Abstract – In this paper short introduction in dielectric lens antennas at mm-waves will be given. Dielectric lens antennas become more popular as applications start to migrate to higher frequencies where lens dimensions and weight become small enough and allow easy integration. Typically used feeds and lens shapes will be discussed together with global optimization techniques and analyzing kernels employed for lens antenna optimizations and synthesis with special emphasis to methods used by the author. Finally some remarks regarding lens production will be given.

Keywords – Lens antennas, millimetre waves, antenna synthesis

1. INTRODUCTION

The millimeter-wave frequency bands are very attractive for various modern indoor and outdoor applications such as point-to-point and point-to-multipoint links, radar systems including collision avoidance devices, radio-astronomy, satellite communications, and mm-wave imaging. At these frequencies (>30 GHz) lenses become acceptable in size and weight for many applications. Lens antennas consist of two main parts: the feeding antenna that can be any other type of antenna (horns, dipoles, microstrip (patch) antennas, and even arrays of antenna elements) and lens that collimate incident divergent energy to prevent it from spreading in undesired directions.

There are primarily two different lens designs used for realizing different goals. Canonical (hyperbolical, bihyperbolical, elliptical, hemispherical…) or shaped lens antennas are used for collimating the radiated energy, or, in case of shaped designs, for shaping the beam to required radiation patterns, while cylindrical and spherical lenses are mostly used for beam scanning with single, or multiple feed possibility.

2. PRIMARY FEEDS

Lenses, same as the reflectors with reflector antennas, are used for directing the radiation. The radiation has to come from source that is typically called the feed. Feed can be almost any other type of antenna, but practically horns (or just open ended waveguides) and patches are mostly used, or, in some cases, arrays of the named elements.

2.1. Horns

Horns are, in case of standard dielectric materials, inherently wide-band, so it is advisable to match them with wideband source if the highlighted characteristic is to be exploited. Horns, as the feeding element, are also broadband. The bandwidth is usually determined at lower boundary by the cutoff frequency of the feeding waveguide and at the higher boundary by the propagation of higher order modes. Horns are widely used as a feed element for reflectors and lenses. They are common element of phased arrays and serve as a universal standard for calibration and gain measurements of other high-gain antennas. Its widespread use comes from simplicity in construction, ease of excitation, versatility, and large gain [1]. The biggest shortcoming of horns lies in their bulkiness that makes integration problematic. In that cases open ended waveguides (with and without ground plane) can be used, but they reduce optimization opportunities in case we can optimize feed and lens simultaneously. Additionally, open ended waveguides are still quite cumbersome for integration in many cases.
2.2. Microstrip (patch) antennas

In applications where size and weight are important parameters, low-profile antennas can be required. In these cases, microstrip antennas can be used. They are low-profile, usually lightweight antennas that can conform to planar and non-planar surfaces. Major disadvantage arises from the typically very narrow frequency bandwidth and low efficiency [1]. The radiating patch can come in many shapes including among others rectangular, circular, elliptical, and triangular configurations. Dimensions of patch antennas at millimeter wavelengths becomes small enough so planar arrays can be constructed, Arrays can be used to make the main beam narrower or, in case of active antennas, for beam steering. Radiating element or array of the same can also be conformal, so that they follow the surface whose shape is primarily determined by considerations other than electromagnetic. Possible reasons can be aerodynamic, hydrodynamic, or even aesthetic. Microstrip antennas are usually constructed on dielectric layer whose losses typically increase as operating frequency increases. Losses can become quite high at frequencies above 30 GHz, which can limit usefulness of microstrip antennas.

3. SYNTHESIS

Dielectric lenses have received lots of attention in open literature, especially spherical lenses constructed obeying the Lunebergs law. Parameters of these kinds of lenses can analytically be derived, but it was shown that, for instance, Luneberg lenses don’t necessarily offer optimal performance in regards to complexity of construction [2]. Rapid development of modern computers and their performance, together with optimized analyzing kernels has offered us opportunity to optimize and even synthesize lenses with desired characteristics via global optimization techniques. There are many global optimization techniques available, but so far in electromagnetics only few have extensively been used. They are particle swarm optimizations, genetic algorithms and the multidimensional conjugate gradient method. All the global optimization techniques prove to be usable. The genetic algorithm approach is probably the most widespread and has been applied to many problems [3]. It constitutes a particular class of evolutionary algorithms (also known as evolutionary computation) that use techniques inspired by evolutionary biology such as inheritance, mutation, selection, and crossover (also called recombination). The particle swarm optimization is more recent technique that is stochastic evolutionary computation technique based on the movement and intelligence of swarms [4]. Although previous research has suggested that limited number (< 30) of particles in swarm should be used, some new results with more complex optimization routines suggest that number of particles should be increased if the search space is more complex [5]. Finally, multidimensional conjugate gradient method based on iterative technique has also been successfully used for optimization of complicated arbitrarily shaped lens designs [6].

