Banknote Characterization using a Thermal Infrared *'THz Torch'* Spectrometer

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***Abstract*-In this paper, a thermal infrared spectrometer based on the *'THz Torch'* concept is reported and used to characterize both paper and plastic banknotes. The spectrometer consists of a thermal infrared emitter with near-ideal blackbody radiation characteristics and a low-noise pyroelectric detector. A filter bank with 16 narrow band-pass optical coating filters is selected to define a coarse set of 16 discrete spectral data points between 20 to 80 THz. Both transmission and reflection modes of operation are demonstrated *'over the THz horizon'* (within the extended THz range). This work shows the potential of this emerging low-cost technology for non-destructive and non-invasive testing, material characterization, material identification from a pre-characterized database, process variation monitoring and gas sensing.**

I. INTRODUCTION

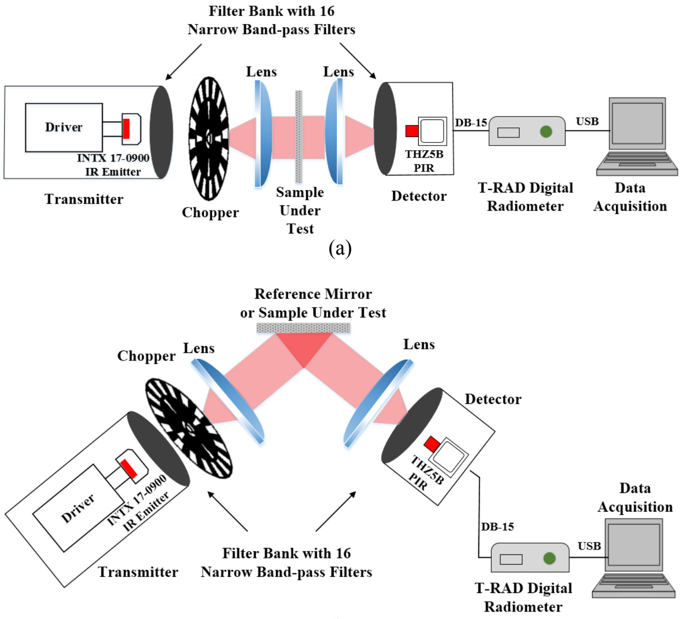
Molecules can exhibit strong absorption lines (due to vibrational and rotational resonances) within the conventional terahertz (THz) spectrum (0.1 to 10 THz); giving a unique spectroscopic fingerprint in the frequency domain. This enables THz time-domain spectroscopy (THz-TDS) to be widely used for identifying chemical and biological materials non-destructively and non-invasively. However, commercial THz-TDS systems [1], [2] and infrared spectrometers (0.3 to 750 THz) [3] are very bulky and/or very expensive. In addition, an experimental wideband THz-TDS (operating from 0.1 to 15 THz) has been developed, capable of operating at room temperature [4]. However, measurements have to be performed within a vacuum-tight enclosure, in order to reduce water vapor absorption that dominates below *ca.* 10 THz. Within the cost-performance application space, end users would like to minimize the bulk and/or expense of test equipment while meeting their performance needs.

The thermal infrared '*THz Torch*' technology was first introduced for short-range secure wireless communications [5]-[8]. It fundamentally exploits engineered blackbody radiation, by partitioning thermally-generated spectral power into pre-defined frequency channels; the incoherent energy in each channel is then independently pulsed modulated. By extending the *'THz Torch'* concept, this technology can be used to implement course frequency-domain thermal infrared spectroscopy [9]. In this paper, a room temperature, compact and low cost thermal infrared '*THz Torch*' spectrometer, operating between 20 and 80 THz is presented, giving experimental results for the characterization of banknotes.

II. *'THZ TORCH'* SPECTROMETER

A. *Basic Architecture*

The basic architecture for the thermal infrared *'THz Torch'* spectrometer is illustrated in Fig. 1, showing both transmission and reflection modes of operation. The complete spectrometer consists of a thermal infrared emitter having high emissivity radiators (INTX17-0900), an optical chopper for lock-in measurements, a pair of Potassium Bromide (KBr) plano-convex lenses, 16 pairs of narrow band-pass optical coating filters (supplied by Northumbria Optical Coating Ltd) [10], a THz-5B pyroelectric detector with a microprocessor-based T-RAD digital radiometer and data acquisition software. The modulation frequency of the optical chopper is set to 25 Hz, which is the optimized modulation frequency for T-RAD. The KBr plano-convex lenses are used to either collimate or focus the radiation beams, reducing spreading loss.



(a)

(b)

Fig. 1. Basic architecture for the thermal infrared *'THz Torch'* spectrometer (a) transmission mode and (b) reflection mode.

