

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, STAR, full duplex, 3D printed

I. INTRODUCTION

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

A number of approaches for self-interference cancellation in the propagation domain have been suggested, ranging from use of (magnetic and nonmagnetic) circulators [3] to separation and isolation of bistatic antenna units [4,5] to cross-polarized transmission and reception [4,5]. However, a particularly well-tailored one assumes using inherent isolation rooted in the symmetry of shared circular polarization to decouple Tx and Rx ports [6]. In comparison with the other aforementioned methods, it does not use extra circuitry at the antenna interface, take space for separation, isolation and dedicated Tx/Rx antenna units or consume additional multiplexing resources, respectively. Moreover, it can be

combined with, for instance, the first two stated techniques in order to increase the total cancellation.

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 [7], 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 [6,8]. This way, properties like rejection of single reflections to combat multipath fading can be maintained.

In relation to metal waveguides, use of typical waveguide polarizers [9,10], 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 [9] 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 [11]. It can be seen as a modification of widely used horn ridges [12]. 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.

Accordingly, a new twisted quad-ridged conical horn antenna is proposed in this paper, efficiently adding IBFD capability into high-performing waveguide technology. This way, CP IBFD radio is extended into realm with significant high-frequency, high-directivity, high-power, and shielding for spurious coupling potential. It can not only double but quadruple data throughput in conjunction with standard polarization duplex.

With their geometrical demands and less stringent conductivity and structural requirements, these antennas also exceptionally lend themselves for additive manufacturing (3D printing using metal materials [11] or polymer materials with surface metallization [13]).

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II. ANTENNA CONSTRUCTION

The conical ridged horn antenna described in this paper and depicted in Fig. 1 uses the most common 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.

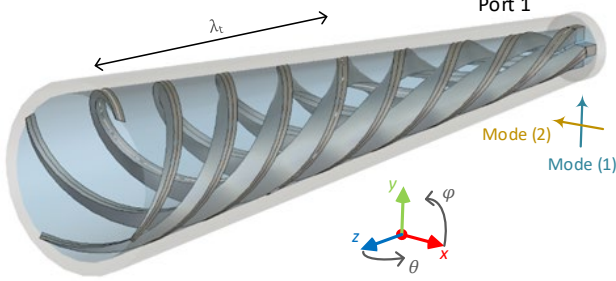


Fig. 1. 3D view of the proposed conical horn antenna with emphasised intertwined exponential ridges.

One practical way to additively model the twisted ridge is by analytically describing the centrally spread surface and then applying the shape tool to thicken this sheet and create a solid. Another one directly available from the program environment is to build rotating bricks inside a loop in small steps along the z -direction. The step bricks are in radial directions, and they have varying position and length in accordance with the flares.

Here, the first approach has been applied, where the analytical surface is given by parametric equations¹

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

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

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

where

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

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_t stands for distance along the z -axis after which the ridge completes a full revolution around it. The surface is eventually thickened by $w_R/2$ on each side. A peculiarity of the chosen way of modelling is that the thickness $w_R/2$ is in the direction orthogonal to the analytically set surface rather than orthogonal to the z -axis.

This particular horn described until now is LHCP, using the IEEE definition of left-handedness of a wave radiated by

it as spinning counterclockwise from the point of view of the source. This holds for both the Tx and Rx parts, as Rx polarization is likewise determined from the transmitting regime (IEEE Std 145-1993). In addition, the matching antenna (for theoretical unit polarization loss factor) on the opposite side of communication link is exactly the same physical LHCP unit, just oppositely directed. For RHCP communication, the direction of ridge twisting is reversed.

The remaining three ridges can be modelled simply by sequential right-angle rotation of the copies of this initial twisted ridge. In effect, the polarizer and the beam shaper segments of the horn are combined in the same space. Dimensions are labelled on the layout of the antenna in Fig. 2.

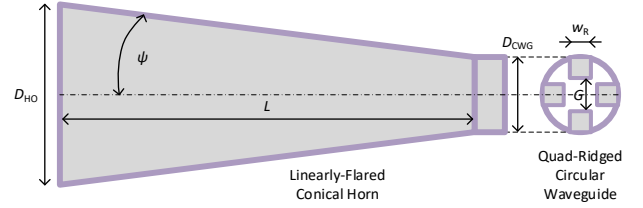


Fig. 2. Layout of quad-ridged waveguide-fed conical horn with annotations of dimension variables.

