Intensifying Aerial Vehicle Communications with High–Performance Millimeter–Wave Conical–Beam and Multibeam Planar Antennas

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***Abstract*—Recent robust developments of aerial vehicle have revolutionized traditional wireless communication, inspiring the emerging of innovative non-terrestrial communication architectures across diverse scenarios. To maintain seamlessly and reliable communications, high performance millimeter-wave antennas with planar structures for benefiting aerial vehicle aerodynamic are strongly demanded. However, most existing millimeter-wave antennas for aerial vehicle either have bulky non-planar structure or exhibit limitations in critical parameters like beam-coverage, radiation gain, and bandwidth. This study introduces three novel high-performance planar antennas with extraordinary radiations for intensifying aerial vehicle communications. Particularly, a high-gain conical-beam planar antenna and beam flaring-angle reconfigurable metasurfaces are proposed for targeting to the scenario of air-to-ground communication at Ka-band, while air-to-air communication is empowered by a proposed high-gain elevational-scanning multibeam planar leaky-wave antenna array at V-band frequencies. These innovations promise to meet the challenges of aerial vehicle communication, thus enabling next-generation wireless connectivity with improved performance and aerodynamic suitability.**

Keywords—Aerial vehicle communication, 6G non-terrestrial networks, conical-beam antenna, multibeam antenna, high-altitude platform station (HAPS).

I. Introduction

The exploding developments of aerial vehicles have been witnessed in the recent years. Owing to their high mobility, flexible operations, and the ability to reach remote and hard-to-reach area, aerial vehicles have brought cutting-edge solutions and found their stands in diverse applications including surveillance applications, emergency response, urban-air-mobility for intra- and inter- city passenger/cargo transportation, and especially high-altitude platform station (HAPS) implementation for 6G wireless communication non-terrestrial network. Such broad range of applications has driven to an ever-increasing strongly demand for warranting seamlessly and reliable communications between aerial devices (known as air-to-air communication) and between aerial devices with ground-based facilities, (known as air-to-ground communication) [1–3].

The increment of frequency spectrum towards millimeter-wave for enhancing communication data rate has spurred signification research efforts on millimeter-wave antenna with planar structure for aerodynamically implemented on aerial devices without struggling their aerial operations. Despite the diversity of reported designs, most existing millimeter-wave antennas for aerial vehicle either have bulky non-planar structure or exhibit limitations in critical parameters like beam-coverage, radiation gain, and bandwidth [3–5].

This paper introduces three novel planar structures with high-performance and extraordinary radiations for intensifying aerial vehicle communications. Particularly, the proposed ideas focused on two radiation types of conical-beam (CB) for air-to-ground (A2G) communications and multibeam (MB) for serving the necessity of air-to-air (A2A) communications. Firstly, a novel high-gain conical-beam planar antenna with gain enhancement is proposed. By architecting the side-reflections which are in-phase with the main radiation of conical-beam, the proposed structure can significantly exhibit an enhancement in the radiation gain while maintaining a compact planar structure, thus enhancing both aerial devices service-coverage and communication quality. Secondly, a radial-periodic (RP) metasurface (MS) was introduced for enabling the reconfigurable capability of CB radiation. This idea has been inspired by the fact that typical CB antenna performs a fixed beam flaring-angle (BFA) and the only reported solution for steering the BFA is to utilize mechanical mechanism. As such, this reported technique is not suitable to be implemented with small and medium-sized aerial devices. Lastly, while the previous structures focus on A2G communication at Ka-band, our last proposed structure is for A2A communications. In this scenario, there will be different aerial devices operating at different altitudes, driving to the necessity of simultaneously communication with multiple targets. Since the communication range of A2A is shorter than A2G, our proposed work focus on V-band frequency to maximize the potential transfer data-rate while performing a high-gain frequency-scanning multibeam radiation covering full azimuth plane and utilizing negligible antenna ground plane.

II. High-Gain Conical-Beam Planar Antenna with Gain Enhancement Using In-phase Side-Reflections

The propose structure is built using a via-based monopole antenna and a series of annular-distributed via-walls acting as side-reflectors, as depicted in Fig. 1. By carefully adjusting reflector distance to the source antenna and height of the via-walls, it is possible to synchronize side-reflections to align in-phase with central radiations of source monopole antenna. This alignment substantially boosts the peak radiation gain of proposed antenna at the desired beam-flaring angle while maintaining a fully planar structure. Finally, whole structure is investigated above an electrical large metallic plane.