3.1. Analyzing kernels

The most important part of the antenna synthesis is the analyzing kernel used to estimate the fitness or quality of the selected design. It basically has to fullfill two main requirements. It has to be accurate and fast enough. Typical optimization runs take at least thousands of fitness evaluations; so analyzing kernel has to be fast enough that results can be obtained in reasonable amount of time.

Probably the most often used kernel for synthesizing dielectric lens antennas is the one based on rules of geometry (GO) or physical optics (PO) [6]. GO is an approximate high-frequency method for determining wave propagation for incident, reflected, and refracted fields. Solving of problems by its principles can be called ray tracing as we, in fact, trace ray propagation throughout media that can have different refraction indexes. When entering new media, the Snell's law determines new ray direction. When the refractive-index profile is graded the trajectory of a ray is determined by the eikonal equation. Light intensity, in GO, is governed by the conservation of energy [7]. This is usually an extremely fast method that is also memory efficient but works well only in cases where lens dimensions are large in regards to wavelength and when primary radiator can be considered as a point source. Multiple internal reflections in case that dielectric has high relative epsilon can also prove to be problematic [8]. Potential user of this technique has also to take care on caustics - regions (points or lines) where infinite number of rays passes through. In that regions GO predicts infinite field which is not physically possible, although at that regions fields are usually exceptionally strong. In cases where GO fails, its extension PO (Physical Optics) can prove valuable. PO is a bit slower method as it requires integration of equivalent currents by radiation integrals.

The Method of moments (MOM) or boundary element method (BEM) is a numerical computational method of solving linear partial differential equations which have been formulated as integral equations (i.e. in boundary integral form). It can be applied in many areas of engineering including electromagnetics. MoM is applicable to problems for which Green's functions can be calculated which usually involve fields in linear homogeneous media [9]. This is a full wave method
that can be efficient in terms of computational resources for problems where there is a small surface/volume ratio, but computational time tends to grow according to the square of the problem size. In most general sense, MoM is usually too computationally intensive to be used for global optimization of complex problems if some assumptions aren’t made in advance.

Finite-difference time-domain (FDTD) is a very popular computational technique [10]. It is considered easy to understand and easy to implement in software. Since it is a time-domain method, solutions can cover a wide frequency range with a single simulation run. This is also a full-wave analysis whose complexity typically rises linearly with the problem size [11]. It is very demanding in regards to computational time and especially memory so full 3D optimizations based on FDTD are still quite unrealistic. By reducing the calculation domain to 2D or to rotationally symmetric structures, computational time as well as memory consumption can be reduced considerably.

Beside typical, general analyzing kernels, it is possible to develop special techniques optimized for some subgroup of problems. By utilizing some assumptions, special techniques can offer satisfactory accuracy and great speed which makes them suitable for global optimization techniques. One example of this kind of analyzing kernel is G1DMULT capable of working with 1D planar, cylindrical or spherical structures [12]. G1DMULT is fast, memory efficient, full-wave analysis, but is limited to 1D structures. This algorithm allows computing spectral domain Green’s functions of planar, circular cylindrical and spherical multilayer structures. The far-field radiation patterns are obtained using the spectral domain method. For instance, in case of cylindrical symmetry, the following Fourier transformation is applied in directions where the structure is homogeneous

$$f(p,m,k_z) = \sum_{m=-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x,y,z)e^{jm\phi}e^{jkz}dxdz$$

(1)

Therefore, the original 3D problem is transformed into a 1D problem. The feed is replaced with equivalent aperture currents by using free-space equivalent principle. The equivalent excitation currents are transformed into the spectral domain. The far-field excitations are transformed via Fourier into harmonic current tubes (in case of cylindrical transformation). Original problem is interpreted as a 1D problem consisting of 1D multilayer structure and harmonic 1D sources in the form of current tubes. For each spectral value $m$ and $k_z$, the field values are determined by fulfilling the boundary conditions at the interface between each dielectric layer of the lens antenna. The far-field patterns in the spatial domain are determined after performing the inverse Fourier transformation.

$$E^\phi(r,\theta,\phi) = \frac{e^{-jm\phi}}{r} \pi \sin \theta \sum_{m=-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x,y,z)e^{jm\phi}e^{jkz}dxdz$$

(2)

The algorithm allows computing the radiation patterns in full 3D and comparison with full-wave analysis of various lenses (using commercial software CST Microwave Studio®) has demonstrated that the accuracy of G1DMULT is very satisfactory provided the length of the lens is large enough. Reader should take note that G1DMULT presumes that the cylindrical lenses are of infinite height. The major advantage of this modeling technique is that the determination of the radiation performance of cylindrical lenses is extremely fast, which makes feasible the electromagnetic optimization of lenses of moderate or even large size.

![Comparison between far-field radiation patterns obtained by G1DMULT and CST Microwave Studio® for circular-cylindrical lens.](image)

Fig. 2. Comparison between far-field radiation patterns obtained by G1DMULT and CST Microwave Studio® for circular-cylindrical lens. The matching is extremely good, in case that the height of the cylinder is large enough so truncation effects do not significantly contribute to far-field pattern.

