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This is a copy of the author's accepted version of a paper subsequently published in the proceedings of the IEEE International Workshop on Antenna Technology (iWAT), University of Liverpool, 23 - 27 Mar 2026.

The final published version will be available online at:

<https://doi.org/10.1109/iWAT66946.2026.11501895>

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Circularly Polarized Twisted Quad-Ridged Horn Antenna for In-Band Full-Duplex

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Abstract— A circular horn antenna for in-band full-duplex communication with a quadruplet of equidistant ridges twisted to follow conical spiral contours is presented. Twisted ridges, apart from the role of extending the bandwidth, also act as polarizers. Both orthogonal linear polarizations of the ridged waveguide feed, representing transmitter and receiver sides with zero cross coupling between them in the ideal case, are transformed into the same circular polarization determined by the ridge twist direction and vice versa. This gives rise to full-duplex capability without sacrificing additional resources like different polarizations in the communication channel. For antenna designed for the frequency band 20–40 GHz, full-wave electromagnetic simulation shows Tx-Rx isolation greater than 70 dB, return loss greater than 21 dB, while boresight axial ratio as well as gain are respectively less than 2.3 dB and between 10.9 and 13.8 dBi.

Keywords—horn antenna, ridged horn, circularly polarized, IBFD, full duplex, 3D printed

I. INTRODUCTION

In-Band Full-Duplex (IBFD) technologies have been recently spurring formidable research activity by promising to double frequency spectrum utilization through simultaneous transmission and reception of signal in time without change of the frequency band [1]. Nevertheless, because of extremely high levels of in-band interference, the cancellation process, which can in practice go past 100 dB, is delivered over different stages in propagation, analog and digital domains [2]. As the first line of defence against the interference occurs in the propagation domain, building antennas that have excellent interference rejection capability is paramount.

Circularly polarized (CP) EM waves have certain distinguishing properties like insensitivity to the mutual orientation between the communicating transmitter and receiver antennas that make CP antennas stand out as a choice for the radiating elements in wireless systems [3], with well-known use cases such as in Global Navigation Satellite Systems (GNSS). In that respect, CP antennas for IBFD are in direct contrast with CP antennas for more ubiquitous polarization duplex, with polarization orientation desired to stay the same in both communication directions [4,5]. This way, properties like rejection of single reflections to combat multipath fading can be maintained.

Use of typical waveguide polarizers [6,7], which have a same plane of symmetry as one that exists between the two

linear polarizations, is adequate precisely for the usual conversion of two orthogonal linear polarizations into RHCP and LHCP. To maintain the same CP type, when thinking of a counterpart to the bilaterally symmetrical corrugated polarizer [6] a shape based on helical symmetry appears to go in the desired direction and a threading akin to a nut for a bolt can be conceived. Such polarizers have been devised for use in converting single linear into single circular polarization [8]. Since we deal with a polarizer of finite length and in our case there are two orthogonal linear waves, a rotational symmetry of order 4 of the polarizer is needed. Hence, the twisted quad-ridged design is reached.

In the receiving regime, CP waves matching the antenna are converted to linearly polarized waves of both the transmitter and the receiver. Nevertheless, since these signals are of low power, those that end in the transmitter, although spurious, are not of much concern. Furthermore, the level of received signal stays the same as if only a dual-ridged receiver antenna was used.

With their geometrical demands and less stringent conductivity and structural requirements, these antennas also lend themselves very well for additive manufacturing (3D printing using metal materials [8] or polymer materials with surface metallization [9]).

II. ANTENNA CONSTRUCTION

The conical ridged horn antenna described in this paper and depicted in Fig. 1 uses the most frequent combination of linear sidewall flare and exponential ridge flare. It has been modelled, and subsequently simulated and optimized using time-domain solver, in CST Microwave Studio software package.



Fig. 1. 3D view of the proposed conical horn antenna with emphasised intertwined exponential ridges

One practical way to model the twisted ridge is by analytically describing the surface and then applying the shape tool to thicken this sheet and create the solid. Another one is to build rotating bricks in the radial direction with varying position and length in small steps along the z-direction inside a loop. Here, the first approach has been applied, where the analytical surface is given by parametric equations

$$x_{u,v} = [f_e(u) + v f_s(u)] \sin\left(2\pi \frac{uL}{\lambda}\right),$$

$$y_{u,v} = [f_e(u) + v f_s(u)] \cos\left(2\pi \frac{uL}{\lambda}\right),$$

$$z_{u,v} = uL,$$

where

$$f_e(u) = Ae^{\alpha u}, A = \frac{G}{2}, \alpha = \ln \frac{D_{HO}}{G}$$

sets the exponentially increasing distance from the z-axis in the cylindrical coordinate system with

