Multicolor Images of Hidden Materials with Interferometry Using THz QCLs

ABSTRACT

Researchers from Beijing, China and Leeds, UK, have developed a self-mixing interferometry system using terahertz (THz) quantum cascade lasers (QCLs) for multicolor imaging of opaque objects. This self-mixing interferometry design enables high sensitivity in detecting a few milligrams of opaque powder inside a polytetrafluoroethylene tablet. By utilizing lasing frequencies of 2.5, 3.3, and 4.2 THz, researchers achieved multicolor spectral images of the tablet samples, illustrating distribution patterns of concealed substances and providing detailed information on the complex refractive index and thickness variation of the samples. This system demonstrates detection capabilities better than microgram-level in the THz band. By using 'fingerprint' spectra from THz spectroscopy for various materials, inspection and identification of explosives, drugs, and biological tissues can be further explored and optimized.

THz DETECTION

Optical detection has become a significant technique for rapid sample inspection and identification. With advancements in lasers, different regions of light can be utilized for unique detection, giving way to non-destructive inspection and identification through spectroscopic characteristics. Many regions of the light spectrum are used for optical detection, but certain bands can take advantage of the unique properties of light and a sample.

In the terahertz (THz) region, lying between the microwave and infrared regions on the electromagnetic spectrum, THz waves can induce THz photon resonance absorption of molecular vibrations and dipole rotations. These properties contain information about the composition, structure, and function of molecules and can only be achieved in the THz region.[1]

THz technology can be useful for imaging, spectroscopy, communications, and interferometry because of these distinct features:

1. Non-destructive testing & non-invasive
2. Spectroscopic fingerprinting a unique absorption spectra in the THz range for identification
3. Real-time imaging and analysis
4. Penetration into non-conductive and non-polar materials which have no complex permittivity changes
5. Non-ionizing and biologically harmless

Other regions have weak interactions with molecular resonances or are limited by poor penetration in solids or liquids. Some regions can be harmful with ionizing radiation. THz waves penetrate non-conductive, non-polar materials effectively because they do not interact with electronic transitions or atomic nuclei. They have better spatial resolution for imaging due to shorter wavelengths (unlike microwaves), and THz waves pass through most non-polar materials with less absorption and don't excite strong vibrational resonances (like infrared). With these characteristics, THz technology can be used for the development of hidden trace residue inspection in military and security applications with hazardous materials.

PROBLEMS AND GOALS

Although THz spectroscopy can be extremely useful for examining concealed substances, there can be challenges with the weak THz signals emitted that are used for analysis. Because the signals need to either penetrate the substance or reflect off the sample, the THz signals captured after emission can be too weak for accurate and repeatable measurements. Many methods for signal enhancement have been implemented in designs: crystal fibers, grating waveguides, metamaterials, and more.[1] Although some of these methods have proven to achieve fast, spectrally selective detection in the THz band, their design and manufacturing can be both time-consuming and costly. Another issue with these techniques is the inability to distinguish and identify different trace-amount substances in complex systems with high sensitivity and accuracy through coherent detection.

For highly sensitive spectroscopy applications, coherent detection can be realized by exploiting the self-mixing (SM) effect in THz quantum cascade lasers (QCLs).[1] This occurs when the laser's emission is reflected into the laser cavity after interacting with an external sample and interferes with the intracavity THz wave. This process turns the THz QCL into a type of oscillator, mixer, and detector due to the sensitivity of the optical feedback of QCLs. With this effect, even small powers of several pW can be detected, ensuring the detection of intrinsically weak scattered signals that THz interactions can produce. Most SM QCL systems operate in a single longitudinal mode or scans within the range of a few GHz due to the complexity of SM interference theory and the performance limit of the laser. This risks losing the 'fingerprint' spectra of THz waves used for analyzing and identifying unknown materials.[1]

A highly sensitive and accurate method is essential for applications detecting and inspecting hidden trace residue. With the right technique, multiple unknown substances can be identified with a simplified and fast spectroscopy system utilizing a special self-mixing design.

METHOD

Researchers from Beijing, China and Leeds, UK, have developed a self-mixing (SM) interferometry system using terahertz (THz) quantum cascade lasers (QCLs) for multicolor imaging of hidden substances in opaque objects. In this design, three THz QCLs are used at different frequencies to obtain multicolor images of a tiny amount of powder inside a polytetrafluoroethylene (PTFE) tablet. With multiple lasers at different frequencies in the THz region, spectroscopic characterizations of the substances can be obtained.

