Microwave/millimeter wave sensors

Plasma Characterization Using a Silicon-Based Terahertz Frequency Comb Radiator

Sam Razavian[1*], Jia Han[2], Babak Jamali[1**], Patrick Pribyl[2], Mostafa Hosseini[1*], Yash Mehta[1*], Mahdi Forghani[1*], Walter Gekelman[2], and Aydin Babakhani[1***]

[1]Department of Electrical and Computer Engineering, University of California, Los Angeles, CA 90095 USA
[2]Department of Physics, University of California, Los Angeles, CA 90095 USA
[*]Student Member, IEEE
[**]Member, IEEE
[***]Senior Member, IEEE

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Abstract—In this letter, temporal evolution of plasma density is characterized in the time-domain using a low-power THz frequency-comb radiator in the 130-nm SiGe BiCMOS process. The frequency-comb radiator covers from 10 s of GHz up to 1.1 THz where the spacing between tones is programmable and can be set by the frequency of an external trigger signal to as high as 10.5 GHz. Due to the complex permittivity of plasma, electromagnetic waves experience a phase and amplitude change as they pass through the plasma. The THz-pulse radiator used in this letter is locked to a low-phase noise external source. Hence, the phase-noise of the radiated tones is extremely low, which enables detecting small phase changes. In this measurement, phase and amplitude changes of THz waves are captured from 333 to 495 GHz for different plasma parameters by varying gas pressure, plasma pulse rate, and plasma excitation power.

Index Terms—Microwave/millimeter wave sensors, BiCMOS, frequency comb, inductively coupled plasma (ICP), interferometry, plasma, terahertz (THz), THz pulse radiator.

I. INTRODUCTION

Due to myriad applications, the Terahertz (THz) band has been of great interest to researchers over recent years. Electronic silicon-based technologies enable the integration of THz radiators and detectors at the system level providing an efficient low-cost solution for high-resolution radars, imaging, remote sensing, and high-speed communication. THz continuous wave (CW) [1] and pulse-based approaches have been improving constantly for different types of applications. In particular, for broadband remote sensing applications and spectroscopy, pulse-based radiators and detectors have been demonstrated to be a more viable solution compared to CW systems due to broadband spectral information, and ultralow-phase-noise THz tones. In [2] and [3], a THz pulse radiator is used to recover and reconstruct the sound from vibrations on the surface of a scattering radar target using micro-Doppler effect. THz waves can also be used to characterize the propagation medium based on its complex permittivity [4]. As a result, THz waves have been considered for plasma characterization. For instance, a THz-TDS system is utilized in [5] and [6] to probe and characterize the plasma across a wide band.

Among conventional approaches for plasma characterization, interferometry is a well-established nonintrusive method to measure the line integrated density of a plasma [7]. The general concept is to measure the phase shift of an electromagnetic wave in the plasma relative to that in vacuum. For high density plasmas, optical instruments utilizing lasers are used for interferometry [8]–[10]; however, this is challenging at low densities where the characteristic plasma frequency is orders of magnitude smaller than the frequency of the laser and capturing the phase shift due to plasma is not feasible. For low density plasmas, microwave radiation is widely used for interferometry [11]–[14]. In order to measure a broad range of plasma density ($10^9 - 10^{13}$ cm^{-3}) for devices such as the Large Plasma Device [15], the microwave frequency must be sufficiently higher than the plasma frequency so that the beam stays coherent after traveling through a nonuniform plasma volume, but also low enough such that a phase difference is measurable at low density.

THz pulses/frequency comb can be used to probe and characterize plasma physics. Utilizing a broadband frequency comb increases the dynamic range of the measurements and is more suitable for the measurement of different plasma densities. Additionally, by investigating the measurement data in different frequencies, ambiguity in the measurements can be minimized. Moreover, the THz frequency comb can be used to detect the rotational states of molecules and identify the gas species present in the chamber. Considering that broadband THz radiators and receivers [16] can be implemented in silicon, they are superior to other types of sources in terms of the cost and integration.

