Detection and identification of illicit drugs using terahertz imaging

Meihong Lu,[a] Jingling Shen,[b] Ning Li, Yan Zhang, and Cunlin Zhang
Department of Physics, Capital Normal University, Beijing 100037, China

Laishun Liang and Xiaoyu Xu
The First Research Institute of Ministry of Public Security of China, Beijing 100044, China

(Received 25 April 2006; accepted 21 August 2006; published online 30 November 2006)

We demonstrated an advanced terahertz imaging technique for detection and identification of illicit drugs by introducing the component spatial pattern analysis. As an explanation, the characteristic fingerprint spectra and refractive index of ketamine were first measured with terahertz time-domain spectroscopy both in the air and nitrogen. The results obtained in the ambient air indicated that some absorption peaks are not obvious or probably not dependable. It is necessary and important to present a more practical technique for the detection. The spatial distributions of several illicit drugs [3,4-methylenedioxymethamphetamine, methylenedioxyamphetamine, heroin, acetylcodeine, morphine, and ketamine], widely consumed in the world, were obtained from terahertz images using absorption spectra previously measured in the range from 0.2 to 2.6 THz in the ambient air. The different kinds of pure illicit drugs hidden in mail envelopes were inspected and identified. It could be an effective method in the field of safety inspection. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2388041]

I. INTRODUCTION

Illicit drugs have been smuggled easily because of the absence of nondestructive inspection technique for illicit drugs hidden in envelopes or luggage. At present, several inspection techniques have been used such as x-ray scanning, canine detection, trace detection, developing millimeter-wave imaging, and infrared imaging. However, each of the techniques has its limitation for the inspection of illicit drugs. The ability of x-ray scanners is limited to identifying the shape but not the type of the drugs. Trace detection and canine detection can be used only if there are detectable signs outside the envelope. Development is also underway in the field of millimeter-wave imaging, but the identification of the drug type is difficult because of the lack of fingerprint spectra in this region. As for infrared imaging, in which fingerprint do exist, has an inexact measurement because of the high absorption and scattering. Therefore, an effective technique is necessary to make up the limitations of the enlisted techniques for the inspection and identification of illicit drugs, considering the facts of the emergence of new-style illicit drugs and the increasing smuggling rampancy.

The terahertz spectral region (10^{11}–10^{12} Hz), which occupies an extremely large portion between the infrared and microwave bands, is a scientifically rich frequency band. Because of the low energy of 1 THz photon and the transparence of terahertz ray for paper, plastic bags, etc., and a nondestructive inspection can be achieved. In the detection of illicit drugs, we have studied the spectra features of several illicit drugs in the terahertz wave band.[1,2] Experimental and calculated results had demonstrated that terahertz time-domain spectroscopy (TDS) technique can be an effective way to inspect illicit drugs. However, the inspection will not be feasible if the inspected samples have not obviously absorption peaks. Therefore, it is necessary to present another technique. Terahertz imaging is a promising nondestructive technology based on its high transmission through selected dielectric materials and its capability to provide spectral information. Although there have been a report on the terahertz imaging of 3,4-methylenedioxymethamphetamine (MDMA) and methamphetamine (MA) using terahertz parametric oscillator,[3–5] there are few studies on the identification of a series of illicit drugs.

The absorption and refractive index spectra of ketamine measured with terahertz TDS were obtained. Results demonstrated that the detection for illicit drugs with terahertz TDS must depend on the fingerprint spectrum and dry surrounding environment. By using the technique of terahertz imaging, the spectra and images data of several different illicit drugs were obtained in the ambient air. Results confirmed that the detection and identification of illicit drugs hidden in mail envelopes were feasible and credible. In the process of identification, what we need were only data of image and absorption spectral information of samples; no specific features of samples spectra were required. Compared with other inspection techniques, not only the shape but also the type of illicit drugs can be determined accurately by using the terahertz imaging technique.

