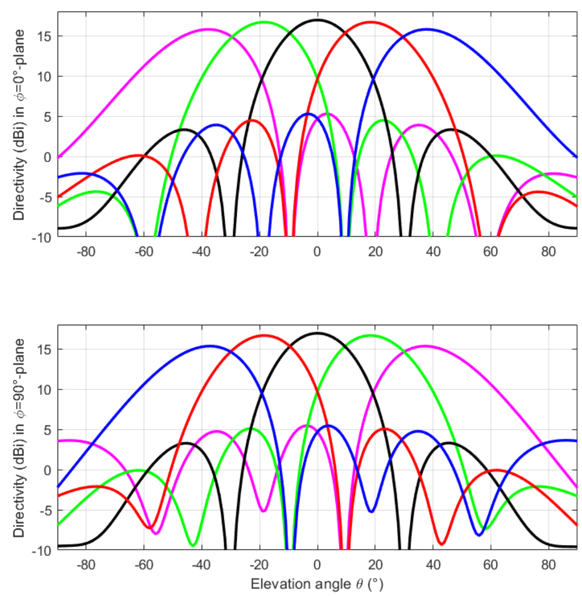

Fig. 6. Directivity of a four tiles with beam steering over elevation angle in $\phi = 0°$-plane and in $\phi = 90°$-plane (azimuth angle).

IV. Conclusion

A concept for highly scalable and easy to fabricate modular antenna arrays for use in 5G pico-cell base stations was introduced. A design proposal for the modules was presented, based on BF-ICs integrated together with antennas into a multilayer packaged structure. Flexibility in beam steering performance of the tile style modular array based on BF-ICs was shown by simulations.

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