In this letter, an experimental setup using a single custom-designed silicon-based THz frequency-comb radiator [17] is presented to probe a pulsed inductively coupled plasma (ICP) at different frequencies in the low-THz band. I/Q analysis have been used to calculate the phase and amplitude change of THz tones. Measurements have been performed under various plasma pulse repetition rates, pressures, and RF excitation powers. Based on the results, plasma characteristics including the electron density and plasma frequency are calculated. The remainder of this letter is as follows. Section II elaborates on theories of plasma physics and illustrates how a broadband THz frequency-comb radiator can benefit the measurements. In Section III, the operation of the chip and the main specifications are presented. Section IV describes the details on the experimental setup, and Section V reports on the measurement results. Finally, Section VI concludes the letter.

(Sam Razavian and Jia Han are co-first authors.)

Corresponding author: Sam Razavian (e-mail: Samrazavian24@ucla.edu).
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II. THEORY: PLASMA PHYSICS

The main parameter of the relevant unmagnetized plasma physics is the plasma frequency (ω_p). The plasma behaves as an opaque medium below the plasma frequency and a transparent medium above it. Plasma frequency can be calculated as

$$\omega_p = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}} \tag{1}$$

where n_e is the electron density, e is the electron charge, and m_e is the electron mass. Equation (1) shows that the plasma frequency increases for higher densities, thus necessitating a probing source with higher frequency of radiation. Normally, a microwave source with an order of magnitude higher frequency than the plasma frequency is used. This is done to prevent beam refractions. Therefore for each density, the microwave source frequency range is limited for correct measurements. THz frequency-comb sources have tones over a wide bandwidth (e.g., 50–500 GHz), which can be utilized to improve the dynamic range of measurements.

The complex index of refraction $n = \sqrt{\epsilon/\epsilon_0}$ in plasma is frequency dependant and in the absence of magnetic field is given by

$$\frac{\epsilon}{\epsilon_0} = \left(1 - \frac{\omega_p^2}{\omega^2 + \nu^2}\right) - i\left(\frac{\omega_p^2}{\omega^2 + \nu^2}\frac{\nu}{\omega}\right) \tag{2}$$

where ω is the radiation frequency, and ν is the average momentum collision rate. Note that the collision frequency in this experiment is more than five orders of magnitude smaller than the microwave frequency, so the imaginary part is negligible.

The amount of the phase shift is

$$\Delta\phi \approx \frac{\omega}{c}\int\left[\left(1 - \frac{\omega_p^2}{\omega^2 + \nu^2}\right)^{\frac{1}{2}} - 1\right]dx. \tag{3}$$

With $\nu << \omega$, the plasma density can be calculated by

$$\Delta\phi \approx \frac{e^2}{2c\omega m\epsilon_0}\int n_e dx. \tag{4}$$

III. THZ RADIATOR CHIP

A custom designed frequency-comb/pulse radiator in 130-nm SiGe BiCMOS is used as the source [17]. The chip radiates frequency comb from 10 s of GHz up to 1.1 THz using a broadband on-chip slot bow-tie antenna. A high-resistivity silicon lens is employed to increase the efficiency and gain of the antenna. The lens prevents the THz power from being trapped in the substrate in the form of substrate wave-guide modes. The spacing between the radiated tones is determined by the pulse repetition rate, which is tunable up to 10.5 GHz. The pulse generation mechanism of this chip is based on the nonlinearity of a p-i-n diode device in reverse recovery. A block diagram of the chip operation is illustrated in Fig. 1(a). The driver stage, which is fed by an external trigger, pushes the p-i-n diode into reverse recovery mode. Due to the high nonlinearity in reverse recovery of a p-i-n device, ultrashort pulses with picosecond duration can be generated and radiated using an appropriate matching circuit. Note that the generated pulses are locked to a low-phase-noise external trigger signal rather than an on-chip oscillator. Thus, the radiated tones have a low phase noise, which is critical for high-resolution remote-sensing and spectroscopic applications where the modulated THz tones contain the phase information. Fig. 1 shows a micrograph of the chip and a time-domain waveform of the radiated signal measured by an optical THz-TDS setup. The total power consumption of the chip is 45 mW, and the repetition rate of the pulses is set to 9 GHz in the experimental plasma setup.

