A CMOS Microwave Broadband Adaptive Dual-comb Spectroscopy System with AI Calibration for Liquid Chemical Detection

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***Abstract*—Microwave broadband dielectric spectroscopy (MBDS) systems have a broad range of applications in chemical/biological sensing, oil exploration and processing, food and drug quality control, disease diagnosis and bio-threat detection. This report discusses the progress on developing first CMOS integrated microwave broadband dual-comb spectroscopy (DCS) system for liquid chemicals detection. A 3-10 GHz microwave time domain DCS system with two on-chip frequency combs with a tunable and slightly different repetition frequency rates, two on-chip coplanar waveguide (CPW) planar transmission line sensor units, and a UWB mixer to generate the dual-comb output that represents the properties of the material under test (MUT) from microwave frequencies mapped to low-frequencies are developed, respectively. To verify the chemical detection, MUTs including methanol, ethanol and water results are presented. As the project progresses, these results will be used to extract the complex permittivity of the unknown MUTs through an artificial intelligence (AI) algorithm network system.**

***Index Terms*— Microwave dielectric spectroscopy, CMOS, frequency combs, dual-comb, time domain, broadband pulse, ultra-wideband (UWB), on-chip sensor, coplanar waveguide (CPW).**

I. Introduction

MICROWAVE broadband dielectric spectroscopy (MBDS) systems defines the dielectric properties of many materials over RF/microwave frequency range. Due to the strong development of microwave sensing and measurement techniques, MBDS systems precisely extract the complex relative permittivity, $\varepsilon^{*} = \varepsilon' - j\,\varepsilon''$, of a material under test (MUT), which is a unique response to an external microwave electric field at different frequencies. To characterize the complex permittivity, traditional MBDS systems utilize either frequency-domain (FD) or time-domain (TD) techniques while they require bulky and expensive equipment. Due to recent advances in CMOS technology, a silicon-based integrated broadband spectroscopy system provides significant cost reduction, better system integration, high accuracy and a smaller sample volume of the MUT. Recently, to characterize the complex permittivity of MUTs, a miniaturized first CMOS TD MBDS system with a homodyne ultra-wideband (UWB) dc-free RF transceiver architecture has been reported [1]. Although, it offers significant size reduction, the system requires an on-chip analog-to-digital converter (ADC) with approximately ~2 GHz BW. Dual-comb spectroscopy (DCS) is a novel powerful self-sustained TD technique for broadband optical spectroscopy systems, which enables miniaturization, rapid real-time characterization, cost reduction with high-precision solution for broadband spectroscopy [2], while it characterizes MUTs' complex permittivity and utilizes lower complexity than existing TD MBDS systems by eliminating the need to a high-speed oscilloscope or ADC to capture the data.

In this project, which was generously supported by the IEEE MTT-S Graduate Fellowship, the first integrated TD CMOS adaptive microwave DCS system is implemented and characterization of the dielectric permittivity of different MUTs over the 3-to-10 GHz frequency span is presented in this report. A novel approach is utilized to stabilize and phase lock the entire system resulting in accuracy enhancement for material characterization.

II. UWB CMOS Time-domain DCS System Implementation

Fig. 1 shows the conceptual block diagram of the proposed dual-comb based spectroscopy system. In this project, to overcome the known main challenges of the comb-based systems, following main techniques are utilized for the proposed DCS system. System basically consists of two comb generators (Comb_{RF} and Comb_{LO}) along with a tunable offset frequency (Δf_r= 10 KHz) and slightly different pulse repetition frequencies f_{rep} (40 MHz) and $f_{rep}+\Delta f_r$ (40.01 MHz), two UWB LNAs after the two identical sensors, a UWB heterodyning mixer yielding a downconverted low-frequency IF baseband comb uniquely representing one of the tones in the Comb_{RF} which interrogates the MUT and carries the dispersive effects of the material permittivity. Comb_{IF} teeth are sampled every $1/f_{rep}$= 25 ns and repeated with the period of $1/\Delta f_r$= 0.1 ms. To lock and stabilize the sampling rate for accurate MUT phase characterization, the oscilloscope is externally triggered by Δfr generated by mixing two on-chip frequency combs via an off-chip low frequency mixer. Simultaneous generation of both combs on the same chip from a single source synchronizes the pulse trains of two combs. To achieve the mutual coherence between two combs, a single external reference source (f_{in}) is

