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Lens design and verification used for terahertz space transmission

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Abstract: Terahertz beams are a kind of Gaussian beam with a big divergence angle and its wave front cannot be simplified to a plane or a spherical wave. All the theoretical derivations from the classical electromagnetic theory and ABCD laws support the following conclusions: firstly, a positive lens converges the terahertz beam in front of the focal plane instead of on the focal plane; secondly, a negative lens which matches the radius of the Gaussian beam's wave front is more appropriate for terahertz beam collimation. Experiments show that a negative lens with $f' = -188$ mm at the matching position, $z = 100$ mm, can improve the terahertz beam collimation from 6° to 0.1°. And 20-m terahertz space transmission was realized with a very simple optical scheme.

Key words: terahertz, lens, lasers, transmission

PACS: 42.15.Eq, 87.50.Wp, 78.20.Ci

用于太赫兹空间传输的透镜设计及验证

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摘要:太赫兹激光作为大角度发散的高斯波束不能简化为平面波或球面波.经典电磁理论和 ABCD 法则传输理论建模显示:正透镜实现太赫兹激光束的会聚,会聚后其像距明显小于透镜的焦距;焦距和太赫兹激光光束波前半径相匹配的负透镜可以实现太赫兹激光束的准直.实验证实 $f' = -188$,的负透镜位于与太赫兹激光光束波前半径相匹配的位置时,即 $z = 100$ mm,太赫兹激光的发散角从 6°提高到 0.1°,20 m 传输实验中,负透镜准直探测方案比正透镜准直探测方案更加简单有效.

关 键 词:太赫兹;透镜;激光;传输

中图分类号:O439 **文献标识码**:A

Introduction

A terahertz (THz) wave is a type of electromagnetic wave with a frequency between 0.1 and 10 THz. Both the optical and electric methods can generate terahertz radiation. However, limited by the device size, electric methods cannot generate the terahertz radiations above 1 THz, and the devices are fragile[1,2]. Based on difference frequency generation (DFG) of light and quantum cascade lasers (QCLs), the radiations can cover the full terahertz wave band. Therefore, optically-generated terahertz emission is the preferred source of terahertz radiation[3-4]. However, the poor efficiency of DFG, small effective emission cross-section of QCLs[5-6], and high atmospheric absorptivity drive us to find the best transmission medium for THz wave's transmission[7-8]. Several studies show that free space transmission is more advantageous than any other transmission modes such as a metallic waveguide.

A positive lens is usually used for the detection of terahertz wave[9-10], because it can easily make full use of the terahertz energy, which is favorable to the free space transmission. However, a positive lens has little effect in improving the terahertz beam collimation. Owing to the limitations of terahertz sources and detectors, this study has not yet been conducted. In this paper, the difference between terahertz waves and visible lasers was studied in detail. Theoretical derivations show that negative lenses are more advantageous for terahertz beam collimation than positive lenses. The method to determine the f-number for negative lenses is also given in this pa-

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per. The experimental results demonstrated the validity of the theoretical derivations.

1 Theoretical Analysis

1.1 Classical Electromagnetic Theory

The terahertz source based on the optical method essentially is the stimulated radiative transition of a molecule. Therefore, the terahertz source is a type of laser[11], and it can be described by Gaussian optics:

$$u(x,y,z) = \frac{\omega_0}{\omega}\exp(-\frac{x^2+y^2}{\omega^2})\exp(-jkz)\exp(-jk\frac{x^2+y^2}{2R})\exp j\phi \quad , \quad (1)$$

where

$$\phi = \tan^{-1}\left(\frac{\lambda z}{\pi\omega_0^2}\right) \quad , \quad (2)$$

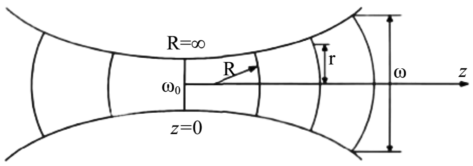


Fig. 1 Gaussian beam transmission along the z-axis. ω_0 is the beam waist, r is the distance between point (x, y) and the z-axis, R is the spherical wave radius, and W is the spot radius transmission along the z-axis

图 1 高斯光束沿 z 轴的传输. ω_0 表示光束的束腰, r 表示波前上的任意点(x,y)到 z 轴的距离, R 表示波前的球面半径, W 表示波沿 z 轴传输时的光斑半径

