Design of Wide Angle Scanning Characteristics in a Shaped Dielectric Lens Antenna

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1. Introduction

Recently, communication and car safety systems are under developing in ITS (Intelligent Transportation Systems) at millimeter wave frequency bands. As a typical example, lens antennas were fabricated for a radar system of adaptive cruse control (ACC) of automobiles[1]. In this case, beam scanning capabilities were requested. Lenses satisfying the Abbe's sine condition were shown to have wide angle beam scanning capabilities[2]. Moreover, lens shape designing equations were given. On the other hand, a shaped lens design method that can achieve any aperture illumination distribution is well known[2],[3].

In this paper, an application method of the Abbe's sine condition to shaped lens design method is discussed. We expect that this combination can expand shaped lens usage to wide angle scanning. It is shown that the Abbe's sine condition can be successfully involved in the shaped lens design method. Wide angle radiation characteristics are calculated. Here, loci of focal points become very important to achieve excellent wide angle beam scanning. As another example, a bifocal lens that can achieve very wide angle beam scanning is studied as for the achievement of the Abbe's sine condition. Bifocal lenses, no matter their parameters, satisfy the condition to a certain degree. Wide angle radiation characteristics and adequate loci of focal points are numerically shown.

2. The Abbe's sine condition[2]

An optical lens geometry and parameters are shown in Fig. 1. By imposing the Abbe's sine condition, a coma free lens can be designed. The condition is expressed as the next expression.

$$h = f\sin\theta \qquad (1)$$

The crossing point Q is determined by the ray from a feed and the ray parallel to the Z-axis. The Abbe's sine condition requests that Q lies on the circle which radius is f and center is the feed point. A design method of lens curvatures satisfying Eq. (1) has already been shown[2]. This method is composed of three simultaneous equations such as (1)Abbe's sine condition, (2)equality of path length, (3)Snell's low on the inner lens surface. This method can not yield lenses from any combination of input parameters and modified aperture illuminations like tapered ones.

As for wide angle beam scanning, finding out adequate feed points becomes very important. Feed points can be determined through a received mode analysis in a focal region as shown in Fig. 1. For the incident plane wave coming in the angle ξ, one caustic is given by the next expression[4].

$$R = f\cos^2\xi \qquad (2)$$

Here, there are two caustics for an incident plane wave as shown in Fig. 2. One caustic is in the scanning plane and the other is in the transverse plane. The caustic given by Eq. (2) is the scanning plane caustic. The caustic in the transverse plane is given by the next expression[4].

$$R' = f \qquad (3)$$

In discussing wide angle radiation characteristics, there are two major planes of scanning and transverse. When the locus of feed points is chosen to be Eq. (2) or Eq. (3), side lobe levels in wide angle beam scanning maintain excellent in the corresponding radiation plane.

