A Millimeter-Wave Fan-Shaped Beam Cavity-Backed Slot Antenna based on ENZ Medium

Evandro Cesar Vilas Boas, Rausley Adriano Amaral de Souza, and Felipe A. P. de Figueiredo

Abstract— **This work proposes a fan-shaped beam cavity-backed slot antenna based on epsilon-near-zero (ENZ) medium for millimeter waves. The air-filled metallic cavity is doped by FR4 dielectric slabs enclosed by four metallic rods. The cavity shape is semi-cylindrical and fed by a commercial single waveguide-to-coaxial transition (WR28), exciting a slot at 26.5GHz with a sectorial E-plane radiation pattern. The antenna's radiation pattern is shaped by a rectangular wing-based reflector in a fan-like beam along its impedance bandwidth of 1.91GHz (25.14GHz to 27.05GHz). The antenna numerical analyses show a fan beam of 90-degrees, maximum gain of 10dBi and ripple below 1dB.**

Keywords— **Antenna, ENZ medium, fan-shaped beam radiation, geometry-independent antenna.**

I. INTRODUCTION

Modern wireless communication technologies, such as fifth and sixth-generation mobile networks (5/6G), have emerged to meet the growing demand for higher data throughput and efficient resource usage [1], [2]. Researchers have explored operation bandwidths ranging from microwave frequencies to millimeter waves (mm-waves) to address diverse service requirements and application scenarios. Millimeter waves, in particular, offer unprecedented bandwidth and a worldwide available spectrum. They enable high cell throughput, which is essential for applications like extreme mobile broadband (eMBB) and machine-type communications (mMTC). For instance, mm-waves can support numerous Internet of Things (IoT) devices in smart city applications and enhance systems like remote sensing and aircraft landing operations [3], [4]. These varied applications require antennas capable of tuning their radiation patterns to effectively distribute signals within specific coverage regions. Fan-shaped beam antenna systems suit these scenarios, providing uniform signal strength across a wider beamwidth [3], [4].

Fan-shaped beam radiators have been prototyped using arrays of elements such as patch antennas, cavity-backed patch antennas, and slots implemented through substrate-integrated waveguides (SIWs) [5]–[9]. The fan beam radiation pattern is typically achieved either by weighting the excitation power of the array elements or by adopting an asymmetric element design approach. However, these arrays require a complex feeding network to manage the excitation of each element, resulting in an intricate overall structure. Alternatively, lens-based antennas have also been employed to produce fan-shaped beam patterns [10]–[13]. Examples include Luneberg lenses and gradient refractive index metamaterial lenses, which are used to shape the radiation pattern of a primary radiator. Despite bringing simplicity to the primary source element design, the lens profile poses a challenge when converting the pencil-shaped beams into flat-top ones [11]. Similar issues arise in designs utilizing the parabolic effect with ridge gap waveguides [14]. Consequently, designing fan-shaped beam antennas that balance simplicity and effectiveness remains an ongoing challenge.

Recently, Ren *et al.* addressed this challenge by designing a 3D-printed periodic structure composed of dielectric and air slabs engineered to produce a fan-shaped beam pattern [4]. This design is fed by a commercial single waveguide-to-coaxial transition with a standard WR28 waveguide, simplifying the structure compared to the other works. Herein, we approach this challenge and propose a novel fan-shaped beam cavity-backed slot antenna based on epsilon-near-zero (ENZ) medium, designed to operate in the mm-wave range. The radiator features a geometry-independent antenna leveraging the material's dispersion phenomena to excite a single slot [15], initially achieving a semi-omnidirectional radiation pattern. Henceforth, a rectangular wing-based reflector is integrated, enabling a fan-shaped beam with a 10 dBi gain. To the best of the authors' knowledge, this is the first fan-shaped beam radiator utilizing the ENZ medium's working principle, which is specifically designed for mm-wave applications.

The remainder of this work is as follows. Section II discusses the geometry-independent antenna working principle, which is applied to design the waveguide-fed cavity-backed slot antenna to operate in the mm-wave. The radiator performance metrics regarding impedance bandwidth and gain over frequency are discussed. Section III introduces the rectangular wing-based reflector appended to the initial structure to convert the semi-omnidirectional radiation pattern into a fan beam. It enhances the radiator gain since it works as a corner reflector. Final comments and future works are addressed in Section IV.

