

Analysis and design of concave lens with metallic slit array for terahertz wave band

Takehito Suzuki · Hiroki Yonamine · Takuya Konno · John C. Young · Kotaro Murai · Fumiaki Miyamaru · Keisuke Takano · Hideaki Kitahara · Masanori Hangyo

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Abstract This paper presents a three-dimensional concave lens constructed from a metallic slit array. The effective refractive index is estimated to be $0 < n < 1$. The actual lens requires spacers in the slits. A lens using a low loss dielectric material for the terahertz frequency band is designed. The fast wave effect is enhanced in order to mitigate the slow wave effect of the dielectric material. Full wave analysis results are obtained by ANSYS HFSS and the focusing effect of the three-dimensional concave lens is confirmed in the terahertz frequency band.

1 Introduction

Demand for optical devices in the terahertz wave band is rapidly growing. However, the ability to arbitrarily realize a given refractive index using naturally-occurring materials is difficult. Typical lenses for the terahertz wave band are high density polymer lenses, Tsurupica lenses,

and silicon lenses with refractive indices of 1.52, 1.56, and 3.41, respectively. For microwave frequency bands, there are many kinds of lenses composed of electromagnetic metamaterials, sphere arrays, disk arrays, square plate arrays, and strip arrays [1–5]. The refractive indices of these lenses can be relatively easily controlled by the unit cell dimensions of the metamaterial. A concave lens using parallel plates has also been presented in [1,6]. The effective index of this structure is estimated to be $0 < n < 1$.

In the terahertz frequency band, the works in [7–10] present a metamaterial absorber, that in [11] presents an antireflection coating, that in [12] presents a metamaterial with an unnaturally high refractive index, and those in [13] and [14] present a three-dimensional metamaterial. An artificial dielectric lens with metallic corrugated structures is proposed in [15], and an artificial dielectric lens with metallic rectangular chips is analyzed and designed for the terahertz frequency band in [16]. It is relatively easy to fabricate terahertz electromagnetic metamaterials by metallic processing, semiconductor etching, and chemical reduction [13,14] since the dimensions of the unit element are on the order of microns in the terahertz band. The work in [17] presented experimental results of a two-dimensional concave lens with metallic slit array and that in [18] presented the analysis results of a three-dimensional one.

This paper presents the design of a three-dimensional concave lens that includes the effect of the dielectric material Zeonor Film, with refractive index of 1.53. The lens structure, which is hollow with a hemispherical shape, is shown in Fig. 1. This three-dimensional structure is useful for the realization of a photoconductive antenna. The excitation is a TEM mode where the electric field is parallel to the metallic plates such that TE_1 mode propagates

T. Suzuki (✉) · H. Yonamine · T. Konno
Department of Electrical and Electronic Engineering,
Ibaraki University, 4-12-1 Nakanarusawa, Hitachi,
Ibaraki 316-8511, Japan
e-mail: takehito@mx.ibaraki.ac.jp

J. C. Young
Electrical and Computer Engineering, University of Kentucky,
Lexington, KY 40506-0046, USA

K. Murai · F. Miyamaru
Department of Physics, Shinshu University, 3-1-1 Asahi,
Matsumoto, Nagano 390-8621, Japan

K. Takano · H. Kitahara · M. Hangyo
Institute of Laser Engineering, Osaka University,
2-6 Yamadaoka, Suita, Osaka 565-0871, Japan

