Direction Finding System Using Planar Luneburg Lens

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Abstract **─** In this paper, a novel two-dimensional Luneburg lens, composed of artificial impendence surfaces (AIS), is proposed for direction of arrival (DOA) estimation. Several detectors are mounted around the Luneburg lens to estimate the DOA of a microwave signal, owing to the surface wave can be focused perfectly on the diametrically opposite side of the lens. The desired refractive index profile of the Luneburg lens is controlled by the variable surface impendence of the unit cells, which is obtained by using an array of complementary unipolar compact photonic band gap (UC-PBG) structure inside a parallel plate waveguide. The proposed Luneburg lens with several probes, which operate in X-band region, are fabricated and measured to demonstrate the direction finding system. Both simulation and measured results show that the system has an excellent focusing ability, and the measured resolution of the system agrees very well with the theoretical value.

Index Terms **─** Artificial impendence surfaces, direction of arrival estimation, Luneburg lens, surface wave.

I. INTRODUCTION

Direction of arrival (DOA) estimation has attracted lots of attentions because it has a great potential in wireless communications and electronic warfare. But the typical direction finding system always need a large number of elements and complex algorithms, which have hindered the development of the DOA estimation.

In the last few years, artificial impendence surfaces (AISs), such as high impendence surfaces (HISs) [1-3], electromagnetic band gap (EBG) surfaces [4], and simply "metasurfaces" [5], drew a lot of attentions because of the great potential values in new antenna applications and technological solutions. Their unique electromagnetic responses, which are difficult to be realized with conventional materials, bring a lot of novel applications. For example, the mushroom surface, which has a high impendence property for plane wave reflection in the EBG frequency bandwidth, can be used in fabrication of low-profile antennas and TEM waveguide.

AISs are usually composed of a grounded dielectric layer covered with a pattern of sub-wavelength conductive patches. According to effective medium theory [6,7], the scattering parameters of the AISs can be artificially tailored with different unit geometries and dimensions, rather than the intrinsically chemical components. By varying the size of the patches, we can control the surface impedance of the unit cells at different position. These features make an attractive approach for designing gradient index lens antennas [8-10].

The Luneburg lens, proposed by R. K. Luneburg in 1944 [11], is a well-known gradient index lens which shows the advantages of broadband, multi-beam and low loss. The refractive index of Luneburg lens varies along the radius, which can be expressed by Eq. (1):

$$n=\sqrt{2-(r/R)^2} \quad (r\leqslant R). \tag{1}$$

Here, R is the radius of the lens and r is the distance from any point to the center of the lens. Because of the varying refractive index, the path of incident wave can be bended while travelling within the lens. It can be demonstrated that the incident collimated beam would be focused perfectly on the diametrically opposite side on the lens [12]. This characteristic makes Luneburg lens widely used in the fields such as navigation and satellite communications.

Traditional Luneburg lenses are fabricated with concentric shells with stepped approximation, and each shell made of different dielectric material, has the desired refractive index. It is complex and expensive to be fabricated, and the high radio frequency loss limit its practical application, Another newly developed method proposed by Xue [13] shows that Luneburg lenses can be realized by using a planar structure, whose permittivity distribution can be modified in two ways. In the central

Submitted On: September 27, 2015
Accepted On: February 20, 2016

region, the permittivity is changed by controlling the density of the holes. While on the edge, it is achieved by controlling the dielectric thickness. All these previous designs are bulky and difficult to be integrated in low profile equipment. Developments in the field of AISs, which overcome the difficulties in traditional way of fabrication, provide an alternative way to realize a planar Luneburg lens structure.

In this paper, a planar Luneburg lens used in direction finding system is proposed and investigated. The diameter of the lens is 120 mm, which is about 4λ (λ is the free-space wavelength). A simplified unipolar compact photonic band gap (UC-PBG) structure is chosen as the unit cell. A focusing wave-front is achieved by changing the size of UC-PBG, which is equivalent to changing the local dispersion and the local phase velocity. The Luneburg lens is applied to calculate the DOA and the experiment results shows the resolution of the proposed estimation method is about than 5°.

