Towards Industrial THz Wave Electronic Gas Sensing and Spectroscopy

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***Abstract*— A demonstration of low-power THz wave electronics (less than 1 mW) for quantitative atmospheric gas absorption spectroscopy in the 220 – 330 GHz frequency band is presented. Measurements are reported for acetonitrile, methanol, and ethanol, VOCs important in the atmosphere and industrial settings. Measurements are demonstrated for the strongly absorbing acetonitrile vapors, comparable in SNR to previous measurements made with THz time-domain spectroscopy methods, and for pure methanol and ethanol vapors at low pressures (5 and 10 Torr).**

I. INTRODUCTION

Human health, safety and prosperity require technologies for effective gas sensing and spectroscopy. Air quality control, fuel efficient combustion, chemical analysis in industrial manufacturing and early disease detection via breath analysis, are only a few examples where identification of gas species and determination of their concentrations are highly relevant.

The global market for gas sensing was valued at around $2 billion in 2016, and is expected to reach $2.5 billion by 2020, expanding at an annualized growth rate of greater than 5% [1]. For the North American market, emission related initiatives and safety regulations put forth by the Occupational Safety and Health Administration (OSHA) has been critical in enhancing market penetration across industries. End users of gas sensors include the medical, industrial, military, automotive, environmental, petrochemical, building automation, and domestic appliances sectors [2]. The gas sensors market includes technologies for the detection of carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxide (NOx), methane (CH_4), ammonia (NH_3), and others. Based on the report by HEXA [1], the global revenue growth is mainly driven by sensors for NOx and CO. The primary use of gas sensors in the medical sector is for the measurement of Volatile Organic Compounds (VOCs). VOCs are organic compounds that easily become vapors or gases. Along with carbon, VOCs contain elements such as hydrogen, oxygen, fluorine, chlorine, bromine, sulfur or nitrogen, and may have adverse short-term and long-term health effects [3].

Currently, gas sensing is performed by a variety of technologies which differ in the mechanism used to sense gaseous species, e.g., electrochemical processes, infrared absorption, electrical resistivity changes in semiconductors, or photoionization [4]. An effective gas sensor provides a high sensitivity for detection of the target species without interference from other species present, i.e., high selectivity. Additional desirable properties are room-temperature operation, speed of detection, the potential to be deployed in the field, size, weight, energy consumption and fabrication cost.

Newly, we propose terahertz frequency electronics for terahertz (THz) wave gas sensing and spectroscopy. THz wave absorption measurements provide selective identification of relevant gas molecules through their characteristic rotational spectra. THz wave absorption measurements provide selective identification of relevant gas molecules through their characteristic rotational spectra. Moreover, THz wave absorption measurements offer high sensitivity because of the particularly high absorption cross sections of relevant molecules in the THz frequency band. THz wave sensing also has an inherent advantage over infrared wave sensing in field applications because THz waves experience orders-of-magnitude less scattering than infrared waves when propagating through the atmosphere or industrial processes, often laden with particles and aerosols. Also, interference of THz wave absorption measurements by atmospheric water vapor is reduced compared to infrared absorption measurement because water vapor absorption lines are sparse in the THz frequency band, compared to the infrared frequency band, particular below 1 THz [5].

Presently, the use of THz waves for gas sensing and spectroscopy is limited to laboratories performing molecular physics research, as well as atmospheric and astronomical high resolution spectroscopy. The limited practical application of THz waves for gas sensing and spectroscopy outside of its traditional niches is due to the complexity, size and cost of the instrumentation.

State-of-the-art THz frequency microelectronics is emerging as a unique platform to develop miniaturized, energy and cost effective THz wave gas sensing and spectroscopy systems [6], [7].

Microchip THz electronic sources and detectors are the solution to bring THz wave gas sensing and spectroscopy out of the research laboratory to the field and realize the advantages of the approach for the betterment of human health, safety and prosperity.

