

Circularly Co-Polarized Full-Duplex Horn Antenna with Twisted Dielectric Polarizer

U. Jankovic ⁽¹⁾, R. Asfour ⁽²⁾, D. Mirshekar-Syahkal ⁽²⁾, and D. Budimir ⁽¹⁾

(1) University of Westminster, Fitzrovia, London W1W 6UW, England, UK (u.jankovic4@westminster.ac.uk)

(2) University of Essex, Wivenhoe Park, Colchester CO4 3SQ, England, UK, <https://www.essex.ac.uk>

A novel conical horn antenna for full-duplex wireless communication with a dielectric polarizing insert and a flare-angle change is presented. Both orthogonal linear polarizations of the circular waveguide feed, carrying transmitter and receiver signals without any cross coupling between them in the ideal case, are transformed to/from the same circular polarization in free space which left- or right- handedness is determined by the direction of insert twist. The polarizer consists of a quadruplet of equidistant dielectric ridges twisted to inscribe conical spirals on the inner metal horn wall. The continuing horn wall towards the aperture with increased flare not only improves the antenna gain but also supports the initiated circular wave polarization. For antenna designed for the 3dB axial ratio frequency band 25.1-28.9 GHz, full-wave electromagnetic simulation shows return loss greater than 14 dB, boresight directivity between 18.7 and 19.8 dBi, and exceptional Tx-Rx isolation greater than 70 dB. The proposed antenna enables directed same-frequency full-duplex capability with benefits of circular polarization and no additional radiating units needed at one node, while avoiding spending additional polarization resource in the communication channel.

I. INTRODUCTION

Full-Duplex or more specifically called In-Band Full-Duplex (IBFD) to distinguish it from its traditional out-of-band variant [1] has a very attractive potential to double the channel capacity within the available bandwidth for two-way communication through simultaneous transmission and reception of signal without change of the frequency band. Although an existing idea with techniques previously used in radars, since self-interference needs to be suppressed at magnitudes on the order of 100 dB, IBFD in radio communications has been burgeoning only since 2010s.

To tackle such a colossal amount of excessive self-interference over the wanted signal, a number of techniques for its cancellation have been developed and are often combined to improve the final result. They are standardly categorized within propagation, analog and digital domains [1]. As the first one in line, the propagation domain stands out with antennas as its principal components.

Two large groups in which IBFD antennas can be divided are, borrowing from radar terminology, monostatic and bistatic. Whereas bistatic antennas offer possibility to prevent spurious coupling in theory to any desired level given enough space separation and usually employ other elements such as high impedance surfaces or vias to make it more efficient [2], [3], a more challenging but also much more compact, economical and in practice more desired monostatic option with shared antenna aperture [4] is taken here.

Another differentiation comes from mutual relationship between Tx and Rx polarizations, namely, cross- and co-polarized possibilities. Even though using orthogonal polarizations is an effective way to discriminate interference signal [5], in this case it is opted for use of the same polarization in the propagation medium. The reason is that use of cross polarization for IBFD annuls many advantages of it that can otherwise be independently used like polarization duplex, polarization diversity and suppression of single reflections in multipath fading.

One more specificity of the new antenna is circular polarization. Although linear polarization is more prevalent in communications, circular polarization offers a unique set of advantages including insensitivity to the relative orientation between the communicating pair of antennas as well as resilience in environments with scattering and Faraday effect [6]. In development of IBFD technology so far, circularly co-polarized monostatic (CCPM) antennas have stood out as distinctive and well-tailored class of radiating components for this application. They have featured implementations in several antenna types like spiral, conical sinuous and moncone, either individually or in arrays [7], [8], [9].

More recently, lending from high-frequency, high-directivity, high-power-handling, and shielding for spurious coupling characteristics of waveguide technology, a wideband quad-ridged CCPM IBFD horn antenna has been developed [10]. As typical feed antennas in directed telecommunications, CCPM horns are an excellent option for point-to-point links that can quadruple the throughput by merging benefits of polarization duplex and IBFD technologies, as each of them individually can double the channel capacity.