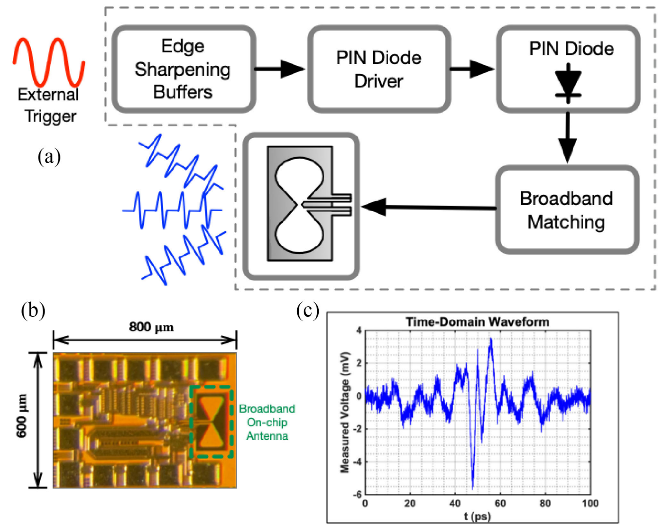

Fig. 1. (a) Block diagram of the chip operation. (b) Micrograph of the THz radiator chip. (c) Time-domain waveform of the radiated pulses.

IV. EXPERIMENTAL SETUP

Fig. 2 shows the experimental setup designed for probing an ICP [18]. The plasmas are excited using an RF coil on a ceramic window located on the top of the chamber. In this setup, the plasma is investigated with different pulse repetition rates [19]. To probe the plasma properties, the custom-designed frequency-comb radiator of Section III is used, which is fed with by a 9-GHz signal generated from a Keysight E8257D signal generator. The radiation of THz chip is first collimated using a 1-in-diameter off-axis parabolic (OAP) mirror at the opening of the chamber. The collimated beams are then focused on the receiver's antenna using another OAP mirror at the other side of the chamber. To minimize the error in the measurement, precise collimation is critical; therefore, collimation is first performed using visible a light laser, and the laser is later replaced with with the chip at the exact same location. THz tones are down-converted into IF frequency using a VDI spectrum analyzer extender (SAX032), which covers 320–500-GHz band. The IF signal is then measured using a PXA N9030 A Keysight spectrum analyzer.

In pulse-based ICP, the plasma appears and disappears with the frequency of the pulses. In other words, when the RF generator is energized, the antenna excites the gas in the chamber, thereby generating the plasma. As explained in Section II, the plasma causes a phase shift in the probing THz beam (see Fig. 3). When the RF pulse goes low, the plasma disappears from the chamber. As a result, the THz waves reach the receiver at a phase proportional to their vacuum path length. This means that the phase and amplitude of each THz tone in the frequency comb is being modulated by pulsed plasma. To capture the IF I/Q data, Keysight vector signal analysis (VSA) 89 600 is utilized. Using VSA, quadrature demodulation is performed, allowing to calculation of the amplitude and phase of the tones separately over time. The precision of I/Q measurement is limited by the power and phase noise of the THz tones.