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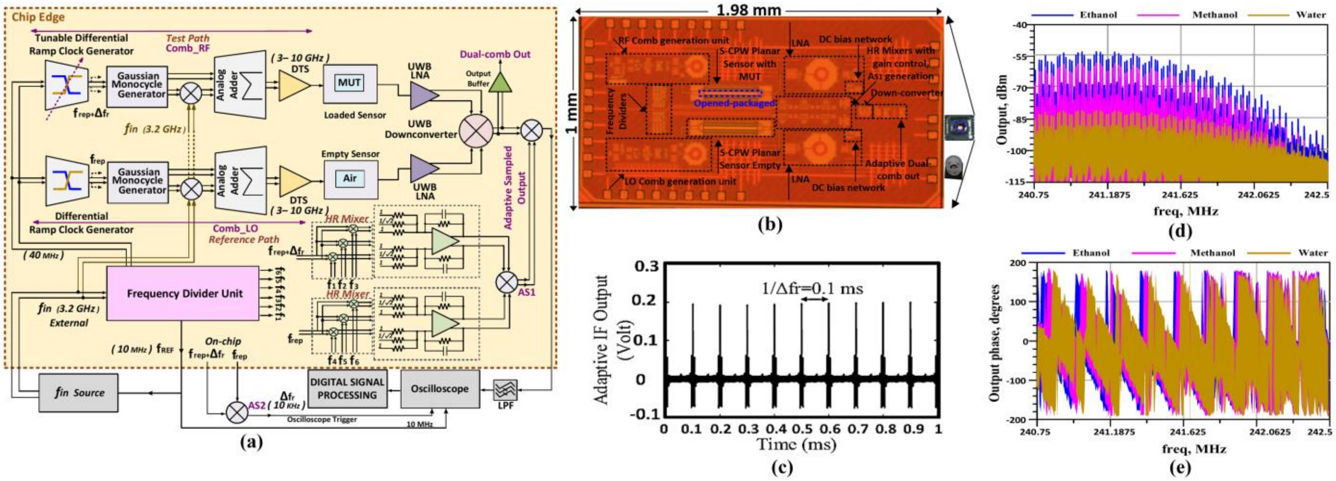

Fig. 1. (a) Block diagram of CMOS TD DCS system, (b) micrograph of the fabricated chip, along with the plastic tube glued on top of chip, and partially packaged chip, (c) TD response of the adaptive DCS system output, (d) magnitude and (e) phase results of the system output in frequency domain representation from captured TD signal for ethanol, methanol, and water, respectively.

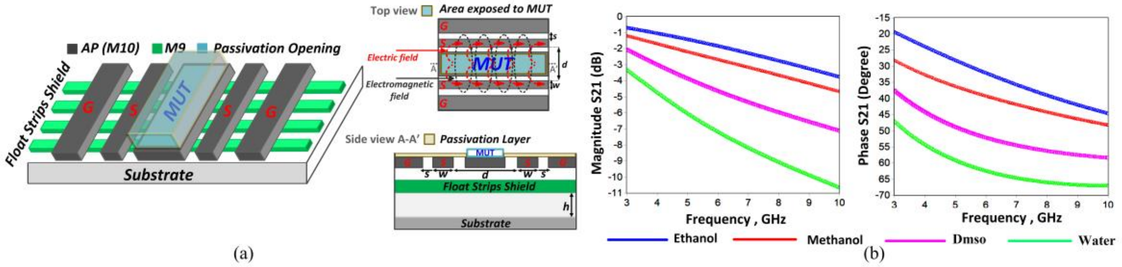

Fig. 2. (a) 3D layout of the S-GCPW sensor along with its top and side views, and (b) simulated sensor S_{21} magnitude and phase response when loaded by corresponding MUTs.

used, and hence all comb tones are locked to the f_{in} and stabilized the repetition frequency and the comb spacing of the $Comb_{IF}$. To make the system setup insensitive to phase and time errors, AS_1, which is generated on-chip through both combs, is mixed with the BB interferograms to compensate phase variations on-chip, and AS_2 is used as an external clock for data capturing while it provides restitution for time variations [2]. Since the input is periodic, the output signal of the UWB comb generator is sampled by the input pulse reputation frequency within 3-10 GHz. The desired microwave BW (Δv= 7 GHz) is mapped to 0.75-2.5 MHz spectrum with 1.75 MHz IF BW for successful one-to-one mapping from RF comb to IF comb. As shown in Fig. 2, formation of two identical sensors for both comb-lines to achieve delay between two paths resulting in on-chip phase and magnitude system calibration. This work has been presented as a conference paper during the IEEE International Microwave Symposium (IMS) 2020 [3]. As a future work, an AI calibration network system will be generated for high accuracy unknown material characterization [4].

III. IMPACT OF FELLOWSHIP AND CAREER PLANS

Receiving the 2020 IEEE MTT-S Graduate Fellowship and being recognized as one of the top Ph.D. students in the area of microwave engineering is a truly honor for me. This award boosted my motivation and increased my confidence to more expand my experience in microwave engineering within a very competitive scientific community. It was an excellent opportunity to attend and participate in the IEEE IMS 2020 conference. It has enabled me to interact with excellent researchers from top-tier universities and companies and have a chance to follow the latest RF/microwave and millimeter-wave research developments. Upon graduation, I plan to pursue an academic career focusing on RF and microwave engineering as a faculty member in one of the top-tier research universities. I am deeply grateful to the IEEE MTT-S society for this award, look forward to participating in future events, and continue to contribute to microwave engineering and the IEEE MTT society.

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REFERENCES

[1] E. Kaya, A. P. Saghati, and K. Entesari, “A 3-10-ghz cmos time-domain complex dielectric spectroscopy system using a contactless sensor,” IEEE Transactions on Microwave Theory and Techniques, pp. 1–16, 2019.
[2] T. Ideguchi, A. Poisson, G. Guelachvili, N. Picqué, and T. W. Hänsch, “Adaptive real-time dual-comb spectroscopy,” Nature communications, vol. 5, p. 3375, 2014.
[3] E. Kaya and K. Entesari, " A CMOS Microwave Broadband Adaptive Dual-Comb Dielectric Spectroscopy System for Liquid Chemical Detection", IEEE MTT-S Int. Microw. Symp., pp. 229-232, Aug. 2020.
[4] E.Kaya and K. Entesari, “A CMOS Microwave UWB Adaptive Dual-Comb Dielectric Spectroscopy System with AI Calibration,” to be submitted.