Focal length of a low permittivity plano-convex lens at frequencies 30–600 GHz

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Due to interest in lenses at telecommunications in the lower frequency range of 30–600 GHz (5G/6G applications) sub-terahertz range lenses have started to make their appearance. Geometrical optics is typically used due to its faster calculation speed, which is faster than finite element methods (FEMs). A 30-mm plano-convex lens was simulated with a COMSOL ray tracing module and CST was used to simulate 30, 60, 300 and 600 GHz FEM simulations. Focal points were 248, 189, 180, 118 and 131 mm with CST and 253 mm with COMSOL.

Introduction: As the frequency range in telecommunications climbs to higher frequencies (30–600 GHz 5G/6G applications), interest in the use of lenses to manipulate the radiation pattern generated by an antenna has grown [1–3]. One of the important parameters in optics is the focal length F of the lens. Focal points and focal length are used with lens antennas in the same way as in optics; antennas are placed in the focus spot to have a strong signal [4]. In the sub-terahertz range, wave lengths are millimetres and the sizes of the lenses are on the same scale [5, 6]. The focal length can be calculated from the lens maker's equation but it's frequency independent. There is one important question; What is the focal length of the lens with different wavelengths? In this Letter, we compared simulations done by geometrical optics (COMSOL) to finite element method (FEM) (CST).

Simulations: A 30-mm plano-convex (half sphere) lens was selected for simulation because of its simplicity and reasonable lens size. In geometrical optics (GOP), the focal length of the plano-convex lens can be calculated using the lens-makers equation [7]

$$\frac{1}{F} = (n - 1) \left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n - 1)d}{nR_1R_2} \right], \quad (1)$$

where F is the focus, n is the refractive index, using relative permittivity this changes to $\sqrt{\epsilon_r}$ [8] and the radii of curvatures R_1 and R_2 (shown in Fig. 1a) where one of the two curvatures is set to infinity. From the equation, a 30-mm plano-convex lens with relative permittivity of 1.13 has a focal point 238 mm from the lens. Fig. 1 shows different simulations in which there are rays coming from the left to the lens as in GOP and (Fig. 1b) in FEMs, instead of rays there is a plane wave.

Fig. 1 Schematic of lens simulations

a Ray-tracing
b FEM full wave

COMSOL was used to do a ray tracing simulation of the 30-mm plano-convex lens as shown in Fig. 2. Ray tracing results in a focus spot in the 200 mm range as it was calculated from the lens makers equation. CST simulations use the FEM to solve full waves using Maxwell's equations [9, 10]. The simulated frequencies were 30, 60, 120, 300 and 600 GHz, the linearly polarised plane wave was set to have an electric field strength of 1 V/m. 30 GHz was chosen as the starting frequency because its wavelength is three times the lens diameter and the rest are multiples of 30 GHz. The simulation model uses $\lambda/10$ precision for frequencies below 300 GHz and from 300 GHz $\lambda/8$ precision and up.

Lower precision at higher frequencies is demanded by the software to plot 2D figures such as Fig. 3. The E-field propagates from left to right

and the simulated area from the lens covers up to 270 mm. In Fig. 3, an E-field is simulated at 30 GHz; the lens has only a minimal effect on the travelling plane wave. Fig. 4 shows the effect from the lens when the frequency is 600 GHz. The lens squeezes the plane wave as is expected by GOP.

Fig. 2 COMSOL simulation of a plano-convex lens

Fig. 3 Simulated 30 GHz wave propagation

Fig. 4 Simulated 600 GHz wave propagation

Fig. 5 Simulated electric field change

In Fig. 5, the electric field values are plotted from 30, 60, 120, 300 and 600 GHz CST simulations. Values are taken from a straight line which goes through the dead centre of the lens and x values cover the entire propagation space. The lens covers the area from 0 to 15, which is marked at dotted horizontal lines and calculated the focal spot (at

253 mm (lens is between 0 and 15 that increases the focal length by 15 mm from the calculated one)) is also represented at the dotted horizontal line. The maximum electric field value for each simulated frequency after the lens is treated as a focus spot and its marked with an asterisk. The maximum E-field values and locations are listed in Table 1. The 30 and 60 GHz electric fields stay quite stable having no clear focus spot. At 300 GHz, the lens does squeeze the plane wave as it was predicted by GOP but the focal spot is off by 119 mm. 600 GHz also misses the focus spot by 115 mm like the 300 GHz simulation. If a reviewer was put to the focus spot and electric field strength is allowed to drop to 9 V/m at 600 GHz and to 6 V/m at 300 GHz then tolerances for placement are ± 7 mm for 600 GHz and ± 27 mm for 300 GHz.

Table 1: Electric field maximums

Frequency, GHz	X, mm	Electric field, V/m
30	248	2.2
60	189	2.8
120	180	3.4
300	118	6.6
600	131	10.1

Conclusion: There is a major difference between the ray tracing and full wave simulation. GOP is an approximation of the wave propagation where the frequency is set to have a value of 0. The GOP is formulated so that the wavelength is zero. This is a good approximation with optical frequencies when lenses are typically much larger than the wavelength. As in these simulations, a 30 mm lens compares to 3λ (30 GHz), 60λ (600 GHz) for the optical frequency lens would be 55000λ in comparison. In other works, full wave simulations are mainly used to study internal resonances at the lenses but not the focal length of the lenses [11]. For a receiver placement, frequency increase means tighter tolerances. As the frequency increases lens size compared to wave length increases when the electric field starts to follow ray traced ray paths. As GOP is limited by the dimensions of the lens and the wavelength of the propagated wave, it is advised to treat GOP calculations with caution when the wavelength is close to the lens size. To continue this work in the future, a point source having different frequencies with lenses would be studied.

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One or more of the Figures in this Letter are available in colour online.

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