A Broadband, High-Gain, Steerable Luneberg Lens

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Luneberg lenses have recently seen revived interest and have moved from being of purely academic interest to greater use as a broadband steerable antenna for satellite applications. Advanced material technologies have enabled high gain, low sidelobe, lightweight lenses to be constructed. A properly designed Luneberg can achieve gain comparable to a dish reflector with the same aperture size. A Luneberg lens combines the high gain of a dish reflector with the steering ease of a phased array at a much lower cost.

Previously, Luneberg lenses have seen application primarily as reflectors or radar beacons since, when combined with ground planes, they will offer a large return over a wide range of angles. Their use as an antenna lens has been limited due to the difficulty in manufacturing resulting in high cost and low performance. New material technologies and design capabilities now enable high-performance, low-cost lenses to be constructed.

Dielectric lens antennas have been used for many years in various applications. Just like in an eyeglass lens, the purpose is to focus incoming plane waves to a point. The most popular and simplest to construct type, Constant-K lenses, consist of a single material with homogenous dielectric constant where lens focusing is determined by shaping of the material. From a material standpoint, these are very easy to make but the cost of machining to shape could be prohibitive. In addition, changing the beam direction of the antenna would entail turning the entire lens. A solution to this issue was found by R. K. Luneberg at Brown University in the 1940s [1]. Termed the Luneberg lens, this is a special case of a class of lenses which create conjugate foci at two points in space. For the Luneberg, one focal point is on the surface of the lens while the other is at infinity. Incoming plane waves are therefore focused to a point on the lens surface. The Luneberg lens is spherically symmetric and uses a dielectric constant gradient dependent on radius conforming to the following equation

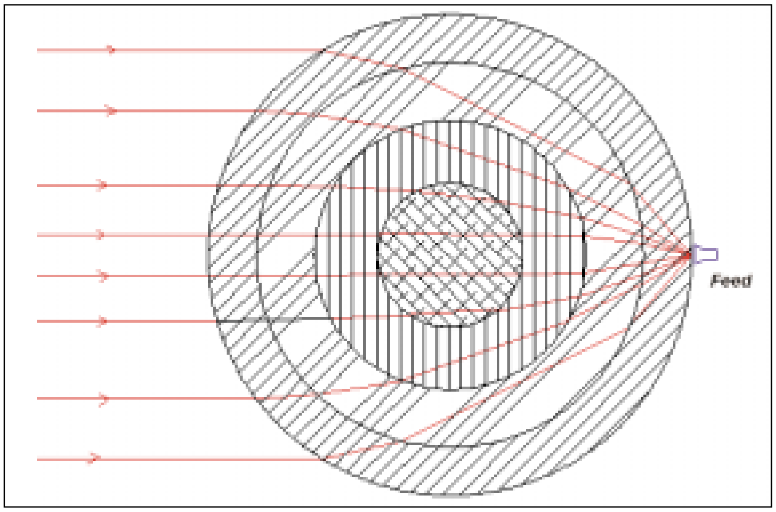
$$\varepsilon_r = 2 - \left(\frac{r}{R}\right)^2$$

where R is the sphere radius and r = distance from sphere center.

In theory, the Luneberg lens requires a dielectric constant gradient running from 2 at the center of the sphere to 1 on the surface of the sphere. In practice, this entails approximating the gradient with discrete dielectric layers where the dielectric constant of the layer is the average of what it should be at its inner and outer diameters. One issue with this approach is that the focal point would be on the surface of the lens. In practice, one would like the focal point to be at a point off the surface of the lens to enable smooth feed movement around the surface of the lens to allow beam scanning. Today, with sophisticated computer software, the design of a lens can be optimized for virtually any feed location.

Applications

Receiving a satellite signal from a geostationary satellite at a ground station requires a high-gain (usually dish reflector) antenna fixed in position and beam direction. However, if either the satellite or the receiver is moving with respect to the other, the antenna must be con-



▲ **Figure 1. Luneberg lens ray trace diagram.**

stantly adjusted to maintain signal.

