

Single-Prism Risley Scanner at Ka-Band

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Abstract—This contribution presents a new Risley scanner architecture for beam-steering antennas. Classical Risley scanners are based on a feed (source) illuminating a system of two prisms. The source usually radiates a directive beam aligned with the central axis of the scanner. The azimuthal positions of the two prisms around their axis controls the pointing direction of the whole system, both in azimuth and elevation. Here, we propose first to reduce the complexity and profile of the system by substituting the source and the first prism of the scanner with a leaky-wave feed. The leaky-wave feed radiates its main beam at about 30° relatively to its normal, and is based on a sinusoidally modulated metasurface fed by a pillbox beamformer. Second, we propose to manufacture the second prism using dielectric loaded metallic waveguides, realized through the combination of two additively manufactured parts. The proposed structure is validated by full-wave simulations and the fabrication and testing of a prototype. The antenna operates in the 19.2-21.2 GHz band for a field of view of 360° in azimuth and 60° in elevation.

Index Terms—Risley scanner, wide scan antennas, 3D printing, metasurfaces, PCB.

I. INTRODUCTION

Future communication systems will heavily rely on highly directive antennas with beam-steering capabilities. Indeed, such antennas enhance the link budget and enable higher data rates by directing the electromagnetic energy toward the end-user terminal. However, these radiating structures should satisfy stringent requirements in terms of compactness, cost and energy consumption to be deployed in real world applications. In this context, different beam-steering mechanisms are competing to address the demands of various applications, namely mechanical, hybrid and electronic steering.

Although electronically-steered antennas are very agile, they still present shortcomings in terms of cost, system complexity and power consumption. Mechanical beam-steering antennas, on the other hand, can allow very effective solutions, even low profile, with minimal movements [1].

The classical architecture of a Risley scanner is shown in Fig. 1(a). The scanner is composed of a feed/source and two prisms. These elements are aligned with the main axis of the scanner. The feed illuminates the prisms with a beam parallel to the axis of the scanner. The position of the prisms dictates the pointing direction of the radiated beam in azimuth and

elevation [2]. Such a structure controls the steering of the main beam by the mechanical rotation of the two prisms around the axis. Although very effective, such a solution is very cumbersome in its classical implementation [3]. To address this limitation, recent works have focused on two aspects. The first one is to remove the focal distance constraint by using printed circuit board (PCB) based, low-profile directive antennas as feed, such as radial-line slot arrays [4], [5] or leaky-wave metasurface [6]. The second one is to replace the bulky refracting prisms by low-profile deflectors, with either metallic patterns (e.g., metasurface [6]) or all-dielectric solutions [4], [5]. All of these solutions rely on the use of a feed with two rotating components on top. In this work, we propose the new architecture shown in Fig. 1(b) in which the first prism and the feed of the classical configuration are replaced by a leaky-wave feed. The leaky-wave feed generates a tilted beam and illuminates a single deflector. In this structure, the relative azimuthal position of the deflector and leaky-wave feed around the main axis of the scanner controls the pointing direction in elevation and azimuth. In this way, a full coverage of the upper hemisphere can be achieved by mechanical rotation of the leaky-wave feed and deflector.

The leaky-wave feed is here realized with a linear polarized metasurface [8], [9] fed by an integrated pillbox quasi-optical beam former [10], [11]. The deflector is made by combining two additively manufactured parts, namely an array of quad-ridged waveguides in titanium, and a dielectric filling in acrylonitrile butadiene styrene (ABS). By properly selecting the dielectric filling ratio, a linear phase profile can be achieved and therefore the deflection. The proposed scanner is designed in the 19.2-21.2 GHz band and covers a field of view of 360° in azimuth and 60° in elevation. The leaky-wave feed is manufactured in PCB technology, whereas the deflector is fabricated through additive manufacturing by combining both metallic and ABS parts. The final size of the Risley is about 250 mm in diameter with a total thickness of less than 50 mm. Measurements demonstrate the capability of the system to cover the required field of view with a maximum measured gain exceeding 25 dBi at 20.2 GHz.

The paper is organized as follows. Section II introduces the architecture and operation of the proposed system. Each component of the system is described. Section III presents the

prototype and measurements. Finally, conclusions are drawn in Section IV.