II. EXPERIMENT SETUP

The schematic experimental setup used for two-dimensional terahertz scanning imaging is shown in Fig. 1, which is similar to a typical terahertz TDS system. A mode-locked Ti:sapphire laser beam with 100 fs pulse duration and an 80 MHz repetition rate at a central wavelength of 810 nm is used. The laser beam is separated into two, the pump light

[a]Present address: Changzhi College, Changzhi City of Shanxi Province 046011; electronic mail: lmhxueer@sohu.com
[b]Author to whom correspondence should be addressed; electronic mail: sjl-phy@mail.cnu.edu.cn

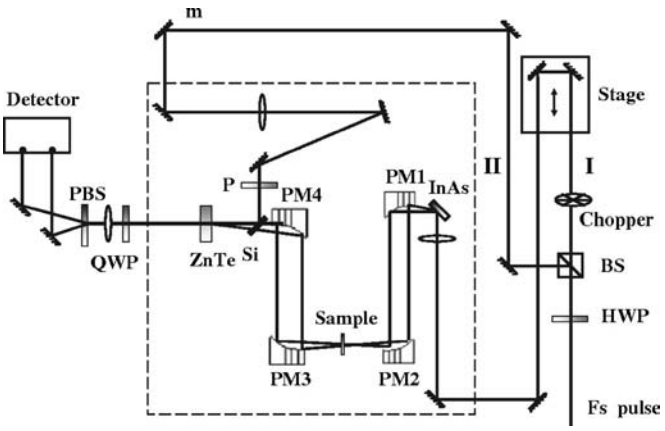

FIG. 1. Schematic diagram of the terahertz imaging system.

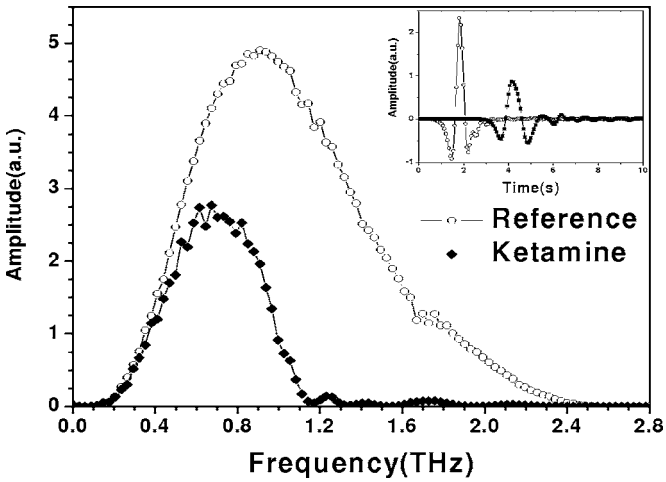

FIG. 2. The time-domain spectra and the corresponding frequency-domain spectra.

to illuminate terahertz emitter and the probe light to drive the terahertz detector. Terahertz pulse is generated from the semiconductor surface of ⟨100⟩ InAs crystal. After the emitter, the first pair of parabolic mirrors in the path of terahertz beam collimates and focuses the terahertz beam onto the sample to be imaged, producing a nearly frequency-independent focal spot size of 1.5 mm. The sample is mounted on a translation stage that can be moved in the *X*-*Y* plane perpendicular to the terahertz beam and be controlled by computer during the data acquisition. The other pair of parabolic mirrors collects and recollimates the transmitted pulse and focuses it onto the ⟨110⟩ ZnTe crystal. The output signal is fed to a lock-in amplifier. The time constant of lock-in amplifier is 100 ms. After passing through an analog-to-digital (A/D) conversion board the output signal of the lock-in amplifier is recorded and stored in the computer during the continuous motion of the sample. This system measures the far-infrared spectrum between 0.1 and 2.6 THz with a spectrum resolution better than 10 GHz. The dynamic range is greater than 3000 and the signal-to-noise ratio (SNR) at the peak value position is about 600. In the experiment, the atmospheric moisture near the sample is less than 22% and the temperature is around 21 °C.

