Terahertz Trace Gas Spectroscopy Based on a Fully-Electronic Frequency-Comb Radiating Array in Silicon

M. Mahdi Assefzadeh, Babak Jamali, Aleksander K. Gluszek, Arkadiusz J. Hudzikowski, Jacek Wojtas, Frank K. Tittel, Aydin Babakhani
Department of Electrical and Computer Engineering, Rice University, Houston, TX, USA
mahdi@rice.edu, aydin.babakhani@rice.edu

Abstract: A silicon integrated circuit is reported for radiating picosecond pulses with tunable repetition rate, covering frequencies from 30 GHz to 1.03 THz. This source is used in a gas spectroscopy setup to measure the absorption lines of ammonia and water in the terahertz region.
OCIS codes: (120.6200) Spectrometers and spectroscopic instrumentation; (300.6495) Spectroscopy, terahertz; (320.5550) Pulses;

1. Introduction

In recent years, terahertz spectroscopy based on frequency combs has become an effective technique for high-precision spectroscopy [1-2]. Terahertz spectroscopy allows the measurement of absorption lines in gases due to transitions between rotational states in the GHz-THz spectral range. A tunable source that can generate a wide range of frequencies with a high resolution and frequency stability will enable broadband terahertz trace gas spectroscopy.

In this work, for the first time, we introduce an electronic source with an on-chip antenna that can generate picosecond pulses to perform broadband THz gas spectroscopy. A single-chip source provides us with a highly compact and cost-effective system comparing to a laser-based source. We have performed THz gas spectroscopy using two different gases, NH_3 and H_2O. The NH_3 measurements were performed at 572 GHz, its strongest absorption peak. At this frequency, SO_2 and H_2S can be detected as well.

2. Custom Single-Chip Terahertz Source

Recently, the technique of Direct Digital-to-Impulse (D2I) radiation was introduced that radiates sub-10-ps pulses using a fully-electronic (no laser) integrated chip [3]. Unlike conventional electronic-based methods that use on-chip oscillators to generate high-frequency signals, the D2I method utilizes a fast bipolar switch to release stored magnetic energy in a broadband antenna. This method was used to implement an array of on-chip impulse radiators in [4]. The architecture of the chip and its micrograph, along with the measurement results showing the radiated power from 50 GHz to 1.03 THz, are illustrated in Fig. 1. The radiated impulse-train forms a frequency comb in the frequency domain, which spans from very low frequencies (30 GHz) up to 1.03 THz. The measured 0.75-THz component has a 2-Hz spectral width, which makes high-resolution spectroscopy possible. This source is used to perform terahertz spectroscopy on ammonia and humid air as discussed in Sections 3 and 4. The radiated frequency tones can be swept by changing the repetition rate of the input trigger source

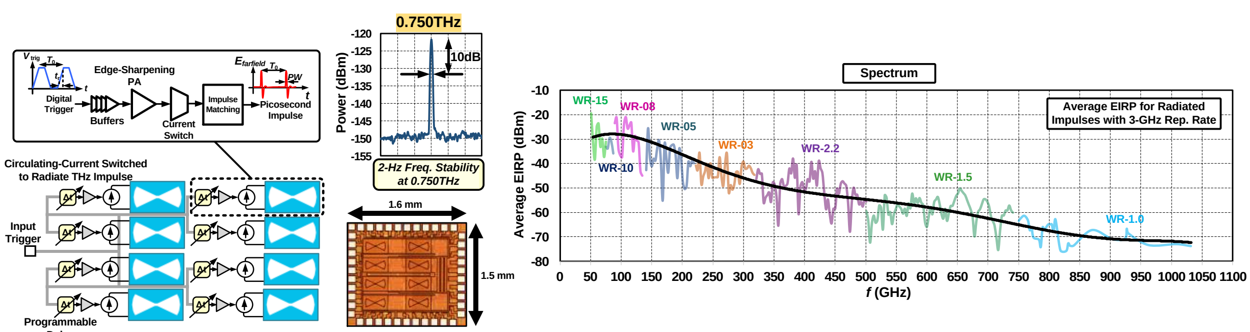

Fig. 1. Custom silicon source for radiating picosecond pulses

3. Experimental Setup

The experimental setup is shown in Fig. 2. The absorption cell consists of a 50 mm diameter and 150mm long aluminum tube with Teflon lenses at each end, which are transparent in the THz spectral range. The absorption cell is connected to an oil free vacuum pump via a pressure controller in order to regulate and reduce the gas flow in the cell. The terahertz-radiating chip is assembled on a printed circuit board, which has a silicon lens attached to its backside. The silicon lens helps to reduce the substrate modes caused by the planar geometry of the silicon chip. A Teflon lens, placed as the window of the absorption cell, collimates the propagating waves in the cell. The cell has a controlled pressure and is filled with 1% ammonia (99% nitrogen) calibrated gas in the first experiment. It is then filled with humid air in the second experiment. There is a second Teflon lens at the output end of the cell, which focuses the wave on the receiving antenna. The receiver is a commercial product of Virginia Diodes Inc., which includes a horn antenna and an extension module for the spectrum analyzer that works in the 500-750GHz frequency band. A Keysight E8257D signal generator is used to provide an input trigger to the chip (source). The repetition frequency is fixed at 3 GHz for the first few measurements and then changed by steps of 10 MHz. By changing the repetition rate, the frequency tones in the frequency-comb are varied (harmonics of the repetition rate). A Keysight N9030A spectrum analyzer is connected to the VDI module to capture the spectrum on the receiver end.

