

Terahertz Spectroscopy and Imaging for the Detection and Identification of Illicit Drugs

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Abstract—Recently, Terahertz technologies, due to the extensive research and tremendous progress achieved in the field of Terahertz radiation, promise countless potential applications in the fields of security and defense. A particular interest is the development of new technologies that enable the identification of concealed prohibited drugs. This paper surveys the existing research which investigates the utilization of Terahertz spectroscopy and imaging in the detection and identification of illicit drugs. It sheds light on the terahertz time domain spectroscopy which is used to obtain the Terahertz fingerprint spectra of drugs-of-abuse. It also focuses on various Terahertz imaging techniques that are used to probe the presence of illegal drugs by penetrating packaging and concealment materials. Furthermore, this paper addresses current challenges and future research areas for the security application of Terahertz technologies.

Index Terms—Terahertz Spectroscopy, Terahertz-TDS, Illicit Drugs, Terahertz Fingerprint Spectra.

I. INTRODUCTION

The recent increase in worldwide criminal and terrorist action rates has led to a dire need of enhanced security sensing and screening technologies at border lines. The latest research and development of defense and security applications prove that Terahertz technologies are promising for the detection and identification of concealed weapons, explosives and illicit drugs [1]. The Terahertz (Terahertz) Band is the band that conventionally spans frequencies between 0.1 Terahertz and Terahertz. Terahertz radiation occupies a large portion of the electromagnetic spectrum between microwaves and infrared light waves, as shown in Fig. 1 [2].

Slight variation to the range of the Terahertz band is adopted by different authors [3]. Due to the extensive research and tremendous progress achieved in the field of Terahertz radiation in the span of two decades, the once-known 'terahertz band gap' promises countless potential applications in the field of science and technology [4]. Such applications include the fields of communication [2], biology and medical sciences [5], [6] and space instrumentation [7].

In particular, there has been an interest in implementing Terahertz technologies in the disciplines of defense and security and utilizing them for the detection and identification of concealed prohibited items [8]. This technique would prove to be beneficial in preventing illegal movement of weapons, drugs and contraband, while promoting lawful entry and exit

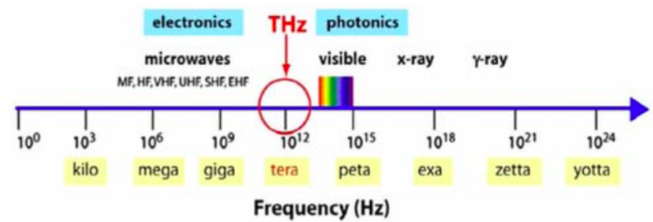


Fig. 1: Terahertz radiation occupies the electromagnetic spectrum between microwaves and infrared light waves [2]

of a country in question. There are several factors contributing to the interest in using Terahertz radiation in security systems. One attractive feature of Terahertz radiation is its capability to be transmitted through non-polar and non-metallic materials such as paper packaging, plastics, cardboard boxes and clothing. This enables non-destructive or non-invasive Terahertz imaging of potentially dangerous material since Terahertz screening devices are able to 'see' past barriers concealing such items [9].

Another point of interest stems from the fact that Terahertz waves are characterized by their low photon energies that would not cause detrimental photoionization in organic tissue. Thus, Terahertz imaging and sensing may be regarded as a safe alternative to X-ray scanning techniques for both the operators and targets [9], [10]. An additional promising aspect of Terahertz technologies is the ability of many prohibited materials to possess distinctive absorption features at the Terahertz range. These features, which form the 'fingerprint spectra', enable the unique identification of proscribed chemical agents [9], [10].

While developments in detecting concealed weapons and explosives through Terahertz spectroscopy and imaging techniques are on the rise [11]–[13], the rate of drug smuggling through air mail and packages across international borders and provincial cities is skyrocketing as well. In fact, there are scarce amounts of literature published on the detection of drugs-of-abuse. According to [14], this may be attributed to the lack of non-destructive and non-invasive inspection techniques. Violating the contents of envelopes and packages to examine them for drugs is considered a federal offence if a search warrant is not granted. An alternative inspection

technique involves scanning the packages through an X-ray scanner, which could only detect shapes of possible drug bags or tablets without classifying drug types [14]. One could argue that canine or trace detection procedures are sufficient; however, the author in [14] clarifies that such techniques are only efficient if there are traces of the concealed chemical outside the package.