The schematic diagram of terahertz wave front is shown in Fig. 1, where w_o is the beam waist at the position $z=0$, R is the spherical wave radius, and ω is the spot radius along the z-axis. In Eq. 1, $u(x,y,z)$ is the field amplitude of the lowest-order mode along the z-axis, where z is the distance between the wave front and laser waist; $r=\sqrt{x^2+y^2}$ is the distance between point (x,y) and the z-axis; the items at the right-hand side of Eq. 1 represent the Gauss profile, plane wave phase, spherical wave phase, and additional phase, respectively. $\omega(z)$ and $R(z)$ can be calculated by:

$$\omega^2(z) = \omega_0^2\left[1+\left(\frac{\lambda z}{\pi\omega_0^2}\right)^2\right] \quad , \quad (3)$$

$$R(z) = z\left[1+\left(\frac{\pi\omega_0^2}{\lambda z}\right)^2\right] \quad . \quad (4)$$

For a visible light, such as $\lambda = 587.6$ nm with laser waist $\omega_0 = 1$ mm, and $z \leqslant 1\,000$ mm, because of $\frac{\lambda}{\omega_0^2} \ll 1$, Eqs. 2-4 can be simplified as:

$$\phi_{\lambda=587.6\ \mathrm{nm}} = \tan^{-1}\left(\frac{\lambda z}{\pi\omega_0^2}\right) \approx 0 \quad , \quad (5)$$

$$\omega^2_{\lambda=587.6\ \mathrm{nm}}(z) = \omega_0^2\left[1+\left(\frac{\lambda z}{\pi\omega_0^2}\right)^2\right] \approx \omega_0^2 \quad , \quad (6)$$

$$R_{\lambda=587.6\ \mathrm{nm}}(z) = z\left[1+\left(\frac{\pi\omega_0^2}{\lambda z}\right)^2\right] \approx \infty \quad . \quad (7)$$

Equations 5-7 indicate that a visible laser can be described as a plane wave. Thus, it can be described as:

$$u_{\lambda=587.6\ nm}(x,y,z) = \exp(-\frac{x^2-y^2}{\omega_0^2})\exp(-jkz) \quad , \quad (8)$$

For a terahertz beam, for example $\lambda_{1T} = 0.3$ nm with laser waist $\omega_0 = 1$ mm and $z \leqslant 1\,000$ mm, Eqs. 2-4 can only be simplified as:

$$\phi_{1T} = \tan^{-1}\left(\frac{\lambda z}{\pi\omega_0^2}\right) \approx \tan^{-1}\left(\frac{z}{11}\right) \quad , \quad (9)$$

$$\omega^2_{1T}(z) = \omega_0^2\left[1+\left(\frac{\lambda z}{\pi\omega_0^2}\right)^2\right] \approx \omega_0^2\left[1+\left(\frac{z}{11}\right)^2\right] \quad , \quad (10)$$

$$R_{1T}(z) = z\left[1+\left(\frac{\pi\omega_0^2}{\lambda z}\right)^2\right] \approx z\left[1+\left(\frac{11}{z}\right)^2\right] \quad . \quad (11)$$

Equations 9-11 indicate that a terahertz beam described as Eq. 1 cannot be considered as a plane or spherical wave, which is quite different from the description of visible lasers.

For $\lambda = 500$ nm and $\lambda = 0.3$ mm, the $\omega(z)$ and $R(z)$ depending on transmission distance z are shown in Figs. 2(a) and 2(b), respectively. In Fig. 2(a), it is clear that the beam waist for the visible laser almost remains unchanged while the terahertz beam waist changes significantly along the z-axis with a large divergence angle of about 5.7°. A large divergence angle is not good for the free space transmission. From Fig. 2(b), we find that the spherical wave radius for the visible laser is thousands of times larger than its beam waist, which again proves that the visible laser can be described as a plane wave. However, for the terahertz beam, the spherical wave radius has the same order as its beam waist.

In Fourier optics, a lens can be used as a phase converter that can be described by

$$t(x,y) = \exp[-j\frac{k}{2f'}(x^2+y^2)] \quad , \quad (12a)$$

where $t(x,y)$ is the phase conversion caused by the lens, f' is the focal length of the lens, and k is the wave vector. For negative lenses, $f' < 0$, Eq. (12a) can be rewritten as

$$t(x,y) = \exp[j\frac{k}{2|f'|}(x^2+y^2)] \quad . \quad (12b)$$

If a positive lens was put behind a visible laser, for example $\lambda = 587.6$ nm with $\omega_0 = 1$ mm, the field amplitude can be expressed as

$$U'_{\lambda=587.6\ \mathrm{nm}} = u_{\lambda=587.6\ \mathrm{nm}}(x,y,z_0) \times t(x,y) = \exp-\frac{x^2+y^2}{\omega_0^2}\exp(-jkz_0)\exp[-j\frac{k}{2f'}(x^2+y^2)] \quad , \quad (13)$$

where z_0 is the distance between laser and lens and can be measured easily. At position z_0, $\exp(-jkz_0)$ is a constant phase, so Eq. 13 describes a convergent spherical wave. If the positive lens was replaced by a negative lens, a divergent spherical wave will be achieved.