II. SURFACE IMPENDENCE ANALYSIS

Differing from the traditional Luneburg lens, the two-dimensional Luneburg lens is usually placed inside a parallel-plate waveguide (PPW), as shown in Fig. 1. In order to control the propagation of the surface wave, the boundary conditions of one wall of the parallel-plate waveguide must be modified. The effect of changing the boundary conditions is equivalent to change the local dispersion and the local phase velocity. Generally it can be done by changing the geometrical parameters, such as modulating the height of periodic tiny metal posts, changing the loading of transmission lines, varying the size of metallic patches, etc. In this paper, we will focus on a complementary unipolar compact photonic band gap (UC-PBG) structure.

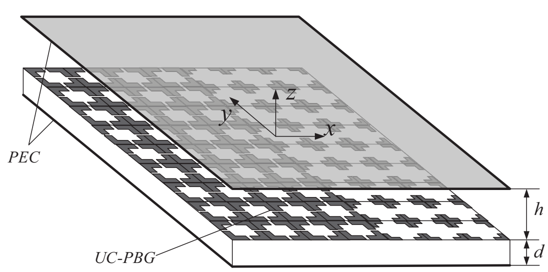

Fig. 1. The variable printed structures is placed inside a parallel-plate waveguide.

The equivalent refractive index n_{eq} can be interpreted as the ratio of the free-space wavenumber k and wavenumber along the propagation (parallel to the plate) k_ρ:

$$n_{eq} = k_\rho / k = \sqrt{1-(k_z^2/k^2)}, \quad (2)$$

where k_z is the wavenumber along the z axis. In order to have a refractive index $n_{eq} > 1$, k_z should be imaginary. In Fig. 2, the transverse resonance equivalent circuit for TM mode of the surface is presented. Using the transmission-line theory, the surface impendence, which depends on the size of the local patch, is derived as:

$$Z_S^{TM}(k_\rho) = -jZ_0^{TM}(k_z)\tan(k_z h) = j\eta_0 \frac{\beta_z}{k}\tanh(\beta_z h), \quad (3)$$

where $Z_0^{TM}=\eta_0 k_z/k$, $k_z=-j\beta_z$ (β_z is positive), η_0 is free space impendence. By combining (1), (2) and (3), we obtain:

$$Z_S^{TM}(k_\rho) = j\eta_0\sqrt{1-(r/R)^2}\tanh(kh\sqrt{1-(r/R)^2}). \quad (4)$$

Equation (4) provides a surface impendence profile corresponding to the Luneburg lens. The diameter of the lens is set to be 120 mm (4λ). A practical height for the top wall h is about λ/2 because this concept is based on single TM mode propagation inside the parallel-plate waveguide. The surface impendence profile is shown in Fig. 3.

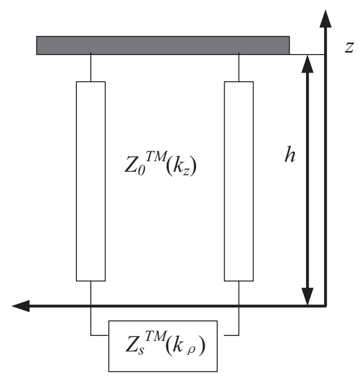

Fig. 2. Transverse resonance equivalent circuit for TM mode.

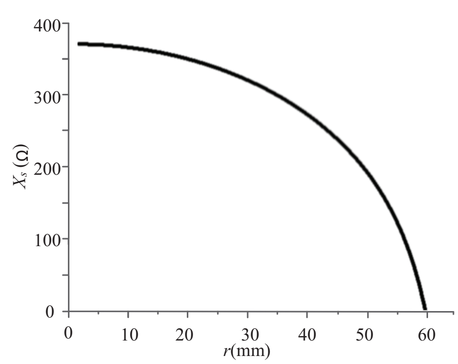

Fig. 3. The surface impendence profile of the Luneburg lens.