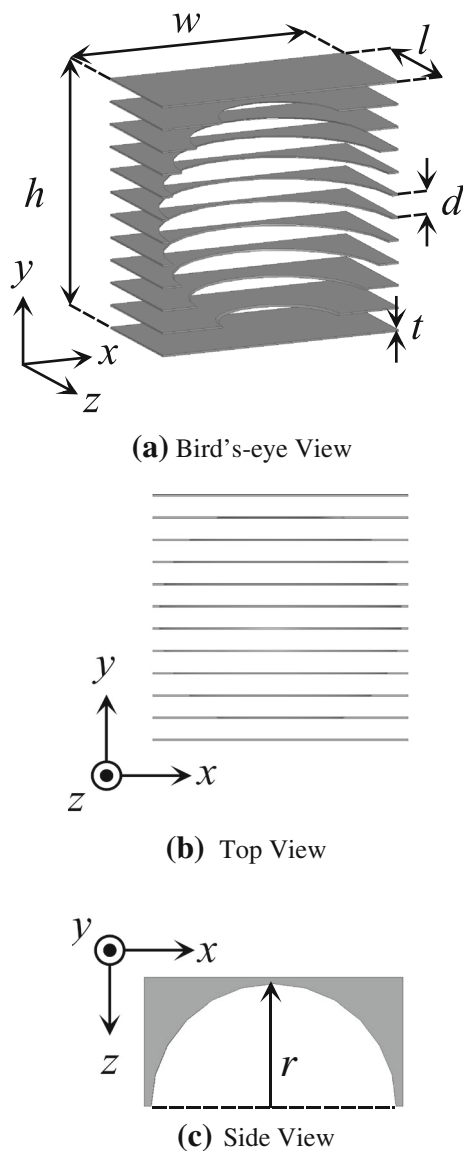


Fig. 1 Terahertz-band concave lens with metallic slit array

as the dominant mode in the parallel plates. The fast wave effect [1,6,18], which can produce a focusing effect, is controlled by the slit spacing. The effective refractive index n is estimated to be in the range $0 < n < 1$. The full wave analysis model, which confirms the focusing effect, is simulating by ANSYS HFSS, and the model dimensions are decreased in order to reduce computation time. The lens structure with the dielectric material Zeonor Film is also analyzed since it is difficult to maintain the uniform slit spacing otherwise. Careful design is necessary due to the fast wave effect in the slits and the slow wave effect in the dielectric material. Section 2 explains the lens structure and dimensions. Section 3 presents the design that includes the dielectric material. Section 4 shows the full model analysis results.

2 Mechanism of concave lens with metallic slit array

Figure 1a shows the concave lens with metallic slit array. The lens is hollow with a hemispherical shape of radius of R . The actual model has the dielectric material Zeonor Film, with low loss at terahertz frequencies, in the slit array for mechanical support. The excitation is a TEM mode whose electric field is parallel to the metallic plates such that the TE_1 mode is the dominant propagating mode. The focusing effect is produced by the fast wave effect of the TE_1 mode in the slit array. The slit spacing controls the effective refractive index of this lens due to the fast wave effect, and the concave shape produces the focusing effect. The effective index approaches zero with narrower spacing and approaches 1 with larger spacing. The reflection due to the impedance mismatch, that is to say, cutoff, increases as the refractive index goes to 0.

The fast wave effect is mitigated by the slow wave effect of dielectric material in between the slits. The slit spacing should be narrow enough to obtain a fast wave effect that is stronger than the slow wave effect.

3 Dimensions of concave lens with metallic slit array

Three lenses with different slit array patterns are analyzed and designed, and the results are compared to those of a reference lens. Table 1 shows the lens parameters for the reference model and the pattern models 1, 2, and 3. The number of slits is different for all cases. The design frequency is 0.5 THz, where the wavelength λ_0 is 0.6 mm. Each lens is hollowed by a hemisphere with a radius $r = 2.0$ mm ($3.3\lambda_0$). The lens width w is 4.2 mm ($7.0\lambda_0$), the lens length l is 2.1 mm ($3.5\lambda_0$), and the slit thickness t is 0.03 mm ($0.05\lambda_0$) for all cases.

The slit spacing d is 0.35 mm ($0.59\lambda_0$) for the reference model. The slit spacings for pattern 1 and pattern 2 are different than the spacing of the reference model. The slit space d is ($0.52\lambda_0$) for pattern 1 and is 0.50 mm ($0.83\lambda_0$) for pattern 2. Pattern 3 uses the dielectric material Zeonor Film to simplify fabrication. The fast wave effect is accelerated by use of a narrower slit spacing of $d = 0.21$ mm ($0.54\lambda_1$), where the wavelength λ_1 in the dielectric region is 0.39 mm. Only one quarter of the full model is analyzed by image theory [19].