The object measured in the experiment contained two groups. One group was consisted of four pure different illicit drugs (MDMA, acetylcodeine, heroin, and morphine) to realize the identification among drugs. The other group was consisted of four samples in which contained two different drugs and two simple chemical samples [ketamine, methylenedioxyamphetamine (MDA), antipsychotic, and vitamin] to realize the identification among drugs and other chemicals. The drugs samples purified above 90%, provided by the First Research Institute of the Ministry of Public Security of China, were all typical illicit drugs abused in the world. In preparing of the samples, the powder drugs were mixed with polyethylene powder in different proportions and pressed into disks of 13 mm in diameter with a force of 5 tons. Both the surfaces of the disks were smooth and parallel and their thicknesses were about 1 mm.

III. EXPERIMENT AND DATA PROCESSING

Since the vibration and rotation states of many organic molecules and the low frequency vibration of crystal lattice lie in terahertz wave band, their identification can be made by terahertz characteristic absorption spectra fingerprint. However, the detection will not be credible in the ambient air. As an explanation, one of the samples, ketamine, was measured with terahertz TDS both in the ambient air and nitrogen. Figure 2 shows the time-domain spectra which passing through nitrogen directly and the corresponding frequency-domain spectra obtained by fast fourier transform algorithm, in which terahertz pulse without passing through any samples is set as the reference while that passing through the drugs is set as the sample. It is clear that the terahertz pulse is delayed due to the refractive index of the sample and the amplitude is attenuated due to its absorption. Figure 3 shows the refractive index spectrum and the absorption spectrum obtained by the formula $-\log(I_s/I_r)$, where I_s is the terahertz intensity of the sample and I_r is the terahertz intensity of the reference. The curve (a) with star symbol and (b) with square symbol correspond to the absorption spectrum measured in the nitrogen and in the ambient air, respectively. Figure 3(a) indicates that ketamine has a high absorbance at the frequencies of 1.16, 1.35, 1.52, 1.94, and 2.38 THz. Analyzing every absorption peak, a visible change is shown between 1.1 and 2.4 THz in the refractive index spectrum,

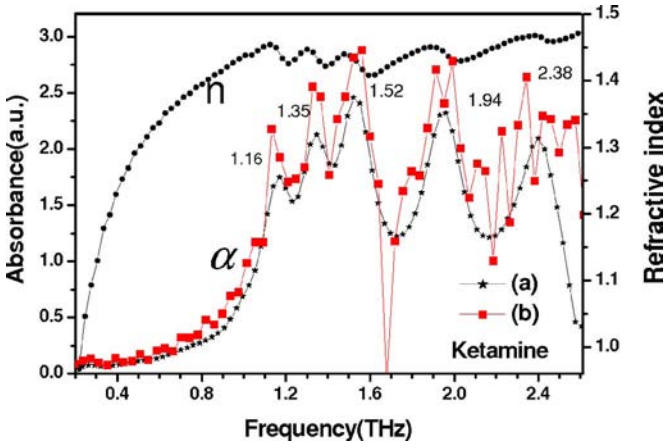

FIG. 3. (Color online) Refractive index (n) and absorption spectra (α) of pure ketamine both in (a) nitrogen and in the (b) ambient air.

which means that the abnormal dispersion is *always accompanied by a corresponding absorption peak*. From Fig. 3(b), it is clearly indicated that some absorption peaks are not obvious or not credible because of the influence of water vapor.

In order to explain the absorption spectrum better, theoretical calculation could be done using GAUSSIAN03 package.[1] The absorption peaks usually correspond to intermolecular modes or lattice vibrations for different crystal structures. Therefore, the existence of fingerprint spectra of illicit drugs in the terahertz band is the base for detection and inspection of illicit drugs nondestructively by using terahertz TDS. Due to the strong penetrability for cloths, paper bags, and leathered or plastic luggage, terahertz TDS would be a promising candidate for illicit drug detection and inspection. However, the detection with terahertz TDS is accurate only if the measurement is made in the nitrogen to eliminate the influence of the water vapor in the air and increase the SNR. While, terahertz imaging, a promising technology introduced on the following can be expected to eliminate the limitation. It will *only depend on the shape of the absorption spectra* instead of the absorption peaks of detected samples.