$$D_{HO} = D_{CWG} + 2L \tan \psi$$

being the diameter of the horn opening, and

$$f_s(u) = \frac{D_{CWG}}{2} + u \frac{D_{HO} - D_{CWG}}{2} - f_e(u)$$

sets the distance in the radial direction between the inner exponentially increasing and outer linearly increasing edge, with independent parameters belonging to the unit interval

$$u, v \in [0, 1].$$

Use of sine and cosine trigonometric functions in expressions for $x_{u,v}$ and $y_{u,v}$ by themselves describes a helix. Variable λ stands for distance along axis z after which the ridge completes a full revolution around it. The surface is eventually thickened by $w_R/2$ on each side. The other three ridges can be modelled simply by sequential right-angle rotation of the copies of this initial twisted ridge. Dimensions are labelled on the layout of the antenna in Fig. 2.

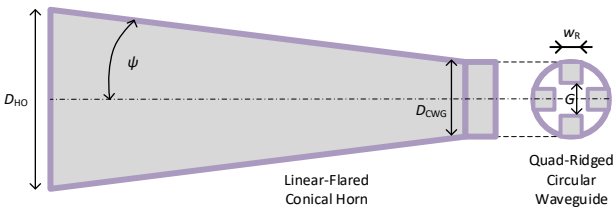


Fig. 2. Quad-ridged waveguide fed conical horn layout with dimension variable annotations

The antenna is fed by circular (straight) quad-ridged waveguide, where pairs of opposite ridges are centred around two orthogonal longitudinal waveguide cross sections that also contain E-fields of two orthogonal linearly polarized TE_{11} mode waves. One of these fundamental waveguide modes is for carrying transmitted signal into the antenna and the other is for bringing signal received by it.

In most applications, however, coaxial lines feed the signal into the waveguide in close proximity to the start of the opened flare of that waveguide. A lot work has been done in order to optimize these adapters with integrated baluns to give balanced feed onto opposite ridges, also known as waveguide launchers. Nevertheless, that topic is not in focus here.

The described model of the antenna was designed for 20–40 GHz frequency band. The related dimensions are given in

Table I. It can be noticed that this horn has relatively elongated shape with small flare angle.

TABLE I. DIMENSIONS OF THE TWISTED QUAD-RIDGED HORN

Horn Dim.	Value	Ridge Dim.	Value
L	105 mm	w_R	1.5 mm
D_{CWG}	6 mm	G	2 mm
ψ	5°	λ	50 mm

III. EM CHARACTERISTICS

Starting with the reflection coefficient, the horn antenna, unsurprisingly, shows excellent characteristic throughout the simulated bandwidth with minimum reflection loss surpassing 21 dB, that is, $VSWR < 1.2$ (Fig. 3). Nevertheless, maintaining it after converting to coaxial feeds through probes between ridges still remains nontrivial task, although extremely wideband results have been obtained so far [10] – much wider than single octave in this application, even if for less stringent levels of reflection loss.

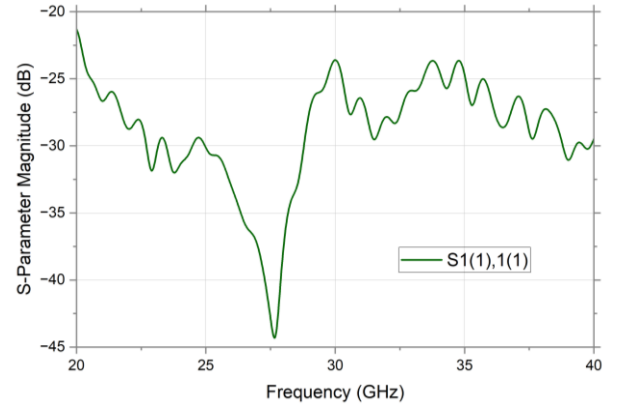


Fig. 3. Simulated reflection coefficient.

Axial ratio (AR) also displays good performance, staying significantly below the threshold 3 dB value (not exceeding 2.3 dB) in the entire frequency band (Fig. 4). A caution should be given that such low AR is not maintained in wide angles θ around the antenna axis.

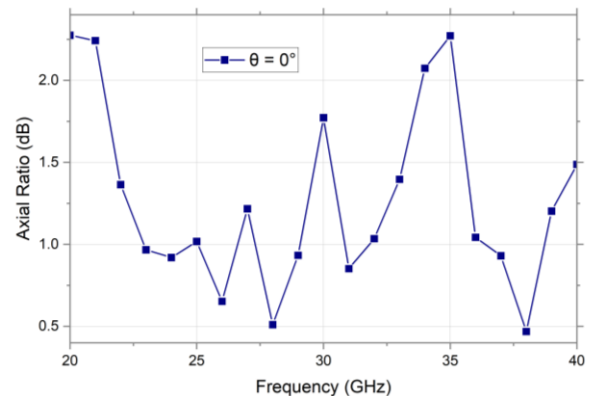


Fig. 4. Simulated boresight axial ratio (500 MHz linear steps).