II. CAVITY-BACKED SLOT ANTENNA DESIGN

Materials and structures with constitutive parameters— such as permittivity (ε) or permeability (μ)—approaching zero are

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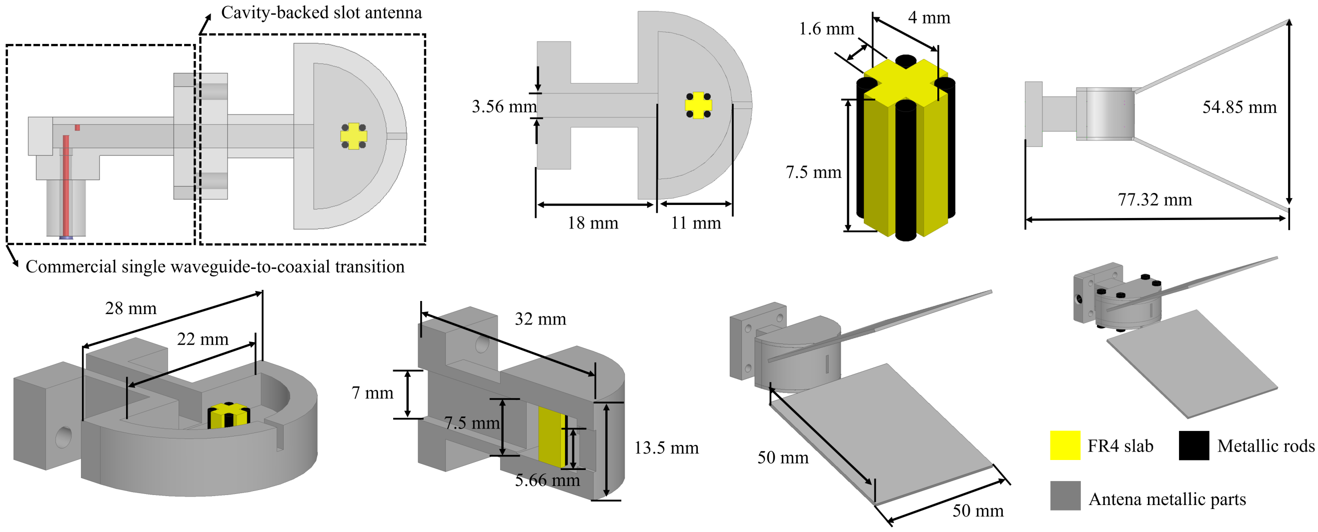

Fig. 1. Proposed cavity-backed slot antenna structure and final dimensions.

referred to as zero-index media (ZIM). These materials exhibit a near-zero index (NZI), where $n = \sqrt{\varepsilon \times \mu} \approx 0$. This property decouples spatial and temporal field variations within a specific frequency range, resulting in unique phenomena such as diverging phase velocities, wavelength expansion, and enhanced electric field intensity [16]–[18]. Notably, ENZ media have been utilized to develop geometry-independent devices that exploit the wavelength expansion effect. For example, a one-dimensional size-invariant antenna was designed using a specific zeroth-order resonant mode [19]. Additionally, this concept has been extended to two-dimensional (2D) ENZ materials, introducing geometry-independent antennas based on the photonic doping concept [15].

The antenna proposed by Liberal *et al.* is consisted of a cavity-backed slot antenna operating at a microwave frequency [15]. Its cross-sectional geometry was modified without altering the operating frequency. The working principle of the geometry-independent antenna was rooted in the material's dispersion phenomena, specifically the frequency at which an epsilon-near-zero (ENZ) medium is achieved. Hence, the metallic cavity was doped using a combination of a dielectric slab and metallic rods. The Drude equation models the cavity's permittivity, $\varepsilon_h(f) = f_p^2 - f^2$ [20]–[22], resulting in a medium equivalent to a homogeneous ENZ material with a relative permeability. This setup ensured uniformity of the magnetic field within the ENZ region. As a result, the structure's resonance frequency is maintained by preserving the cavity's cross-sectional area. Remarkably, its geometric freedom allows tailoring the radiation pattern to suit various application

This work applies the aforementioned ENZ concept to design a waveguide-fed cavity-backed slot antenna element, as shown in Fig. 1, for operation in the mm-wave range. The proposed radiator consists of a metallic waveguide-fed cavity-backed slot with a semi-cylindrical shape, providing a sectorial radiation pattern in the magnetic (E)-plane. The air-filled cavity is photonically doped with a dielectric slab made of FR4 material ($\varepsilon = 4.4$), surrounded by four metallic rods to achieve the ENZ effect. The metallic rods, each with a diameter of 1 mm, are strategically positioned to suppress TM modes. The cavity's cross-sectional area and height are numerically modeled to achieve an impedance bandwidth of at least 1.5 GHz centered around 26.5 GHz, a frequency defining the slot length. The final cavity dimensions are depicted in Fig. 1, alongside the commercial single waveguide-to-coaxial transition feed, which utilizes a standard WR28 waveguide.