In the process of the terahertz point-by-point scanning imaging, the samples were placed on the focal point of the second parabolic mirror and can be moved in the *X*-*Y* plane perpendicular to the terahertz beam by using two crossed motorized translation stages (the range of scanning was 25 $\times 25$ mm^2). At every *x*-*y* position, a complete terahertz time-domain wave form was recorded by scanning the delay line. The obtained time-domain data were converted to frequency domain by Fourier transform. Thus a great deal of spatial and spectral information about the samples was collected.

The absorption spectra of samples in the two groups measured with terahertz TDS in the ambient air are shown in Figs. 4(a) and 4(b). It is clear that the eight different samples have different spectral curves, which result from their different chemical structures. Just the difference between them enabled us to realize the detection and identification.

To implement the identification of the samples, a component spatial pattern analysis method was employed in the data processing.[6] The principle of the method is briefly described as follows. The studied object consisted of M substances that have different spectral characteristics was imaged in the whole useful range from 0.2 to 2.6 THz. *Assuming that the imaging system is linear*, the transmitted intensity can be described as

$$[I] = [S][P], \tag{1}$$

where $[I]$ is a matrix of the observed sample image, $[S]$ is a matrix of the measured absorption spectra, and $[P]$ is a matrix of the spatial distribution of the samples. When this matrix equation is solved by the use of the least-squares method, matrix $[P]$ can be described by

$$[P] = ([S]^T[S])^{-1}[S]^T[I], \tag{2}$$

where T denotes the matrix transposition operate. Therefore, if the matrices $[S]$ and $[I]$ were measured, the spatial distribution of each sample or a specific component in a sample can be obtained. As the incident terahertz waves were mainly attenuated by absorption in the samples, the logarithm of the ratio of the detected intensity of the sample divided by the reference intensity of terahertz frequency spectrum was taken for the elements of matrix $[I]$ in the analysis.