If a positive lens was put behind a terahertz laser, for example $\lambda = 0.3$ nm with $\omega_0 = 1$ mm, the expression for the field amplitude can be written as

$$U'_{1T} = u_{1T}(x,y,z_0) \times t(x,y) = \frac{\omega_0}{\omega}\exp\left(-\frac{x^2+y^2}{\omega^2}\right)\exp[-jk\frac{(x^2-y^2)(R+f')}{2Rf'}] \quad . \quad (14)$$

It means that a positive lens can also convert tera-

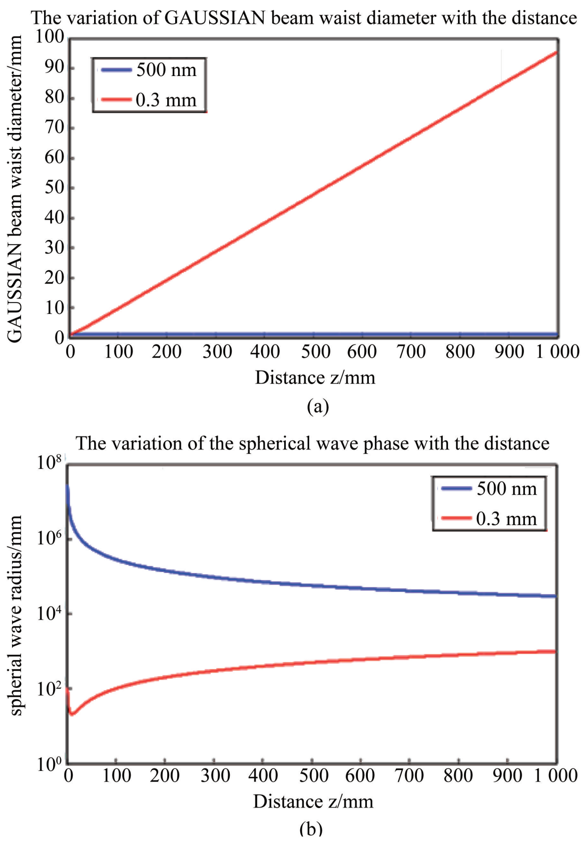


Fig. 2　(a) The changes of the Gaussian beam waist diameter, (b) The changes of the spherical wave radius depending on the transmission distance z.
图 2　(a)高斯光束的半径随传输距离的变化;(b)高斯光束波前半径随传输距离的变化

hertz laser, but the convergent point is located behind the lens about $\frac{Rf'}{R+f'}$ instead of at the focus.

If a negative lens was put behind a terahertz laser, for example $\lambda = 0.3$ mm with $\omega_0 = 1$ mm, the expression for the field amplitude can be described as

$$\begin{aligned} U'_{1T} &= u_{1T}(x,y,z_0) \times t(x,y) \\ &= \frac{\omega_0}{\omega}\exp\left(-\frac{x^2+y^2}{\omega^2}\right)\exp[-j(kz_0-\phi)]\exp\left[-jk\frac{(x^2-y^2)(|f'|-R)}{2|f'|R}\right] \quad . \quad (15) \end{aligned}$$

If $R > |f'|$, the negative lens make the beam divergent behind the lens. If $R < |f'|$, the negative lens focuses the beam behind the lens about $\frac{R|f'|}{R-|f'|}$. If $R = |f'|$, Eq. 15 can be simplified as

$$\begin{aligned} U'_{1T} &= u_{1T}(x,y,z_0) \times t(x,y) \\ &= \frac{\omega_0}{\omega}\exp\left(-\frac{x^2+y^2}{\omega^2}\right)\exp[-j(kz_0-\phi)] \quad , \quad (16) \end{aligned}$$

where

$$f' = -R \quad . \quad (17)$$

It means that when $R = |f'|$, the negative lens changes the Gaussian wave to a plane wave. So the key to achieving terahertz beam collimation is that the focus length of the negative lens should be equal to the spherical wave radius.

