Spatial-temporal dynamics of broadband terahertz Bessel beam propagation

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Abstract. The unique properties of narrowband and broadband terahertz Bessel beams have led to a number of their applications in different fields, for example, for the depth of focusing and resolution enhancement in terahertz imaging. However, broadband terahertz Bessel beams can probably be also used for the diffraction minimization in the short-range broadband terahertz communications. For this purpose, the study of spatial-temporal dynamics of the broadband terahertz Bessel beams is needed. Here we present a simulation-based study of the propagating in non-dispersive medium broadband Bessel beams generated by a conical axicon lens. The algorithm based on scalar diffraction theory was used to obtain the spatial amplitude and phase distributions of the Bessel beam in the frequency range from 0.1 to 3 THz at the distances 10-200 mm from the axicon. Bessel beam field is studied for the different spectral components of the initial pulse. The simulation results show that for the given parameters of the axicon lens one can obtain the Gauss-Bessel beam generation in the spectral range from 0.1 to 3 THz. The length of non-diffraction propagation for a different spectral components was measured, and it was shown that for all spectral components of the initial pulse this length is about 130 mm.

1. Introduction
The unique properties of non-diffractive beams and, in particular, Bessel beams, have led to the various applications and also a great variety of new optical and physical studies. The most common application of the Bessel beams in a terahertz diapason is terahertz imaging, where using Bessel beams one can significantly enhance the depth of focusing and resolution [1].

Another possible application for the Bessel beams is optical wireless communications [2] where Bessel beams can be used to increase a beam propagation distance and to remain the beam intensity and its transverse distribution unchanged for a longer distance. The potential of Bessel beams for the wireless communications was studied, for example, in [3]. It was shown that Bessel beams possess several important features for wireless communications, such as beam robustness against small scale obstacles and dimensional scaling.

For the terahertz communications it is crucial to minimize the diffraction in the propagation channel due to features rising from the frequency shift to the terahertz range, such as higher attenuation and diffraction [4]. In the case of broadband near-field terahertz communications it is even more important to minimize diffraction and increase the propagation distance due to the wide range of propagating

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wavelengths. Therefore, the study of spatial-temporal dynamics of the broadband terahertz Bessel beams is needed.

Here we present a numerical simulation of propagating Bessel beam generated by interaction of the broadband terahertz pulse with conventional conical axicon. The aim of the work is to study spatial-temporal dynamics of the broadband terahertz Bessel beam and to investigate the potential of the conventional axicon for the wireless broadband terahertz communications.

2. Methods
In this work, we have simulated the conversion of the input Gaussian beam into Gaussian-Bessel beam using conventional axicon model. It was show in [3] that conventional axicon is one of the most effective ways for Bessel beam generation. Pseudo-nondiffracting beam generated by an axicon has high quality and the energy conversion is more efficient in contrast to the Fourier filtering, for example.

The initial beam represents 2 ps terahertz Gaussian pulse with frequency range from 0.1 to 3 THz and with central frequency of 0.6 THz (500 mkm). The spatial amplitude distribution of the initial pulse is shown in figure 1(a) and the simulated axicon is shown in figure 1(b). The simulated axicon material is Teflon with refraction index 1.46 for the terahertz range. It should be noted that in this work we are not considering the attenuation and dispersion effects of the terahertz radiation in Teflon and in the air but these effects will be considered in the further work. The maximum thickness of the axicon is 9.1 mm, the diameter is 50 mm and the base angle is 20°.

Figure 1. Spatial amplitude distribution of the initial pulse (a) and simulated axicon model (b).

For the field distribution calculations of the propagated Bessel beam we used an algorithm based on the scalar diffraction theory, which is described in details in [5]. We considered the incident terahertz beam as a sum of monochromatic components and therefore, the propagation of each frequency component was calculated independently taking into account the source spectral shape, which is shown in figure 2b. The field distributions were calculated using angular spectrum method at the distances [5]

\[ l \leq N \frac{\Delta x^2}{\lambda}, \]

where \( N \) – number of elements in a calculation grid, \( \lambda \) – radiation wavelength, \( \Delta x \) – sampling step in the calculation grid. We exploited the convolution method for the field distribution calculation of each monochromatic component of the broadband source spectrum at the distances [5]

\[ l \geq N \frac{\Delta x^2}{\lambda}. \]
3. Results and discussion

Using methods described above, we simulated the formation of an optical vortex in the axicon illuminated by a broadband terahertz pulse with a Gaussian amplitude distribution. The results presented here were obtained at transverse dimensions $D_x \times D_y = 50 \times 50$ mm of the calculation domain and a grid of $256 \times 256$ elements. The field structure is calculated at the distances 10-200 mm.

Figure 3. Transverse distribution of the Gauss-Bessel beam at the distances 10-200 mm from the axicon for the frequencies a) 2.4 THz; b) 1.2 THz; c) 0.6 THz; d) 0.3 THz.

The results of numerical calculations of the transverse amplitude distribution of the Gauss-Bessel beams at the frequencies 2.4 THz, 1.2 THz, 0.6 THz, and 0.3 THz for different distances from the axicon plane are presented in figure 3. The evolution of the Gauss-Bessel beam amplitude distribution at the frequency 0.6 THz (500 mkm) with the propagation distance increasing is shown in a figure 4.
Figure 4. The evolution of the Gauss-Bessel beam amplitude distribution at the frequency 0.6 THz (500 mkm) at the distances from the axicon a) 20 mm; b) 80 mm; c) 140 mm; c) 190 mm.

The length of non-diffraction propagation for a different spectral components was also measured, and it is shown in the figure 5 that for all spectral components this length is about 130 mm. It is also shown in figure 5 that the relative central kern energy decreases with the distance from the axicon plane for all spectral components after 130 mm because of the energy transfer from the central maximum to the collateral maximums.

Figure 5. The dependence of the relative central kern energy from the propagation distance for the frequencies 2.4 THz (125 mkm), 1.2 THz (250 mkm), 0.6 THz (500 mkm), 0.3 THz (1000 mkm).

In conclusion, the simulation-based study of the propagating in non-dispersive medium broadband terahertz Gauss-Bessel beams generated by the axicon is presented. The numerical simulation showed that for the given parameters of the axicon lens one can obtain the Gauss-Bessel beam generation in the spectral range from 0.1 to 3 THz. The length of non-diffraction propagation for a different spectral
components was measured, and it was shown that for all spectral components of the initial pulse this length is about 130 mm. Therefore, the axicon lens can significantly increase the propagation distance for all spectral components of the initial broadband pulse.

Acknowledgments
This work was supported by Ministry of Education and Science of Russian Federation under grant № 3.1675.2014/K.

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