The complementary UC-PBG structure is chosen as the unit cell of the Luneburg lens. As shown in Fig. 4, metal patterns are placed on the dielectric substrate. The permittivity of the substrate is 3.5, and the thickness is 3 mm. The loss tangent of the substrate is smaller than 0.001 at 10 GHz. According to the effective medium theory, the dimension of the unit cell square is set to be 3 mm (0.1λ). The surface impendence of the unit cell can be obtained by using CST Microwave Studio. The eigenmode solver is adopted to calculate the properties of surface waves and extract the effective surface impedance.

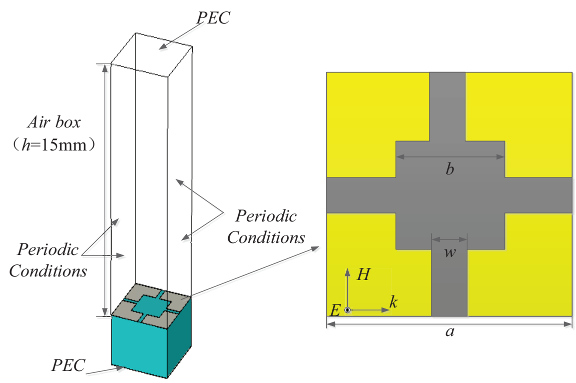

Fig. 4. The boundary conditions settings of the complementary UC-PBG structure.

As shown in Fig. 4, the periodic conditions are applied to the four vertical walls of the simulation volume. The top and bottom walls are both perfect electrical conductors. An eigenfrequency ω, which traverses a unit cell for a given phase difference φ, can be simulated by using the eigenmode solver. The phase difference φ is related to the wavenumber along the propagation k_ρ:

$$\varphi = k_\rho a;\ \ k_\rho = \sqrt{k^2 - k_z^2}. \tag{5}$$

Then the surface impendence, which determined by the geometrical dimensions of the unit cell, can be calculated. By simulating and calculating different unit cells, it shows that the surface impendence decreases when the variable parameters b and w increase, as shown in Fig. 5. Therefore, the unit cell can achieve the corresponding surface impendence of the Luneburg lens.

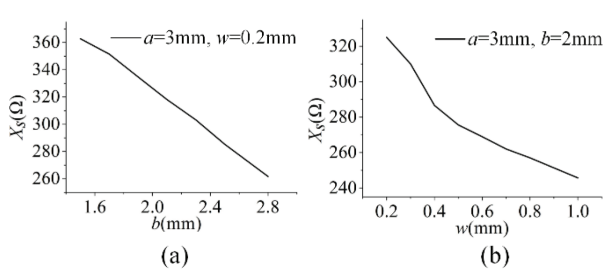

Fig. 5. The relationship between the surface impendence and the dimensions of the complementary UC-PBG structure. (a) a=3 mm, w=0.2 mm, and b is variable parameter. (b) a=3 mm, b=2 mm, and w is variable parameter.

III. LUNEBURG LENS SIMULATION AND EXPERIMENTS

As shown in Fig. 6, a planar Luneburg lens is proposed and designed, which is placed in a parallel-plate waveguide with the height h=15 mm. There are 20 units arranged along the radius. The variation of the surface impendence from the center to the edge of the lens is realized by varying the variable parameters b and w, as shown in Table 1. The Luneburg lens was discretized into seven concentric regions, where the surface impendence is required to be equal at each circle with the same radius. This design consideration makes sure that the structure is more close to the perfect lens.