If Eq. 17 is satisfied, we can convert the Gaussian wave into a plane wave. Before obtaining the parameters of the negative lens, it is necessary to calculate the parameters of the Gaussian wave carefully. A smaller spot helps to achieve a longer distance transmission, which indicates that the distance between the lens and laser waist should be as small as possible.

$$f' = -R = -z\left[1+\left(\frac{\pi\omega_0^2}{\lambda z}\right)^2\right] \quad . \quad (18)$$

1.2　Gaussian Beams and ABCD Law

Consider a Gaussian beam passing through a thin lens and assume the focal length of lens as f'. According to the ABCD law of Gaussian beam propagation[11], the complex beam parameters have the relationship of

$$\frac{1}{q_2} = \frac{C+(D/q_1)}{A+(B/q_1)} \quad , \quad (19)$$

where q_1 and q_2 are the complex beam parameters of the Gaussian beam before and after the lens, respectively. They can be calculated by

$$\frac{1}{q_1} = \frac{1}{R_1} - j\frac{\lambda}{\pi w_1^2} \quad , \quad (20)$$

$$\frac{1}{q_2} = \frac{1}{R_2} - j\frac{\lambda}{\pi w_2^2} \quad , \quad (21)$$

where R_1, and R_2 are the radiuses of the curvature of the equiphasic surfaces before and after the lens, w_1 and w_2 are the spot sizes before and after the lens. The matrix elements of a lens can be given by

$$\begin{vmatrix} A & B \\ C & D \end{vmatrix} = \begin{vmatrix} 1 & 0 \\ -\frac{1}{f'} & 1 \end{vmatrix} \quad . \quad (22)$$

Then we can get

$$\frac{1}{q_1} - \frac{1}{q_2} = -\frac{1}{f'} \quad . \quad (23)$$

Substituting Eqs. 20-21 into Eq. 23 and separately equating the real and imaginary parts we can obtain the following relationships:

$$w_1 = w_2 \quad , \quad (24)$$

$$\frac{1}{R_2} = \frac{1}{R_1} - \frac{1}{f'} \quad . \quad (25)$$

The lens makes the beam parallel, meaning that

$$R_2 = \infty \quad . \quad (26)$$

Based on Eqs. 25-26, we can get the parameter of the lens:

$$f' = -R_1 = -z\left[1+\left(\frac{\pi\omega_0^2}{\lambda z}\right)^2\right] \quad . \quad (27)$$

Equation 18 is just the same as Eq. 27, indicating that both the classical electromagnetic theory and ABCD laws prove that a negative lens can convert the Gaussian wave into a plane wave. The key to achieving terahertz beam collimation is that the focus length of the negative lens should be equal to the spherical wave radius.

Now consider a Gaussian beam, which has a spot size of w_{01} and a plane wave front, entering a lens with focal length f'. We then focus on calculating the beam waist position after the lens and its spot-size value w_{02}. According to the ABCD law of Gaussian beam propagation, the transmission matrix for a lens with a focal length

f', followed by a free-space length z, can be given by:

$$\begin{vmatrix} A & B \\ C & D \end{vmatrix} = \begin{vmatrix} 1-\frac{z}{f'} & z \\ \frac{-1}{f'} & 1 \end{vmatrix} \quad . \quad (28)$$

The complex beam parameter q_2 after the lens with a certain free-space length can again be calculated by Eq. 19, where the A, B, C, D elements are shown in Eq. 28 and $(1/q_1)$ is given by:

$$\frac{1}{q_1} = -j\frac{\lambda}{\pi w_{01}^2} = -\frac{j}{z_R} \quad , \quad (29)$$

where z_R is the Rayleigh range corresponding to the spot-size w_{01} and can be presented by:

$$z_R = \frac{\pi w_{01}}{\lambda} \quad . \quad (30)$$

If now the coordinate z_m after the lens corresponds to the position of the beam waist, according to Eq. (19), we can get z_m by:

$$z_m = \frac{f'}{1+\left(\frac{f'}{z_R}\right)} \quad . \quad (31)$$

Substituting Eqs. 28-29 into Eq. 19 and equating the imaginary parts at the two sides of Eq. 19, we can get the spot size at the focal plane w_{02}:

$$w_{02} = \frac{\lambda f'}{\pi w_{01}\left[1+\frac{f'}{z_R}\right]^{1/2}} \quad . \quad (32)$$

For the visible and infrared region, because of $z_R \gg f'$, we can get $z_m \approx f'$. It is just the same as Eq. 13, meaning that the beam focuses at the focal distance f'. When $z_R \gg f'$, we can simplify Eq. 32 as:

$$w_{02} = \frac{\lambda f'}{\pi w_{01}} \quad . \quad (33)$$

For the terahertz region, z_R and f' are almost in the same order of magnitude, thus $z_m < f'$. Therefore, we can see that the distance z_m from the lens, at which the minimum spot size occurs, is always smaller than the focal distance f'. This is consistent with what Eq. 14 shows.