This paper surveys the existing research which investigates the use of Terahertz spectroscopy in the detection of illicit drugs. It also focuses on characterizing the 'fingerprint spectra' affiliated with specific types of drugs-of-abuse. Terahertz imaging is also regarded in this overview since it is proposed to enable the detection and identification of concealed illegal drugs in air-mail packages. Furthermore, this paper proposes some future research areas.

The rest of the paper is organized as follows. In Section II, we present the terahertz time domain spectroscopy. The characterization and absorption spectra of drugs-of-abuse are described in Section III. In Section IV, Terahertz imaging techniques are exemplified. Finally, we draw our conclusions and summarize the paper in Section V.

II. TERAHERTZ TIME-DOMAIN SPECTROSCOPY

For a relatively long time, the Terahertz band was known as the 'terahertz gap' owing to the difficulty of fabricating solid-state practical technologies for generating and detecting the radiation [1]. Hence, researchers have shifted their focus to creating optical technologies capable of handling Terahertz radiation. A technology widely adopted by researchers is the terahertz time-domain spectroscopy (Terahertz-TDS); a spectroscopic technique in which the properties of a material are probed with short pulses of Terahertz radiation.

A typical Terahertz-TDS arrangement is shown in Fig. 2 [3]. In general, an ultra-short pulsed laser emits short pulses, lasting a few tens of femtoseconds. The pulses are divided by a beam splitter and are directed towards the Terahertz-emitter and Terahertz-detector. In this case, the Terahertz-emitter is a low-temperature-grown GaAs that generates terahertz pulses, where each single pulse contains frequency components covering much of the terahertz range. The emitted Terahertz pulses are focused onto the sample and the reflected pulses are detected by a ZnTe electro-optic crystal. A delay line introduces a variable time delay between excitation and detection of the Terahertz-pulse, enabling the reconstruction of the Terahertz pulse's electric field as a function of time. Successively, a Fourier transform is performed to extract the frequency spectrum from the time-domain data.

While the schematic diagram exhibits a reflection arrangement, it is important to note that various studies employ Terahertz spectroscopy in a transmission mode [3]. Terahertz reflection spectroscopy has a greater potential for stand-off detection of contraband concealed under clothing or 'bulky' packages. In contrast, a transmission arrangement is often adopted for the exposure of small quantities of drugs [9].

The absorption spectra of cocaine free base and cocaine hydrochloride, obtained by Terahertz-TDS, are shown in (Fig.3a)

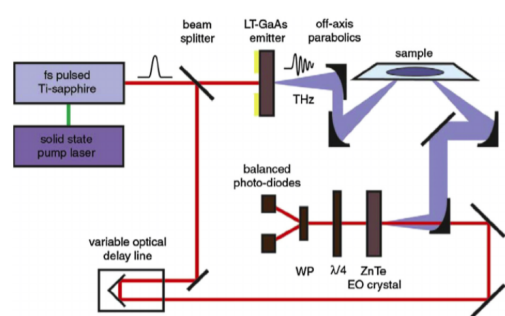


Fig. 2: Schematic of a Terahertz-TDS system. Terahertz pulses are generated by a low-temperature-grown (LT)- GaAs and subsequently detected, by electro-optic sampling using a ZnTe electro-optic crystal [3].

in an effort to validate the utilization of Terahertz technologies in the identification of illicit drugs [3]. Although the two drugs-of-abuse are chemically similar, their absorption spectra in the Terahertz frequency range are visibly distinct. This goes on to show that Terahertz-TDS can provide vital spectral information for sample analysis. The frequency spectra of the same materials, obtained using Raman spectroscopy, are illustrated in Fig. 3b. The spectra are overlapping; thus, demonstrating difficulty in identifying separate drugs.

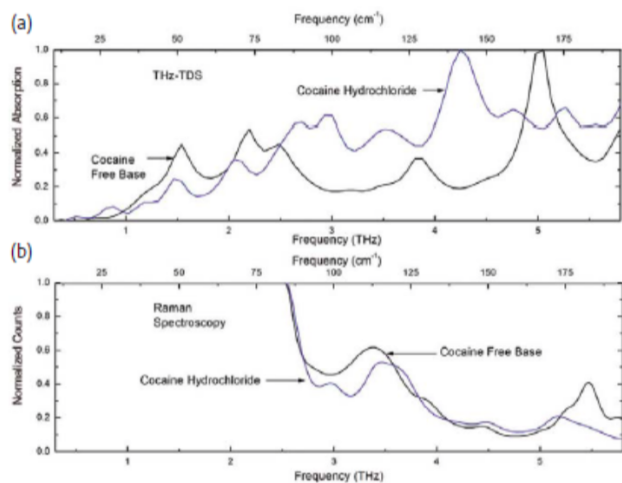


Fig. 3: Absorption spectra of cocaine free base and cocaine hydrochloride obtained by (a) Terahertz-TDS and (b) Raman spectroscopy [3].