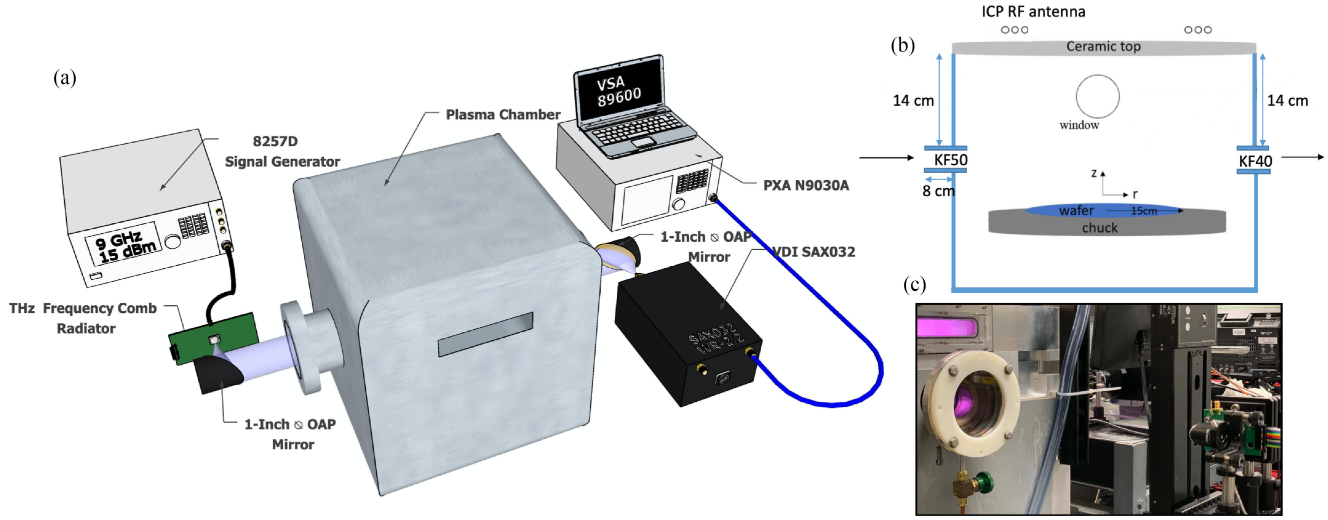

Fig. 2. (a) Three-dimensional view of the experimental setup used for plasma physics characterization. (b) Schematic of the experimental plasma chamber. (c) Picture of the experimental setup.

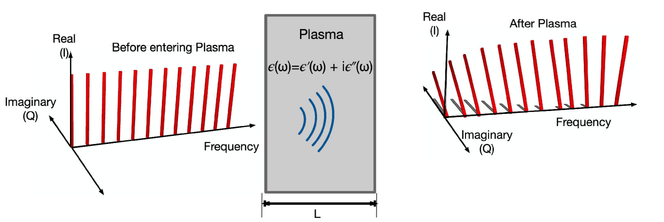

Fig. 3. Illustration of plasma interaction with the THz frequency comb.

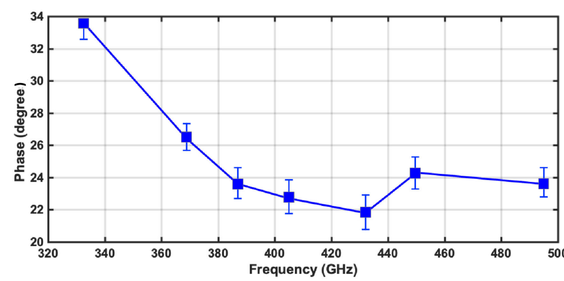

Fig. 5. Phase shift of THz frequency comb through an Ar ICP.

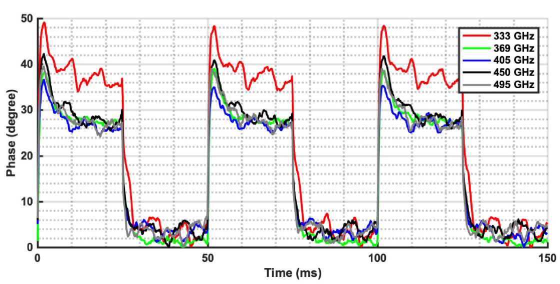

Fig. 4. Time-domain wave-forms of THz tones' phase.

V. MEASUREMENT RESULTS

The results are investigated under different plasma excitation power, pulse rates, and pressures. Fig. 4 illustrates the time-domain phase averaged over 100 pulses across the THz band where the plasma is pulsed at 20 Hz with 700 W excitation power. Fig. 5 plots the phase change for each frequency point, which is in agreement with (4) predicting smaller phase changes at higher frequencies, and Fig. 6 shows the time-domain amplitude of the THz tones. Amplitude fluctuations are caused by refraction and absorption in the spatially nonuniform plasma. At higher frequencies (495 GHz) the change in the amplitude is negligible, which is expected according to (2). Based on (4), ω_p is approximately 6.05 GHz, which corresponds to an electron density of 4.5×10^{11} cm^{-3}. This measurement was verified with a different 60 GHz homodine interferometer [20] and hairpin probe.

