# 24–71 GHz PCB Array for 5G/ISM

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***Abstract*—Millimeter-wave 5G mobile architectures need to consolidate disparate frequency bands into a single, multi-functional array. Existing arrays are either narrow-band, prohibitively expensive or cannot be scaled to these frequencies. In this paper, we present the first ultra-wideband millimeter-wave array to operate across six 5G and ISM bands spanning 24–71 GHz. Importantly, the array is realized using low-cost PCB. The paper presents the design and optimized layout, and discusses fabrication and measurements.**

## I. INTRODUCTION

The growing need for high data rate mobile communications has led to interest in the use of the millimeter-wave spectrum. However, as Table I shows, the unlicensed millimeter-wave Industrial, Scientific, Medical (ISM) bands and the recently allocated Fifth Generation Mobile (5G) bands, are distributed across a large band [1]. Specifically, these allocations span nearly 50 GHz.

TABLE I
ALLOCATED MILLIMETER-WAVE 5G AND ISM BANDS

| Allocation | Frequency (GHz) | Allocation | Frequency (GHz) |
|---|---|---|---|
| ISM | 24–25 | 5G | 38.6–40 |
| 5G | 27.5–28.35 | ISM | 57–64 |
| 5G | 37–38.6 | 5G | 64–71 |

As 5G architectures will require high gain phased arrays to overcome the rapid attenuation at millimeter-wave frequencies, it is important to employ a single aperture for all bands. That is, it is not feasible to employ several such arrays to cover the 5G and ISM bands in Table I. Instead, it is desirable to consolidate all six 5G and ISM bands into a single ultra-wideband (UWB) multi-functional aperture. However, thin UWB arrays such as coupled or connected arrays [2] cannot be scaled to higher frequencies. Pertinent published UWB arrays operate at 8–45 GHz (simulated) [3], 8–40 GHz [4] (using microfabrication), and 9–49 GHz (simulated) [5].

In this paper we present a planar, UWB array (see Fig. 1) that provides continuous coverage across 24–71 GHz, and all six ISM and 5G bands. Moreover, this is accomplished using standard Printed Circuit Board (PCB) fabrication.

## II. DESIGN & SIMULATION

The proposed array leverages intentional mutual coupling between array elements to cancel the inductance of the nearby groundplane [2]. This is combined with an electrically small balun, which further serves as a higher order impedance matching network [6]. However, existing designs at lower frequencies (i.e. [6], [7]) rely on through-plane assemblies, which are not supported at millimeter scales. Indeed, the feed represents the primary challenge in scaling UWB arrays to higher frequencies.

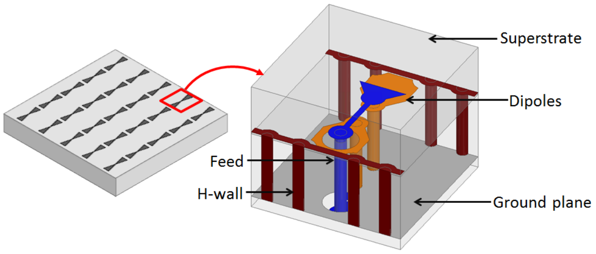

Fig. 1. Illustration of a finite array and the proposed unit cell design.

To overcome fabrication challenges, a planar balun is implemented using three vias and two metalized layers. This balun can be more easily understood using the physical-equivalent circuit diagram in Fig. 2. Generally, bandwidth is maximized when $Z_{short} >> Z_{open}$. To realize a large $Z_{short}$, we employed twin-wire transmission lines for the feed and short-circuit stub. Further, the low impedance series open stub is realized by a patch directly over the dipole arm. But the exposed nature of the feed and shorting pins can lead to cross-polarized fields. Therefore, we elected to bring the feed through the dipole arm rather than around, to maintain symmetry.

In addition to the feeding network, a conducting wall is inserted along the edge of the unit cell to shield each unit cell from backscatter occurring between the feeds of neighboring elements [3], [5]. The unit cell layout and dimensions are shown in Fig. 2.

Full wave simulations of the element design shown in Fig. 2 were carried out, in an infinite array environment. The final design delivered the active VSWR (with all mutual coupling effects accounted for) shown in Fig. 3. The frequency bands of Table I are highlighted for reference. We note that the design is well matched across the desired 24–71 GHz band. Specifically, broadside VSWR $< 2.2$, and for scans up to ±45° VSWR $< 2$ in the E-plane and VSWR $< 3$ in the H-plane. Additionally, the highly symmetric nature of the element leads to very low cross-polarized gain ($< -50dB$ in the principal planes).