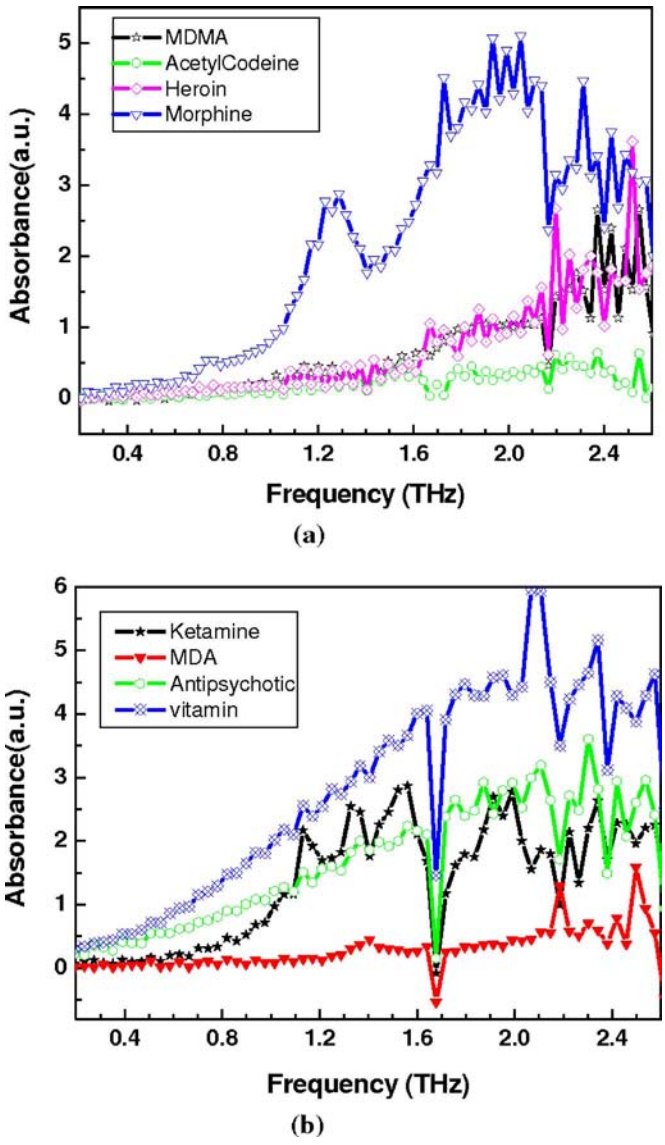

FIG. 4. (Color online) (a) Absorption spectra of MDMA, acetylcodeine, heroin, and morphine. (b) Absorption spectra of ketamine, MDA, antipsychotic, and vitamin.

In the data processing of identification, the *absorbance* of each sample was *extracted* to form the matrix $[S]$. After obtaining the matrix $[I]$ from the observed image and $[S]$ from the absorption spectra, the spatial pattern $[P]$ can be calculated by substituting known $[S]$ and $[I]$ into Eq. (2). As long as the absorption spectra and images of samples were determined, the corresponding spatial patterns were extracted from terahertz images. The terahertz images of the samples and the spatial patterns of different samples in each group extracted from this matrix were showed in Figs. 5 and 6, respectively. Figure 5(a) represents the transmitted terahertz image of the first sample group and each image in Fig. 5(b) corresponds to each of the sample drugs in the group. It can be clearly seen from the images that the four different drugs had been identified and the corresponding spatial patterns