III. FINGERPRINT SPECTRA OF ILLICIT DRUGS

To obtain the Terahertz absorption spectrum of a specific prohibited material, a sample of the material is investigated by Terahertz-TDS. Samples are conventionally prepared by mixing pure drugs with an inert filler material and compressing it to create a pellet [9]. Often, polyethylene (PE) or polytetrafluoroethylenes (PTFE) act as filler materials due to their high transparency in the Terahertz range. This process dilutes

concentrations of pure drugs that would, otherwise, exhibit high absorption characteristics [3],[15].

The Terahertz absorption spectra of seven proscribed drugs-of-abuse are shown in Fig. 4. Common illicit drugs include, but are not limited to, cocaine free base, cocaine hydrochloride, MDMA, ephedrine hydrochloride, amphetamine sulfate, heroin, and morphine sulfate pentahydrate. Each proscribed drug is characterized by a different absorption spectrum with sharp absorption peaks located within the Terahertz frequency range. The authors in [9] created an abbreviated summary of drugs and their absorbance peak positions. The numbers provided, along with the data extracted from [15], are tabulated in Table I.

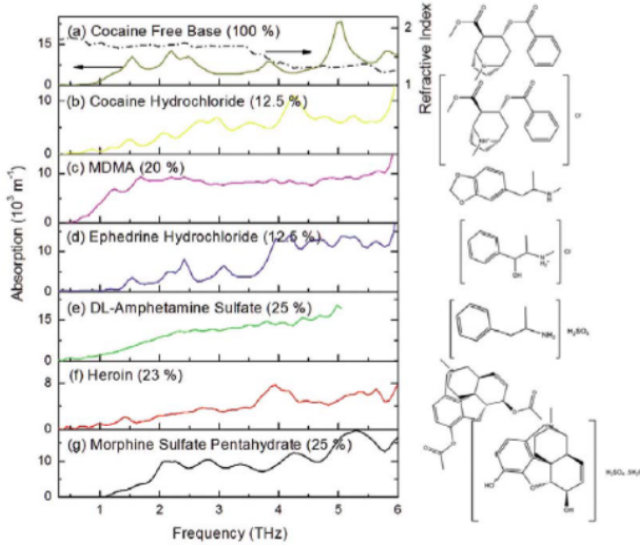


Fig. 4: Terahertz absorption spectra of seven common drugs-of-abuse [9].

TABLE I:
A Collection of Absorbance Peak Positions of Some Drugs [9], [15].

Drugs	Feature band center position frequency (Terahertz)
Cocaine 'Coke'	1.54
Methamphetamine	1.2, 1.7-1.8
MDMA 'Ecstasy'	1.24, 1.71, 1.9
Aspirin, soluble	1.38, 3.26
Aspirin, caplets	1.4, 2.24
Diamorphine 'Heroin'	1.42, 3.94
Acetaminophen	6.5
Terfenadine	3.2

It is worth noting that in real-world 'street' samples, drugs-of-abuse are most likely contaminated with impurities. These impurities are crystalline organic materials such as pharmaceutical drugs, caffeine, or lactose that possess distinctive

spectral features in the Terahertz range. Thus, the sample analysis would result in a challenging identification process. The authors in [15] obtained the Terahertz spectra of 'street' drug samples from the United Kingdom Forensic Science Service. When comparing them to the spectra of pure drugs, it was concluded that various impurities may obstruct the ease of illicit drug identification. Nonetheless, pinpointing drugs-of-abuse in a mixed sample can still be achievable.

IV. TERAHERTZ IMAGING

While the research governing the adoption of Terahertz imaging schemes for security and defense applications is still in its infancy stages, researchers have shown interest in its competency in detecting the presence of illicit drugs, concealed in envelopes or packages, and differentiating between various types of drugs. Although pre-existing x-ray detection technologies can penetrate packages and view their contents, they lack the ability to distinguish between illicit and pharmaceutical/legal drugs. Their incompetency to do so originates from the lack of spectral fingerprints in their frequency range [9], [14]. On the other hand, infrared imaging enables the differentiation between drugs since their spectral fingerprints exist in the infrared region. However, its major drawback is the lack of accuracy due to the high degree of absorption of packaging material that leads to their opacity [9], [14].