4 Full wave analysis of three-dimensional concave lens with metallic slit array

The full wave analysis results are obtained by ANSYS HFSS. The incident electric field is 1 V/m. Figure 2a shows the result for the reference model. Figure 2b shows the electric

Table 1 Lens parameters

	Reference model	Pattern 1	Pattern 2	Pattern 3
r	2.0 mm ($3.3\lambda_0$)			2.0 mm ($5.1\lambda_1$)
d	0.35 mm ($0.59\lambda_0$)	0.31 mm ($0.52\lambda_0$)	0.50 mm ($0.83\lambda_0$)	0.21 mm ($0.54\lambda_1$)
h	4.21 mm ($7.0\lambda_0$)	4.45 mm ($7.4\lambda_0$)	4.27 mm ($7.1\lambda_0$)	4.11 mm ($10\lambda_1$)
w	4.2 mm ($7.0\lambda_0$)			4.2 mm ($11\lambda_1$)
l	2.1 mm ($3.5\lambda_0$)			2.1 mm ($5.4\lambda_1$)
t	0.03 mm ($0.05\lambda_0$)			0.03 mm ($0.08\lambda_1$)
Number of plates	12 plates	14 plates	9 plates	18 plates

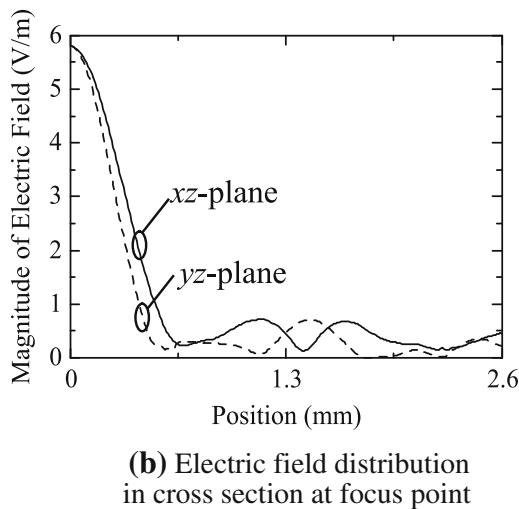
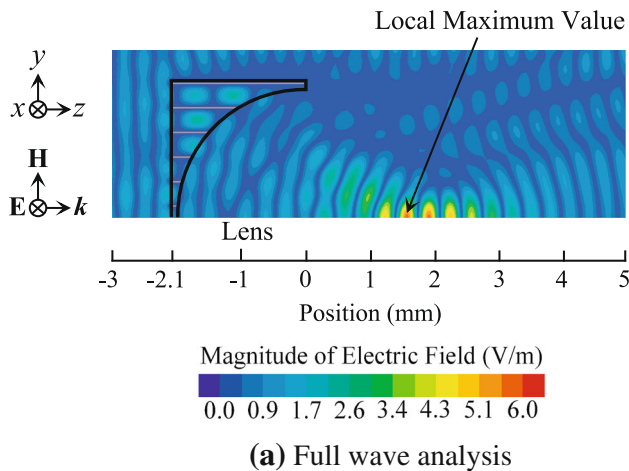


Fig. 2 Full wave analysis results for reference model

field distribution in the cross-section at the focus point. The focusing effect is confirmed for the three-dimensional concave lens with metallic slit array. The local maximum value of the electric field magnitude is 5.8 times that of the incident wave at 1.59 mm ($2.7\lambda_0$). The effective refractive index computed from both the full-wave analysis from the calculation of TE_1 mode wavelength in the slit is 0.52.