SM interferometry has high sensitivity and, paired with the THz QCLs, has advantageous penetrability from the THz waves to achieve spatial differentiation and material identification of hidden matter. If the target subject is treated as a reflector, a three-mirror model can be established using the target and the end faces of the laser. **Figure 1** shows the SM principle and experimental device. The relationship between the dynamic parameters of the laser and the external target can be obtained by studying the effects of the external feedback light on the dynamic stability of the laser.[1] Because the laser effectively changes due to optical feedback, it is critical that the baseline stability of the laser remains constant.

When light interacts with external objects, the amplitude and phase of the SM signal shift. For the complete SM waveform, the interference must be modulated to obtain this amplitude and phase. Although traditional models modulate the SM interference by changing the optical path length, here researchers change the laser's lasing frequency to avoid limits due to mechanical movement speed. This modulation can be achieved by adjusting the refractive index of the laser itself by changing the excitation current of the laser.

In this research, three THz QCLs are used with center frequencies of 2.5 THz, 3.3 THz, and 4.2 THz. They are placed in a helium-flow cryostat and run at 30 K, 45 K, and 30 K, respectively. **Figure 2** shows the periodic oscillations of each laser as the current increases, including changes in amplitude and width of the periodic signal in some cases due to mode hopping. Because the power of the QCLs increases as the drive current increases, the intensity of the re-injected field back into the laser cavity will change. As the QCLs stabilize in new states amplitude changes and mode jumps are manifested in the SM interference signals. The current modulation ranges for the three THz QCLs to obtain sinusoidal-like periodic SM signal are 0.62-0.67 A, 0.73-0.85 A, and 0.55-0.62 A.[1]

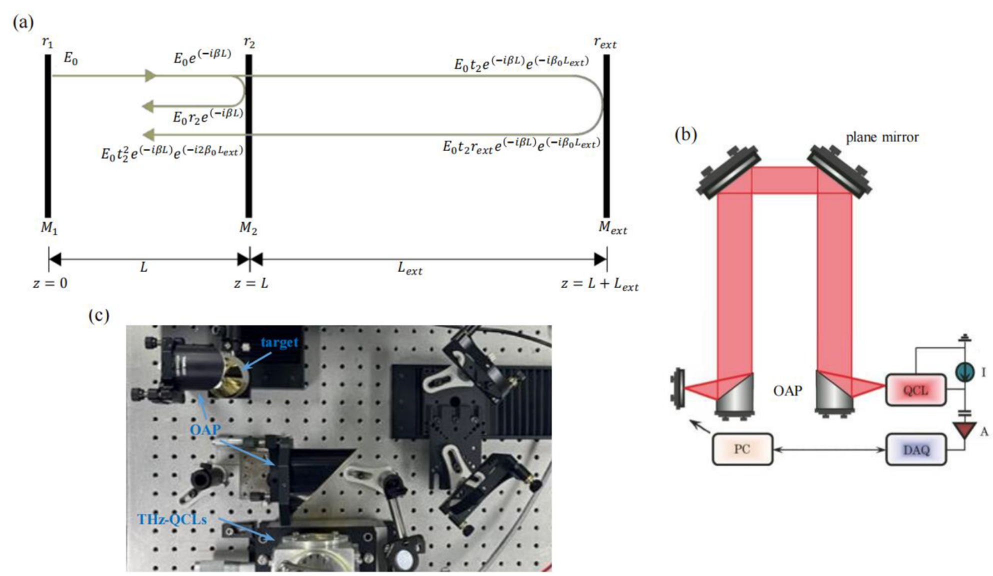

Figure 1. SM interference principle and optical path diagram. (a) SM interference three-mirror model; (b) SM interference detection diagram. DAQ: data acquisition, PC: personal computer, OAP: off-axis parabolic reflector; (c) experimental device photo.[1]