2 Experiment and Analysis

2.1 Design and Manufacture of the Terahertz lens

Lenses are always used in terahertz systems to improve the beam collimation and energy utilization ratio. Depending on the material, lenses used in terahertz systems are divided into two categories: high-resistivity silicon lenses and plastics lenses such as High Density Polyethylene (HDPE), Polytetrafluoroethylene (PTFE), and Picairn lenses. In our experiment, the lens is made of HDPE, whose transmissivity curve in the terahertz region is shown in Fig. 3.

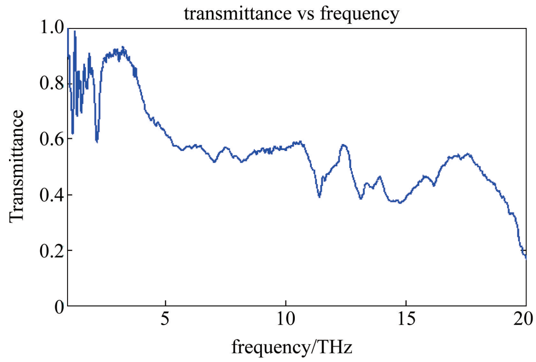


Fig. 3 Transmissivity curve of HDPE.
图 3 HDPE 的透过率曲线

From Fig. 3, it can be found that the transmissivity of HDPE depends on the frequency of the terahertz, which is caused by the characteristic of material itself. The detailed interaction mechanism between terahertz and HDPE is still not clear. However, this has little effect for the monochromatic light employed in our experiments.

In our experiments, the 1T terahertz emission is generated by pumping GaSe using a 1 067.8 nm laser and a 1064 nm Nd:YAG laser from DFB. The terahertz beam has a beam waist of 3 mm. From Eqs. 3-4, we can calculate the spot diameter $\omega = 4.3$ mm and spherical radius $R = 188$ mm at the distance $z = 100$ mm. Based on Eq. 18, the focus length of the negative lens is calculated as $f' = -188$ mm.

2.2 Measurement and Analysis of the Divergence Angle

First, we measure the divergence angle without any lenses. A bolometer is used as the detector working under liquid helium condition. The signal value (unit: mv) can be read directly from an oscilloscope. The background radiation is tested as 4mv. Without any lens, signal is detectable only within 50 cm. Therefore, we measure the spot diameter at three positions $z_1 = 10$ cm, $z_2 = 20$ cm and $z_3 = 30$ cm. The measured results are shown in Fig. 4. The beam width defined as the distance between the two points with the signal value of $\frac{1}{e^2}$ of the peak value. From Fig. 4, we can calculate the divergence angle of the terahertz source as 6°.

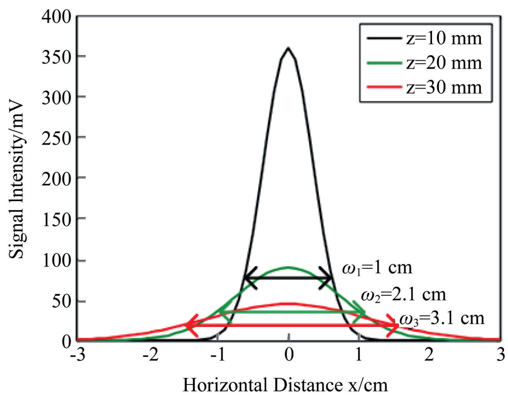
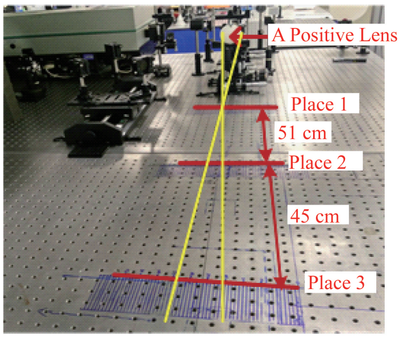
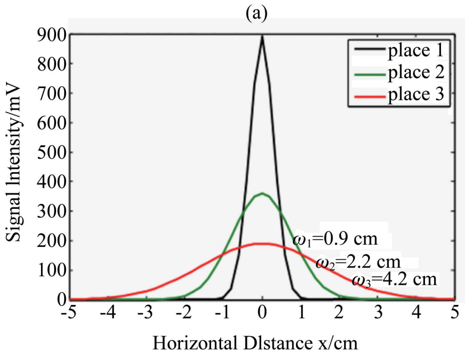