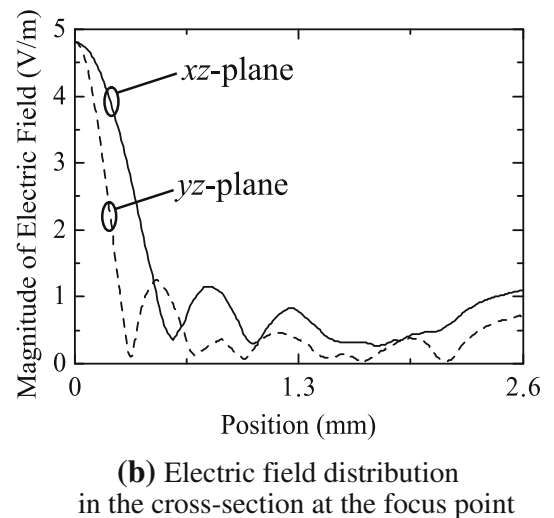
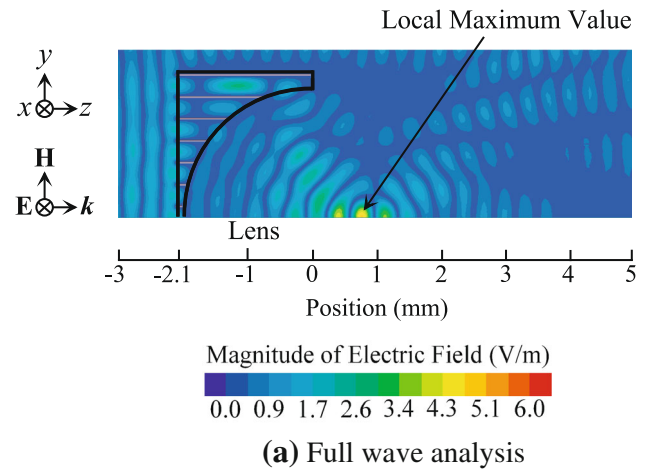


Fig. 3 Full wave analysis results for model pattern 1

4.1 Pattern 1

Figure 3a shows the result for slit array pattern 1. The local maximum value of the electric field magnitude is 4.8 times that of the incident wave at 0.80 mm ($1.3\lambda_0$). The effective index from the full-wave analysis model is 0.32 and is 0.25 from the calculation of TE_1 mode wavelength in the slit.

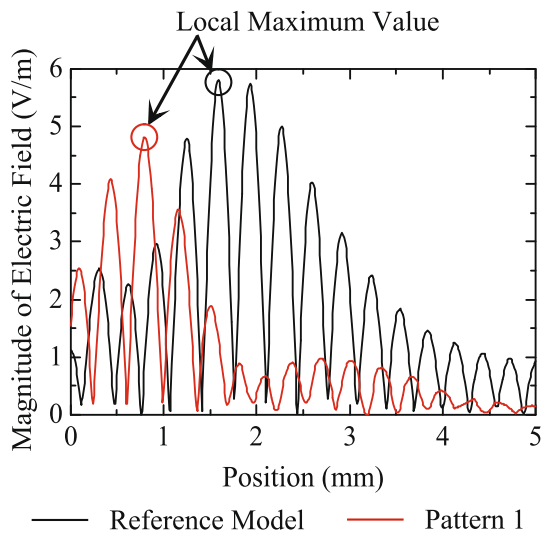


Fig. 4 Electric field in yz -plane for model pattern 1

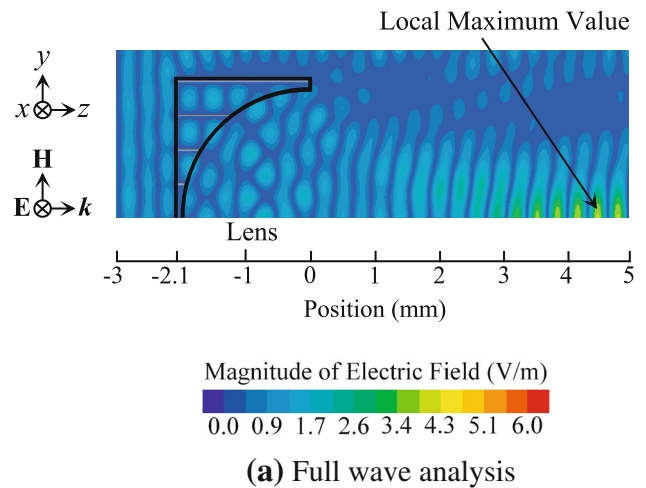
Figure 3b shows the electric field distribution in the cross-section at the focus point. The focusing effect in the yz -plane is stronger than in the xz -plane. Figure 4 shows the electric field in the yz -plane. The focus point is shorter and the effective refractive index decreases to 0 because the slit spacing is narrower than that in the reference model. On the other hand, the electric field at the focus point is weaker due to reflections from the impedance mismatch.