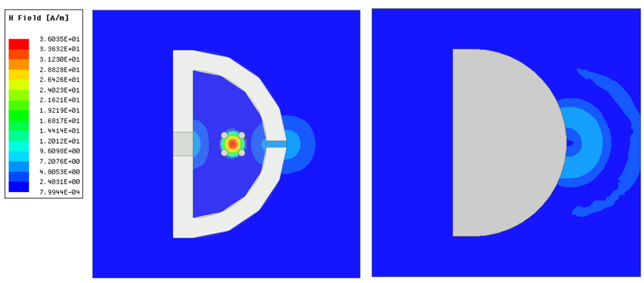

Fig. 2. Magnetic (H) field distribution inside the cavity-backed slot antenna at 26.5 GHz.

The H field distribution inside the cavity is shown in Fig. 2, demonstrating the uniformity of the H field along the ENZ region. Fig. 3(a) shows the simulated reflection coefficient with the -10-dB impedance bandwidth equal to 1.89 GHz (25.03 GHz to 26.92 GHz), resulting in a fractional bandwidth (FBW) of 7.27%. The simulated antenna realized gain (dBi) is depicted in Fig. 3(b) with a nearly flat top gain of 5 dBi inside the operating bandwidth, which is desired to provide a stable gain over the systems' channel.

III. Fan-Shaped Beam Cavity-backed Slot Antenna Design

The proposed cavity-backed slot antenna presents a sectorial radiation pattern at the E plane and a nearly pencil-shaped beam at the magnetic (H) plane. The fan-shaped beam is

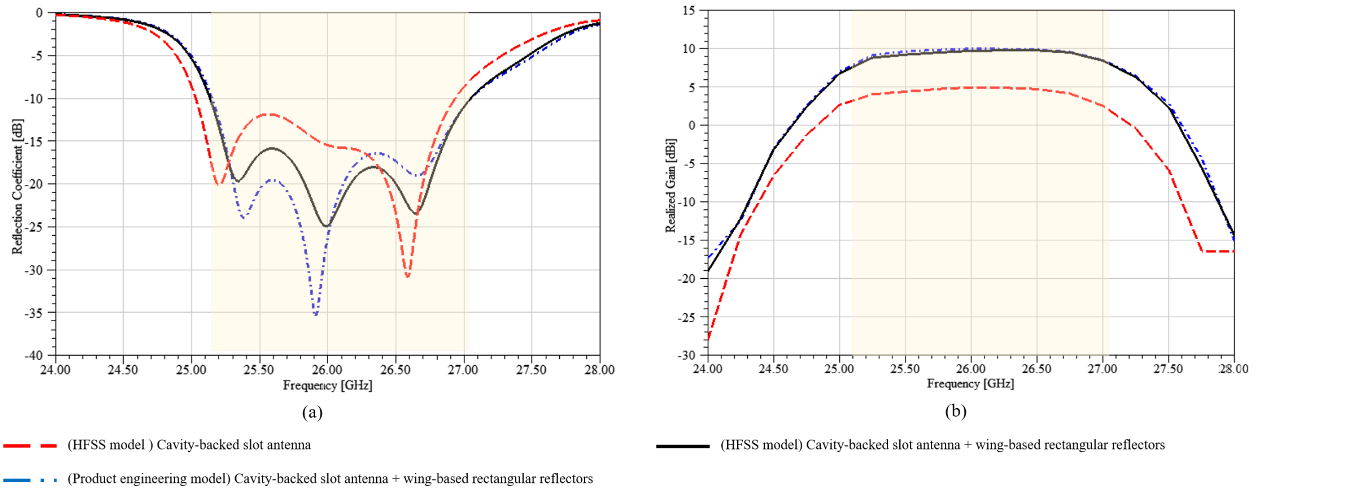

Fig. 3. Proposed antenna (a) Simulated reflection coefficient, (b) Simulated realized gain of the cavity-backed slot antenna with and without the wing-based reflectors.