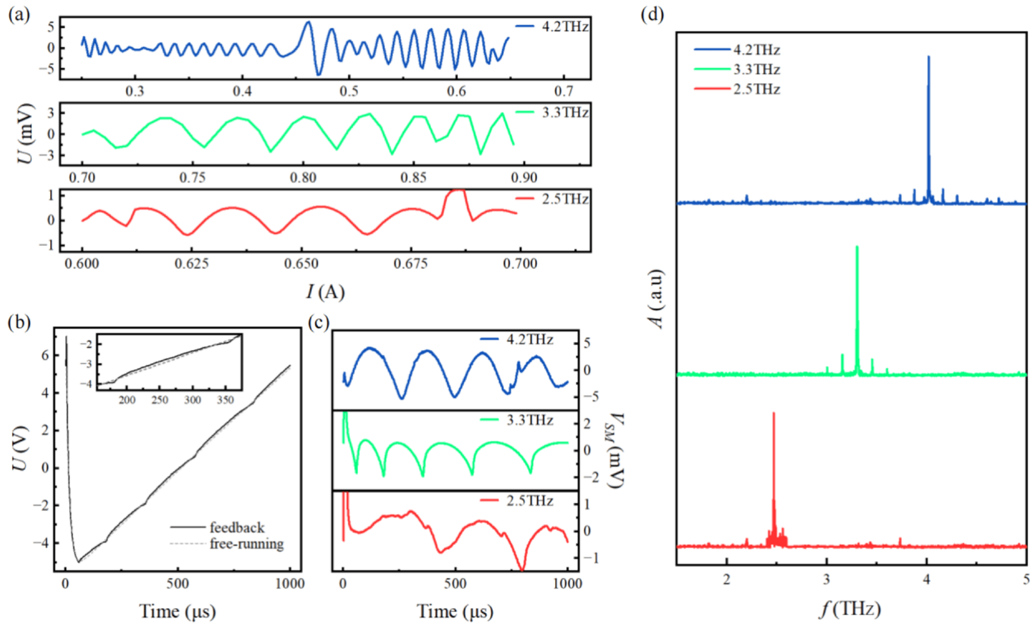

Figure 2. The operating performances of the three THz-QCLs used in this paper. (a) The curves of the SM voltage signal changing with the driving current; (b) the voltage variation in THz-QCLs (3.3 THz) in free running and with optical feedback when loading sawtooth modulation; (c) SM voltage signals under sawtooth modulation; (d) the lasing spectra of the THz-QCLs.[1]

A sawtooth signal was used to modulate the THz QCLs at 1 kHz. **Figure 2**b shows the modulated voltage as free running and optical feedback states. A weak SM signal can be seen superposed on the sawtooth voltage in the inset image. To obtain this SM signal, the voltage signal of the laser in the free-running state is subtracted from the voltage signal of the laser under optical feedback seen in **Figure 2**c.

To test the multicolor imaging system, tiny amounts of glucose and copper oxalate powder were pressed, sandwiched between layers of pure PTFE powder to form sample tablets. The concealed amounts of glucose and copper oxalate are completely opaque in visual light as seen in **Figure 3**. The tablets contain either 2 mg of pure glucose powder or 1 mg of copper oxalate, both of which are invisible to the human eye inside the PTFE table. **Figure 3**g also shows the absorption spectra for the PTFE, glucose, and copper oxalate. These three have different absorption characteristics at the three selected frequency points in the THz region, making sample identification viable.