The antenna is fed by a 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 TE₁₁ mode waves. One of these fundamental waveguide modes is used 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 open-ended flare of that waveguide. A lot of work has been done in order to optimize these adapters in terms of impedance matching. Also known as waveguide launchers, they contain integrated baluns to give balanced feed onto opposite ridges. Nevertheless, that topic is not dealt with here. Still, it is worth highlighting how this specific IBFD antenna architecture thus takes direct benefit of exceptional polarization purity orthonode transducers are able to achieve to repurpose it for Tx-Rx isolation.

The described 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_t	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 this after converting to coaxial feeds through probes between ridges still remains a nontrivial task, although extremely wideband results have been obtained so far [14] -

¹ This specific equation places the axis of the horn interior in the shape of truncated cone along z -axis, with smaller circular base of radius $D_{CWG}/2$ in $z = 0$ plane and larger circular base in $z = L$ plane.

much wider than single octave in this application, even if for less stringent levels of return loss.

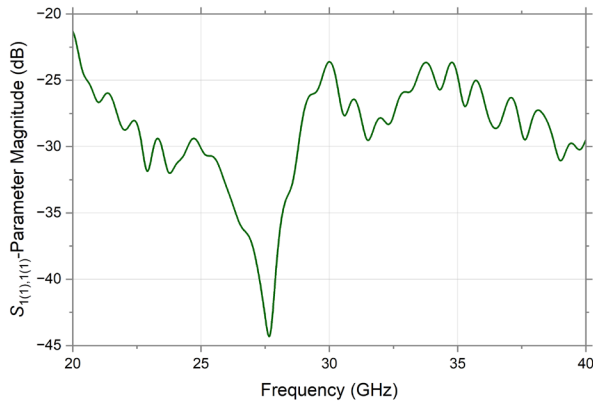


Fig. 3. Simulated reflection coefficient.

Axial ratio (AR) also displays good performance, staying significantly below the threshold 3 dB value (i.e. 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.

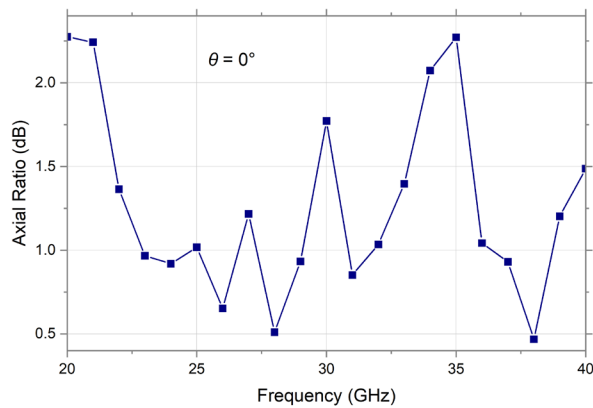


Fig. 4. Simulated broadband boresight axial ratio (500 MHz linear steps).

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 and in line with properties of conical horn antennas with such electrical lengths of the aperture and the horn body itself [15].

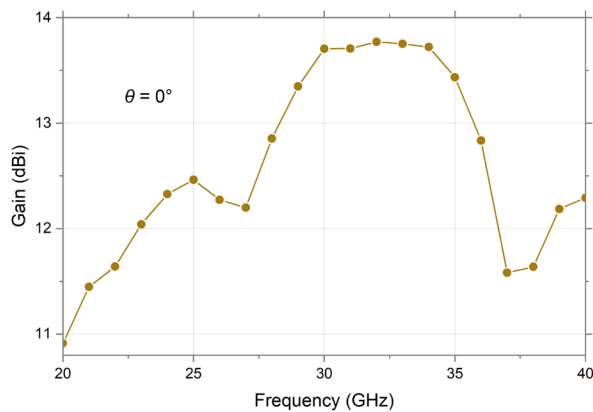


Fig. 5. Simulated broadband gain (500 MHz linear steps).

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 form of a twisted asymmetrical directive pattern. This renders a somewhat spiral shape of the strongest radiation when looking into the antenna. It expresses itself in wider main lobe versus added nulls in various displayed plane projections. In a narrower frequency band, the antenna can be used like sectoral horn for its fan-shaped main lobe, e.g. covering horizontally wide but vertically narrow space angle.