Fig. 4 Measured results without any lenses
图 4 不加透镜的测量结果

Secondly, we measure the divergence angle of terahertz beam after passing through a positive lens with a focal length of $f' = 188$ mm. The lens is positioned at $z = 188$ mm behind the laser. A photo of the experimental system is shown in Fig. 5(a) and we measure the spot diameter at the places 1, 2, and 3. The signal intensity distribution at each place is shown in Fig. 5(b). From Fig. 5(b), the divergence angle of the terahertz beam after the positive lens is calculated as 2.5°. Additionally, we found that the positive lens can convert the divergence beam, which is proved by the fact that there does always exist a position, about 100mm behind the lens, having the maximum signal value. The position is in good agreement with the theoretical value from Eq. 14.



(a)



(b)

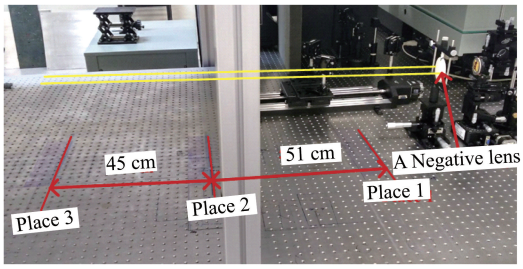
Fig. 5 (a) Schematic of the experimental system and (b) the corresponding measured results when using a positive lens
图 5 (a) 实验测量方案图;(b) 正透镜的实验测量结果

Finally, we measure the divergence angle of terahertz beam passing through a negative lens, which has a focal length of $f' = -188$ mm and its focus is located at $z = 100$ mm. A photo of the experimental system is shown in Fig. 6(a). We measured the spot diameter at places 1, 2, and 3, which are the same as the places in positive lens experiments. The signal intensity distribution at each place is shown in Fig. 6(b). The divergence angle of the terahertz beam after the negative lens is calculated as 0.1°.

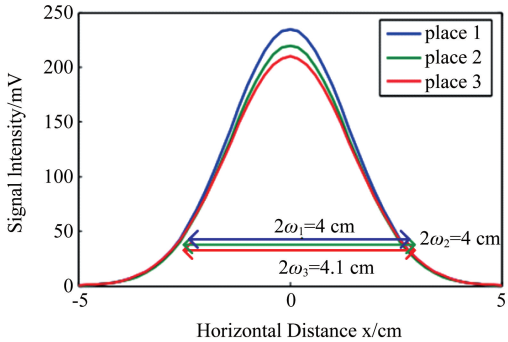
Through the experiments, we can get the following conclusions: terahertz beams have a big divergence angle that is disadvantageous for the space transmission; though a positive lens with a large f-number can improve the energy utilization ratio, it has little improvement to the beam collimation; a negative lens can significantly improve the beam collimation, which is important for the space transmission, terahertz imaging, and so on.

2.3 Experiment of the Terahertz Beam Space Transmission

The space transmission distance, an important goal



(a)



(b)

Fig. 6 (a) Schematic of the experimental system and (b) The measured results when using a negative lens
图 6 (a) 实验测量方案图;(b) 负透镜的实验测量结果

in our program, can be significantly improved when replacing the positive lens with a suitable negative lens at the optimum position. Generally, to achieve a farther transmission distance, more positive lenses should be placed in the path. However, we can only achieve 20m transmission distance when using as many as nine positive lenses, as shown in Fig. 7. Instead, using negative lenses as collimating lens, only three lenses are needed for the 20 m transmission distance, as shown in Fig. 8. In Fig. 8, the first lens, second lens, and the third lens are a negative lens with focus length of -188 mm, a positive length (9 m distance from the first lens) with focus length of 10 m, and a small positive lens with focus of 156 mm, respectively. Additionally, the signal collected in the latter scheme is seven times higher than that of the first. This result indicates that negative lenses in the path are advantageous for terahertz space transmission.