The final design was laminated by two layers of Duroid 5880 (ε_r = 2.2) and Duroid 5870 (ε_r = 2.3) with thickness of

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1.57 mm and 3.18 mm, respectively. By numerical and experimental investigations, measured and simulated results have shown a highly agreement in the 10-dB impedance bandwidth (BW), as given in Fig. 1 (e). Specifically, the comprehensive analysis reveals a 10-dB BW spanning from 26.50–29.96 GHz (12.26%) in the simulated data, while the measured BW encompasses the range of 26.63–29.91 GHz (11.6%). Furthermore, both simulated and measured radiation patterns display remarkable similarity, in which the maximum peak gain of 8.51 dBi is observed at $\theta = 22°$, whereas a null is observed at $\theta = 0°$. The conical pattern from 27–28.5 GHz shows a stable performance with minor fluctuation of 1.42 dB in the peak gain while BFA at $\theta = 22°$ is remained across operating frequency [3].

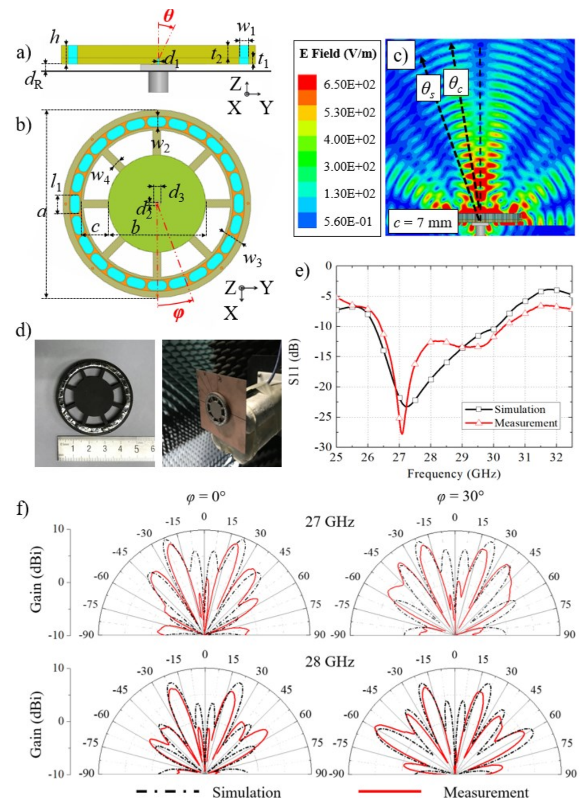

Fig. 1. Proposed high-gain conical-beam planar antenna using in-phase side-reflections and simulated/measured performances.

III. Radial-Periodic Metasurfaces for Manipulating Beam Flaring-Angle of Conical-Radiation

As shown in Fig. 2, the proposed structure in this section is constructed from previous proposed CB planar antenna and RP MSs located at distance $d = 6.65\lambda$ to source antenna. Because of CB unique wave-front, phase-gradient MSs were designed for manipulating BFA of designed structure. Each prototype was constructed from nine circular strip lines with different line widths. To validate proposed method, we examined three RP MS prototypes, as shown in Fig. 2. The final design is fabricated using five 0.51 mm-thickness layers of Duroid 5880 ($\varepsilon_r = 2.2$), which are each separated by 1.5 mm distance. Both simulation and measurement results exhibited a high level of agreement, with measured 10-dB impedance BW of 26.9–30.2 GHz (11.7%), compared to 27.2–30.1 GHz (10.2%) in simulation. Proposed structures exhibit a good BFA manipulation with steered BFA of three prototypes are 6°, 14°, and 18° and respective peak gain of 8.2–9.8, 8.0–8.1, and 7.7–8.3 dBi at 27–28 GHz [4].