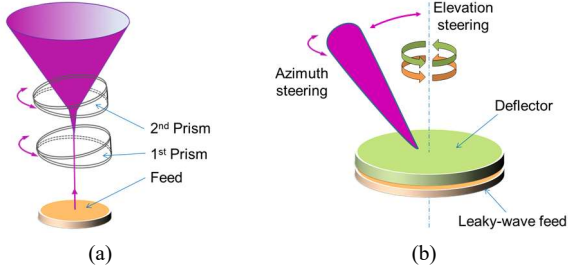


Fig. 1. Risley scanner. (a) Classical implementation. (b) Proposed architecture.

II. REVISITED RISLEY ARCHITECTURE

The proposed Risley architecture is shown in Fig. 2. It consists of a leaky-wave feed fabricated in PCB technology and a single deflector based on additive manufacturing. The angular orientation (Ψ in Fig. 2) of these two elements around their common axis controls the steering direction of the radiated beam. In the following, the two building elements of the scanner are described.

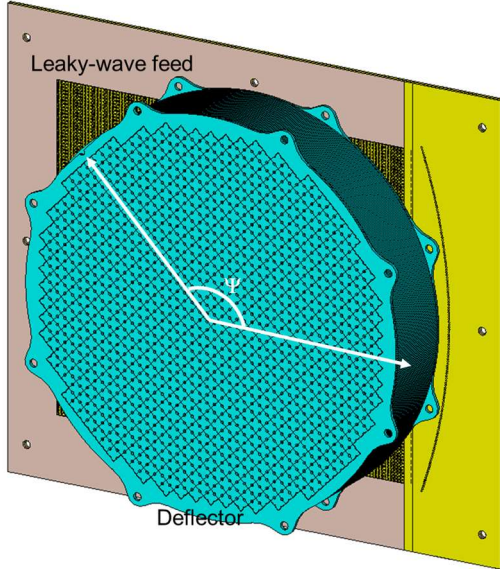


Fig. 2. Perspective view of the proposed Risley scanner.

A. Leaky-wave feed

Fig. 3 shows a perspective view of the leaky-wave feed. It consists of two stacked parallel plate waveguides (PPWs) that serve to implement a pillbox quasi-optical transition [10] feeding a sinusoidally modulated metasurface [8], [12], [13]. The stack-up of the feed is made by two Rogers RT5880 substrates with a thickness of 1.575 mm, relative permittivity 2.2 and $\tan \delta = 0.0009$. The two substrates are glued by a 70- μm thick bonding layer (Taconic fastRiseTM FR-27-0030-25, relative permittivity 2.7 and $\tan \delta = 0.0017$). The final lateral dimensions of the leaky-wave feed are $L_x = 32.6$ cm

and $L_y = 25.8$ cm with a total thickness thinner than 3.3 mm. The pillbox transition connects both PPWs using a 180° bend with a parabolic profile. In this way, a guided transverse electromagnetic (TEM) wave with a plane wave front is generated in the top substrate to illuminate the metasurface. A slotted transition (see the inset in Fig. 3) ensures a smooth transition from the pillbox system to the leaky-wave mode excited by the metasurface. The metasurface layout, modulation and periodicity are chosen to radiate a beam in linear polarization at 32° in elevation at the central frequency of operation of 20.2 GHz. The edge taper of the pillbox system shapes the aperture field amplitude in the H-plane, whereas the metasurface modulation controls it in the E-plane. An aperture efficiency exceeding 55% is obtained. In the band of operation (19.2-21.2 GHz), the pointing angle of the leaky-wave feed changes about 20° in elevation.

B. Deflector

Several concepts have been proposed in the literature to implement the deflection function required by the risley architecture. Among them, dielectric diffractive components offer low manufacturing cost, weight, aspect ratio and high design flexibility [7]. However, when realized with additive manufacturing techniques that use low permittivity polymer such as ABS, such lenses suffer from high grating-lobes and low diffraction efficiency. These shortcomings are due to the coupling between adjacent elementary cells, whose arrangement is designed to obtain the required phase profile. One way of dealing with this limitation is to use printable, high permittivity materials [5], [7]. In this work, we propose an alternative approach by using a plastic part made of standard ABS as dielectric filling for an array of straight metallic waveguides opened at both extremities. By varying the amount of dielectric material inside the waveguides, a given phase profile in transmission can be reconstructed to achieve the desired deflection.