As an essential element of CCPM horn antenna, IBFD waveguide polarizer is distinct from conventional waveguide polarizers [11], which inclusion results in forming of polarization duplex of circularly cross polarized waves. The dielectric polarizer from this paper is newly developed and can be additively manufactured from a dielectric material separately from the metal horn and added inside it as an insert. It can be seen as a co-polarized counterpart of the standard dielectric vane polarizer.

The proposed horn antenna with a dielectric polarizer insert brings important advantages in ease of fabrication, circumventing issues with surface roughness and fabrication tolerances at waveguide launcher, whereas the extension at aperture brings beam-shaping improvements.

II. ANTENNA CONSTRUCTION

The conical horn antenna described in this paper and depicted in Fig. 1 is fed by a standard circular waveguide and uses a 2-phase linear conical flare of its wall: of angle ψ_p in the polarizing section and ψ_b in the beam-shaping section. In effect, there is an uninterrupted axial symmetry of the metal wall, which, including the feed, has three linear sections. The angle of the wall line increases in cross-section planes containing the central axis, $0 < \psi_p < \psi_b$, and there exist two step changes between these sections (Fig. 2).

Although corrugated horns are a traditional solution for achieving good symmetry of radiation between E and H planes, corrugations have not been attempted for use on the smooth wall for the sake of pushing the design with the advantage of simplicity first.

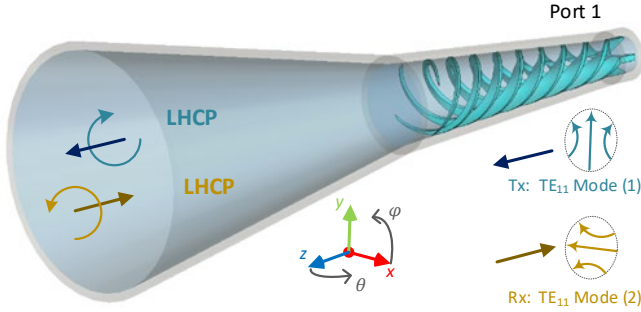


Fig. 1. 3D view of the proposed conical horn antenna with transparent walls and intertwined exponential ridges of dielectric polarizer.

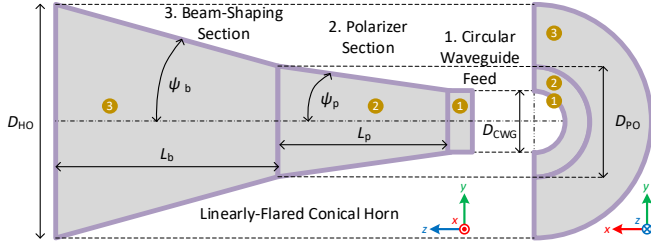


Fig. 2. Layout of waveguide-fed conical horn with annotations of dimension variables: longitudinal (left) and transverse (right) views.

The ridges of dielectric polarizer are highest at the throat of the horn and tapered in both directions up to the circular wall to smooth change in wave impedance. In the direction of the horn mouth, apart from the exponential lowering of the ridges, they are twisted in uniform rate. There is a rotational symmetry of order 4 between the individual ridges.

Although this design leverages the present availability and capabilities in 3D printing that have rapidly progressed in recent times, there are still challenges in this respect. Additional dielectric rings have been added to give support for individual ridges to form a sturdy unit, and at the same time minimally disturb fundamental EM antenna performance. Also, the overhangs need to be adequately addressed during additive manufacturing.

The antenna has been modelled, simulated and optimized using CST Microwave Studio software package. The modelling was done in subtractive manner, starting from concentric

cylinder and truncated cones, where the larger conductive ones extended to the outer wall limits and inner ones where the void inside of them is.

The dielectric polarizer was modelled starting from two orthogonal slabs along directions of the strongest electric field lines of the two fundamental modes in circular waveguide feed. In addition, inside the horn (i.e. in its polarizer section), these slabs were made by rotation of extruded face, effectively twisting the slab at that angle. Firstly, all parts extending over sidewalls were removed, followed by cuboid along the axis having $G \times G$ square base. On the side of horn, inner convex cone whose lateral surface is created by rotating exponential line is further removed. Finally, ridges inside the feed are chamfered. The numerical values of dimensions of horn elements are given in Table I.

As the structure consists of complex-shaped dielectric elements and conductive elements of circular longitudinal cross sections, full-wave EM simulations were carried out combining first narrowband use of finite element method frequency-domain solver with curvilinear tetrahedral mesh, and then wideband use of finite-difference time-domain solver hexahedral mesh.