With the geostationary satellite band filling up, many organizations are turning to low earth orbit (LEO) satellites requiring the ground station to track the satellite. Often, a mobile ground station is desired. In either case it is necessary to track the satellite to maintain signal. Reorienting a dish antenna would require physically moving the entire structure. The next satellite would need to be acquired before the first one drops below the horizon to guarantee no interruption, which would require either two dishes or a very smooth and quick mechanical movement. A Luneberg lens antenna solves both these problems. Due to the spherical symmetry, scanning requires moving the relatively small feed around the lens while the lens itself remains stationary. Acquiring another satellite signal before losing the first could be easily accomplished with the use of dual feeds since the lens can support simultaneous beams.

The Luneberg lens is broadband since dielectric constant shows little variation with frequency in the microwave band. Also, low altitude angles can be scanned. A phased array is usually band limited and has difficulties at low scanning angles in addition to its greater cost and complexity.

Design issues

Designing a Luneberg lens requires approximating the dielectric gradient with discrete layers of a given dielectric constant. A larger number of layers for a given radius lens will better approximate the pure Luneberg lens at the expense of greater cost to manufacture. Diminishing returns, which are seen as additional layers, are added. Also, a smaller number of layers will result in a higher dielectric constant for the outermost layer, which will reduce lens efficiency.

A simple ray tracing program can be used to design a Luneberg lens however this will yield no information regarding gain or sidelobe level. Prediction software using spherical wave functions and boundary value matching can be used for accurate prediction of lens performance. A genetic algorithm or similar method could then be used to find the optimum design. In the past, lenses have been designed with each layer the same thickness. It has been found that optimum designs are seen with different thicknesses for each layer.

Key parameters in the design are lens radius, feed location (distance from surface of sphere) and desired gain. Gain performance close to the theoretical maximum for the aperture size can be achieved.

Manufacturing issues

The manufacture of high-performance Luneberg lenses requires the development of low-loss materials with dielectric constants between 1 and 2. Tight control of the dielectric constants of each layer must be maintained to ensure lens performance. The ability to accurately measure the dielectric constant of the material within +0.005 is crucial. Dielectric constant errors will increase the sidelobe level. Air gaps between the layers will adversely affect both sidelobe level and gain.

Traditional Luneberg lenses have been made from expanded polystyrene (EPS). Each layer was made in a hemispherical shell and then assembled. With this process it is very difficult to avoid airgaps between the layers plus the dielectric loss in EPS affects performance and limits its use in high power applications.

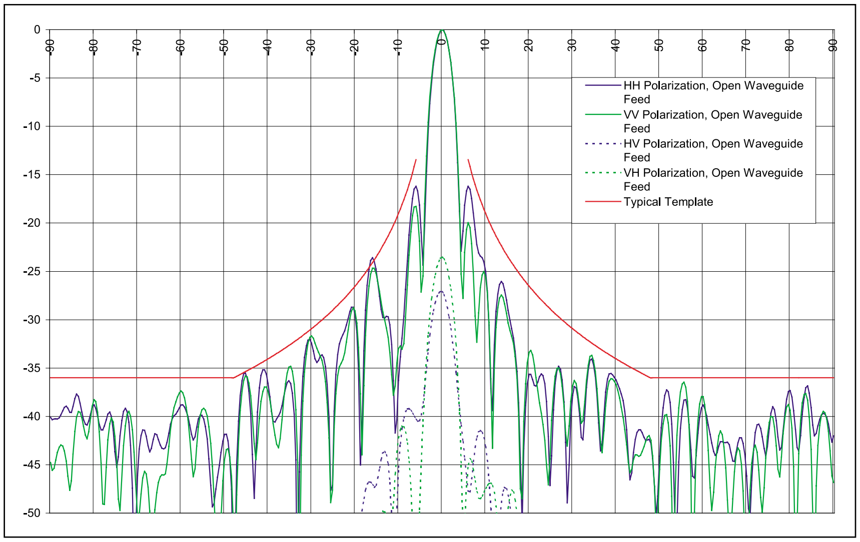
New generation lenses are manufactured using low loss composites with tightly controlled dielectric constants in a manufacturing process that eliminates the airgaps.

