Electromagnetic Simulation Method of a Negative Refractive Index Lens Antenna

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***Abstract*—By changing the refractive index of a lens antenna from positive value to negative value, lens shapes are changed from the convex to the concave. A thick convex lens is replaced by a thin concave lens. In order to examine electromagnetic performances, electromagnetic simulations are effective. However, electromagnetic simulators useful for negative refractive index lens antennas are limited. In this paper, HFSS simulator is utilized. Amplitude distributions of electric fields in the near field region are obtained. Physical performances of the negative refractive index lens are clarified.**

Keywords*—*negative refraction index, lens antenna

I. Introduction

In the 5G mobile communication system, new technical subjects such as millimeter wave, small cell size and multi-beam radiation patterns at a base station will be newly introduced in relation to radio wave technologies [1]. Now, the frequency of 28 GHz is considered in Asian countries. In this frequency, antenna size becomes one tenth of the present base station antenna and the size becomes around 30 cm. Thus, many antenna types such as an array antenna and an aperture antenna can be candidates. In an aperture antenna, a dielectric lens antenna has a simple structure and it is considered a promising candidate. In designing a lens antenna, when natural dielectric (positive refractive index) is selected, lens shape becomes convex and the lens thickness becomes large. When the negative refractive index is selected, the lens shape becomes concave and the lens thickness becomes very thin [2]. Here, electromagnetic simulation tools that can calculate negative refractive index material are limited.

In this paper, the HFSS electromagnetic simulator is selected. In order to ensure simulation ability, the most simple lens shape is used. At many refractive index values, electric field distributions in the near field region are calculated. Through the near field distributions, the effects of lens performances that convert the spherical wave to the plane wave are ensured.

II. Antenna Structure

A. Lens Antenna Structure

The geometry of the lens antenna is illustrated in Fig. 1. The lens has an axis-symmetrical structure around the Z-axis. The conical horn antenna is used as a feed. The lens material has negative refractive index. The lens shape is the most fundamental, and its inner surface is designed and its outer surface is flat [3], [4]. The focal length is *F*=100mm, the diameter is *D*=100mm and different refractive indexes are *n*=-1.2; *n*=-2 and $n=-\sqrt{2}$. T indicates the lens thickness. The rays from the feed horn are refracted at the inner lens surface and the flat wave front is achieved.

Here, θ_i and θ_r indicates an incident angle and refracted angle, respectively. These angles satisfy the next equation.

$$n = \frac{sin\theta_i}{sin\theta_r} \tag{1}$$

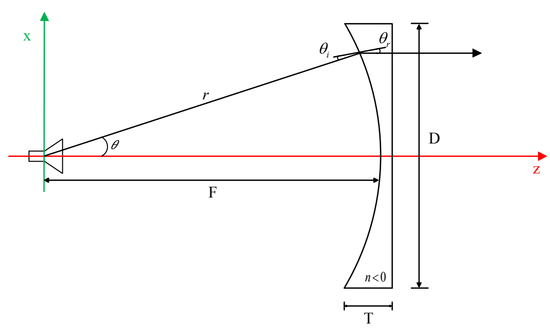

Fig. 1. Negative refractive index lens antenna structure.

B. Lens Shape Design

The lens has axis-symmetrical structure around Z-axis. The expression for points on the inner lens surface is given by the equation [5]:

$$r = \frac{(n-1)F}{ncos\theta-1} \tag{2}$$

Where

r: Distance from focal point to inner lens surface

F: Focus of lens

θ: Angle from focal point to inner lens surface

n: Refraction index

$$n = \sqrt{\varepsilon_r}\sqrt{\mu_r} \tag{3}$$

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ε_r: Relative permittivity (minus value)

μ_r: Relative permeability (minus value)

The points on the upper inner lens surface on the XZ plane with different negative refractive indexes are shown in Table I.