3 Discussion

It is well known that when the diameter of a lens is much bigger than the wavelength of light, we can use the geometrical optics, i. e. regarding light beam as a straight line, to analyze problems. However, the terahertz waves have a long wavelength, close to the diameter of an ordinary lens. Thus, geometrical optics is not applicable to the terahertz waves because of diffraction effect. Instead, the classical electromagnetic theory and ABCD laws can be used to design lens for terahertz transmission as shown in section 2. All the theoretical derivations support the following conclusions: firstly, a positive lens converges the terahertz beam in front of the focal plane instead of on the focal plane, which is quite differ-

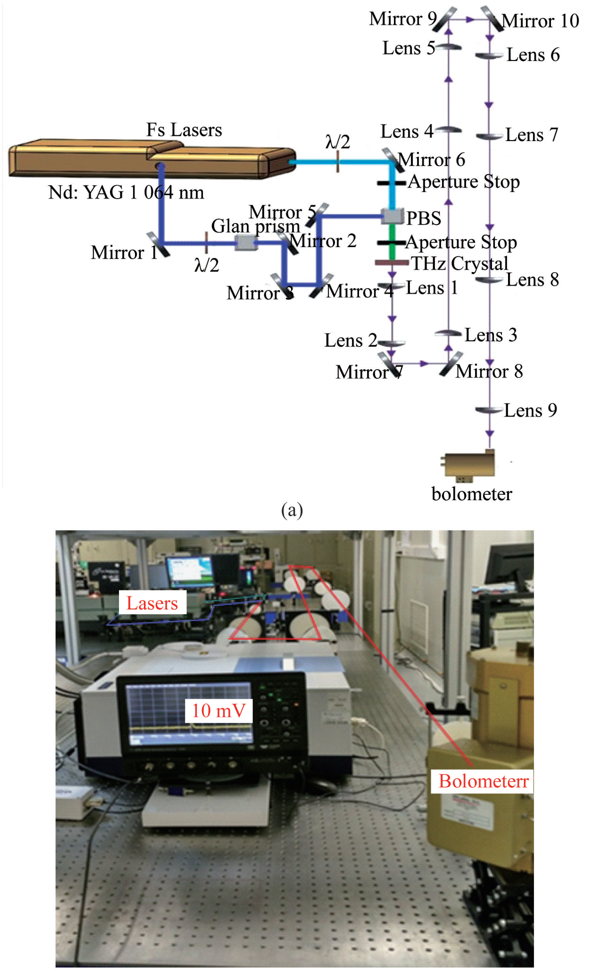


Fig. 7 (a) Schematic diagram of the experimental system for 20 m terahertz transmission employing positive lenses and (b) Photo

图 7 (a) 实验方案;(b) 使用正透镜准直实现的太赫兹 20 m 传输

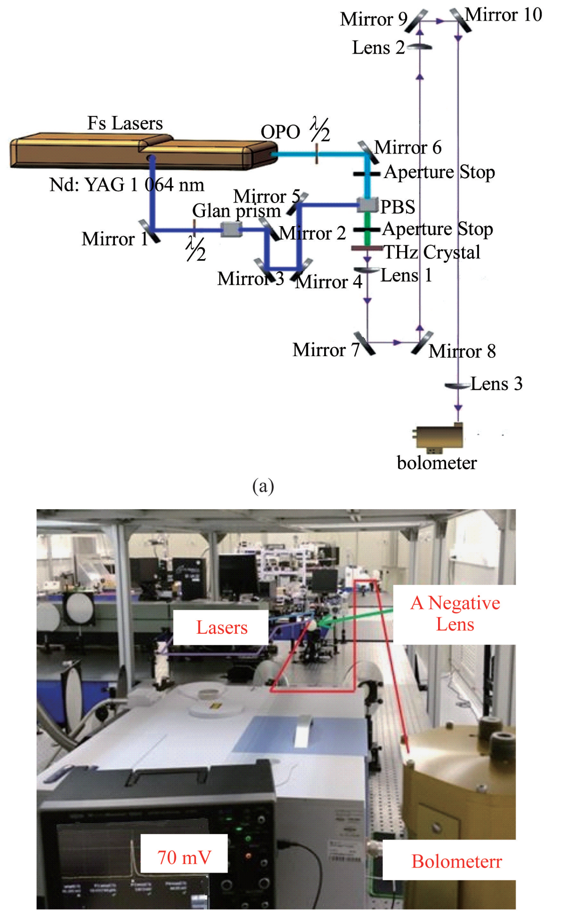


Fig. 8 (a) Schematic diagram of the experimental system for 20 m terahertz transmission based on negative lens and (b) Photo

图 8 (a) 实验方案;(b) 使用负透镜准直实现的太赫兹 20m 传输

ent from the fact that it makes the visible or infrared lasers converge on the focal plate; secondly, although a negative lens can make the terahertz Gaussian beam divergence, convergence or parallel, how the beam performance behind the lens depend on the focus length of the negative length; thirdly, a negative lens which matches the radius of the Gaussian beam's wave front is more appropriate for terahertz beam collimation.

