Short-Focus Lens Design for Terahertz Ray

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Abstract – Polyethylene and polypropylene, which have high transmittance in the terahertz band, are commonly used for terahertz lens systems. However, it is rather difficult to provide small lens systems, because the refractive indexes of polyethylene and polypropylene are small. In this research, we designed a small terahertz lens system by using a thin lens with a high-refractive index material, in addition to polyethylene or polypropylene.

Keywords – Terahertz Time Domain Spectroscopy; thin lens; lens design; sapphire; polypropylene

1. Introduction

Compact lens systems for terahertz array sensors are desired for high resolution imaging [1]. Polyethylene (PE) and polypropylene (PP) are known to have very high transmittance in the terahertz band and are used as lens materials for terahertz system. However, since the refractive index is low, it is difficult to miniaturize the optical system using only PE and PP. In general, the refractive index of optical materials such as germanium and sapphire used in the infrared communication band is higher than that of PE, but there is a problem that the transmittance in the terahertz band is low. In this research, a compact doublet lens with high transmittance and high refractive index in the terahertz band is designed by combining a thick lens using PP and PE with a thin lens using germanium, sapphire, etc.

2. THz condenser lens design

Figs. 1 and 2 shows the refractive indices and transmittance of samples (details are shown in Table 1), measured using terahertz time domain spectroscopy (TDS). The dispersion of each material is small in the terahertz band, and a terahertz system is less affected by the chromatic aberration. From the viewpoint of the reliability of the measurement data, we used the data in the frequency region of 0.5 to 2 THz to design terahertz lens systems.

To provide a compact condenser lens, we designed doublet lens systems with the materials shown in Table 1, by using the CODE V optical system design software. Geometrical optical analysis was used to estimate which combination of materials is effective. The lens parameters are optimized to achieve the minimum root-mean-square (RMS) of the spot diameter, where the parameters shown in Table 2 is fixed to design a compact lens system. The material for the lens 1 is PE or PP. The thickness of the lens 2 is much smaller than that of the lens 1, to reduce the total insertion loss of the lens systems.

The RMS spot diameters for various lens materials are shown in Table 3. We also approximately estimated the average transmittances of the lens systems, by using the measured transmittance shown in Fig. 2, where the incident light was assumed to be parallel ray, and the beam diameter was set to 30 mm. Table 4 shows he estimated average loss for the frequency region of 0.5 to 2 THz.

Table 1. Material list measured by THz-TDS.

Material	Abbr.	t [mm]
polyethylene	PE	1.010
polypropylene	PP	1.038
silica	SiO_2	3.015
calcium fluoride	CaF_2	2.041
Sapphire	Sap	2.038
Silicon	Si	3.011
Germanium	Ge	3.009

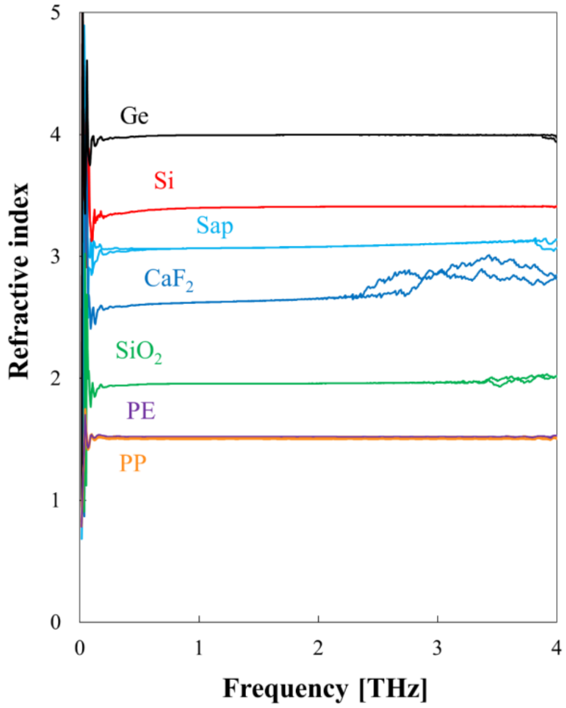

Figure 1. Frequency characteristics of refractive index.