TABLE I. POINTS ON INNER LENS SURFACE (F=D=100)

n \ θ	-1.2		$-\sqrt{2}$		-2	
	x	z	x	z	x	z
0°	0	100	0	100	0	100
2°	3.491	99.972	3.491	99.975	3.491	99.980
4°	6.985	99.889	6.986	99.899	6.987	99.919
10°	17.510	99.304	17.521	99.365	17.542	99.488
15°	26.372	98.422	26.409	98.560	26.484	98.838
20°	35.365	97.166	35.455	97.411	35.635	97.906
25°	44.538	95.512	44.716	95.894	45.077	96.669
28°	50	94.310	50	94.790	50	95.701

III. SIMULATION METHOD

A. Simulation Conditions

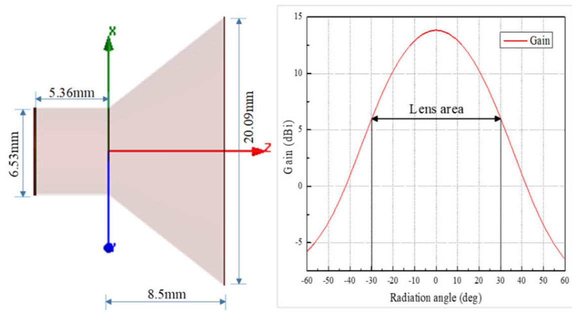
The specifications of a personal computer and simulation parameters are shown in Table II. In calculation, the HFSS simulator that can use the Multilevel Fast Multiple Method (MLFMM) is applied in order to save the computer memory and speed up the calculation time. The relative permeability $\mu_r = -1$ and relative permittivity $\varepsilon_r = -4; -2; -1.45$ are employed to calculate negative refractive indexes. The thickness (*T*) values of the lens are 9.08mm; 10.13mm and 10.64mm agree with the refractive indexes of the lens *n*=-2; *n*=$-\sqrt{2}$ and *n*=-1.2. Calculation time and memory capacity are approximately 2 hours and 27GB, respectively.

TABLE II. SIMULATION PARAMETERS

Computer Specification	CPU	Intel (R) 3.20GHz		
	Loaded memory	32GB		
	Software	HFSS (ANSYS Electronics Suite 17.2)		
	Simulation method	MLFMM and ACA		
Negative refractive index lens	Lens diameter [mm]	100		
	Focus [mm]	100		
	μ_r	-1		
	ε_r	-4	-2	-1.45
	Lens thickness (*T*) [mm]	9.08	10.13	10.64
Frequency		28GHz		
Calculation time [h]		02:30	01:50	01:40
Used memory [GB]		26.8	27.5	27.3

B. Feed Horn Design

The wide flare angle conical horn is used to illuminate a wide angle for the lens as shown in Fig. 2(a). The focus of the lens insists at the center of the horn throat in the setup of this lens. Fig. 2(b) shows the radiation pattern of the conical horn antenna. The horn has the gain of 13.84dBi. The lens region is located in the radiation angle (θ) from -28.5 to 28.5 degrees.



(a) (b)

Fig. 2. Parameters and radiation pattern of conical horn.

IV. SIMULATION RESULTS

A. Electronic Field Amplitude Distributions

The electrical field distributions of the lens antenna are shown in Fig. 3. The spherical wave fronts are converted to the flat wave fronts. Also inside a lens, wave front conversion from the spherical to the plane is observed. The Adequateness of lens performance is ensured [6].