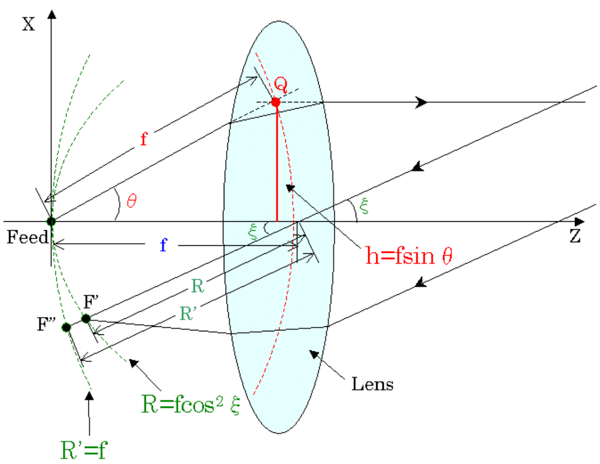

Fig. 1 The Abbe's sine condition

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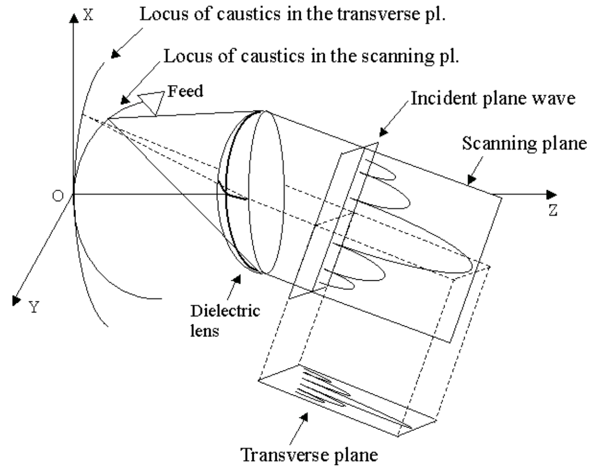


Fig. 2 Geometry of radiation pattern

3. Designing of a shaped lens for wide angle scanning

The design method of shaped lenses has been reported by one of authors[3]. Antenna geometry and parameters of a shaped lens antenna are shown in Fig. 3. Rays from a feed horn are refracted twice at the surface-1 and 2. On the surface-1, refracted condition is shown by the next expression.

$$dr/d\theta = \{r\eta\sin(\theta-\phi)\}/\{\eta\cos(\theta-\phi)-1\} \quad (4)$$

And, on the surface-2, refracted condition is shown by the next expression.

$$dz/d\theta = \{\eta\sin(\phi)\}/\{1-\eta\cos(\phi)\}x\{dx/d\theta\} \quad (5)$$

Lens surface's curvatures are determined by the directivity of the feed horn $E_p^2(\theta)$ and the aperture illumination $E_d^2(x)$. And energy conservation condition of rays is expressed by the next expression.

$$dx/d\theta = \{Ep^2(\theta)\sin(\theta)/P_t\}/\{Ed^2(x)x/D_t\} \quad (6)$$

Here, P_t indicates total radiated energy from a feed horn, and D_t total energy distributed on an antenna aperture.

In this report, lens structural parameters of F=100mm, D=100mm, η=1.643 are utilized. Then, f value in Eq. (1) becomes about 120mm. So, the Abbe's sine condition in this case is expressed by the next relation.

$$x=120\sin\theta \quad (7)$$

From Eq. (7), the next differential relation is given.

$$dx/d\theta = 120\cos\theta \quad (8)$$

By applying Eq. (7) to Eq. (6) and comparing Eq.(6) with Eq. (8), the next relation between power function is given.

$$E_p^2(\theta)/E_d^2(x)=A\cos\theta \quad A: \text{constant} \quad (9)$$

When θ is small, Eq. (9) implies that $E_p^2(\theta)$ and $E_d^2(x)$ become the same function.

As for the directivity of the feed horn $E_p^2(\theta)$, the next expression is employed.

$$E_p^2(\theta) = \cos^{20}\theta \quad (10)$$

In order to satisfy the Abbe's sine condition, the next expression is employed for $E_d^2(x)$.

$$E_d^2(x)= \cos^{20}[\mathrm{asin}(x/120)] \quad (11)$$

Designed lens shape is shown in Fig. 4. And incident and refracted rays and Q points determined by the same process explained in Fig. 1 are also shown in Fig. 4. Dotted line shows the circle centered at F. It is clear that Qs exist on the circle all of lens area. And Δx and $\Delta\theta$ are nearly equal since lens edge angle is about 27°.