TABLE I. DIMENSIONS AND PARAMETERS OF THE IBFD HORN

Horn Dimension	Value	Polarizer Dimension	Value
L_p	65 mm	w_R	1.4 mm
L_b	90 mm	G	2.5 mm
D_{CWG}	8.33 mm	L_{pd}	60 mm
D_{PO}	18.83 mm	λ_t	27 mm
D_{HO}	54.93 mm	Dielectric Parameters	
ψ_p	5°	ϵ_r	5
ψ_b	11.34°	$\tan \delta$	0.0036

Here, polymer 3D printing is targeted, as plastics are the most widely available materials for 3D printing and fabrication using them is available at the lowest cost. Preperm ABS500 filament [12] having relative permittivity $\epsilon_r = 5$ and loss tangent 0.0036 at 2.4 GHz was selected. Extrapolation of dielectric properties up to antenna band was done using causal model.

Metal surfaces are smooth without details like ridges; curvatures are on dielectric which can easily be 3D printed and its surface roughness is not critical. Also, there are no more critical fabrication tolerances as in high-frequency waveguide launcher areas of tightly spaced quad-ridged feeds with coaxial probes.

Omitted here are the parts that hold the dielectric ridges together in the insert. The best way to produce least disturbance is to make them air-like, which can be mimicked by use of very low infill and in combination with another low-loss low-permittivity filament. Structurally, they should be positioned at least as rings at throat and mouth of the polarizer section.

The proposed antenna can be fed by a standard orthomode transducer, offering exceptional levels of polarization purity [13].

III. EM CHARACTERISTICS

The overview starts with the axial ratio (AR) bandwidth, as the limiting factor of wideband antenna performance. For the designed antenna, it spans in the range 25.04 GHz – 28.90 GHz (Fig. 3) for 3 dB threshold in the direction of maximum radiation, which is 14.3% fractional bandwidth.

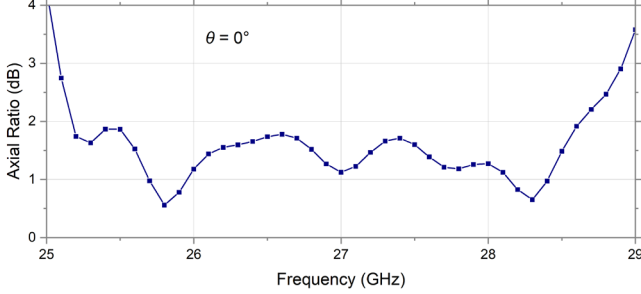


Fig. 3. Simulated broadband boresight axial ratio (100 MHz linear steps).

Instrumental in achieving the low AR is the right amount of twisting of the dielectric slabs. Too little of it keeps the radiation predominantly linear, as it is with complete straight slabs or no insert at all. Too much of it disturbs the radiation diagram and splits the main lobe.

There is a tradeoff between antenna gain and AR angle, so it drops at the center frequency from 30° when no beam shaping section is used to less than 10° after it is added. In contrast, the beam former section has improved the 3 dB AR bandwidth.

Reflection coefficient does not have any problematic bandwidth constraints above the cutoff frequency of the pair of dominant modes in this non-resonant/traveling guided wave aperture antenna. As it can be inferred from Fig. 4, it is above 14 dB (VSWR) in the same frequency span, and it can be improved if needed by making more gradual impedance transition with the dielectric insert. Furthermore, orthomode transducer and coaxial to waveguide adaptors in the feed do not impose any additional difficulty for good impedance matching.

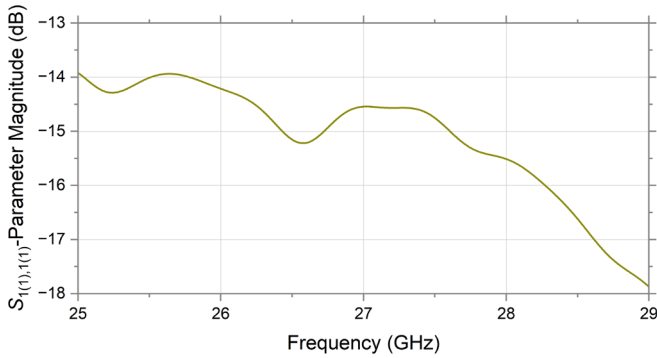


Fig. 4. Simulated reflection coefficient.