The main challenge in realizing such a deflector is to reduce the dispersion. Several geometries of dielectric loaded waveguides have been studied to reduce this dispersion, while obtaining with a limited thickness, a phase excursion sufficient to implement the requested phase profile. We have adopted here quad-ridged square waveguides with a variable dielectric loading to form a 250-mm diameter hybrid deflector with 49-mm thickness. In particular, these waveguides are assembled in a periodic way, with a unit-cell of 4 waveguides, as depicted in Fig. 4(a) and (b). This geometry was chosen to deviate an incoming plane wave at normal incidence by an angle of -32° , thus fully compensating the inclination of the leaky-wave feed radiated beam at the central frequency.

The metallic waveguide array was printed in titanium with selective laser sintering (SLS), while the dielectric loading part was obtained by fused deposition modeling (FDM).

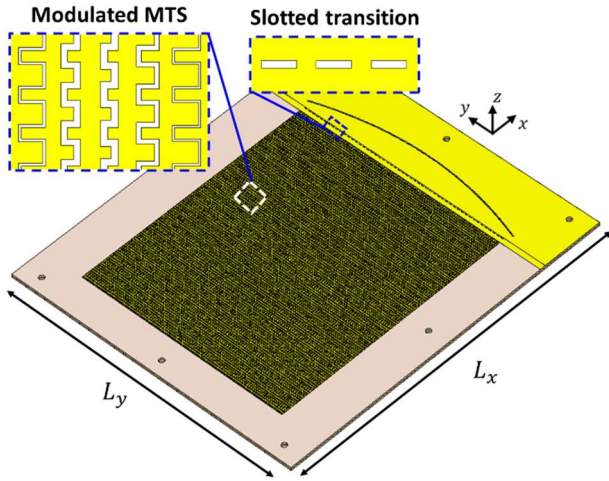


Fig. 3. Perspective view of the proposed leaky-wave feed.

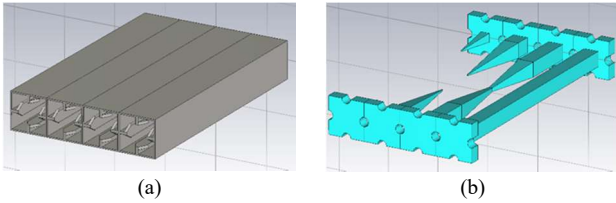


Fig. 4. (a) Metallic and (b) dielectric complementary parts of the deflector unit-cells.

III. PROTOTYPE

The final structure is shown in Fig. 5 while mounted in the anechoic chamber. The leaky-wave feed and the deflector can be easily recognized. A metallic support was used to install the antenna on the mechanical positioner. The relative position of the deflector and leaky-wave feed are controlled manually. However, in a final implementation of the structure an automatic mechanical control should be considered.

Preliminary measurement results of the radiated beam in the upper hemisphere are shown in Fig. 6 at the central frequency of 20.2 GHz. Two relative positions in azimuth of the deflector and the leaky-wave feed are considered to illustrate the capability of the system to achieve beam-steering. In particular, Fig. 6(a) shows the radiated beam at broadside with a gain of 25.4 dB and side lobe level (SLL) lower than -13.3 dB in the considered half hemisphere. Fig. 6(b) reports the measured beam at 50° in elevation with a gain of about 22.6 dB and SLL better than -12.5 dB. For both elevation angles a well-defined beam is observed, showing the capability of the system to scan over a large field of view. Although not shown for brevity, a good agreement is observed between simulations and measurements for the radiated beams and pointing direction.

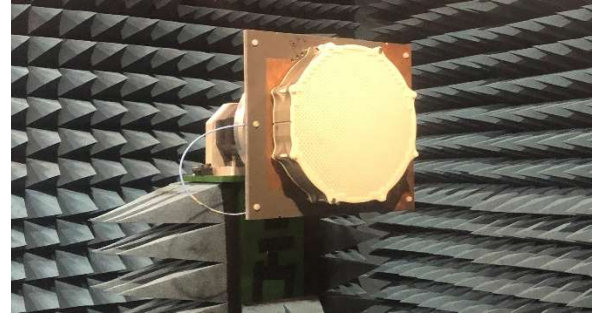


Fig. 5. Prototype mounted in the anechoic chamber during measurements.

