Reflection Characteristics of an Extended Hemispherical Lens for THz Time Domain Spectroscopy

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***Abstract*—We analyze the Gaussian character of multiple reflections in extended hemispherical lenses which are widely used in terahertz spectroscopy. In particular, the first, second and third order reflections from a high-refractive-index extended hemispherical lens illuminated by a plane wave are characterized using high-frequency approximation. To demonstrate the importance of the Gaussicity of the incident and reflected beams on coupled power levels, we study a quasi-optical link involving a horn antenna and an off-axis parabolic reflector. Although such multiple reflections with distinctly different Gaussian character can be time-gated in time-domain spectroscopy systems, care must be exercised in continuous wave systems. Depending on the quasi-optical link, i.e. positioning of the antennas and reflectors, second and third-order reflections may induce significant variations of the sensed signal.**

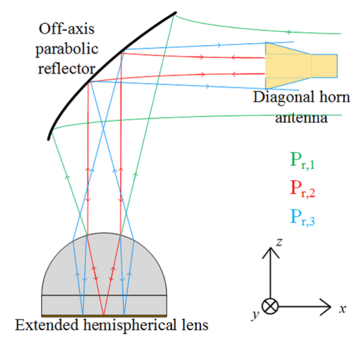

Fig. 1. Part of a terahertz time domain spectroscopy setup modeled in this work.

I. Introduction

Terahertz time-domain spectroscopy (THz-TDS) is an effective method of characterizing the frequency dependence of electrical properties of materials such as absorption, refractive index, and conductivity [1]. It provides a broad fractional bandwidth and sub-picosecond time resolution, as well as an ability to detect both the amplitude and phase information, making it appealing in application areas including security, biomedical imaging and sensing [1]–[4]. In THz-TDS, ultrafast lasers are used to generate and detect terahertz pulses by exciting or triggering photoconductive antennas. The standard transmitter/receiver structure is an extended hemispherical lens integrated to an antenna. These structures are ideally thought to produce perfectly Gaussian beams that can effectively be used to transmit the signal. However, in practice, due to the internal reflections of the lens, the antenna pattern exhibits a non-ideal behavior. Furthermore, these reflections cannot be dealt with via time gating for narrowband or continuous wave systems. The main objective of this work is to characterize the effects of dominant reflections from an extended hemispherical lens illuminated by a plane wave. The effect of the off-axis parabolic mirror is also reflected into the analysis. A diagram of the modeled system is shown in Fig. 1.

II. First, Second and Third Order Reflections from a High-Index Extended Hemispherical Lens

A ray-optics/field integration approach was employed by Filipovic et al. in [2] and [3] to find the radiation pattern of the extended hemispherical lens integrated with a double-slot antenna. This approach was extended in [5] to model the effect of internal reflections within the lens on the radiation pattern, which is also adopted here for characterization of the effect of reflections from the lens and the off-axis parabolic mirror. The modeled system consists of a horn antenna, an off-axis parabolic reflectors, and an extended hemispherical lens, as shown in Fig. 1. A Gaussian beam with a frequency of 246 GHz and a waist radius of 2.1 mm is considered as an example. This incident field is transmitted onto an off-axis parabolic mirror, which serves to reflect a collimated beam. The mirror is placed $5r_l$ away from the lens, where r_l is the radius of the lens and is taken as 6.85 mm (5.62λ). With this setup, the collimated beam exhibits a radius of 4 mm and is subsequently guided onto extended hemisherical lens. The extension length of the lens, L is selected as 2.6 mm. This length is known to yield the best approximation in the operation frequency of 246 GHz of an elliptical geometry in terms of the increased Gaussicity and the absence of spherical aberrations. A significant portion of the beam is reflected from the hemispherical surface of the lens due to the high permittivity of lens material (high resistivity Silicon, $\epsilon_r = 11.7$). This is denoted as the first-order reflection, viz., E_{r1}. The initial reflected beam E_{r1} is re-focused by the off-axis parabolic mirror in form of a Gaussian beam, whose dominant field component becomes $E_{z,r1}$. The magnitude of $E_{z,r1}$ after reflection from the mirror is shown in Fig. 2(a) for the E-plane cut, while the field incident to the mirror is shown in Fig. 2(d).