Measured spectral responses for the 16 pairs of narrow band-pass filters are shown in Fig. 2. For each sample under test, the measured transmittance/reflectance spectrum consists of 16

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discrete frequency-domain sampling points; each point located at the center frequency of the corresponding filter represents an average power measured over its bandwidth.

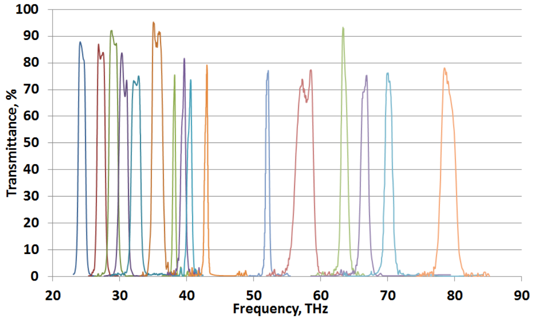
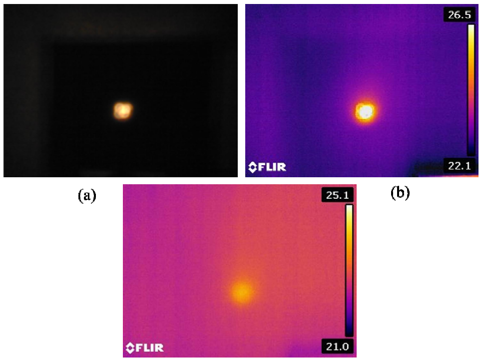


Fig. 2. Measured spectral responses of 16 narrow band-pass optical coating filters sourced from Northumbria Optical Coatings Ltd [10].

Initially, a data set containing 16 raw power measurements is obtained for the sample under test. The reference path is then measured, without the sample, to give another data set. In the transmission mode, Transmittance T is calculated as the ratio of the sample measurements to the line-of-sight reference measurements; while Reflectance R is calculated as the ratio of the sample measurements to the mirror reference. Here, the gold coated mirror is used as a reference, due to its high reflectance (~99.5 % below 100 THz). The Absorptance A then can be calculated using $A = 1 - T - R$.

B. *Spot-size Characterization*

KBr plano-convex lenses are used because of their high transmittance (> 90%) over a wide spectral range (12 to 1,303 THz). Fig. 3(a) and 3(b) show spot size for a 5-bulb array thermal source from the transmitter's lens. It can be seen that the diameter of the spot size is ~4 mm, in both visible and thermal spectra; indicating that the refractive index of KBr is constant throughout the visible and infrared ranges. Fig. 3(c) also shows the spot size of the thermal source when a long-wave pass filter (>7.4 µm or <40 THz) is placed in front of the thermal source. Comparing Fig. 3(b) and 3(c), it can be seen that with the filter the power density from the source decreases but the spot size does not change.



(a) (b)

(c)

Fig. 3. Measured spot size from the 5-bulb array thermal source with KBr lens (a) visible image, (b) thermal image, and (c) thermal image with a long-wave pass filter (>7.4 µm or <40 THz) in front of the thermal source.

III. EXPERIMENTAL RESULTS

The experiment setup for the thermal infrared *'THz Torch'* spectrometer is shown in Fig. 4. The total path lengths between the thermal emitter and thermal detector were set to ~8 cm and ~12 cm in the transmission and reflection mode, respectively. The incident angle for reflection measurement was 45º.

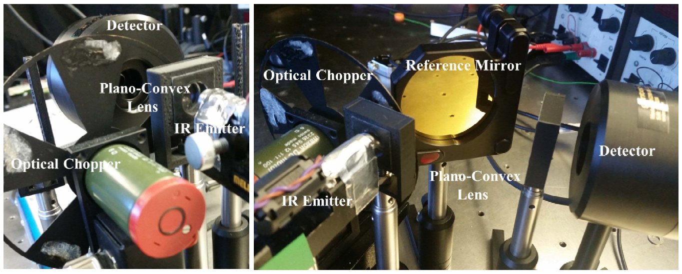


Fig. 4. Experimental setup for thermal infrared *'THz Torch'* spectrometer in transmission mode (left) and reflection mode (right).

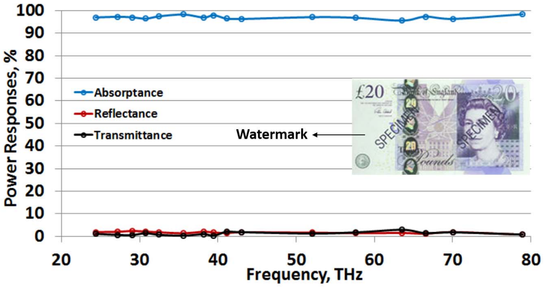
Most banknotes are made from 100 µm thick cotton paper, which is sometimes mixed with linen, abaca or other textile fibers. Both the British Pound (GBP) and Chinese Yuan (CNY) banknotes have a watermark and a 1 or 2 mm wide metallic strip for GBP and CNY, respectively. British banknotes also have a holographic pattern on a foil patch, to further enhance their counterfeit resilience. Canadian Dollar (CAD) banknotes are made from a 100 µm thick polymer. It has a transparent window and a holographic region.