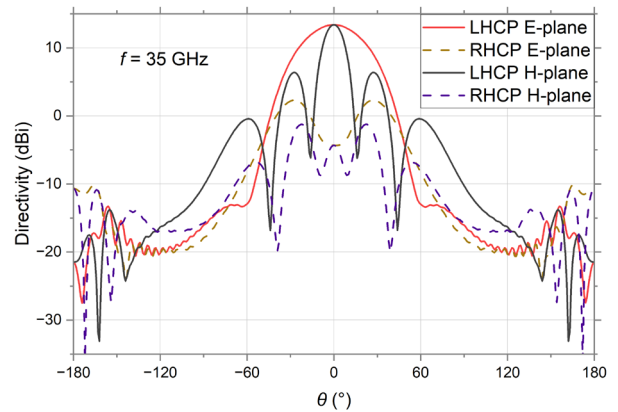
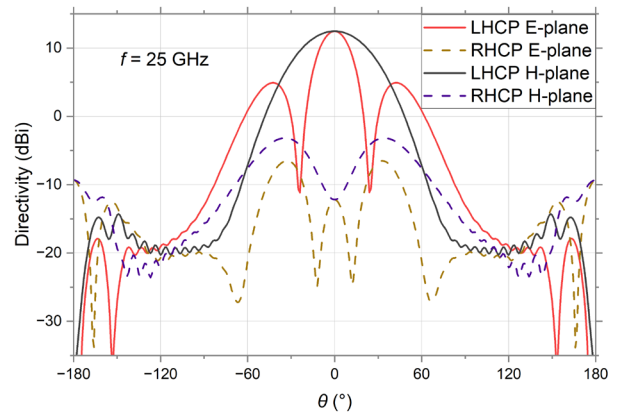


Fig. 6. Simulated radiation patterns at 25 and 35 GHz.

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

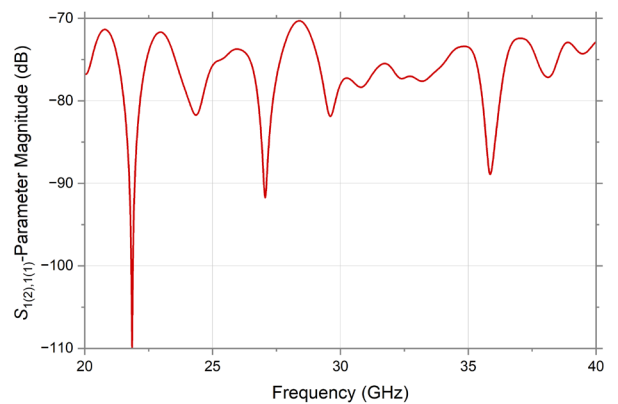


Fig. 7. Simulated transmission coefficient between Tx and Rx orthogonal TE_{11} modes.

It should be noted that there exists a perfect symmetry in the model when exciting the antenna with orthogonal TE_{11}

modes. Therefore, $S_{1(1),1(1)} = S_{1(2),1(2)}$ along with $S_{1(2),1(1)} = S_{1(1),1(2)}$ for reciprocity, apart from numerical errors.

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 in quadrature 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. These properties can be observed using reciprocity with the transmitting regime.

It should be mentioned that co-polarized EM radiation from a shared antenna is not an exclusive property of circular polarization. Co-linearly polarized monostatic IBFD antenna designs have been likewise proposed [16]. In addition, putting another pair of conventional polarizers between two CP IBFD antennas and having propagation of linearly polarized waves inside the communication channel would not disturb the core principles of this IBFD technique, but its practical feasibility and usefulness are questionable. Circular polarization has regardless important advantages in interference suppression stemming from symmetrical geometry as well as in environments with local scattering, Faraday rotation and without fixed antenna orientations.

IV. APPLICATION IN DOUBLING THE CAPACITY OF POINT-TO-POINT LINKS WITH POLARIZATION DUPLEX

A chief use case for the proposed co-polarized IBFD antennas is in directional point-to-point wireless links. The concept for fourfold total increase in channel capacity in comparison with a standard link is depicted in Fig 8. Here, coupling between adjacent antennas with opposite polarizations can be reduced to the needed level by use of absorbers, chokes and spacing, akin to [4].

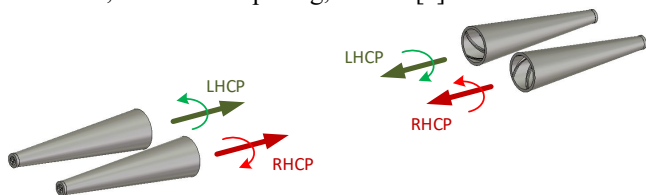


Fig. 8. P2P communication using polarization duplex of circularly co-polarized horn antennas.

V. 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. The possibility of its application for in-band full-duplex wireless has been confirmed and explained, highlighting substantial isolation between transmitter and receiver it can offer, which is greater

than 70 dB in 2:1 range. Further research is ongoing to interface the antenna to terminations with negligible effect on the quantified self-interference suppression.

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