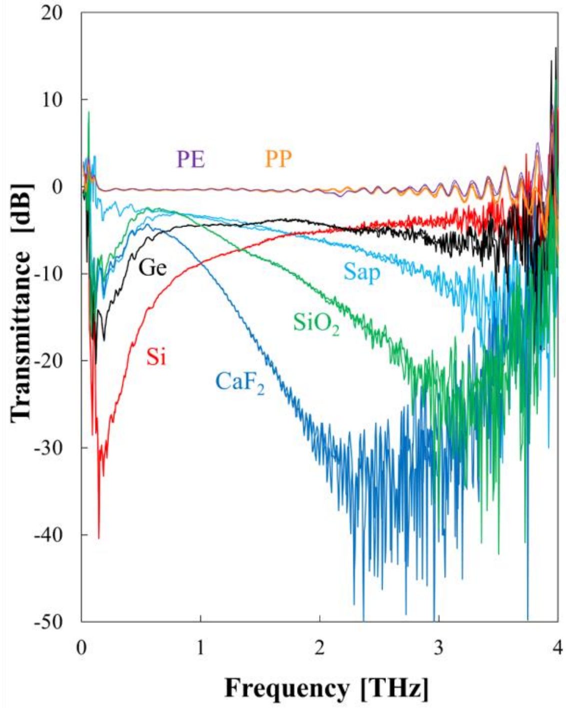

Figure 2. Frequency characteristics of transmittance.

Table 2. Fixed design parameters of the THz lens.

Items	Value [mm]
center thickness of lens 1	20
center thickness of lens 2	3
back focus	20
beam diameter	30

3. Analysis of designed lens systems

As shown in Table 3, the RMS spot diameter can be reduced by using combination of various materials. On the other hand, the loss would be larger than in the conventional lens systems with PE or PP, due to the small transmittance in the materials. We roughly estimated the peak power of the terahertz wave in the focused spots by using a figure of merit defined by $(T/T_0)(R_0/R)^2$. T/T_0 and R/R_0 are the transmittance and RMS spot diameter of a doublet lens system, normalized by those in the reference lens system, consisting of PP (lens 1) and PE (lens 2). R_0 and T_0 are shown in the first rows in Tables 3 and 4. As shown in Fig. 3, the doublet with PP and sapphire (PP-Sap) would provide the largest peak power at the center of the spot, while the total insertion loss of the lens system is larger than in the reference lens system (PP-PE). Figs. 4 and 5 show configurations of the lens systems. The thickness of the lens 2 is set to be much smaller than that of the lens 1 to suppress the loss in sapphire. Point spread functions (PSF) are shown in Figs. 6 and 7, where the 3-dB diameters for PP-PE and PP-Sap are 0.28mm and 0.23mm, respectively.

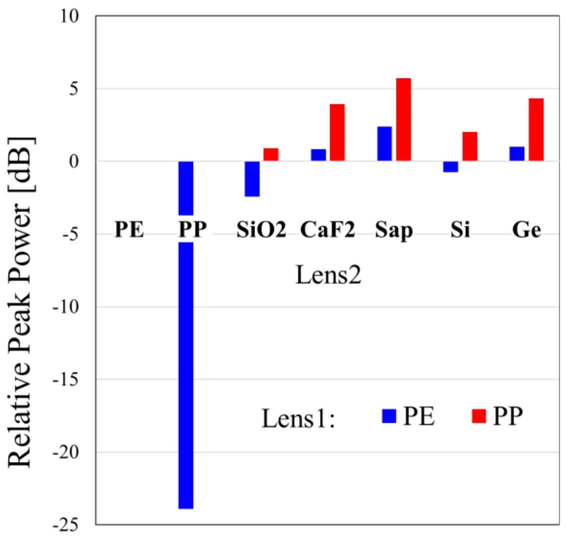

Figure 3. Peak power for various lens material.

