

Low-Cost mmWave Passive Metasurfaces for In-Building Radio Coverage Enhancement

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Abstract—This paper reports a low-cost mmWave passive metasurface based on concentric ring unit-cell design. The design is optimized for FR4 laminates and requires a single metallization layer only. We demonstrate the measured performance of the 40 GHz reflector by mounting the reflector on a drywall. The measured performance shows more than 35 dBi of SINR and 40 dB array gain using a 100 MHz baseband signal. The co- and cross-polarization response is also reported. Our proof-of-concept passive metasurfaces are useful for in-building mmWave radio coverage enhancement.

I. INTRODUCTION

The propagation characteristics of millimeter-wave (mmWave) frequencies, notably their susceptibility to blockage and high path loss, pose significant challenges for in-building radio coverage. This paper introduces an innovative solution to this problem: the deployment of low-cost passive metasurfaces designed to enhance mmWave signal propagation within buildings. Metasurfaces, engineered with sub-wavelength structures, have emerged as a promising technology capable of manipulating electromagnetic waves in novel ways [1]. By leveraging these unique properties, mmWave passive metasurfaces can be tailored to redirect, focus, or scatter mmWave signals, thereby mitigating the limitations inherent in mmWave propagation. The concept of using metasurfaces for radio wave manipulation is not new; however, their application at mmWave frequencies presents unique design challenges and opportunities [2], [3].

This paper presents a comprehensive exploration of the design, implementation, and performance of these metasurfaces, emphasizing their cost-effectiveness and ease of integration into existing infrastructure. Furthermore, we present experimental validation and simulations that demonstrate the efficacy of these metasurfaces in enhancing in-building mmWave coverage. The results highlight the potential of this technology to not only improve signal strength and quality but also to enable more efficient use of the mmWave spectrum.

II. DESIGN AND EXPERIMENTAL VALIDATION

The unit-cell shown in Fig.1 are designed and optimized for FR4 (a low-cost laminate) substrate. The unit-cell consists of three concentric rings, namely, inner disk, variable ring, and an outer ring. The diameter of inner disk and outer ring is kept constant while varying the middle ring. The variable middle ring is swept from 0.55 mm to 2.1 mm which provides a linear phase response of 360° . The performance of the surface doesn't deviate more than 2% with and without a standard solder mask.

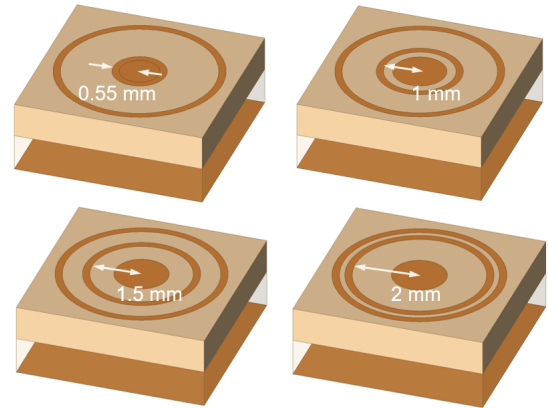


Fig. 1. Phase variation in the unit-cell by varying the middle concentric ring.

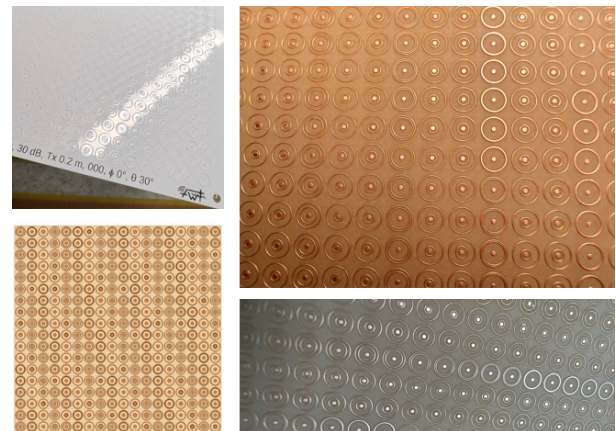


Fig. 2. Fabricated metasurfaces with different solder mark. Bottom left image shows the top view of the designed surface.

We developed design utilities in-house to compute the phase and the phase code-book is fed to a custom designed utility which stitches the complete surface in few minutes for full wave 3D EM simulations. The photographs of the fabricated surfaces are shown in Fig. 2, highlighting varying diameter of middle concentric ring.

Initially, the unit-cell is optimized for a linear phase profile using full-wave 3D EM in Ansys HFSS and utilizing our in-house design utilities, a full 28 cm surface is simulated in HFSS to further validate the performance. Typically, the unit-cell performance is reported by using Floquet ports, but it doesn't provide complete information such as interference, co-cross polarization, total realizable gain etc. A full solution on a typical 8-core CPU with 64 GB memory could take a couple

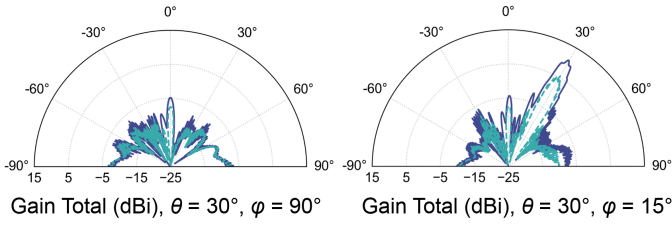


Fig. 3. Gain Total (left) $\theta = 30^\circ$, $\phi = 90^\circ$, (right) $\theta = 30^\circ$, $\phi = 15^\circ$.