Here, we present a case for the application of THz wave electronic sources, with high bandwidth, low noise, fast spectral scanning capabilities, and MHz level spectral resolution, for gas sensing in industrial settings. A frequency multiplier source is used to generate radiation in a frequency range from 220 – 330 GHz at powers less than 1 mW from a radio frequency (RF) input of 12.22 – 18.33 GHz. Following transmission through a gas cell, a quasi-optical detector utilizing a Schottky diode was used for the determination of the spectral absorption for three VOCs: methanol, ethanol, and acetonitrile.

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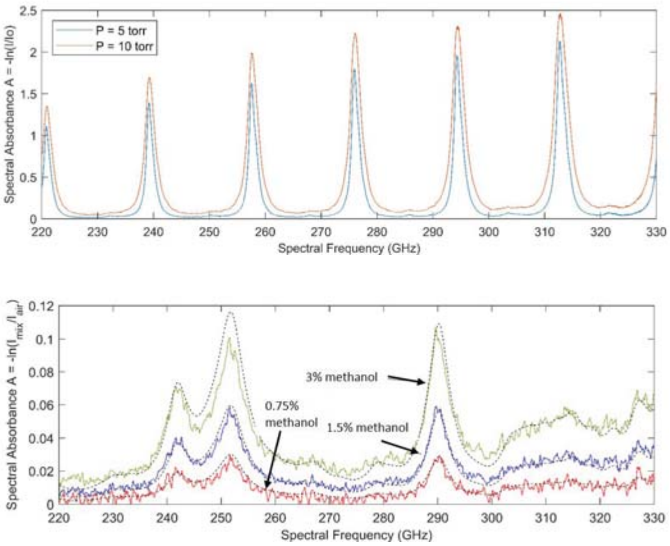

Fig. 1 Top: Spectral absorbance of pure acetonitrile vapor at two different pressures. Bottom: Spectral absorbance of methanol and ethanol at 10 Torr pressure.

II. II. Experimental Arrangements

The THz wave source is a signal generator extension module procured from Virginia Diodes Inc. (VDI model number WR3.4SGX). This module multiplies a radio frequency input from the RF synthesizer (HP model # 83752A) by 18 to output a THz radiation beam in the desired spectral range 220 – 330 GHz. The THz wave source is equipped with a rectangular waveguide and diagonal horn antenna [8] that produces a vertically polarized beam with a full 3 dB beam-width of 10 degrees – half the output power in contained within 10 degrees from the beam axis. The typical output power of the THz wave source across the spectral range is -6 dBm (0.631 mW), decreasing from 1 mW to 0.3 mW with increasing spectral frequency. A quasi-optical detector utilizing a Schottky diode was procured from Virginia Diodes Inc. It is equipped with a silicon lens and a broadband antenna, allowing high responsivity (500 – 1000 V/W) across a wide spectral range (0.1 – 1 THz) [9]. A low frequency pulse modulation input (1 – 3 kHz) is supplied to the THz wave source and the lock-in amplifier which demodulates the detected signal to reduce ambient optical noise.

III. Results

Fig.1 (top) shows the spectral absorbance of acetonitrile vapors measured at different pressures. The absorbance spectra agree well with calculations by [10], [11] and experimental data obtained by photonic THz techniques [12].
Ethanol and methanol are candidates with an order of magnitude lower absorption than acetonitrile but could potentially attract significant practical interest for gas sensing, owing to their presence in industrial applications. To our knowledge, very limited studies exist for these candidates using THz wave techniques particularly at or near atmospheric pressures [7], [13]. Fig.1 (bottom) shows the respective absorbance spectra of methanol and ethanol at a gas cell pressure of 10 Torr. Despite the effects of line broadening at high vacuum, characteristic differences are observed between the spectra of these pure compounds.

IV. Conclusions

A demonstration of low-power THz electronics (less than 1 mW) for quantitative atmospheric gas absorption spectroscopy in the 220 – 330 GHz frequency band is presented. Measurements are reported for acetonitrile, methanol, and ethanol, VOCs important in the atmosphere and industrial settings.
Measurements are demonstrated for the strongly absorbing acetonitrile vapors, comparable in SNR to previous measurements made with THz-TDS methods, and for pure methanol and ethanol vapors at low pressures (5 and 10 Torr).

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