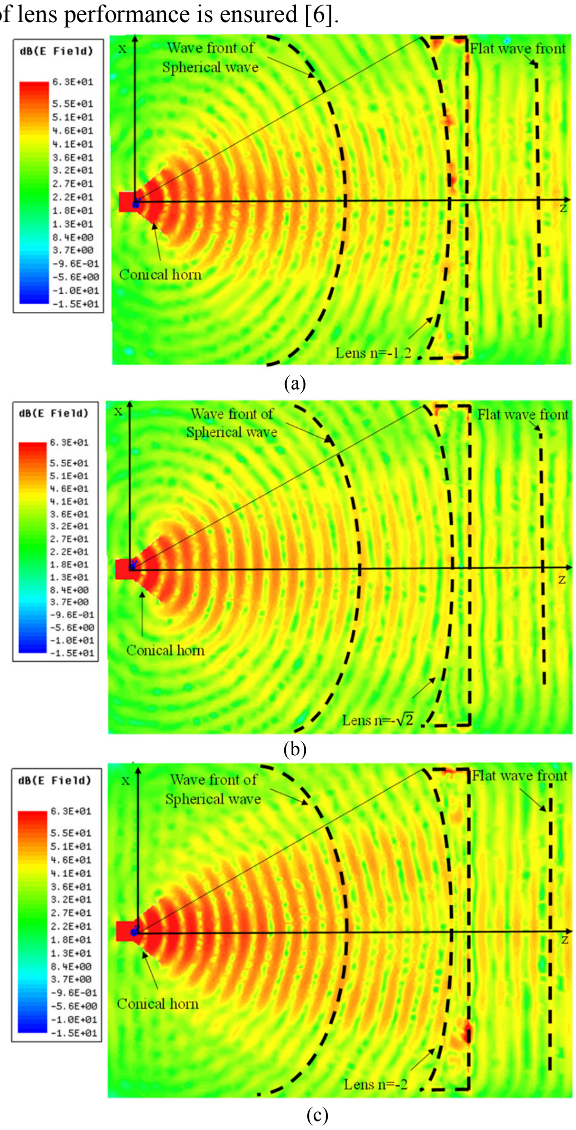


Fig. 3. Electric field distributions on the xz plane, (a) *n*=-1.2, (b) *n*=$-\sqrt{2}$ and (c) *n*=-2.

B. Radiation Pattern

The radiation patterns of lens antenna with different negative refraction indexes are presented in Fig. 4. The black solid line illustrates the pattern with n=-1.2; the red dash line shows the pattern with n=-2 and the blue dash dot represents the pattern with $n=-\sqrt{2}$. The gains of the lens antennas with the negative refractive indexes n=-1.2, n =-2 and $n=-\sqrt{2}$ are 25.4dBi, 26.6dBi and 25.4dBi, respectively. These gain values are lower than the theoretical gain of the aperture antenna (27dBi). The main beam radiation patterns of the lens antennas with n=-1.2 and $n=-\sqrt{2}$ are almost the same.

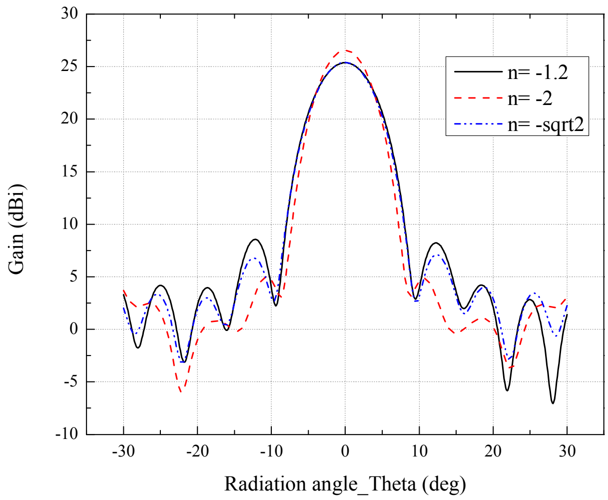


Fig. 4. Radiation patterns of lens antenna with different negative refraction indexes.

The calculation results of the lens antennas with different negative refractive indexes and the comparison with the theoretical results of the aperture antennas are shown in Table III. The half-power main bandwidths calculated with $n=-1.2$, n=-2 and $n=-\sqrt{2}$ are 8.07^0, 6.78^0 and 7.79^0, respectively while that of the aperture antenna is theoretically 8^0. In addition, the gain of the side lobe level reaches the lowest of -21.52dBi when the lens refractive index is n=-2 and the highest of -16.82dBi when n=-1.2 whereas in theory, the side lobe level of the aperture antenna is 17.6dBi

TABLE III. COMPARISION RESULTS

	n	θ_B[deg]	Gain[dBi]	SL[dBi]
Theoretical aperture antenna [6]		8	27	-17.6
Calculated lens antenna	-1.2	8.07	25.4	-16.82
	-2	6.78	26.6	-21.52
	$-\sqrt{2}$	7.79	25.4	-18.31

C. Electric Field Amplitude Distribution on Aperture Plane

The electrical field amplitude distributions on the aperture plane with different negative refraction indexes are shown in Fig. 5. Electrical field distributions on the aperture planes in n=-1.2, n=-2 and $n=-\sqrt{2}$ are relatively uniform and symmetrical about the z axis.

The amplitude distributions along the antenna radius direction are shown in Fig. 6. Amplitude tapers to the lens edges are observed. Amplitude ripples may be produced by reflections at lens surfaces.