4.2 Pattern 2

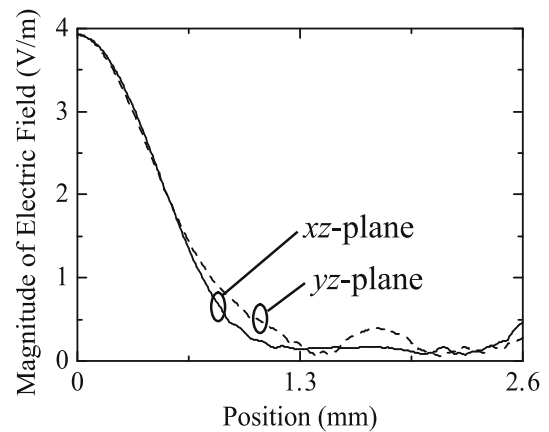
Figure 5a shows the result for slit array pattern 2. The local maximum value of the electric field magnitude is 3.9 times that of the incident wave at 4.51 mm ($7.5\lambda_0$). The effective index from the full-wave analysis is 0.79 and is 0.80 from the calculation of TE_1 mode wavelength in the slit. Figure 5b shows the electric field distribution in the cross-section at the focus point. The focusing effect in the xz -plane and in the yz -plane are almost same. Figure 6 shows the electric field in the yz -plane. The focus point is further from the lens, and the effective refractive index increases to 1 because the slit spacing is larger than that of the reference model. The electric field at the focus point is smaller due the weak focusing effect even though the reflection from the impedance mismatch is small.

4.3 Pattern 3

Figure 7a shows the result for slit array pattern 3 which includes the dielectric material Zeonor Film. The local maximum value of the electric field magnitude is 4.8 times that of the incident wave at 1.93 mm ($3.2\lambda_0$). The effective index



(a) Full wave analysis



(b) Electric field distribution in the cross-section at the focus point

Fig. 5 Full wave analysis results for model pattern 2

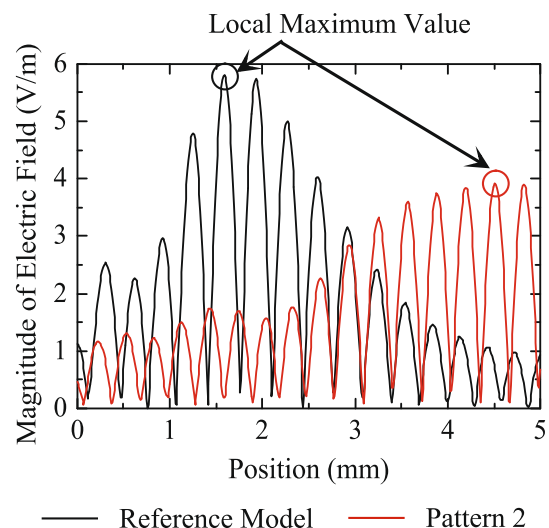


Fig. 6 Electric field in yz -plane for model pattern 2

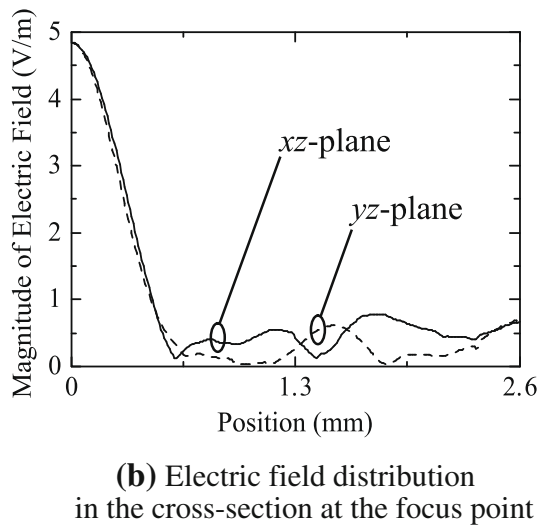
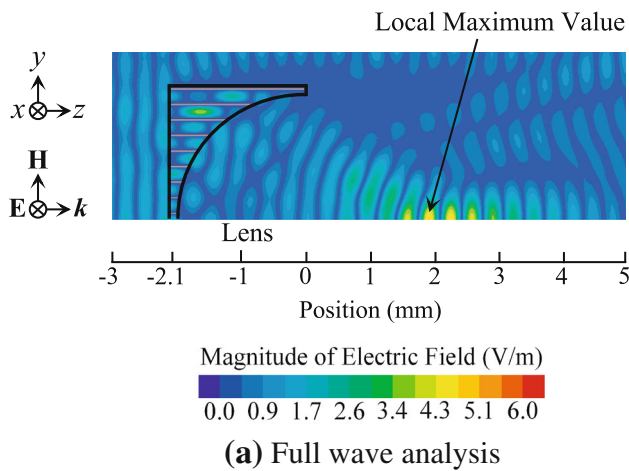