The terahertz beams generated by the DFG are a kind of Gaussian beam with a big divergence angle, which is disadvantageous for the space transmission. Generally, three methods can be used to collimate the beam: a lens with big focus length, a beam expander, and a negative lens. However, in the first two methods, the big diameter of the parallel beam leads to a short transmission distance. Therefore, consequently, the negative lens is the best way to achieve the beam collimation and a longer transmission distance simultaneously.

Comparing the two schemes shown in Figs. 7-8, we can summarize the disadvantages of the scheme in Fig. 7 as following. Firstly, too many lenses are used. In Sect. 2, we have learned that the beam emitted from the terahertz crystal has a divergence angle up to 6 degree. At least two lenses are needed to realize laser beam collimation. If we put the first lens 10 cm distance behind the crystal, in order to get a collimating beam after the second lens with the divergence angle about 1 degree, the aperture of the second lens should be set as 6.3 cm. Without taking atmospheric absorption into account, the spot size of the beam becomes 41.3 cm after 10 m propagation. It is too big for the weak power of terahertz laser. In order to reduce the atmospheric absorption, especially the water vapor absorption, the spot size should be as small as possible. So series of lenses should be used in Fig. 7 to restrict the spot size. Secondly, as shown in Fig. 3, the transmissivity of HDPE with the thickness about 2 mm for the 1 THz wave is about 0.85. Therefore, only 23 percent of energy is left when the beam passes through nine lenses as showed in Fig. 7. This is the reason why the scheme in Fig. 7 has a small SNR than that in Fig. 8.

Based on the generation method, terahertz sources can be divided into two categories: the optical terahertz sources and electric terahertz sources. The optical methods consist of photoconductive antenna, optical rectification, air Plasmon, THz parametric sources, optically-pumped THz laser and semiconductor laser. The terahertz beams generated by the optical sources are Gaussian beams with big divergence angles. The theory proposed in this paper only applies to the optical terahertz sources. There are some differences for these optical THz sources in transmission efficiency. Accurate physical modeling for each optical terahertz source should be set up to calculate the transmission efficiency precisely. So, here, we just evaluate the transmission efficiency for each optical terahertz source roughly. Firstly, photoconductive antenna is a kind of omnidirectional antennas. The transmission efficiency for photoconductive antenna is much smaller than optically-pumped THz laser and semiconductor laser. Secondly, the fundamental principles for optical rectification, air Plasmon and THz parametric sources all are nonlinear optical effects. So the transmission efficiency for them has little difference with that for optically-pumped THz laser and semiconductor laser.

4 Conclusion

Different with visible and infrared lasers, the wave front of terahertz beams cannot be simplified to a plane or spherical wave. It is a Gaussian beam with a big divergence angle which is disadvantageous for the space transmission. Though a positive lens with a large f-number can improve the energy utilization ratio, which is helpful for the space transmission, it can only slightly improve the beam collimation. Both the theoretical derivations from the classical electromagnetic theory and ABCD laws show: firstly, a positive lens converges the terahertz beam in front of the focal plane instead of on the focal plane as visible or infrared lasers do; secondly, the positive lens used in front of the detector can improve the energy utilization without significantly enhancing the beam collimation; thirdly, the negative lens matching the radius of the Gaussian beam's wave front is more appropriate for terahertz beam collimation. The parameter for negative lenses is determined by $f' = R = -z[1 + (\frac{\pi w_0^2}{\lambda z})^2]$, where z is the distance from terahertz crystal to the lens, w_0 is the beam waist, and λ is the center wavelength of the terahertz beam. Experiments show that a negative lens with $f' = -188$ mm at the match place, $z = 188$ mm, can improve the terahertz beam collimation from 6° to 0.1°, while a positive lens with $f' = -188$ mm at the optimum position, $z = 188$ mm, which is determined by classical optic, only can converge beam at $z' = 100$ mm with an angle of 2.5°. We realized 20-m terahertz space transmission with a negative lens in a very simple optical scheme. The signal obtained is seven times greater than that obtained with the positive lens scheme. The work shown in this paper will play an important role in free space transmission and terahertz imaging.

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