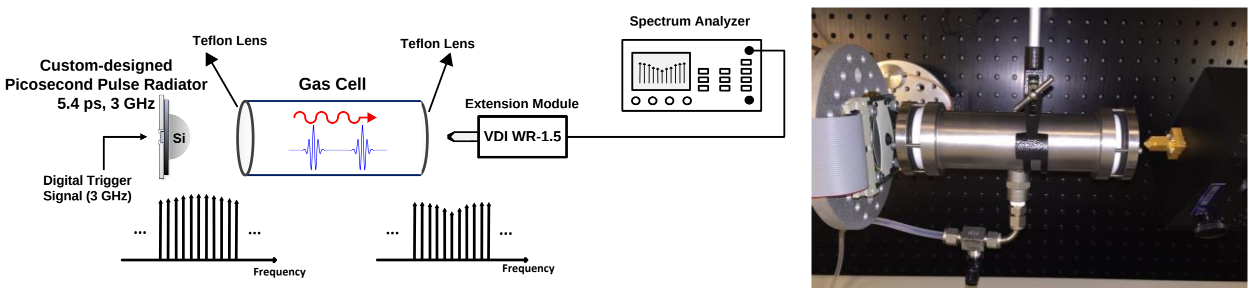

Fig. 2. Experimental setup

4. Results

For each frequency component, the received power was measured twice. First, the cell is filled with pure nitrogen gas and then evacuated using a pump and filled with the trace gas. The absorption of the gas is calculated by comparing the received signals in two experiments. The measured absorbance of ammonia and water are plotted as a function of frequency as shown in Fig. 3. The ammonia concentration in the measured gas was kept at 1% while its pressure varied from 500 to 950 Torr to demonstrate the effect of pressure broadening. In the second measurement, the humidity of the air was approximately 50%, which causes 1.7dB peak absorption at 753.5 GHz.

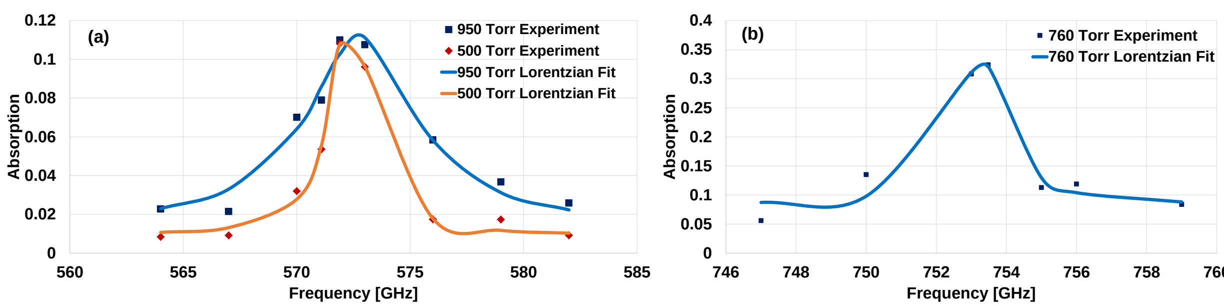

Fig. 3. Absorption spectra for NH_3 (a) and H_2O (b)

In summary, we demonstrated the performance of a single-chip terahertz source that produces broadband frequency combs from 30 GHz up to 1.032 THz. This is the first demonstration of THz gas spectroscopy using a fully-electronic single-chip silicon source. The chip is used to detect the absorption lines of NH_3 and H_2O at 572 and 753 GHz, respectively. Fast response time caused by high-power generation of broadband THz pulses using a fully-electronic silicon chip makes this method a viable choice for trace gas THz spectroscopy.

5. References

[1] Y. Hsieh, et al., "Terahertz Comb Spectroscopy Traceable to Microwave Frequency Standard," IEEE Trans. Terahertz Sci. Technol. **3**(3), 322–330 (2013).

[2] A.S. Skryl, et al., "High-resolution terahertz spectroscopy with a single tunable frequency comb," Opt. Express **22**, 32376-32281 (2014).

[3] M. Assefzadeh, A. Babakhani, "An 8-psec 13dBm peak EIRP digital-to-impulse radiator with an on-chip slot bow-tie antenna in silicon," IEEE Intl. Microwave Symp. Dig. papers**,** Jun. 2014.

[4] M. Assefzadeh, A. Babakhani, "Broadband 0.03-1.032THz Signal Generation and Radiation with Peak EIRP of 30dBm Based on a Fully-Integrated 4×2 Impulse Radiating Array with Programmable Delay per Element in 90nm SiGe BiCMOS," submitted to IEEE Intl. Microwave Symp.**,** 2016.