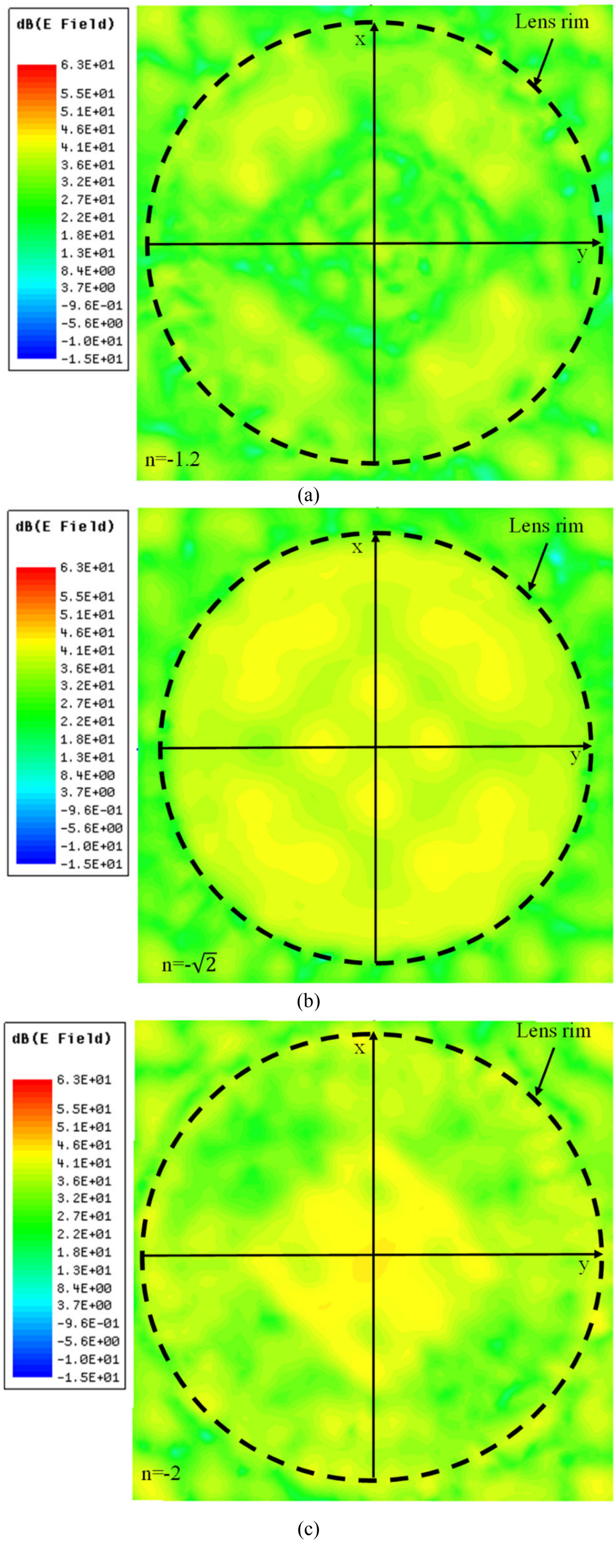


Fig. 5. Electric field amplitude distributions on the aperture plane, (a) n=-1.2, (b) $n=-\sqrt{2}$ and (c) n=-2.

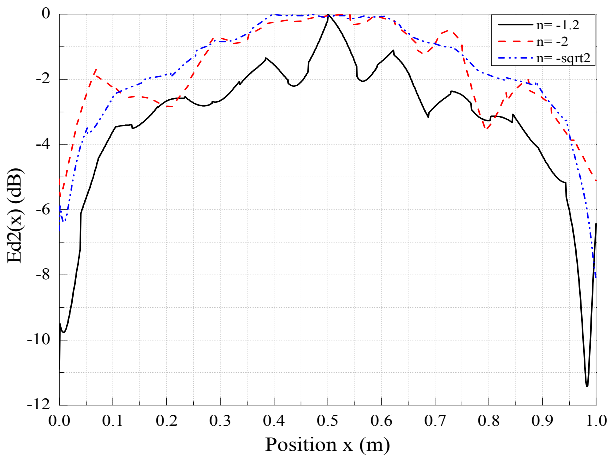


Fig. 6. Aperture illumination distribution.

V. CONCLUSION

By using HFSS's electromagnetic field simulation software (ANSYS Electronics Suite 17.2), the authors performed a simulation of the negative refractive index lens antennas. The accuracy of the results is ensured through simulating the antennas with different negative refractive indexes and comparing with theoretical calculation results of the aperture antennas.

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