The measured power responses for different banknotes are shown in Fig. 5, for different features. The watermark regions for GBP and CNY banknotes have both low reflectance and low transmittance, resulting in a high absorptance (> 95%), which is relatively constant throughout the spectrum of interest. As expected, the holographic regions on GBP and CAD banknotes have a low transmittance (< 5%) that is constant with frequency, but a relative high reflectance (> 50%) with a unique spectral signature. The reflectance of the 2 mm wide metallic thread on CNY banknotes lies between 10% and 20%, which is less than expected. This is because the diameter of the focused spot size is twice that of the metallic thread.

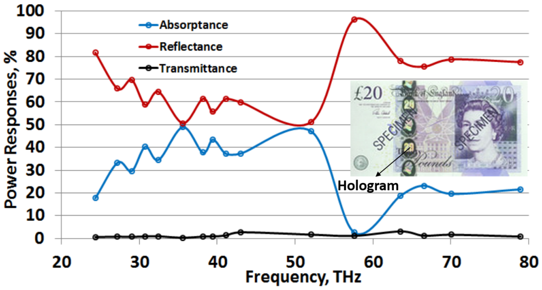
The modern CAD banknote shows completely different spectral signatures, due to the new materials being used. For example, with the visually transparent window, transmittance varies between 40% and 85%, while reflectance is relatively constant (between 5% and 10%) across the spectrum of interest.

IV. CONCLUSION

In this paper, we reported on the development of the thermal infrared *'THz Torch'* spectrometer for paper and plastic banknote characterization. The transmittance and reflectance of different features were measured for banknotes from three different sovereign nations. This shows the capability of characterizing banknotes using this technology. The thermal infrared *'THz Torch'* spectrometer has the benefits of room temperature operation, being compact and low-cost. In contrast to conventional spectroscopy, the *‘THz Torch’* spectrometer has low spectral resolution and sensitivity. However, this technology can find itself in a unique region at the lower corner of the cost-performance application space; include non-destructive and non-invasive testing, material characterization, material identification from a pre-characterized database, process variation monitoring and gas sensing.



(a)



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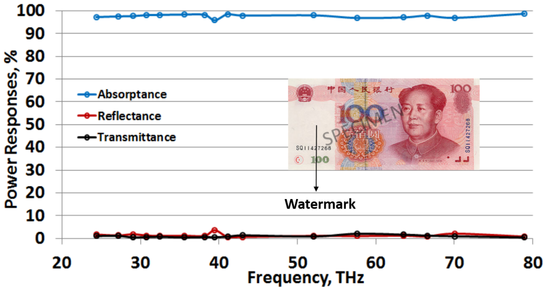

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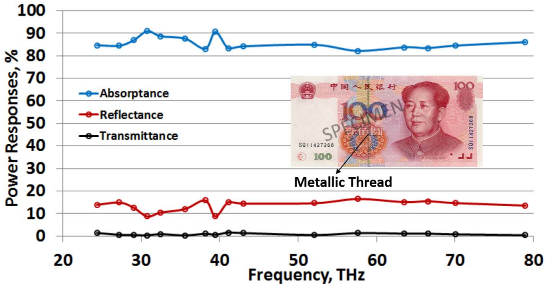

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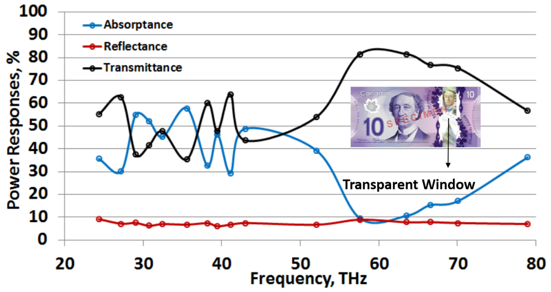

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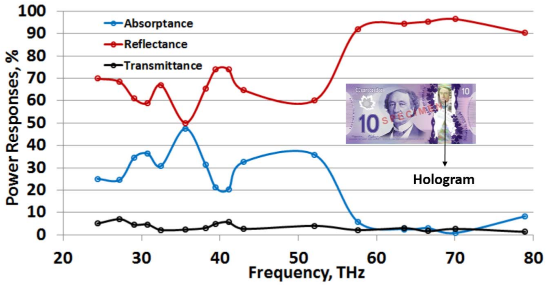

(f)

Fig. 5. Power spectral responses for (a) watermark of GBP £20, (b) hologram of GBP £20, (c) watermark of CNY 100, (d) metallic thread of CNY 100, (e) transparent window of CAD $10, and (f) hologram of CAD $10.

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