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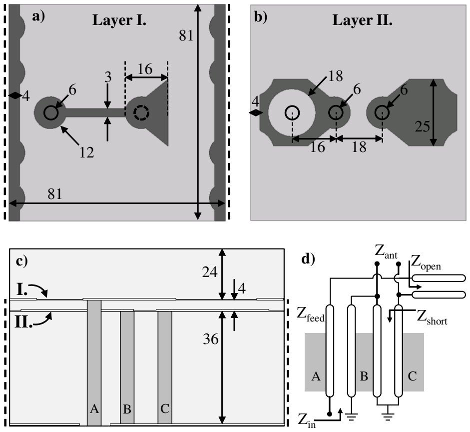

Fig. 2. Design layout and parameters of the new array element: a) top layer, b) bottom layer, c) side view, d) equivalent circuit of the balun. All dimensions are given in mils. Placement of the conducting H-wall is indicated with dashed lines in a) and c).

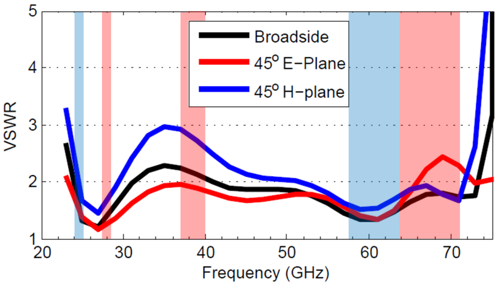

Fig. 3. VSWR performance of the infinite array using the optimized design. The 5G (red) and ISM (blue) allocations given in Table I are highlighted.

## III. FABRICATION & MEASUREMENT

Several $5 \times 5$ prototype arrays are currently being fabricated. For the central element, the $5 \times 5$ array is large enough to accurately compare against the infinite-array environment used in simulation. The use of PCB results in scalable and low-cost production, while maintaining high enough tolerance to accurately realize the nominal design. At these frequencies it is necessary to use a test fixture to interface with the Vector Network Analyzer (VNA) for measurement. However, the large size of the fixture (approximately 20 mm feedline, as shown in Fig. 4) distorts the response of the embedded test article. A de-embedding network is shown in Fig. 4, with the measurement fixture represented as a two-port S-matrix, $S_{ij}$. We observe the measured reflection coefficient, $\Gamma_{Meas}$ relates to the antenna reflection coefficient, $\Gamma_{DUT}$, according to

$$\Gamma_{Meas} = S_{11} + \frac{S_{12}S_{21}\Gamma_{DUT}}{1 - S_{22}\Gamma_{DUT}}. \tag{1}$$

From 1, we can then extract $\Gamma_{DUT}$, given by

$$\Gamma_{DUT} = \frac{S_{11} - \Gamma_{Meas}}{S_{11}S_{22} - S_{12}S_{21} - S_{22}\Gamma_{Meas}}. \tag{2}$$

That is, by isolating the two-port scattering parameters $S_{ij}$ of the test fixture, the desired measurement can be de-embedded from the raw data. These scattering parameters can be determined by measuring identical test fixtures, with the DUT replaced with open, short, and matched loads. For these cases, $\Gamma_{DUT} = 1$, $\Gamma_{DUT} = -1$, and $\Gamma_{DUT} = 0$, respectively. As $S_{12} = S_{21}$, the test fixtures allow determination of $S_{ij}$. Results of these measurements will be discussed at the conference.

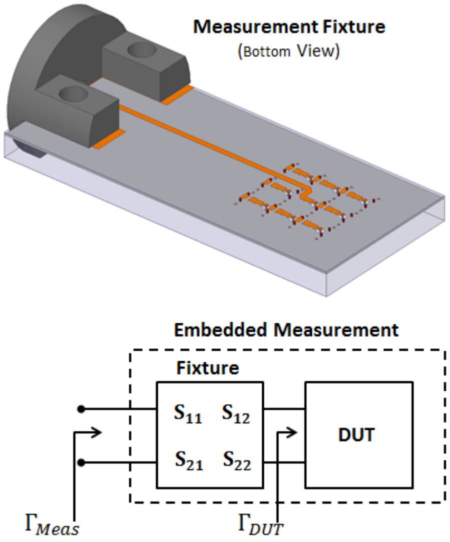

Fig. 4. Rendering of the test fixture, including 1.85mm coaxial connector and microstrip input trace feeding a single element of the $3 \times 3$ array (top), and S-parameter model of the embedded measurement setup (bottom).

## IV. CONCLUSION

For the first time, we presented a low cost, UWB, millimeter-wave array that employs a simplified feeding network requiring only three vias and two metal layers. The design process and a new array design was presented demonstrating low VSWR across six 5G and ISM bands, spanning 24–71 GHz. Unlike other designs in the literature, the presented work accounts for feature size and via spacing limitations, making its fabrication possible using large-scale and low-cost PCB approaches. Fabrication results and measurements will be presented at the conference.

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