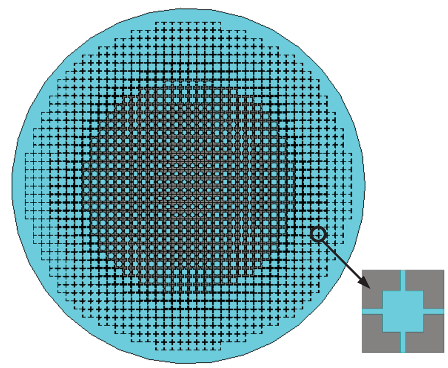

Fig. 6. An array of complementary UC-PBG structure with the surface impedance profile corresponding to the Luneburg lens.

Table 1: Dimensions and surface impendences of the unit cell in the different concentric regions of the lens

Region	b (mm)	w (mm)	$X_s^{TM}(\Omega)$
1	1.5	0.2	362.7
2	1.7	0.2	351.5
3	1.8	0.3	322.4
4	2.0	0.4	291.3
5	2.5	0.5	242.9
6	2.7	0.6	194.0
7	2.8	1.0	43.4

CST Microwave Studio is used to simulate the electric field distribution of the Luneburg lens. The plane waves incident from the right side of the lens. It is obvious that the wave front is changed gradually when it passes through the lens, and finally focused at the opposite side of the lens. From Figs. 7 (a) to 7 (d), we can find that the focusing point keeps the same at different operational frequency.

The proposed planer Luneburg lens shows excellent focusing ability from 9 GHz to 12 GHz, which means it can operate very well in a broad bandwidth. In order to evaluate the isotropy of Luneburg lens, the incident angle α is changed, as shown in Fig. 8. Since the unit cell has a symmetric structure, the focusing performance keeps very well at 10 GHz with different incident angle. It is important to note that, the polarization of the incident waves must be perpendicular to the Luneburg lens, because only in this case, a virtual current circuit can be constructed by the complementary UC-PBG structure and the upper ground plane. The transverse resonance dispersion equation is obtained by solving the equivalent circuit in Fig. 2. So the proposed planar Luneburg lens in this paper is designed for the TM incident wave.

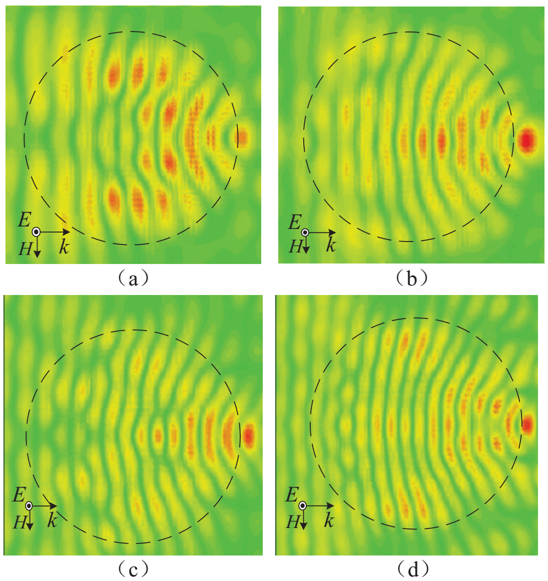

Fig. 7. Distribution of the electric field inside the Luneburg lens: (a) f=9 GHz, (b) f=10 GHz, (c) f=11 GHz, and (d) f=12 GHz.

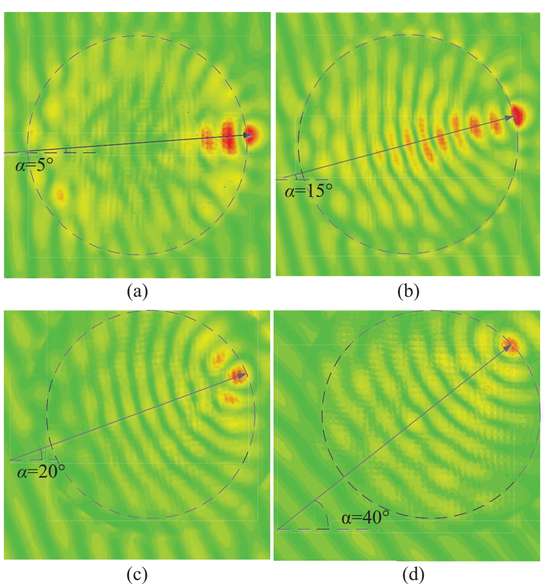

Fig. 8. Distribution of the electric field with different incident angles at 10 GHz.