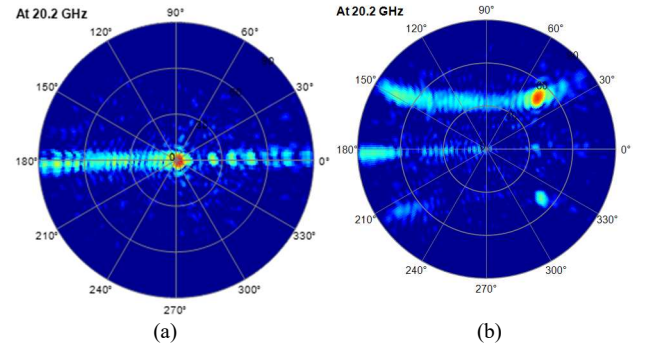


Fig. 6. Measurements of the radiated beam in the upper hemisphere. (a) Broadside radiation ($\Psi=180^\circ$ in Fig. 2). (b) Radiation at 50° in elevation ($\Psi=90^\circ$ in Fig. 2).

IV. CONCLUSION

This contribution has presented a revisited Risley configuration. The proposed system is based on a leaky-wave feed in PCB technology illuminating a deflector made by additive manufacturing. The leaky-wave feed replaces the source and first prism in classical Risley scanners, with the aim to provide a lower profile solution. Here, such a feed is based on a modulated metasurface fed by a pillbox system, radiating in linear polarization. Measurements of the radiated beam have shown the system's capability to steer the main beam 360° in azimuth and up to 60° in elevation with a well-formed beam, low SLL and a maximum measured gain exceeding 25 dBi. The final size of the antenna is about 250 mm in diameter with a total thickness of less than 65 mm.

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REFERENCES

- [1] W. W. Milroy, S. B. Coppedge, and A. C. Lemons, "Variable inclination continuous transverse stub array," U.S. Patent 6 919 854 B2, Jul. 19, 2005.
- [2] C. T. Amirault and C. A. DiMarzio, "Precision pointing using a dual wedge scanner," *Appl. Opt.*, vol. 24, no. 9, pp. 1302–1308, May 1985.
- [3] H.D. Griffiths and M.R. Khan, "Antenna beam steering technique using dielectric wedges," *IEE Proc. Pt. H*, Vol. 136, No. 2, Apr. 1989.
- [4] M. U. Afzal, K. P. Esselle, and M. N. Y. Koli, "A beam-steering solution with highly transmitting hybrid metasurfaces and circularly polarized high-gain radial-line slot array antennas," *IEEE Trans. Antennas Propag.*, vol. 70, no. 1, pp. 365–377, Jan. 2022.
- [5] T. Q. V. Hoang *et al.*, "Low-profile highly directive 2D-beam-steering antenna in Ka-band with 3D-printed all-dielectric sub-wavelength deflectors," presented at the EuMW conference, Milan, Italy, 2022.
- [6] F. Caminita *et al.*, "Phase gradient metasurface for wide angle beam scanning antennas with highly reduced sidelobes," presented at the 16th EuCAP Conference, Madrid, Spain, 2022.
- [7] R. Czamy *et al.*, "High permittivity, low loss, and printable thermoplastic composite material for RF and microwave applications," 2018 IEEE Conference on Antenna Measurements & Applications (CAMA), 2018, pp. 1–4.
- [8] A. M. Patel and A. Grbic, "A printed leaky-wave antenna based on a sinusoidally-modulated reactance surface," *IEEE Trans. Antennas Propag.*, vol. 59, no. 6, pp. 2087–2096, Jun. 2011.
- [9] J. Ruiz-García, M. Faenzi, A. Mahmoud, M. Ettorre, P. Potier, P. Pouliguen, R. Sauleau, and D. González-Ovejero, "Multi-beam modulated metasurface antenna for 5G backhaul applications at K-band," *Comptes Rendus. Phys.*, vol. 22, no. S1, pp. 47–52, 2021.
- [10] K. Tekkouk, M. Ettorre, E. Gandini, and R. Sauleau, "Multibeam pillbox antenna with low sidelobe level and high-beam crossover in SIW technology using the split aperture decoupling method," *IEEE Trans. Antennas Propagat.*, vol. 63, no. 11, pp. 5209–5215, Nov. 2015.
- [11] O. Yurduseven *et al.*, "Multibeam Si/GaAs holographic metasurface antenna at W-Band," *IEEE Trans. Antennas Propagat.*, vol. 69, no. 6, pp. 3523–3528, Jun. 2021.
- [12] M. Faenzi *et al.*, "Metasurface antennas: new models, applications and realizations," *Sci. Rep.*, vol. 9, pp. 10178, 2019.
- [13] G. Minatti, D. González-Ovejero, E. Martini, and S. Maci, "Modulated metasurface antennas," in *Surface Electromagnetics: With applications in antenna, microwave, and optical engineering*, F. Yang, Y. Rahmat-Samii, Eds. Cambridge University Press, 2021.