This advancement in Luneberg lens technology is made possible by the development of the new composites, which possess these critical characteristics:

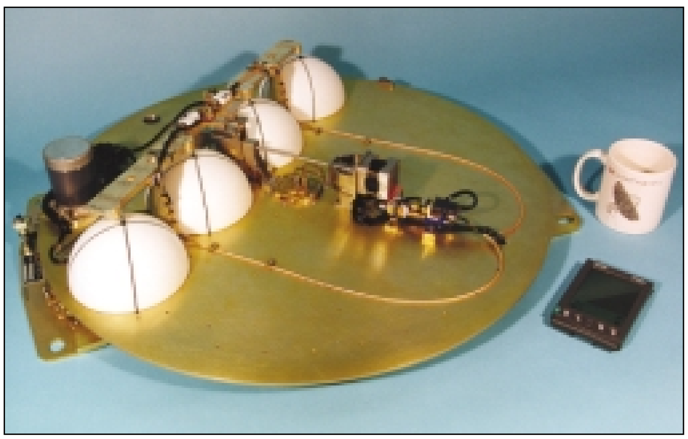
- Low dielectric constants and loss tangents within the range needed for Luneberg lenses.
- Dielectric constant and specific gravity that does not change during the curing/hardening process. These properties simplify the manufacturing process which improves the homogeneity within the lens and eliminates air voids.
- The dielectric constant of a specific composite is directly proportional to its density and can be calculated using an equation of the following form:

$$\ln k' = b\ \mathrm{SpG}$$

where k' is the dielectric constant, SpG is the specific gravity of the composite and b is the slope parameter. The slope parameter is in the range of 1.15 to 1.30.



▲ **Figure 2. Antenna pattern of a six-layer, 16-inch diameter Luneberg lens.**



▲ **Figure 3. A Luneberg lens cut in half and placed on a ground plane can duplicate the performance of a full spherical lens at half the height, making it ideal for airborne applications which would require a low profile to reduce wind drag.**

Using this relationship and the fact that the specific gravity does not change during the hardening process permits the control of the dielectric constant to ±0.005.

As a result, Luneberg lenses can be manufactured with consistent performance both from all angles of view and from lens to lens.

Performance

Figure 2 shows an antenna pattern of a six layer 16 inch diameter Luneberg lens. Measured gain is 31.5 dB at 10.7 GHz. Sidelobe level and polarization symmetry is very good. Figure 3 shows a Luneberg lens, which has been cut in half and placed on a ground plane. This can duplicate the performance of a full spherical lens at half the height, making it ideal for airborne applications requiring a low profile to reduce wind drag.

Conclusion

Luneberg lenses have seen revived interest recently due to the need for a broadband, lightweight, high-gain easily steerable antenna for satellite applications. New composite technologies enabling the manufacture of low dielectric, low loss materials coupled with sophisticated design techniques have improved performance and reliability to be comparable to dish antennas with the scanning ease of a phased array at a much reduced cost. ■

References

1. R. K. Luneberg, *Mathematical Theory of Optics*, Brown University Press, 1944.

Author information

Paul Dixon received a bachelor of science degree in astrophysics from Michigan State University in 1982 and a master of science degree in microwave engineering from the University of Massachusetts in 1986. In 1986, he joined Emerson & Cuming, where he was responsible for design and electromagnetic modeling of microwave absorbers. He was co-founder and technical director of Microsorb Technologies from 1992–97. In 1997, he rejoined Emerson & Cuming (now Emerson & Cuming Microwave Products), where he is responsible for electromagnetic modeling of microwave absorbers and dielectric materials. He can be reached via E-mail: pdixon@eccosorb.com; or Tel: 781-961-9600.