Terahertz imaging technologies are broadly categorized as passive and active techniques [16]. Passive technologies, which are commonly used in body-scanning security systems, utilize the radiation emitted off bodies to detect the shape. Active techniques, on the other hand, use a Terahertz-emitter, that generates Terahertz radiation which illuminates the object, and a Terahertz detector, that measures the reflected or transmitted waves. The innovative active technology proposed by Kawase et al. is considered the first milestone in the development of terahertz imaging [14]. They explored the possibility of identifying illicit drugs packed in mail envelopes. Using a widely tunable Terahertz-wave parametric oscillator (TPO) as a Terahertz source, Terahertz-TDS was used to image and identify specific chemicals by obtaining their Terahertz absorption spectra.

Twenty grams of methamphetamine, MDMA and aspirin (used as a reference) were each placed in a polyethylene bag and, ultimately, inserted in an air-mail envelope, as shown in Fig. 5a. Then, seven Terahertz multispectral images were recorded at different Terahertz frequencies. By analyzing the obtained images using component spatial pattern analysis, the spatial distribution of drugs inside the envelope was extracted. In addition, the authors in [14] experimentally verified the hypothesis of using this technology to extract the spatial patterns of drugs when they are mixed together. Following their breakthrough, the same group of researchers has recently developed a higher power imaging system that uses injection-seeded Terahertz parametric generation (is-TPG) and detection [17]. While Terahertz-TDS was used successfully in the penetration of thin envelopes to detect illicit drugs, it could not

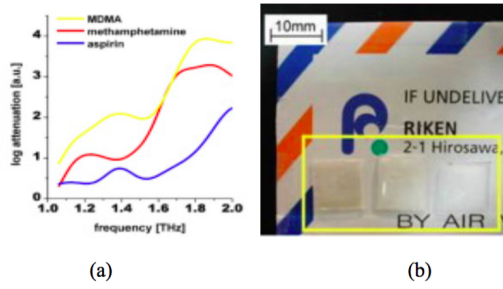


Fig. 5: (a) The polyethylene bags contain from the left: methamphetamine, MDMA and aspirin (b) The distinct absorption spectra of the drugs [14].

be used to penetrate thick packaging materials to probe for the presence of drugs-of-abuse due to its sensitivity to scattering.

Alternatively, Kawase et al. tested the is-TPG as a Terahertz source in a Terahertz imaging system [17]. The samples consisted of three saccharides: glucose, maltose and fructose. Each sample was placed in a polyethylene bag and three types of covering material (EMS envelopes, cardboard and bubble wrap) were used to create a dense barrier. Through spectroscopic imaging in Fig. 6, the three saccharides were correctly identified despite the thick packaging material. The authors [17] point out that spectral imaging could be applied to inspect mail and identify illegal drugs, regardless of the fact that they might be mixed with other chemicals. Further experiments are included in [18].

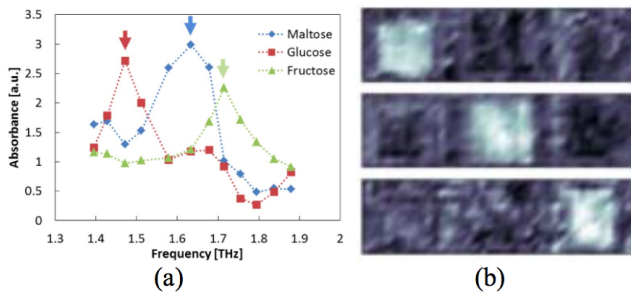


Fig. 6: (a) The distinct absorption spectra of the materials (b) The spectral imaging results (from top: maltose, glucose, fructose) [17].

V. CONCLUSION

This paper presented an overview of the Terahertz spectroscopy and imaging of illicit drugs. The paper addressed Terahertz time domain spectroscopy, the fingerprint absorption spectra of illicit drugs, and the Terahertz imaging systems. The paper also discussed the development of Terahertz security systems as a potential research area. Power and noise levels, attenuation losses and real-world compatibility are few aspects that should be carefully regarded in any upcoming research associated with this field.

ACKNOWLEDGMENT

This work was supported by the National Plan for Science, Technology and Innovation (MAARIFAH), King Abdulaziz City for Science and Technology, Saudi Arabia, under Award 12-INF 2743-03. The authors also acknowledge with gratitude the Science and Technology Unit in King Abdulaziz University for providing technical support.

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