Measurement and improvement of beam profile for terahertz quantum cascade laser

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Abstract: The divergence of the laser beam generated by Quantum Cascade Laser is relative large, which is not conducive to the process of experiment and the acquisition of the desirable results. Thus, a convex lens would be utilized in the propagation path to optimize the laser beam.

Keywords: Terahertz, Quantum cascade laser, Gaussian beam, Divergence

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1. Introduction

Quantum cascade lasers (QCLs) [1] are unipolar semiconductor devices based on intersubband transitions between quantized subband states in a multiple quantum well heterostructure. Since their invention in 1994 [2], the performance of QCLs has been improved dramatically by optimizing the material quality and processing technology. Now QCLs are capable of covering the wavelength range of 3-120 μm, which makes them acceptable sources for technological applications such as gas sensing, industrial process monitoring and space communication. However, the manufacture of Quantum Cascade Laser is still a tough and challenging task in terms of the high precision requirements for characteristic parameters of laser beams. In other words, the quality of the laser beam generated by Quantum Cascade Laser is not that desirable. To be specific, the value of the divergence is relative large.

Due to this, two negative impacts would be brought about and should be considered. Firstly, spot size would expand quickly after a short distance along the axis of propagation. It may occur that the size of the spot exceed that of the image plane of THz imager at a given position along the axis of propagation. Secondly, the limited energy would disperse rapidly owing to the larger divergence, and THz imager may receive small amounts of energy to such an extent that even no clear and complete spot would be figured out. Undoubtedly, these two adverse influences are not conducive to the process of experiment and the acquisition of the favorable results.

Therefore, in this paper, a solution has been brought forward to optimize the laser beam generated by Quantum Cascade Laser. A convex lens would be utilized in the propagation path, because it could lower the divergence. This method would largely improve the quality of the beam generated by Quantum Cascade Laser.

2. Experiment

Setups for experiment Ⅰ and experiment Ⅱ are schematically depicted in figure 1. The operating frequency of THz source is set to 3 *THz* (100 *μm*), and the average output power is 20 *mW*. The divergence of the Gaussian beam generated by THz source is 22.5°, so the beam waist width is 0.075 *mm* theoretically. As to the THz imager, the number of pixels is 320×240. The pixel size is 23.5 *μm*×23.5 *μm*, so the active area is 7.52 *mm*×5.64 *mm*. The frequency response is in 1-7 *THz* range. To detect the continuous-wave power, there is a frequency chopper enclosed inside. The chopping frequency is set at 30Hz. Besides, the effective focal length of the convex lens is 25.8 *mm*, the material of which is TPX.

In experiment Ⅰ, the distance between THz laser and the convex lens is 19 *mm*, and the distance between the convex lens and the THz imager could be changed from 36 *mm* to 52.5 *mm*, for the position of the THz imager could be altered.

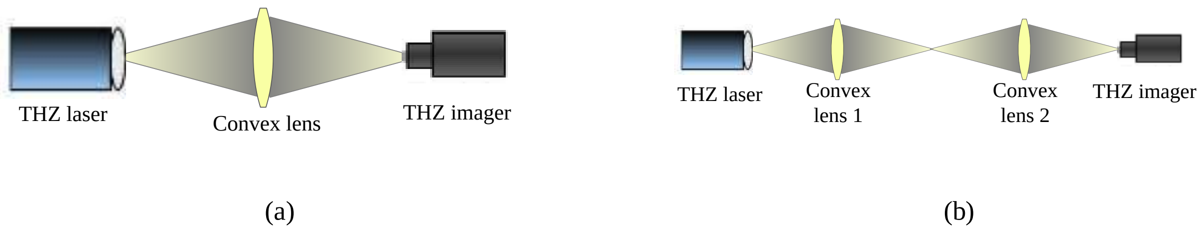


Fig. 1 Setups for experiment Ⅰ (a) and experiment Ⅱ (b)

However, the divergence of the output Gaussian beam in experiment Ⅰ is still not satisfying, which would be interpreted later, though it does have been improved a lot. To reduce the divergence further, two convex lenses are exploited in experiment Ⅱ. The specifications of the equipment in experiment Ⅱ are the same as experiment Ⅰ, including the newly added convex lens (convex lens 2). The distance between THz laser and convex lens 1 is 23 *mm*, between the two convex lenses is 41.5 *mm*, between convex lens 2 and THz imager ranges from 43 *mm* to 163 *mm*.

3. Results and discussion

In experiment Ⅰ and experiment Ⅱ, the spot size expands gradually as the THz imager moves away from the convex lens in the propagation axis. Three spot imaging results are selected for each experiment from numerous results to demonstrate this trend, as is shown in figure 2 and figure 3.