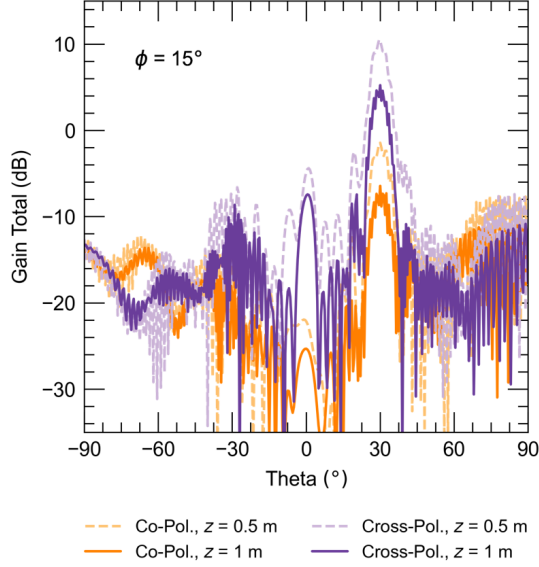


Fig. 4. Co- and cross-polarization when the change in incident signal.

of days. We simulated the surfaces of our Dell R750 servers cluster with 512 cores and 2 TB of memory and due to the massive compute power, we could reduce the simulation time to less than 2 hrs.

The response of a metasurface designed for $\theta = 30^\circ$ and $\phi = 15^\circ$ is demonstrated in this paper. Fig. 3 shows the total gain on a semi-polar plot for two different ϕ . The co-polarization and cross-polarization response is shown in Fig. 4 for varying incident signal distance over $\theta = -90^\circ$ to $+90^\circ$ demonstrating more than 12 dB of difference.

To further demonstrate the benefit of such passive metasurfaces, we setup a transmitter (a horn antenna) with 44 GHz Keysight M9484C connected directly and the baseband signal is generated with 100 MHz bandwidth with a total carrier power of -14 dBm/100 MHz. The transmitter and receiver are placed in separate rooms as shown in Fig. 5. The receiver (a horn antenna) is directly connected to Keysight N9042B 50 GHz UXA Signal Analyzer to monitor the signal received. With no metasurface on the drywall, as shown in Fig. ??, the received antenna didn't receive any non-LoS signal from the transmitter. With a passive reflector mounted on the drywall as shown in Fig. 6, a clean 100 MHz signal is received with 35 dB of SINR (results shown in the inset of Fig. 6).

For in-building radio coverage, passive reflectors offers a low-cost option to enhance mmWave signals without any need of wiring, special mounting, or service requirements. Once

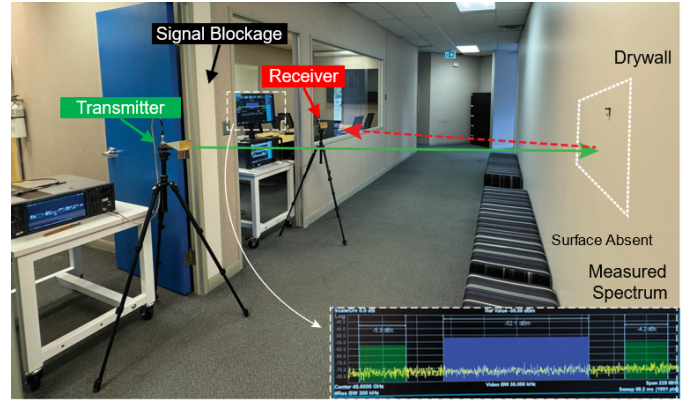


Fig. 5. Measured spectrum at the receiver without a passive metasurface.

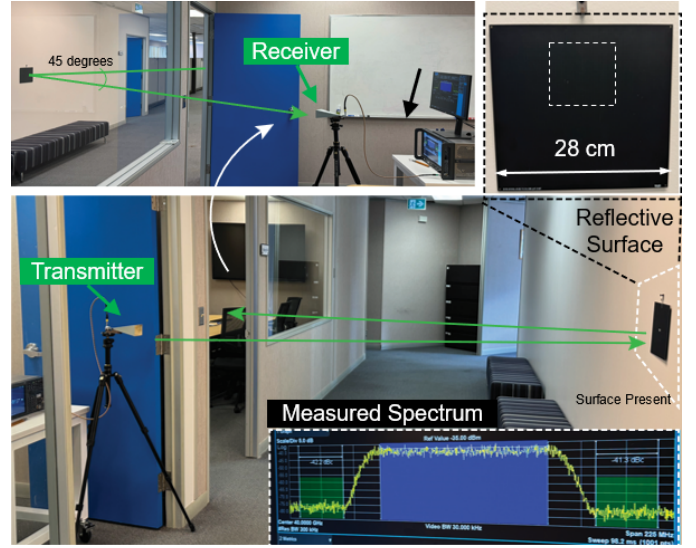


Fig. 6. Measured spectrum at the receiver with a passive metasurface on a drywall, providing better than 35 dB of gain with 100 MHz baseband signal.

installed for a specific layout, the total cost of ownership of such metasurfaces becomes almost negligible.

III. CONCLUSION

Passive metasurfaces are developed on low-cost substrate as a solution for mmWave in-building radio coverage improvements. Full-wave EM simulations are carried out for the unit-cells and for the complete surface at 40 GHz. Experimental results demonstrate the exceptional value of this technology for 5G-Advanced and 6G wireless communication.

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