To verify the design, a planar Luneburg lens placed inside a PPW is fabricated. As shown in Fig. 9, three nylon hexagonal standoffs of 15 mm height are used to support the top plate of PPW. It can be seen that 11 probes with a separation of 5 degrees are mounted on the surface of the lens. The source and probes are connected to a vector network analyzer (VNA) to measure the magnitude of the electric field at different position. In this case, all the values from the 11 probes are normalized to the probe which directly facing the source, so that the attenuation between transmitter and receiver could be ignored. The normalized electric field magnitudes are shown in Fig. 10. The probe which placed in the direction of the incident wave, has the maximum value. This characteristic can be used in direction of arrival (DOA) estimation. The resolution is determined by the separation of the probes. In the proposed design, the resolution is limited to be 5° due to the space around the lens couldn't allow us to mount more probes.

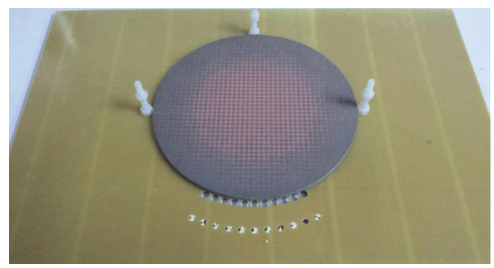

Fig. 9. Top view of the fabricated Luneburg lens.

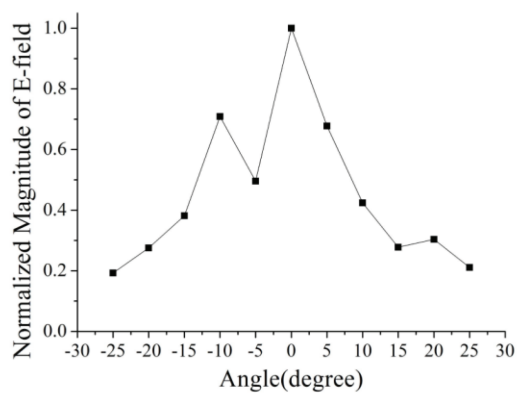

Fig. 10. Normalized E-field magnitude.

IV. CONCLUSION

In this paper, a novel direction finding system using planar Luneburg lens is proposed. The Luneburg lens is composed of multilayer arrays of complementary UC-PBG structure which printed on a dielectric substrate inside a parallel-plate waveguide. By changing the boundary conditions of the plate, the converging wave can be obtained. The relationship between the surface impendence and dimensions of the unit cell has been studied through numerical simulations. The distribution of the electric field inside the lens has been simulated. The proposed Luneburg lens shows a good focusing ability in X-band region. When the incident angle is rotated, the focusing performance of the proposed Luneburg lens keeps very well. The proposed Luneburg lens can be used in direction of arrival estimation. Using the proposed system, the DOA estimation can be achieved accurately and effectively, which makes our design a good option for practical applications.

ACKNOWLEDGMENT

This work is supported by National Natural Science Foundation of China (No. 61571155, No. 61371044, No. 61401025). This work is also supported by Beijing Natural Science Foundation (4154085) Shanghai Academy of Spaceflight Technology (SAST 201439), and the Basic Research Foundation of Beijing Institute of Technology, China (Grant No. 20140542002).

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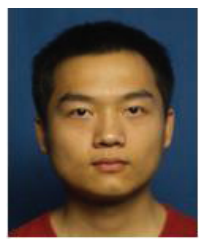

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