Although not going above 20 dB as practical horn antennas with higher directivity are capable of, the simulated gain fluctuating around 12.3 dBi and reaching near 14 dBi at 32 GHz (Fig. 5) is respectable.

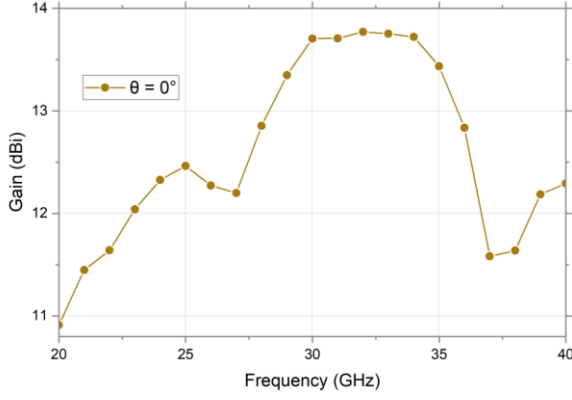


Fig. 5. Simulated gain (500 MHz linear steps).

At single frequencies (Fig. 6), LHCP gain has typical boresight directive shape, in contrast with suppressed RHCP gain, which differs greatly both in shape and magnitude. The LHCP 3D radiation pattern, similar to the ridged opening of the horn, also has a somewhat spiral shape. It expresses itself in wider main lobe versus added nulls in various displayed plane projections.

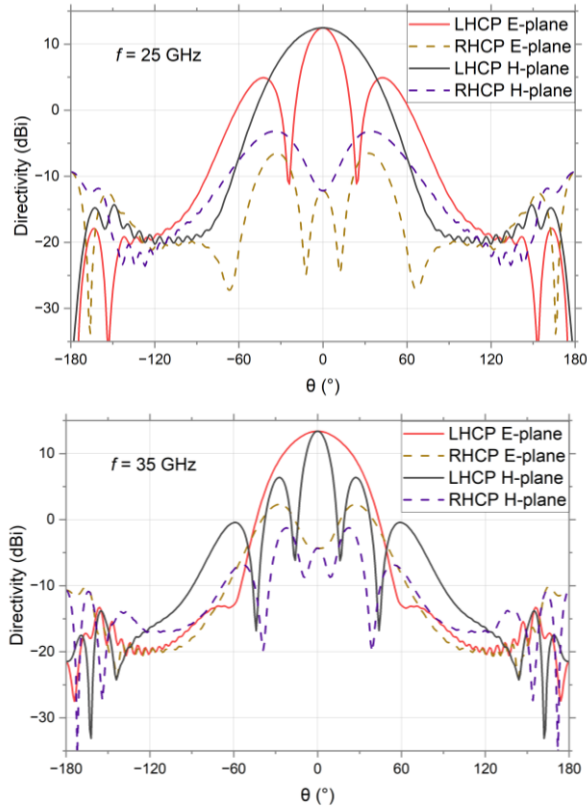


Fig. 6. Simulated radiation patterns at frequencies of 25 and 35 GHz.

Finally, the isolation between the two orthogonal waveguide modes representing the transmitter and the receiver (Fig. 7), as the key parameter for IBFD application, is in excess of 70 dB, which is a promising level of interference suppression for a monostatic antenna.

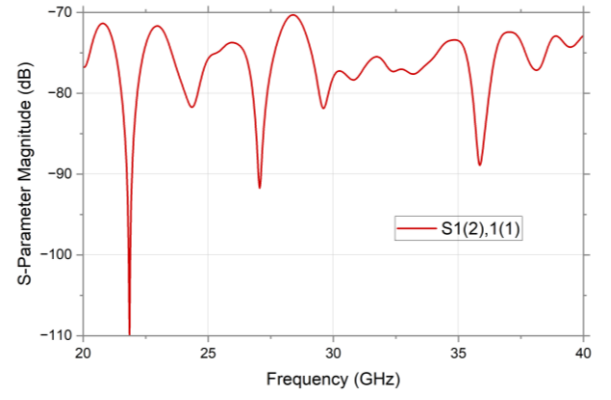


Fig. 7. Simulated isolation.

It should be noted that in the model exists perfect symmetry when exiting the antenna with orthogonal TE_{11} modes. Therefore, $S_{1(1),1(1)} = S_{1(2),1(2)}$ and $S_{1(2),1(1)} = S_{1(1),1(2)}$, apart from numerical errors.

IV. CONCLUSION

The undertaken investigation of applying twisting to ridges of a quad-ridged conical horn antenna in order to produce a single circular polarization from two linear polarizations has been reported. It has confirmed possibility of its application for in-band full-duplex with substantial isolation between transmitter and receiver that is greater than 70 dB in 2:1 range.

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