4. LENSES

Dielectric lenses can be divided to two main categories: lenses used for shaping or just collimating the beam and lenses that can be used for beam scanning. Dielectric lenses of canonical shapes (hyperbolical, bihyperbolical, elliptical, hemispherical) are used for collimating the radiated energy. Lenses can also be shaped for obtaining the desired radiation pattern of single feed or feed array. While performing synthesis of shaped antennas of moderate and small size, special attention has to be paid to analyzing kernels.

For emitting mode, GO/PO has been successfully applied for a number of lenses if low index materials have been used [6], but for receiving mode inaccuracies of GO/PO algorithms have been
observed [8]. Inaccuracies arise from internal resonances that cannot be accounted for by multiple reflections with GO/PO approach.

![Diagram of spherical multiplayer lens antenna fed by horn capable of beam scanning in both axis.](image1)

**Fig. 3.** Spherical multiplayer lens antenna fed by horn capable of beam scanning in both axis.

Cylindrical and spherical lenses are attractive because they allow launching multiple pencil- or fan-beams, each of them originating from one primary feed. The beams can be scanned by moving the feed around the surface of the lens or by switching between one feed and an adjacent one. Such radiation characteristics are of particular interest for many applications, like Doppler-weather radar, aircraft landing system or imaging systems at millimeter waves. Lots of study, especially with spherical lenses, has been concentrated on lenses constructed to follow Lunebergs law [13]. Lunebergs law states that for focusing the rays from a point source on the surface of the lens into a collimated beam on the diametrically opposite side of the lens, lenses index of refraction ($n$) should follow equation:

$$n(r) = \sqrt{2 - r^2}, \quad (3)$$

where $r$ is the normalized radial dimension ($0 \leq r \leq 1$). In microwave applications it is difficult to obtain point source on the surface of the lens. Horns, for example, don’t have phase center in the aperture plane. In that case effective point source is placed outside of the lens which results in aperture phase errors and radiation characteristics degradation. There has also been lots of research on modifications of the law of refraction to minimize phase errors [14]. Luneberg law asks for continuous change of index of refraction, which would be practically impossible to produce. Most built lenses have been made with shells of dielectric material, i.e. by approximating the law in number of points. Older designs usually had ten or more layers [15], but more recent studies have shown that for many applications only couple of layers can offer satisfactory performance [2][5].

When shaping the lens for desired radiation pattern, the lens is usually made of single layer dielectric, possibly with matching layer if $\varepsilon_r$ is higher to reduce reflections. Matching layers for arbitrary shaped lenses can be problematic to produce. They can be implemented as a coating of different material, or by introducing corrugations on lens surface. The latter solution limits the operational bandwidth, as it is resonant in nature. Fitness functions are usually quite complex and are based on desired farfield radiation pattern template. Lenses with quite complicated radiation patterns have successfully been synthesized, produced and measured [6].

![Cross-section view of a canonical dome lens antenna fed by microstrip square patch antenna.](image2)

**Fig. 4.** Cross-section view of a canonical dome lens antenna fed by microstrip square patch antenna

Synthesis of cylindrical or spherical lenses for beam scanning purposes can usually use simpler fitness functions. Typically we want to maximize gain, while keeping sidelobes low enough or make beams as narrow as possible while keeping sidelobes low enough. Usually we can optimize number of layers, layers radius and permittivity of each layer. Designs following Lunebergs law usually have many layers, but for many purposes two or three layers should be enough. Some authors also suggested using one layer with higher permittivity (> 2) and, if required, a matching layer [2][16].

![Graph showing influence of air gaps on radiation performance for single layered cylindrical lens antenna made of twenty slabs.](image3)

**Fig. 5.** Influence of air gaps on radiation performance for single layered cylindrical lens antenna made of twenty slabs.

Dielectric lenses are usually made of standard materials that include Foam ($\varepsilon_r \approx 1.69$), Teflon ($\varepsilon_r \approx 2.1$), Rexolite ($\varepsilon_r \approx 2.53$), and Silicon ($\varepsilon_r \approx 11.7$) among others. Used materials limit the selection of
available $\epsilon_r$, so if we were to construct multilayered spherical lens obeying Luneberg’s law, inhomogeneous materials should be used.

Change of $\epsilon_{\text{eff}}$ of given material can be made by drilling small air holes in material with higher $\epsilon_r$ than required. For mm-waves, inclusions have to be very small so production can prove to be problematic. By drilling holes we also reduce the strength of materials, so lenses can become more fragile. Therefore it is advised to try to synthesize lenses with some predefined $\epsilon_r$ values that are obtainable in practice.

Also special care has to be taken if the final lens is produced from many parts. In that case the final radiation performance can greatly be reduced as a result of air gaps between layers or lens parts.

5. CONCLUSIONS

Dielectric lens antennas, in the millimeter-wave frequency band, are becoming more popular for various indoor and outdoor wireless applications. Their dimensions and weight, at frequencies above 30 GHz, become small enough; while at the same time they offer beam shaping and beam scanning abilities to primary feed antennas. Conventional dielectric antennas are also quite inexpensive so we can conclude that they will be more and more used as modern applications start to migrate to millimeter-wavelength frequencies.

REFERENCES