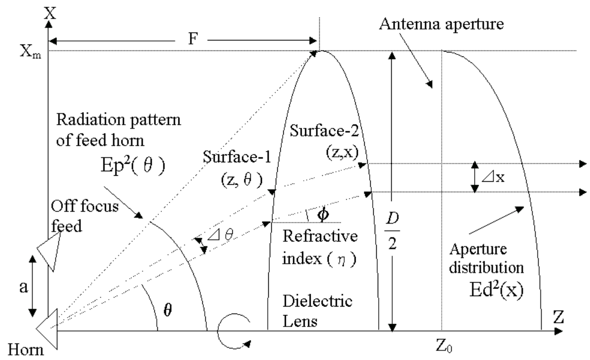


Fig. 3 Lens geometry of a shaped lens

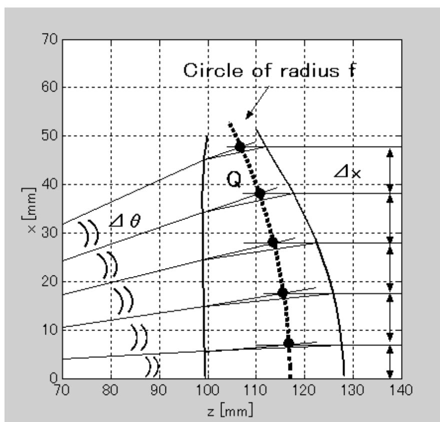


Fig. 4 Features of rays in the shaped lens

4. Conditions of rays in a bifocal lens[5]

Antenna geometry and parameters of a bifocal lens antenna are shown in Fig. 5. A bifocal lens has two conjugate off-axis focal points. Lens surface's curvatures are designed so that rays from the feed horn located at ±a are directed to

$-\alpha$, $+\alpha$, respectively. Lens structure parameters of F=88mm, T=25mm, D=100mm, η=1.643 are utilized. And a=27mm, α=15° are given. Designed lens shape is shown in Fig. 6. Bifocal lenses usually satisfy the Abbe's sine condition to a certain extent no matter their design parameters. In this case, within 40mm of radius the condition is satisfied. Over 40mm, since lens curvatures are large and refracted ray is not parallel to the Z-axis, Q points no longer exist on the circle. However, the curvatures are supposed to work well when beam is scanned. The radiation pattern of the feed horn $E_p^2(\theta)$ is not related to the lens design. However, same as the shaped lens, Eq. (10) is given to calculate the radiation patterns.

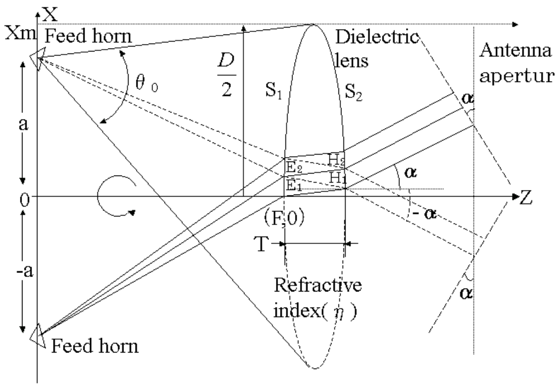


Fig. 5 Lens geometry of a bifocal lens

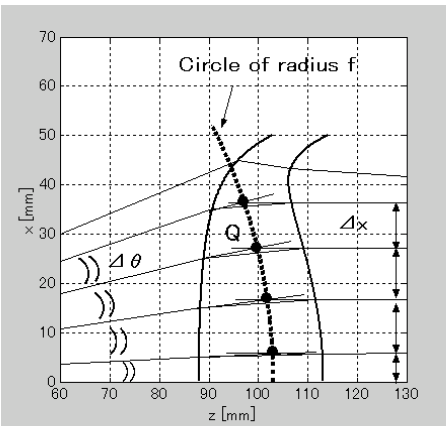


Fig. 6 Features of rays in the bifocal lens

5. Antenna performances

(1) Caustics

In order to seek caustics, ray tracing in the focal region is conducted as shown in Fig. 7. Solid lines show rays on the scanning plane and circle shows the caustic of that. Doted lines show rays on the transverse plane and triangle shows the caustic of that. Fig. 8 shows caustics both of the planes. In each caustic, rays were concentrated at one point same as Fig. 7. Circles show the result of the scanning plane, and triangles show the results of the transverse. Each mark is shown by 5°. Solid lines shown results of Eq. (2), (3) respectively. In Fig. 8, both of these caustics are almost on the lines.