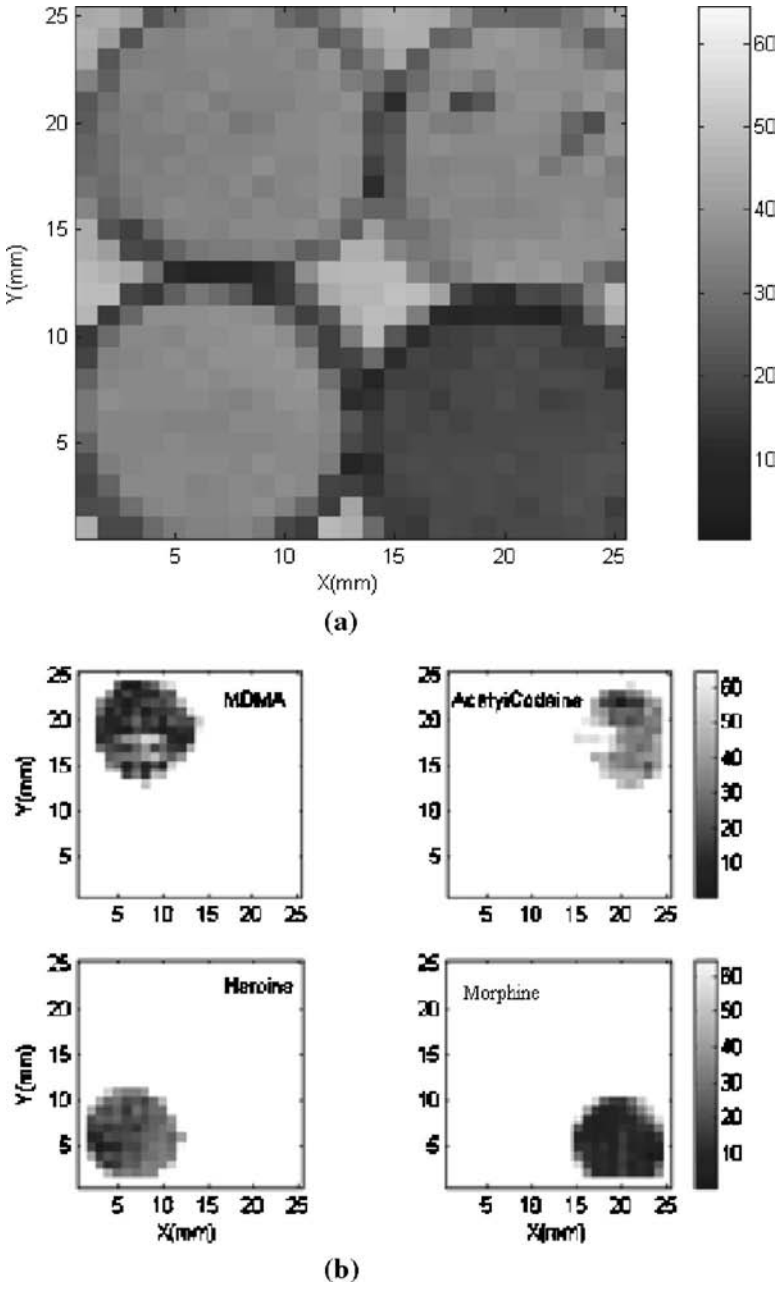

FIG. 5. (a) A scanning transmitted terahertz image generating a matrix [*I*]. (b)The extracted spatial patterns of MDMA, heroin, acetylCodeine, and morphine. The four different illicit drugs contained in an envelope are clearly separated and corresponding spatial patterns obtained.

were obtained. Meanwhile, as it was evident from Fig. 6, which is the corresponding images of the second sample group, the identification between drugs and other chemical samples, vitamin and antipsychotic, were also realized.

IV. CONCLUSION

The above terahertz imaging technique by introducing component pattern analysis has particular advantages in the use of inspection and detection. Whenever a collective image of an object, in which several separated pure chemicals or a single mixture are included, and an absorption spectral information of the each chemical in the object are measured, patterns of each chemical as well as the components in the mixture can be extracted from the terahertz image. Especially, a rough difference in the shape of terahertz absorption curve is enough for the extraction. Therefore, this technique is especially suitable for the detection and identification of the samples, which have no characteristic absorption peaks in the terahertz range. In addition, the measurement in the air makes the identification more practical. These make up for the insufficiency that fingerprint spectra and dry condition needed in using the terahertz TDS for the detection and inspection. Along with the demonstration of the identification ability of different samples, the measurements for accurate concentrations of contents in mixtures or overlapped samples are deserved to be explored and the detection of components and even their percentages is possible.[7]

In conclusion, we have given the fingerprint spectra of drugs and demonstrated the identification and separation of illicit drugs using terahertz imaging technique. We determined the existence, the type, and the spatial distribution of different illicit drugs. Results confirmed that the nondestructive detection of prevalent illegal drugs hidden in envelopes were feasible. Much better results will be obtained with im-

