Reviews of Electromagnetics
Vision Paper

The Water Drop Lens: Revisiting the Past to Shape the Future

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Abstract
This vision paper provides a brief overview on recent developments related to a new solution of quasi-optical beamformer, referred to as the water drop lens. This parallel plate waveguide beamformer, which is a revisited geodesic lens with a shaped profile, is attracting attention for applications in the millimetre-wave range, where more conventional dielectric lenses prove to be too lossy and standard geodesic lenses are still too bulky. On-going investigations include satellite and terrestrial communication systems, radar systems and imaging systems with wideband operation at centre frequencies ranging from about 20 GHz to over 120 GHz.

Key terms
Quasi-optical beamforming techniques; Rinehart-Luneburg lens; geodesic lens.

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Received: 30/1/2021, Accepted: 17/3/2021, Published: 1/1/2022

1. Introduction

With various large scale applications moving up in frequency to the millimetre-wave range, such as satellite and terrestrial communications, radar systems, including airborne and automotive radars, new antenna solutions are required to provide high gain, multiple beams, wide scanning range with relatively low-cost implementation. Most of the beam forming techniques still in use today were devised during a very productive period for microwave engineering ranging from the 1940's to the 1960's. Two major families of solutions emerged in that period of time, the beam forming networks (BFNs), composed of interconnected elementary components such as couplers and phase shifters, which may be categorized as discrete beamforming techniques, and quasi-optical beamformers, including reflector-based and lens-based solutions, which are generally continuous beamforming techniques.

Among existing BFN solutions, the Butler matrix received, and still receives, a great deal of attention [1]. Another solution, the Nolen matrix [2], was proposed at about the same time. Although its implementation is generally more complex than that of the Butler matrix, it does provide greater flexibility. The Nolen matrix received very little attention up until recently, when the topic was revisited by the author with a simple design procedure exploiting the link between Nolen and Blass matrices, supported with experimental validation in S-band [3].

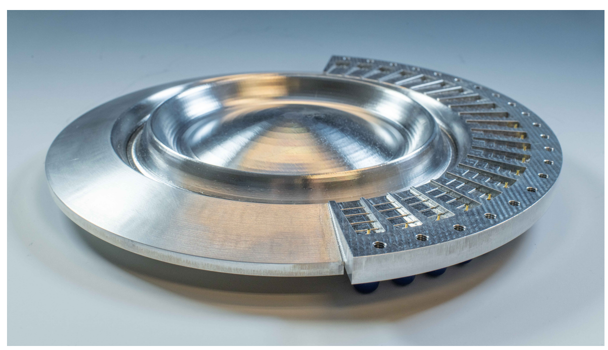

Figure 1: Part of a water drop lens prototype designed for applications in Ka-band (© ESA–SJM Photography).

Since then, several works have been reported with practical implementations of Nolen matrices in printed technology [4–8].

Interestingly, there are some historical similarities with quasi-optical beamformers, the Luneburg lens [9] being also a very popular solution. Much like the Nolen matrix, an alternative to the planar Luneburg lens, known as the Rinehart-Luneburg lens [10, 11] or the geodesic lens in its more general form, has received very little attention over the years, with very few practical works reported [12, 13]. Most planar quasi-optical beamformers, including pillbox antennas [14–19], Rotman lenses [20–30] and continuous delay lenses [31–33], have a finite number of focal points. Luneburg lenses have instead an intrinsic rotational symmetry that provides focusing in any angular direction. This is attractive for applications requiring very stable radiation patterns over a wide angular range, typically in azimuth. Fully metallic designs are also of interest for highly efficient antenna solutions, hence the regain of interest for geodesic lenses. This paper discusses the recent introduction of a modulated geodesic lens, referred to as the water drop lens, and its possible use in practical millimetre-wave and sub-terahertz applications, both as a stand-alone antenna and as a sub-system in more advanced beamforming structures [34–37].

2. The Water Drop Lens

2.1. Revisiting the past

Recent advances on metamaterials and transformation optics (TO) have triggered many developments of quasi-optical systems, mostly Luneburg lenses, in the microwave, terahertz and optical domains [38–43]. Fully metallic designs were proposed to avoid losses resulting from the use of dielectric materials at the expense of an increased mechanical complexity [44]. Geodesic lenses would provide a much simpler mechanical design. However, their profile is less compact, with a height of about a third of the lens diameter, which is less appealing for applications requiring high integration.