Table 3. RMS spot diameter for various lens materials.

lens2 \ lens1	PE	PP
PE	–	1.0046
PP	10.5964	–
SiO_2	0.5544	0.5475
CaF_2	0.1656	0.1648
Sap	0.2872	0.2867
Si	0.2237	0.2506
Ge	0.4052	0.4120

Table 4. Average loss in dB for various lens materials at optimum design.

lens2 \ lens1	PE	PP
PE	–	4.92
PP	8.37	–
SiO_2	12.51	9.30
CaF_2	19.75	16.69
Sap	13.42	10.10
Si	18.70	14.96
Ge	11.80	8.32

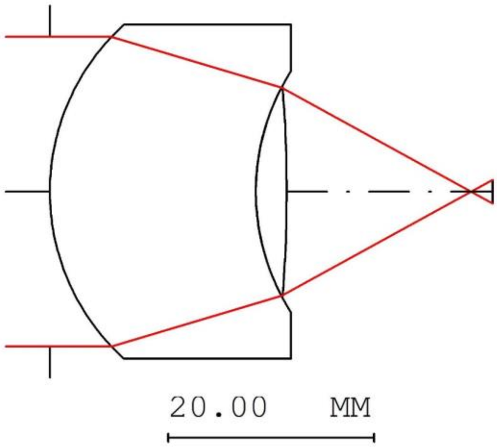

Figure 4. Doublet Lens for THz band. lens1: PP, lens2: PE

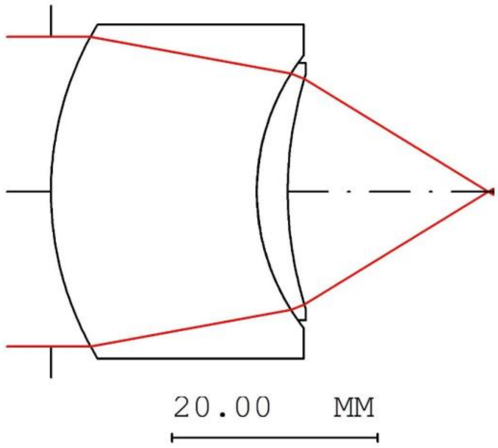

Figure 5. Doublet Lens for THz band. lens1: PP, lens2: Sapphire

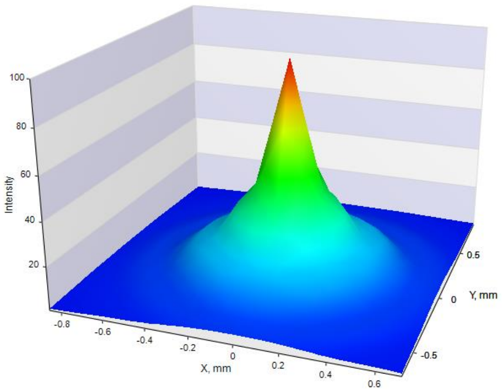

Figure 6. The point spread function. lens1: PP, lens2: PE

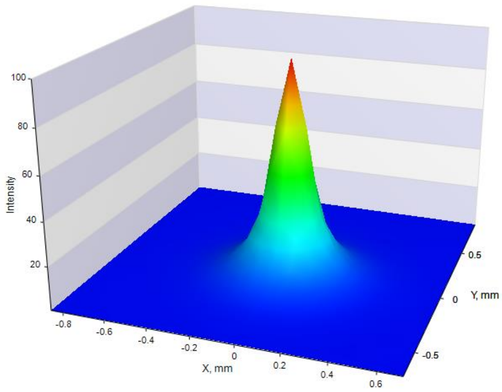

Figure 7. Point spread function. lens1: PP, lens2: Sapphire

4. Conclusion

Doublet terahertz lens systems are designed by using measured transmittance and refractive index of various materials. The material dispersion is small enough in the terahertz band, to design lens systems for wideband operation.

By combining a thick lens using low refractive index and high transmittance material and a thin lens using high refractive and low transmittance material, the compact optical system for the terahertz band could be designed, where the peak terahertz power would be enhanced.

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