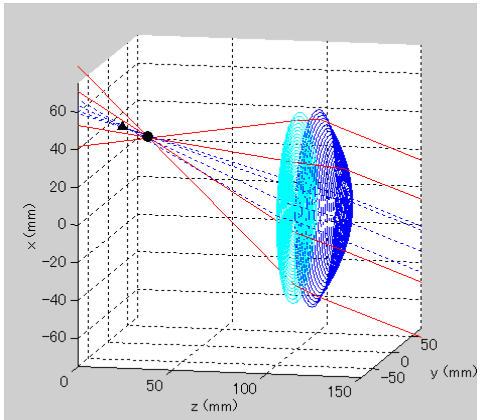
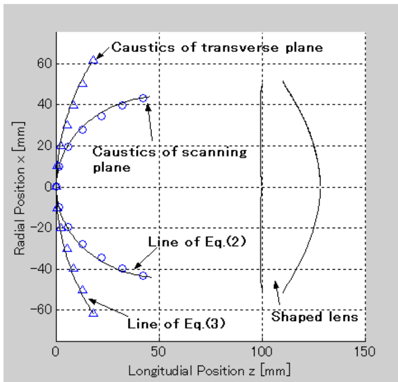
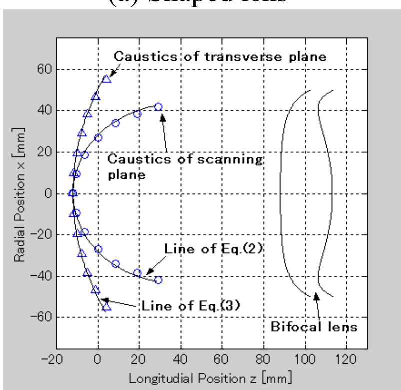


Fig. 7 Ray tracing in the focal region



(a) Shaped lens



(b) Bifocal lens

Fig. 8 Lens shapes and caustics

(2) Radiation patterns

Radiation patterns on the scanning plane, and the transverse plane are shown in Fig. 9, 10. In this case, the feed horn moves on the X-Z plane and radiates from each caustic. Frequency of 60GHz was employed, which wave length was 1/20 of lens diameter.

Fig. 9 shows the radiation patterns of feeds from the caustics in the scanning plane Both of the shaped lens and bifocal lens, scanning plane radiation patterns maintain narrow beam width and low side lobe level. However, transverse radiation patterns deteriorate especially in beam width as beam is scanned. And it results in more gain losses than the decreases of the effective aperture size as beam is scanned .

Fig. 10 shows the radiation patterns of feeds from caustics in the transverse plane. Compare to Fig. 9, scanning plane radiation patterns deteriorate in both of beam widths and side lobe levels. However, transverse plane patterns remain narrow beam widths. The opposite phenomena of Fig. 9 are happen. However, the decreasing of gains is almost same as Fig. 9.

6. Conclusion

It was shown that the Abbe's sine condition can be successfully involved in the shaped lens design method. Through the method, the shaped lens was designed. And as another example, the bifocal lens was designed. It was confirmed that these lenses satisfied the Abbe's sine condition. And, their wide angle radiation characteristics and adequate loci of focal points were numerically shown.