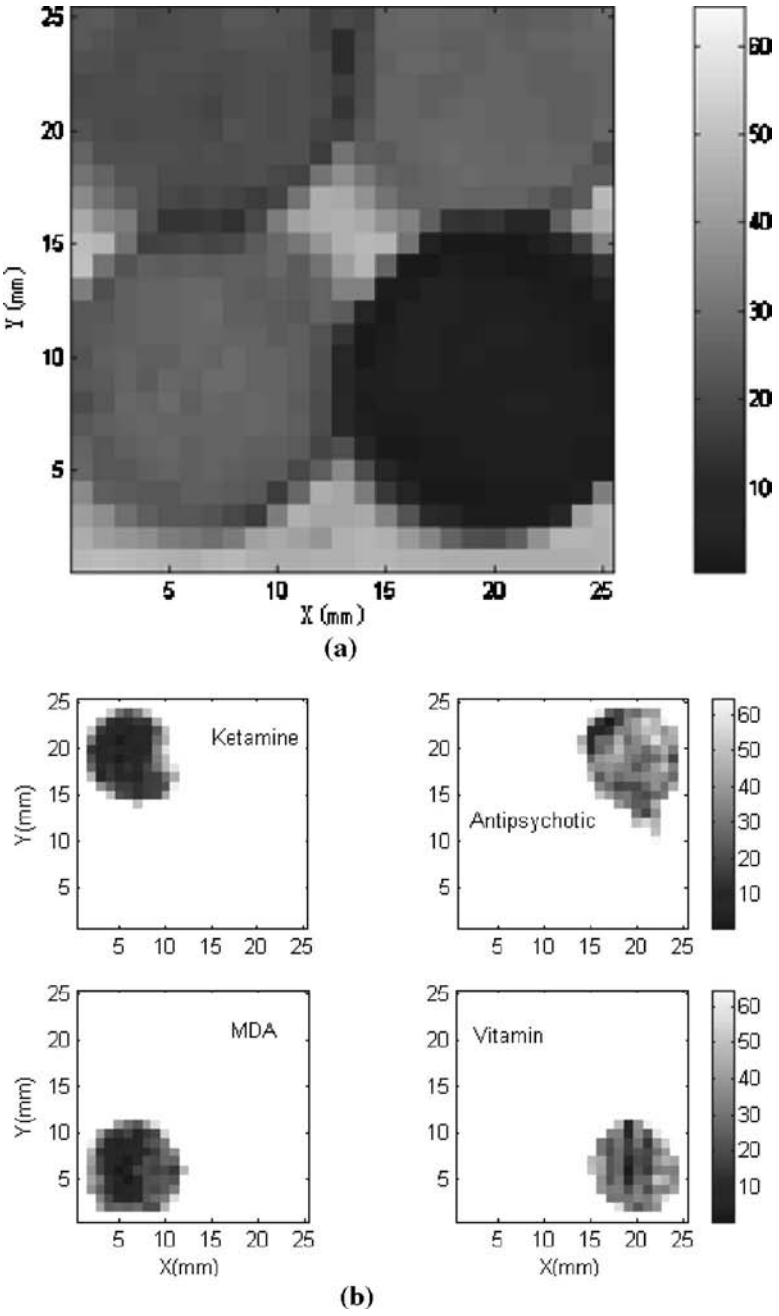

FIG. 6. (a) A scanning transmitted terahertz image generating a matrix [*I*]. (b) The extracted spatial patterns of ketamine, MDA, vitamin, and antipsychotic. Two different illicit drugs and other chemicals contained in an envelope are clearly separated and corresponding spatial patterns obtained.

proved imaging system and a charge-coupled device (CCD) electro-optic sampling system will enable us to shorten the data acquisition time dramatically in comparison with the scanning imaging. This is a *significant development* toward real-world applications of terahertz imaging. This technique provides a new promising approach to detect and identify the illicit drugs, as well as to frisk risk packages, inspect the quality of pharmaceuticals, determine component, etc.

ACKNOWLEDGMENTS

This work is supported by the Natural Science Foundation of Beijing and the Science and Technology Program of Beijing Educational Committee under Grant No. KZ200610028016, the Natural Science Foundation of Beijing under Grant No. 6032006, and the National Natural Science Foundation of China under Grant No. 10390160. The authors thank Li Yan-hong and Chen Si-jia for the informative discussions.

[1]Li Ning, Shen Jingling, Sun Jinhai, Liang Laishun, Xu Xiaoyu, Lu Meihong, and Jia Yan, Opt. Express **13**, 6750 (2005).
[2]Sun Jin-hai, Shen Jing-ling, Liang Lai-shun, Xu Xiao-yu, Liu Hai-bo, and Zhang Cun-lin, Chin. Phys. Lett. **22**, 3176 (2005).
[3]K. Kawase, Y. Ogawa, and Y. Watanabe, Opt. Express **11**, 2549 (2003).
[4]Y. Watanabe, K. Kawase, T. Ikari, H. Ito, Y. Ishikawa, and H. Minamide, Appl. Opt. **42**, 5744 (2003).
[5]K. Kawase, Opt. Photonics News **15**, 34 (2004).
[6]S. Kawata, K. Sasaki, and S. Minami, J. Opt. Soc. Am. A **4**, 2101 (1987).
[7]Y. Watanabe, K. Kawase, H. Ito, Y. Ishujawa, and H. Minamide, Opt. Commun. **234**, 125 (2004).