With the use of beam shaper, the initial directivity of the polarizer section of just about 11 dB has been increased to be just short of 20 dB (Fig. 5). Due to metal and dielectric losses, associated gain drops for about 1 dB (i.e. radiation efficiency is $\eta \approx 80\%$), which is not too significant cost for the overall performance, especially considering the relatively high operating frequency.

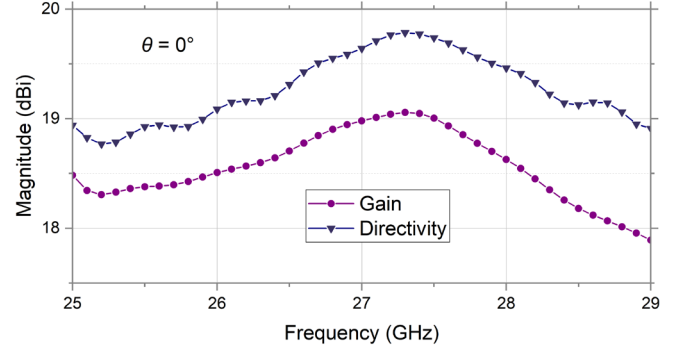


Fig. 5. Simulated broadband directivity and gain (100 MHz linear steps - resolution).

More details about antenna directivity are given by radiation patterns in principal cross sections in Fig. 6.

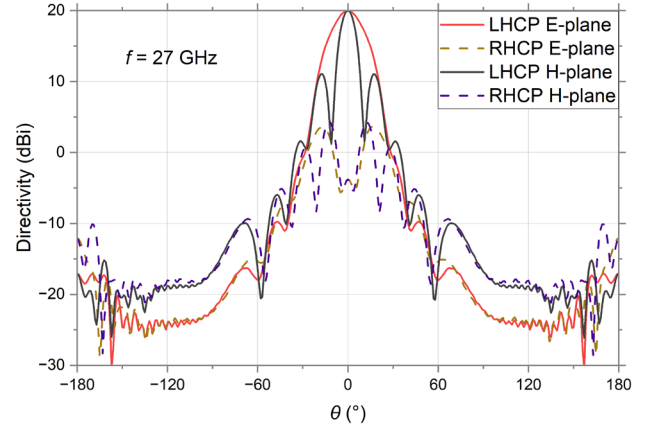


Fig. 6. Simulated radiation pattern at 27 GHz.

As the key parameter in this IBFD application, the isolation between the two orthogonal waveguide modes at the feed representing connection with the transmitter and receiver is greater than 69 dB (Fig. 7), whereas typical level goes about 10 dB higher, which is a very high level of interference suppression for a monostatic antenna.

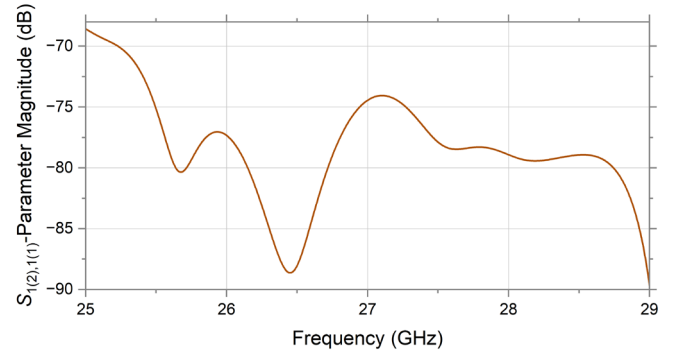


Fig. 7. Simulated transmission coefficient between Tx and Rx orthogonal TE_{11} modes.

IV. CONCLUSION

A new type of monostatic horn antenna for in-band full-duplex radio that transforms the dominant degenerate

orthogonal modes at its feed into co-polarized circular radiation has been studied. This component is very practical for manufacturing, separating metal and dielectric fabrications, and can be used for building high-capacity microwave links. The designed sample antenna at K/Ku bands of 14.3% fractional bandwidth shows good gain and extraordinary Tx-Rx isolation of 70 dB.

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