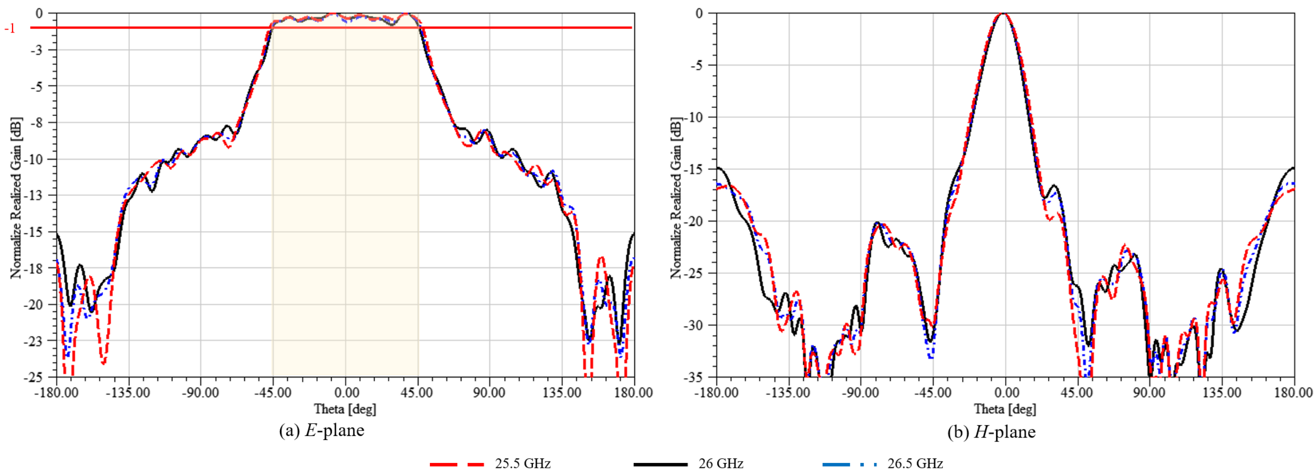

Fig. 4. Simulated radiation patterns in the E and H-planes at 25.5, 26, and 26.5 GHz for the structure with the reflectors.

desired at the E-plane to provide an appropriate beamwidth with a flat-top gain coverage. Hence, we explore the usage of a rectangular wing-based reflector that is easily attached to the initial structures without requiring re-design [23], [24]. First, the wing-based reflector enhances the structure gain while holding its simple feeding structure and avoiding arraying elements. Later, the reflector's rectangular shape allows for controlling the phase distribution across the proposed antenna aperture to produce a fan-shaped beam in the E-plane. Fig. 1 shows the final dimensions of rectangular wing-based reflectors achieved by full-wave numerical simulations.

The wing-based reflector works as a corner reflector that enhances the antenna gain by focusing its beam in the H-plane, relying on the electric image concept and the array theory [23]–[25]. Typically, this gain enhancement technique requires that the apex angle between the wing-based reflectors is set to an integer sub-multiple of 180° to optimize the final structure gain. Its mathematical model also establishes the usage of semi-infinite planes, which is practically not feasible with the planes being truncated by setting physically small values, while moderately electric large to obtain gain increment. However, the goal was to enhance gain while holding a flat-shaped beam radiation pattern, resulting in a gain increment below the reported by related works since the apex angle is not an integer sub-multiple of 180°.

The full-wave analysis of the simulated reflection coefficient, as depicted in Fig. 3(a), shows that the antenna impedance bandwidth equals 1.91 GHz (25.14 GHz to 27.05 GHz) with an FBW of 7.31%. At the same time, the reflector append has minimal influence on it. Meanwhile, the realized gain over the operating frequency range is incremented by 5 dBi, as seen in Fig. 3(b), maintaining the flat top maximum gain over the impedance bandwidth. The rectangular reflector shape produces a phase distribution that enhances the radiation between $-45°$ and $45°$ degrees, resulting in a flat-shaped beam over a 90° with a ripple less than 1 dB, as seen in Fig. 4(a). Simultaneously, the H-plane half-power beamwidth was reduced as expected due to the gain increment (see Fig 4(b)). Finally, the proposed antenna has been product engineered as shown in Fig. 1 to enable prototyping the structure. Since it required introducing screws to fix its parts, a full wave analysis has been conducted to evaluate the frequency response of this model, resulting in a simulated reflection coefficient that held the impedance bandwidth and gain performance, as seen in Fig. 2.

IV. Conclusion

We have proposed the design of an mm-wave cavity-backed slot antenna that leverages the ENZ medium concept. By photonically doping an air-filled cavity with a dielectric slab, we have achieved a geometry-independent resonator with an FBW equal to 7.29% and a nearly flat top gain of 5 dBi, providing stable performance across the operating bandwidth. Further, a rectangular wing-based reflector, which functioned as a corner reflector to optimize the phase distribution and produce a 10-dBi fan-shaped beam radiation pattern over a 90° degree beamwidth with a ripple less than 1 dB has been introduced. The reflector design has maintained simplicity by avoiding complex feeding structures or array configurations to search for gain increments or provide means to fan-shape the radiator beam using complex element excitation distribution. Future work regards prototyping and measuring the antenna performance, while the authors envisaged exploring the fan-shaped beam for a multi-band operation.

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