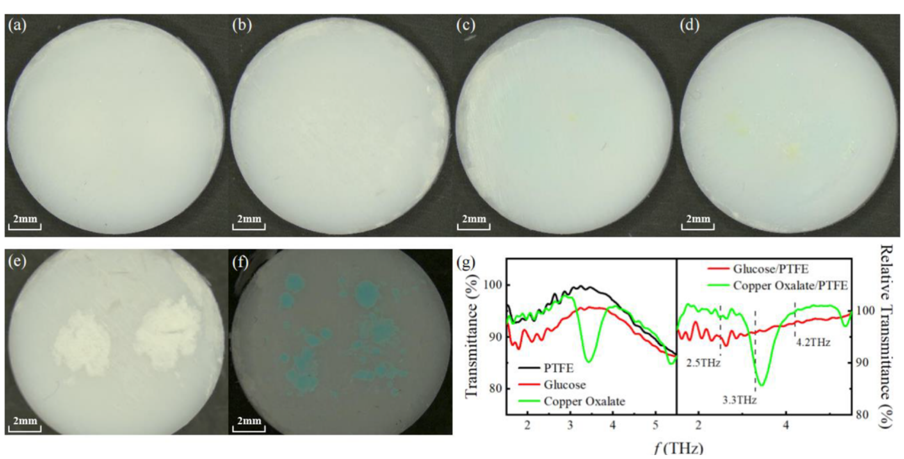

Figure 3. The preparation and characteristics of the samples. (a,b) A front and back optical photograph of a PTFE tablet containing glucose; (c,d) a front and back optical photograph of a PTFE tablet containing copper oxalate; (e) an optical photograph of glucose inside the tablet; (f) an optical photograph of copper oxalate inside the tablet; (g) the transmission spectra of PTFE, glucose and copper oxalate and the relative transmittance of the two powders compared to PTFE.[1]

RESULTS

To test the developed SM interferometer with the three THz QCLs, researchers measured the absorption spectra of the tablets at three frequencies: 2.5 THz, 3.3 THz, and 4.2 THz to obtain multicolor images of the hidden substances. For each QCL, imaging took about 20 minutes for 75 x 150 pixels, and the signal obtained was processed by fast Fourier transform to obtain its amplitude and phase.[1] Amplitude images for each lasing frequency of the THz QCLs are shown in **Figure 4**. The tablets on the left of each image show the concealed glucose, and the tablets on the right of each image show the concealed copper oxalate.

Because each sample has different absorption features at different frequencies, not all three of the frequencies of the THz QCLs will show high-contrasting characteristics or clear spatial distributions in the captured images. In the experiment with glucose and copper oxalate powders, different frequencies show more detailed features for each sample. At 2.5 THz and 3.3 THz, the images of the concealed glucose and copper oxalate show much clearer spatial distributions which correlates to stronger absorption than at 4.2 THz. As the lasing frequency increases for glucose, the absorption contrast decreases. Copper oxalate showed high contrasting imaging at 3.3 THz and lower contrasts at the other two frequencies as its characteristic absorption is found around 3.4 THz.[1] Although some frequencies provide lower contrast or spatial distributions, all three are used for a full absorption profile.

With the separate images, red, green, and blue colors were assigned to the amplitude images at the three THz frequencies. **Figure 4**d shows a synthesized multicolor image that exhibits the distribution patterns of the glucose and copper oxalate substances in the tablet. The concealed samples can be identified by color as each one has different absorption features based on frequency.

For identification, green-colored areas indicate the existence of copper oxalate, red-colored areas indicate the existence of glucose, blue-colored areas indicate pure PTFE and no evidence of the hidden substances, and some white-colored pixels are shown to imply information of a relatively high glucose content across all frequency points.[1]

Figure 5 shows the phase values of the tablets which can be used to provide a complex refractive index and thickness variation information to ensure the design is a coherent detection technology. As the images show, the substances' thicknesses are nonuniform which plays a dominant role in the phase variation. However, the change in the absorption coefficient of the sample has a greater impact on the phase than the change in the topography or thickness of the sample.[1]

Based on the beam spot and average mass of the powders, the system has at least microgram-level substance detection capabilities for THz multi-spectral detection. Based on these images and phase information, researchers have demonstrated a new multicolor imaging method in the THz band. This technology obtains intensity and phase images of the target sample and can achieve spatial differentiation and material identification using the THz fingerprint spectra of trace substances for military and security scenarios and inspection of hazardous materials applications.