The gas pressure in the chamber affects the plasma density, and consequently the phase shift of the microwaves. In general, plasma

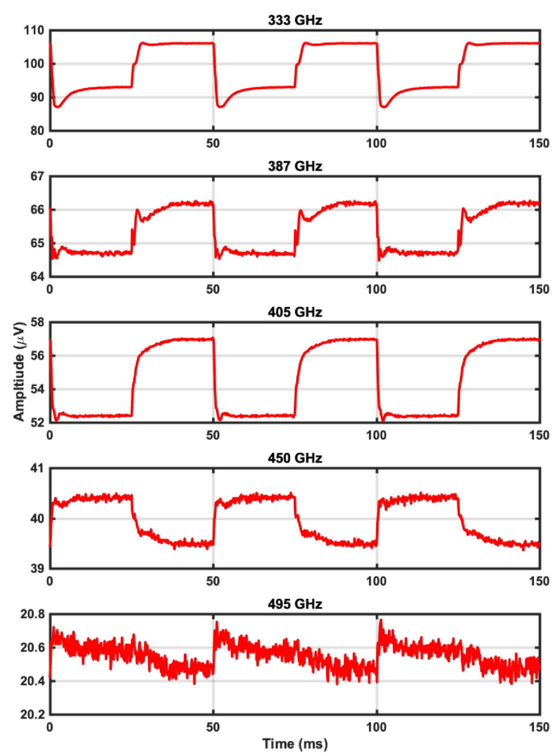

Fig. 6. Amplitude of the THz tones versus time.

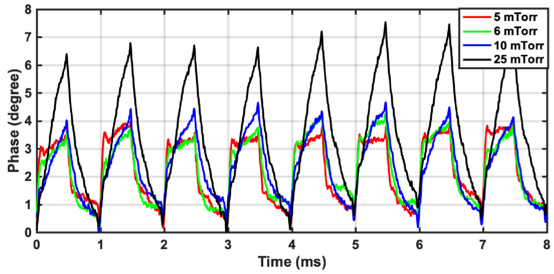

Fig. 7. Phase change for different gas pressures.

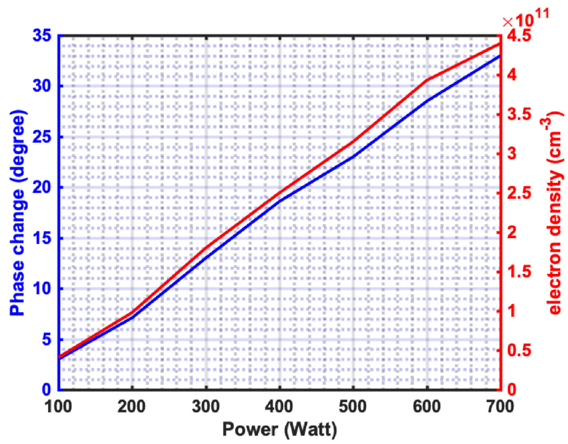

Fig. 8. Measured phase shift and calculated electron density versus various excitation power.

in an ICP is generated by electron neutral collisions, so increasing the pressure results in denser plasmas, therefore higher phase shift is expected. Fig. 7 shows the measured results for gas pressures of 5, 6, 10, and 25 mTorr at the plasma pulse rate of 1 kHz. At higher pressure, the plasma on-time is not long enough for the density to reach steady state. This is consistent with previous observations [19].

Plasma frequency and the phase change depend on the plasma excitation power. With the increase in the excitation power, the plasma becomes more dense, which results in higher plasma frequency. Thus, for the same probing frequency (333 GHz), higher phase shift is observed at higher power. Fig. 8 shows the amount of the phase shift and corresponding electron density when the excitation power is swept.

VI. CONCLUSION

In this letter, a new technique for pulsed plasma characterization using a low-power silicon-based THz frequency-comb radiator is introduced. Using the THz frequency comb, the spectral information of plasma is captured over a wide band. The plasma frequency and electron density are calculated by measuring the phase shift across the THz band using a VSA tool. Since the frequency comb extends from 10 to 500 GHz, the system is capable of measuring a broad range of densities. Low power consumption, high spectral resolution, high integration capability, and broadband radiation make this silicon-based THz radiator a low-cost solution for plasma sensing applications.

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