Fig. 7 Full wave analysis results for model pattern 3

computed from the full-wave analysis is 0.58 and is 0.55 from the calculation of TE₁ mode wavelength in the slit. Figure 7b shows the electric field distribution in the cross-section at the focus point. The focusing effect in the *xz*-plane and in the *yz*-plane are almost same. Figure 8 shows the electric field in the *yz*-plane. The focusing effect is confirmed even though the dielectric material produces a slow wave effect.

4.4 Effective refractive index

Figure 9 shows the effective refractive index for the reference model, model pattern 1, and model pattern 2. The effective index decreases to 0 with narrower slit spacings and increases to 1 with larger slit spacings. The reflection due to the impedance mismatching increases as the effective refractive index approaches 0 even though the numerical aperture is larger.

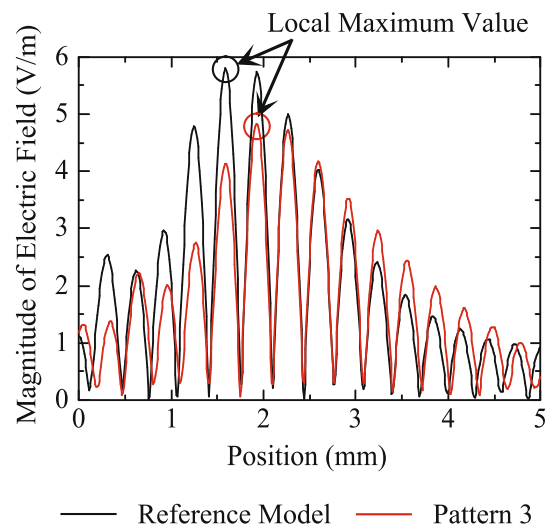


Fig. 8 Electric field in *yz*-plane for model pattern 3

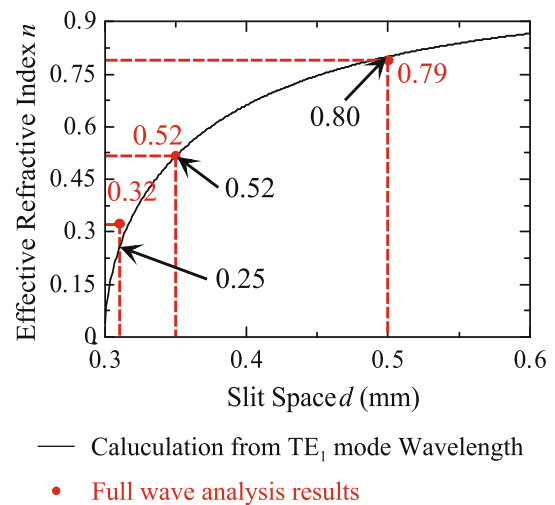


Fig. 9 Effective refractive index

5 Conclusions

This paper presents the design of a three-dimensional concave lens. The fast wave effect is enhanced by the use narrower slits in order to mitigate the slow wave effect in the dielectric material. The effective refractive index decreases to 0 with narrower slit spacing even though the reflection increases. The effective refractive index increases to 1 with larger slit spacings. It is difficult to fabricate the lens without spacers in the slits. A lens using the dielectric material Zeonor Film is designed and the focusing effect is confirmed. We are planning to fabricate the lenses and measure the focusing effect.

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