References

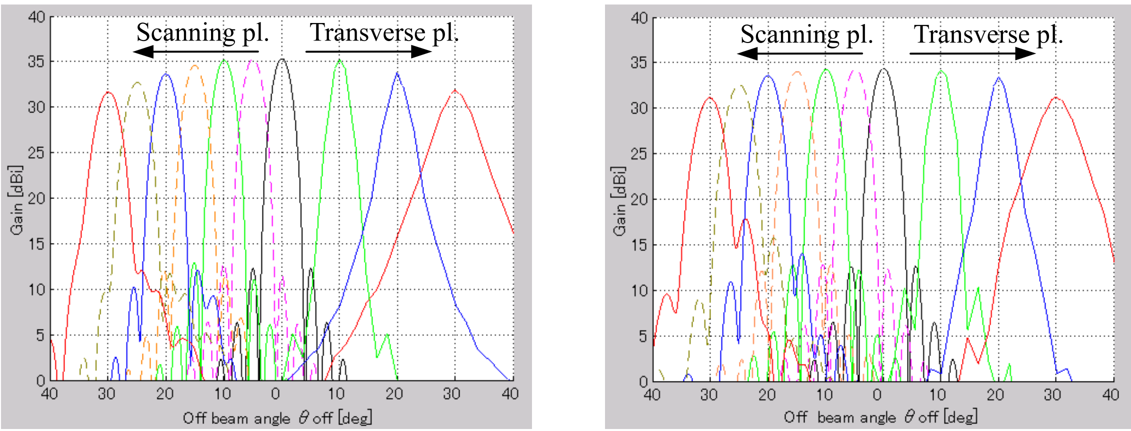
[1]T. Kato et al, "76GHz High Performance Rader Sensor Featuring Fine Step Scanning Mechanism Utilizing NRD Technology", IEEE Intelligent Vehicles Symposium, pp. 163-170, May 2001

[2] Y. Loo and S. Lee, "Antenna Handbook", Kluwer Academic Pub. pp. 16,19 - 16,23, 1993

[3] Y. Yamada and T. Takano, "Dielectric Lens Antenna with Shaped Surfaces", IEICE Int'l Sympo. On Ant, and Prop., pp. 239-242, 1978

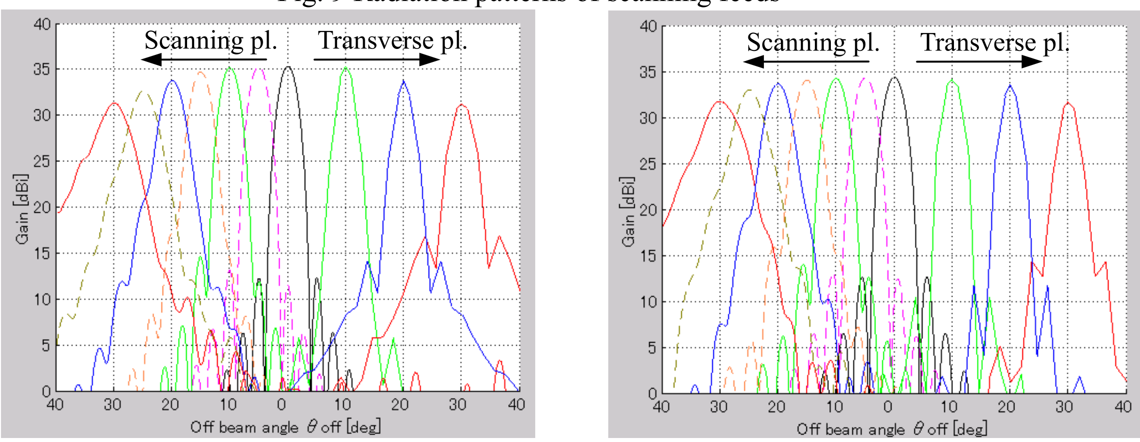
[4]R. M. Brown, "Dielectric bifocal lenses", in IRE Nat. Conv. Rec., pp. 180-187, 1956

[5] Ann Lee Peebles, "A Dielectric Bifocal Lens for Multibeam Antenna Applications", IEEE Transactions on Antennas and Propagation, Vol. 36, No. 5, pp. 599-606, May 1988



(a) Shaped lens (b) Bifocal lens

Fig. 9 Radiation patterns of scanning feeds



(a) Shaped lens (b) Bifocal lens

Fig. 10 Radiation patterns of transverse feeds