In fact, Gaussian profile could not be revealed from the above imaging results. However, at each plane perpendicular to the propagation direction, the beam does show a Gaussian profile. 3-D Gaussian beam image is shown in figure 4(a). Figure 4(b) displays 2-D Gaussian beam image when we choose a vertical plane which passes the highest irradiance point in figure 4(a).

From the designer's point of view, beam width is one of the most interesting parameters. The function *w(z)* describes the evolution along the propagation direction z of the points having a decrease of *1/e* in amplitude, or $1/e^2$ in irradiance with respect to the amplitude at the propagation axis, which can be described by equation 1.

$$w(z) = w_0\sqrt{1+\left(\frac{\lambda z}{\pi w_0^2}\right)^2} \tag{1}$$

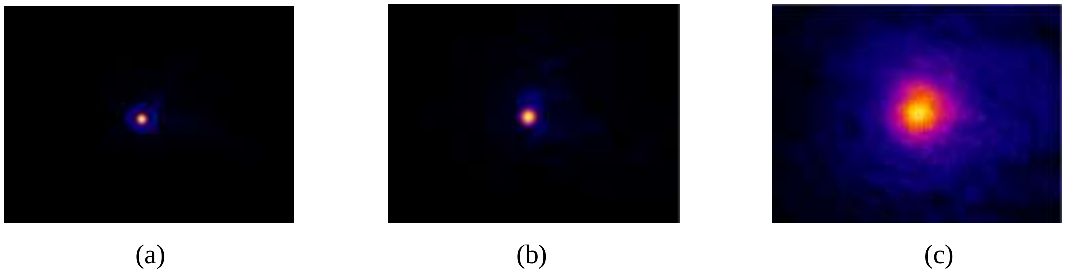

(a) (b) (c)

Fig. 2 The spot size in experiment Ⅰ at the distance (between the convex lens and THz imager) of (a) 37.2 *mm*, (b) 39.5 *mm* and (c) 45.5 *mm*.

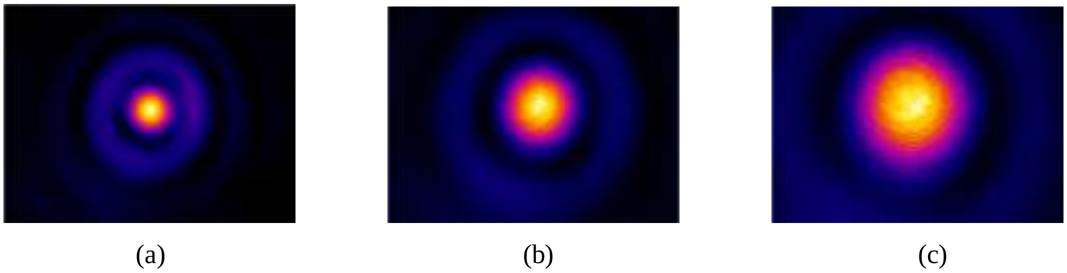
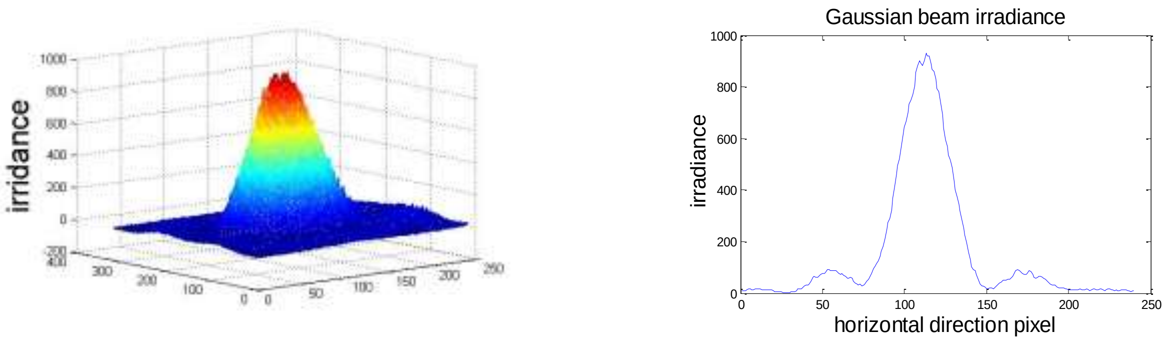

(a) (b) (c)

Fig. 3 The spot size in experiment Ⅱ at the distance (between convex lens 2 and THz imager) of (a) 76 *mm*, (b) 115 *mm* and (c) 150 *mm*.