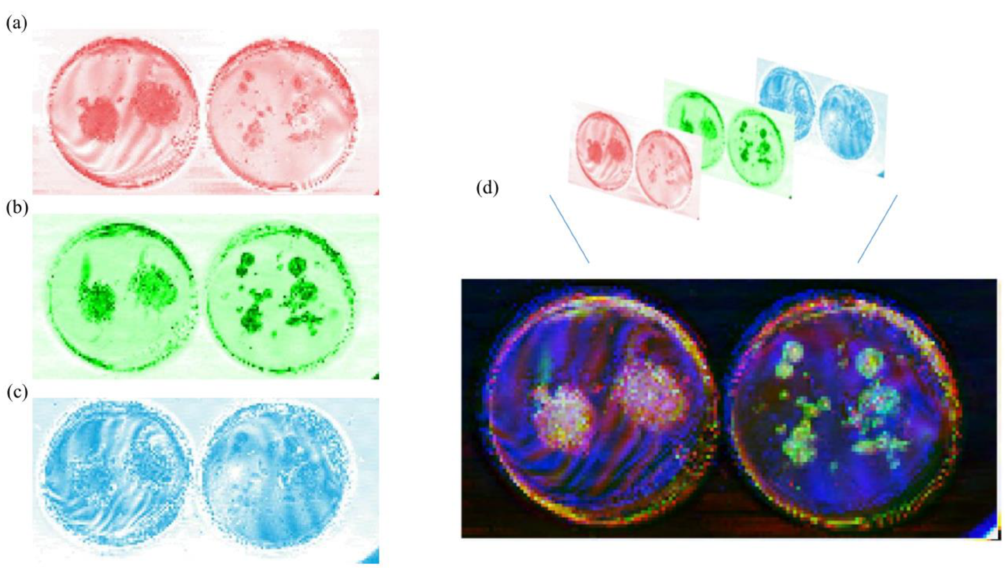

Figure 4. The results of scanning the sample using THz-QCLs with three frequencies: (a) 2.5 THz; (b) 3.3 THz; (c) 4.2 THz; (d) a synthesized multicolor image.[1]

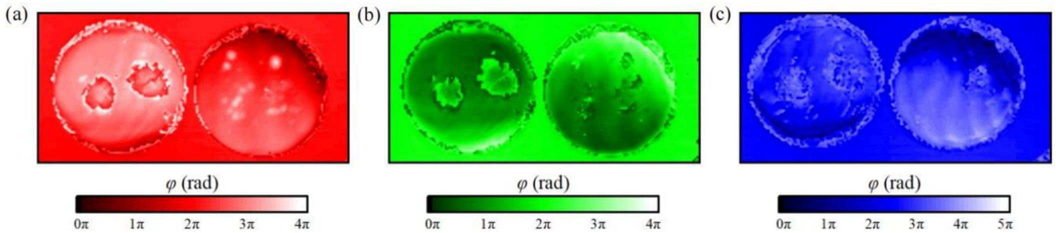

Figure 5. Phase images obtained by scanning the sample using THz-QCLs at three frequencies: (a) 2.5 THz; (b) 3.3 THz; (c) 4.2 THz.[1]

WAVELENGTH'S ROLE

In the multicolor imaging design using THz QCLs, Wavelength Electronics provided critical QCL drivers that ensured the stability and accuracy of the system's absorption spectroscopy measurements. The precise control of laser wavelength, current, and linewidth was essential for capturing images at multiple frequencies effectively. Due to the self-mixing technique, laser stability was essential for obtaining accurate results with absorption spectroscopy.

Researchers utilized the QCL2000 OEM QCL Driver from Wavelength Electronics to manage the drive current of the three QCLs used at 2.5 THz, 3.3 THz, and 4.2 THz. This driver provides up to 2 A of drive current with noise as low as 1.3 μA RMS up to 100 kHz and an average current noise density of 4 nA/√Hz. As the self-mixing interference technology is based on current modulation, accurate and precise current output with modulation is critical for the QCLs used. The currents of the QCLs were ramped and modulated using the QCL2000 OEM driver and required minimal adjustments for precise changes. The driver has additional features including current limit, setpoint, remote capabilities, and bandwidth of 2-3 MHz.

The current stability of the QCL2000 OEM allowed researchers to show the capabilities of SM interferometry for multicolor imaging of concealed substances based on absorption profiles. By using THz-QCLs in a simple optical system, the developed design provides a more practical solution to THz multi-spectral detection.

PRODUCTS USED
QCL2000 OEM

KEYWORDS
Self-mixing interference, material identification, multicolor imaging, quantum-cascade laser, coherent detection, terahertz, THz, QCL, QCL2000, wavelength electronics

REFERENCES

1. Cai, J., Xie, Y., Wang, Y., Chen, M., Li, L., Salih, M., et al. Terahertz Multicolor Imaging of Opaque Objects Using Self-Mixing Interferometry with Quantum-Cascade Lasers. *Photonics* **12**, 109 (2025). **https://doi.org/10.3390/photonics12020109**

USEFUL LINKS

- QCL2000 OEM **Product Page**

PERMISSIONS

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REVISION	DATE	NOTES
A	April 2025	Initial Release