A recent work discussing graded-index lenses on curved surfaces [45] brought our attention back to the original works on geodesic lenses and in particular the work of Kunz [46]. Besides a discussion on the equivalence between rotationally symmetric guides with variable index, generalizing the work of Rinehart, Kunz also proposed a folding approach to reduce the height of geodesic lenses, noting that a symmetry with respect to any plane parallel to the beamforming plane keeps the focusing properties of the lens unchanged. This approach was implemented successfully for the first time in [47], folding twice its profile to reduce the height of the lens by a factor of 2.5. However, this approach requires careful design as the folding leads to singularities in the lens profile, affecting the performance in a practical implementation.

2.2. Shaping the future

In parallel with the investigations on the folding approach proposed by Kunz, a more general design approach was also envisaged. In fact, if one needs to optimize the transitions at the folding points to minimize reflections and phase aberrations within the parallel plate waveguide, one might as well optimise the full profile of the lens as this provides more freedom in the overall design performance. This is the simple idea behind the water drop lens concept (Fig. 1), a modulated geodesic lens with a shape that resembles the ripples, or capillary waves, produced by a water drop at the surface of a fluid, hence its appellation. The first numerical results with simple quadratic functions were promising [48,49]. Further height reduction was achieved using spline functions (Fig. 2) and a dedicated ray-tracing tool based on the equivalence with a planar graded-index lens [50]. The first experimental data, presented at the 40th ESA Antenna Workshop in 2019, attracted quite some attention. The contribution [51] was among the 5 papers shortlisted to be pre-

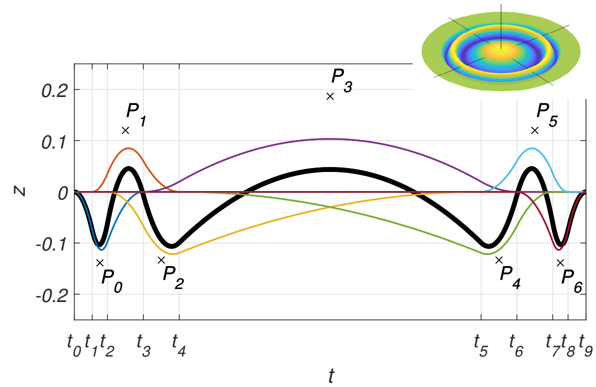

Figure 2: Modulated geodesic lens profile using spline functions (inset: medium surface obtained by rotation of the modulated lens profile) [50].

sented again in the frame of a dedicated Scientific Workshop at EuCAP2020 [52]. A generalized ray-tracing tool is under development to investigate further the capabilities of modulated geodesic lenses [53].

3. Applications and Perspectives

Besides the space applications for which it was originally conceptualized, there are new applications emerging as interest in the water drop lens develops. Ericsson (SE) is involved in technology transfer activities for terrestrial millimetre-wave 5G and beyond 5G communications, considering a stack of water drop lenses combined with an elevation beamforming network to produce a two-dimensional multiple beam coverage [54]. Satcube (SE) is also looking into the technology to complement their portfolio of satellite-on-the-pause user terminals. The development aims at using the wide scanning range of the water drop lens to connect with low Earth orbit (LEO) satellites, possibly leading to a solution simpler and cheaper than more conventional phased arrays. The research group IMS Bordeaux (FR) has also interest in the technology for non-destructive testing at sub-terahertz frequencies and is leading an early technology development with the support of R&D Vision (FR) and Arianespace (FR). Finally, there is some interest in using this solution for radar systems on board atmospheric satellites and drones, as the power supply is limited and power efficient antennas are highly desirable. Other applications are expected to develop as the technology matures and experimental results validate its potential, confirming that old concepts can help shape future products.

Acknowledgments

The author would like to thank Prof. Oscar Quevedo-Teruel, from the Royal Institute of Technology KTH, Stockholm, Sweden, who contributed greatly to the development of the water drop lens concept, since its inception, and Dr. Qingbi Liao, also from KTH, Stockholm, Sweden, for her support to the first experimental validation, as well as all partners involved in on-going developments.

Disclaimer

The opinions expressed in this paper are the author's own opinions and do not necessarily represent the official view of the European Space Agency.

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