（a） (b)

Fig. 4 3-D (a) and 2-D (b) Gaussian beam image

It should be noted that *w(z)* depends on λ, where λ is the wavelength in the material where the beam is propagating. From equation 1, we can see that it reaches a minimum at $z = 0$, this being the minimum value of w_0. This parameter, which governs the rest of the evolution, is usually named as the beam waist width. The width reaches the minimum at the waist and then the beam expands. [3]

Using the theory mentioned above and the definition of beam width, the beam widths at various positions in experiment Ⅰ and experiment Ⅱ are calculated.

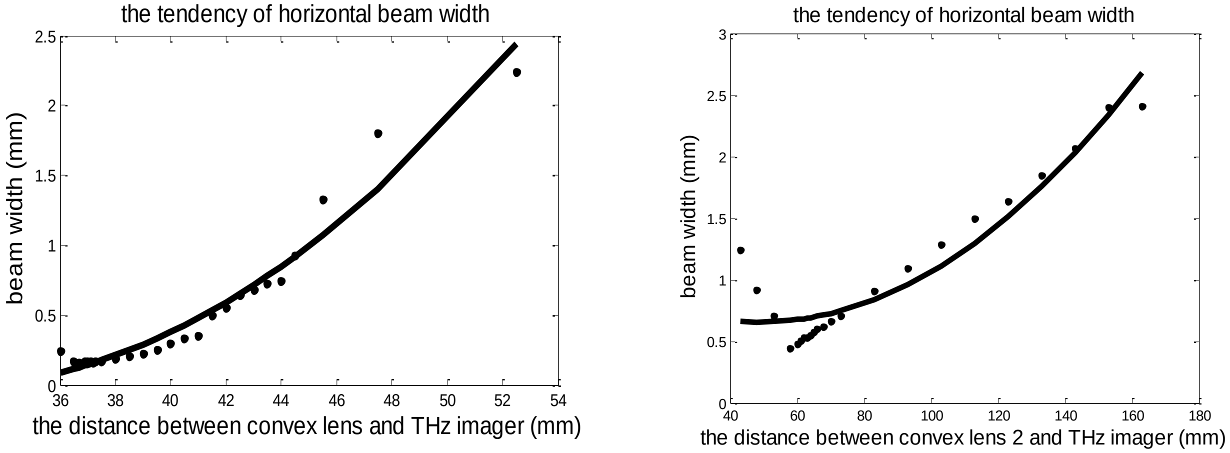
For simplicity, two figures concerning beam width in the horizontal direction are put forward, one for each experiment, as the variation trend of beam width in the horizontal and vertical direction has no significant difference in the both experiments. To illustrate the tendency of beam width, the method of curving fit is used in the data processing. From figure 5, it can be concluded that the tendency shows good agreement with corresponding theory.

Last but not the least, we turn our attention to the optimization of divergence. Divergence of the Gaussian beam describing the spreading of the beam when propagating towards infinity can be expressed as

$$\theta_0 = \frac{\lambda}{\pi w_0} \tag{2}$$

From this equation, we see that the divergence and the width are reciprocal parameters. This means that the larger values of the width mean the lower values of the divergence, and vice versa. Using this relation, we can conclude that a good collimation (very low value of the divergence) will be obtained when the beam is wide. On the contrary, a high focused beam will be obtained by allowing a large divergence angle [4].

In table 1, it can been seen that the usage of one convex lens results in the decrease of divergence from 22.5° to 10° or so in the experiment Ⅰ. Correspondingly, the beam waist width experiences an incline as well. In the experiment Ⅱ, the divergence has dropped sharply to 3.2° in the horizontal direction and 2.6° in the vertical direction by virtue of the two convex lenses. Moreover, the beam waist widths jump to 0.528 *mm* and 0.646 *mm* respectively.



(a) (b)

Fig. 5 The tendency of horizontal beam width in experimentⅠ(a) and experimentⅡ(b)

Tab. 1 Beam waist width in in experimentⅠ and experimentⅡ

Experiment	**Direction**	**Beam waist width（mm）**	**Divergence(°)**
experimentⅠ	horizontal	0.16568	10.3199
	vertical	0.16332	10.4687
experimentⅡ	horizontal	0.52875	3.2337
	vertical	0.64625	2.6457

4. Conclusion

In summary, convex lenses are used to narrow beam divergence in the both experiments. In experimentⅠ, one convex lens results in the decrease of divergence from 22.5 °to 10 °or so with the increase of beam waist width. In experimentⅡ, the divergence has dropped sharply to 3.2 ° in the horizontal direction and 2.6 °in the vertical direction by virtue of the two convex lenses. Moreover, the beam waist widths jump to 0.528 *mm* and 0.646 *mm* respectively.

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