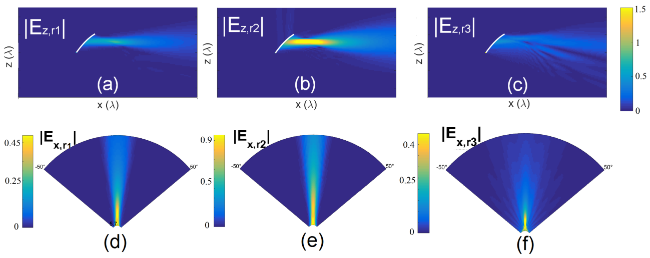

Fig. 2. (a)-(c) A view of the electric field after reflection from the off-axis parabolic mirror for E_{r1}, E_{r2} and E_{r3} (E-plane); (d)-(f) Fields incident on the mirror (transmitted from the lens) for E_{r1}, E_{r2} and E_{r3} (E-plane).

While a notable fraction of the initial incident beam is reflected back, rest of it is transmitted into the extended hemispherical lens. The transmitted field, E_{t1}, is reflected back from the ground plane placed at the focal point of the extended hemispherical lens. The reflected field, E_{r2}, is very similar in appearance to the field incident on the focal plane. Part of E_{r2} then refracts through the air from the Silicon-air boundary. The magnitudes of the fields reflected from the boundary and transmitted through the air are determined by decomposing the incident wave to perpendicular and parallel components and applying the Fresnel reflection and transmission coefficients, respectively. The portion of E_{r2} transmitting through the air is focused by the off-axis parabolic mirror similar to E_{r1}. This field constitutes the second order reflection captured by the receiving horn antenna shown in Fig. 1. The magnitude of the dominant component of this reflection, $E_{z,r2}$ is shown in Fig. 2(b) for the E-plane cut, and the incident field to the mirror is displayed in Fig. 2(e).

The portion of E_{r2} reflected from the lens-air boundary back into the Silicon is also worth considering. This field is denoted as E_{t2}. The field resulting from the reflection of E_{t2} from the ground plane, denoted as E_{r3}, is also transmitted through into the air (Fig. 2(f)). In fact, this third order reflection ($E_{x,r3}$) forms the third most dominant component observed on the spectrum of the reflections from the extended hemispherical lens. Compared to E_{r1} and E_{r2}, the field reflected from the mirror does not seem to produce a highly focused beam or a field with Gaussian characteristics (Fig. 2(c)). However, despite being unfocused, the level of the third order reflection still is significant.

The most powerful reflections captured by a diagonal horn antenna are expected to be the three types that have been analyzed, namely, the first, the second and the third order reflections. Here, the spatial variations of the power densities for three types of reflections are compared after they are focused by the mirror. The origin represents the beam waist, and the power density is calculated for E_{r1}, E_{r2}, and E_{r3} along x. The change of the power density is shown in Fig. 3 from the mirror up to a distance of 50λ from the location of the beam waist at $z = 0$. It can be observed that the second order reflection has the highest power level, while the first order reflection comes second and the third order reflection has the least power.

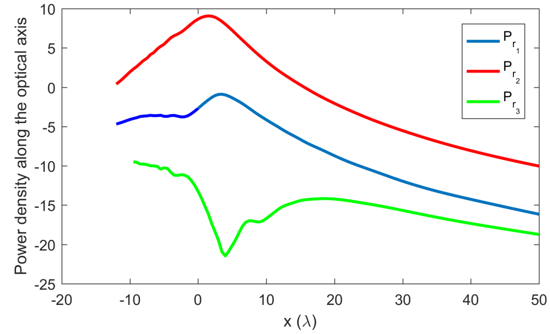

Fig. 3. The power densities for P_{r1}, P_{r2} and P_{r3} along the optical axis at $z = 0$.

III. Conclusion

We presented a study of the dominant reflections coming from an extended hemispherical lens geometry terminated by a ground plane. A high-frequency approximation via ray-tracing and field integration was employed to calculate the electric fields due to the reflections from the lens surface, from the focal plane of the lens, and from the radiation after an internal bouncing from the lens-air boundary and cylindrical wall, respectively. The effect of the reflection from an off-axis parabolic mirror was also taken into account. It was demonstrated that the most dominant reflection is the second-order reflection (from the focal plane), while the first- (from the lens surface) and third-order reflections (after an internal bounce within the lens) exhibit the next two highest contributions, respectively. As such, these internal reflections can impact signal quality in continuous-wave THz spectroscopy systems.

References

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