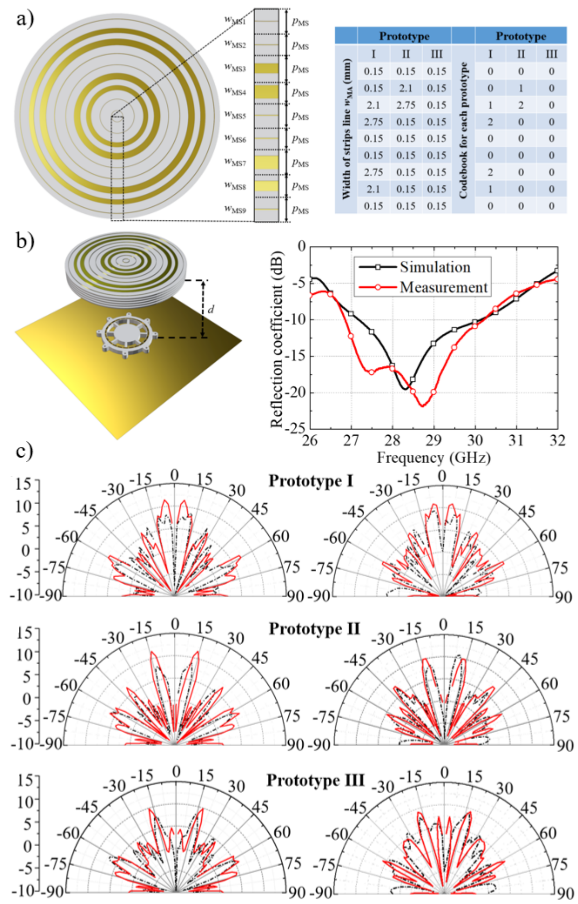

Fig. 2. Proposed radial-periodic MS CB planar antenna for achieving beam flaring-angle reconfigurable and simulated/measured performances.

IV. High-Gain Elevation-Scanning Multibeam Planar Leaky-Wave Antenna with Full Azimuth-Coverage

The proposed structure is constructed based on a novel even-mode spoof-surface-plasmon-polariton (SSPP) transmission line, which create dual-peak field intensity propagating along the TL longitudinal direction. By creating a dual-peak field intensity SSPP TL, each circular patch in the proposed LWA is dual-fed, resulting to the surface current in circular patches majorly distributed parallel with longitudinal direction. Such mechanism would separate the feeding points and radiating points of proposed leaky-wave antenna, thus achieving a high-gain low back-radiation frequency-scanning beam with single-layer planar structure while using negligible ground plane which could benefit for the fluent integration of other electronic components into the design.

The final prototype was fabricated using 0.51 mm-thickness Duroid 5880 ($\varepsilon_r = 2.2$) and was numerically and experimentally investigated, as demonstrated in Fig. 3. Full-wave analysis shows 10-dB impedance bandwidth (BW) of 52.52–67.86 GHz, corresponding to 25.5% of the fractional BW, while the measured data achieves 27.1% with the frequency from 52.33–68.7 GHz. The proposed structure exhibits a high gain multibeam radiation with 360° azimuth coverage and a multibeam-scanning ability for covering 22–58° in elevational plane. Specifically, the maximum peak gain of 12 dBi is observed at 61 GHz at the elevational angle of 27°. In addition, a low back-radiation is achieved while the proposed antenna array remains a considerable large ground clearance with 85% of non-copper area [5].

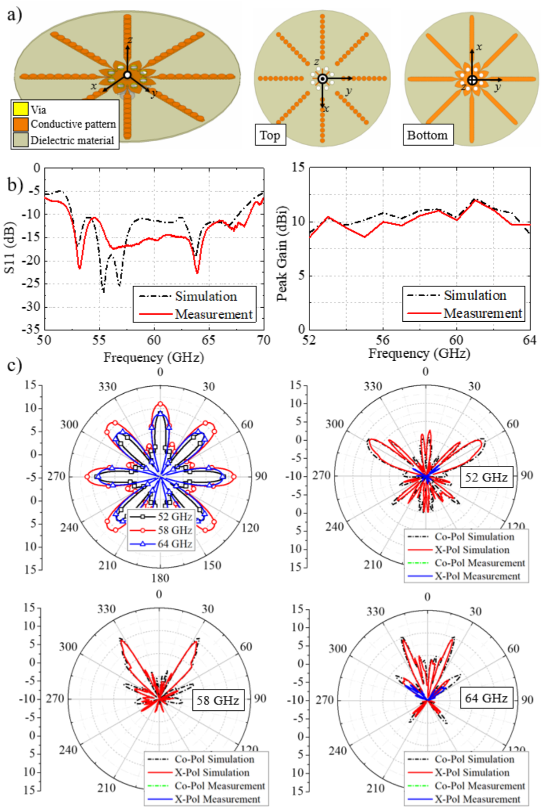

Fig. 3. Proposed multibeam planar antenna using even-mode SSPP TL with dual-peak field intensity and simulated/measured performances.

V. Conclusions

This paper has introduced three novel designs of millimeter-wave planar antenna with high-performance and extraordinary radiation for accelerating the applicability of aerial vehicle communications. In particular, a Ka-band high-gain conical-beam planar antenna with novel gain-enhancement techniques (section II) and metasurface-based BFA controlling techniques (section III) are proposed for targeting the air-to-ground communication. Meanwhile, section IV has presented a V-band high-gain elevational-scanning multibeam single-layered planar antenna with full azimuth coverage and large ground clearance, for serving the air-to-air communications between different aerial devices. All designs have shown superb performances in terms of radiation gain and bandwidth while remaining planar structure which is expected to provide significant aerodynamic benefit for implementing on practical aerial devices.

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