Multi-Spectral THz Micro-Doppler Radar Based on a Silicon-Based Picosecond Pulse Radiator

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Abstract—In this paper, THz vibrometry using a custom picosecond pulse radiator is demonstrated. THz vibrometry is based on the micro-Doppler phenomenon, in which the periodic movement of radar targets modulates the frequency of the electromagnetic waves reflected from their surface. The modulation depth depends on the amount of surface displacement and the carrier frequency. Since the micro-Doppler effect is stronger at higher frequencies, vibrometry in THz band benefits from higher sensitivity compared to RF and mm-wave. In this experiment, sound vibrations with the frequency ranging from 100 Hz to 1 kHz were used to modulate THz carrier tones produced by a broadband THz pulse radiating silicon chip. A music track, a chirp sound, and multiple frequency tones were produced by a speaker, and then were recovered by the downconversion of the modulated THz tone and analog demodulation at the receiver. Additionally, a phase-noise reduction technique is introduced to boost the sensitivity of low-frequency micro-Doppler detection.

Keywords — Doppler, displacement, depth of modulation, FM, micro-Doppler, radar, terahertz, THz source, vibrometry.

I. INTRODUCTION

The Doppler effect has been widely used in radar engineering to classify and measure the speed and moving objects such as drones and airplanes. Similarly, the micro-Doppler phenomenon, which roots from the Doppler effect, is used to detect the micro-motion signatures of objects. This effect has been used to characterize, identify, and distinguish moving objects [1]. In [2], the frequency of heart beat is measured using an ultra-wide band radar. In [3], a 160-GHz radar is used to sense throat vibrations and reconstruct the speech.

Micro-Doppler phenomenon in THz regime can be used for non-contact based vibrometry [4]. Long distance propagation of THz waves enables remote sensing and vibrometry of distant targets [5]. The surface micro-vibrations can modulate the frequency of the incident electromagnetic waves. Hence, by demodulating and processing the reflected waves, the signature of the vibrations can be recovered. Due to strong Doppler effect at THz frequencies, THz band has been of great interest to researchers for non-contact based vibrometry applications. In this paper, we have shown how reflected THz waves from a target are modulated by vibrations and how we can capture the signature of these vibrations. As one of the applications of vibrometry, the original sound waves are reconstructed by demodulating the THz carrier tones modulated by sound vibrations.

In section II, we review the theory of Frequency Modulation (FM) caused by sound vibrations. Section III describes the details of the experimental setup, and elaborates on the phase-noise reduction technique. In section IV, the micro-Doppler measurement results are discussed and section V concludes this paper. For THz radiation, a custom picosecond pulse radiator [6] is used. This chip produces a broadband frequency comb ranging from 10s of GHz to 1.1 THz. The spacing between adjacent tones is set by the frequency of input trigger.

II. MICRO-DOPPLER ANALYSIS

Fig. 1 illustrates the micro-Doppler effect on the reflected beam from a surface that vibrates with an angular velocity of \( \omega_s \). The reflected signal can be expressed as:

\[
R(t) = A \cos(2\pi f_c t + 2\pi \int f_d(t) dt)
\]

and

\[
f_d(t) = \frac{2v(t) \cos(\theta)}{c} f_c
\]

\[
v(t) = D \omega_s \cos(\omega_s t)
\]

where \( f_d(t) \) is the instantaneous frequency shift, \( f_c \) is the carrier frequency (frequency of the tone), \( v(t) \) is the instantaneous velocity of the reflecting surface, \( D \) is the amplitude of the vibration (displacement), \( c \) is the velocity of the electromagnetic wave, and \( \theta \) is the angle between the vibration direction and the incident wave. (1) can be expanded in the following explicit form:

\[
R(t) = A \cos(\omega_s t + \frac{2D \cos(\theta) \omega_s}{c} \sin(\omega_s t))
\]

\[
= A \sum_{k=-\infty}^{\infty} J_k(\beta) \cos((\omega_s + k\omega_s) t)
\]

where \( J \) is the Bessel function and \( \beta \) is the modulation index (modulation depth) of the FM modulation, which is directly proportional to the carrier frequency. Hence, by increasing the carrier frequency, a larger modulation depth and a wider bandwidth is achieved. Table I shows the power of the modulated tones in dBc for different displacements when \( \theta = 0 \), and \( f_c = 400 \text{ GHz} \).

<table>
<thead>
<tr>
<th>( D ) (( \mu m ))</th>
<th>1000</th>
<th>500</th>
<th>200</th>
<th>100</th>
<th>50</th>
<th>10</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta )</td>
<td>16.7</td>
<td>8.4</td>
<td>3.3</td>
<td>1.7</td>
<td>0.84</td>
<td>0.19</td>
<td>0.017</td>
</tr>
<tr>
<td>( L_{\beta f_s} ) (dBc)</td>
<td>-14.6</td>
<td>-11.3</td>
<td>-14</td>
<td>-4.9</td>
<td>-8.4</td>
<td>-21.5</td>
<td>-41.5</td>
</tr>
</tbody>
</table>

One of the key factors that determines the lower limit of the detectable vibration frequency and overall quality of
the recovered sound is the linewidth of the carrier frequency tone. Narrow spectral linewidth and low phase noise are necessary for the detection of low-frequency vibrations. Specifically, this issue is more critical at millimeter-wave and THz frequencies, where oscillator-based radiators suffer from poor phase noise and frequency instability. To mitigate this problem, the frequency of the radiated tones is locked to a low-phase noise external source. However, due to the inherent frequency multiplication in pulse radiators, the phase noise of the high-frequency radiated tones degrades based on the following:

$$L_{Nf_0} = 20 \log(N) + L_{f_0}$$

(5)

where $N$ is the multiplication factor and $f_0$ is the input trigger frequency of the chip. It should be noted that 10-dB linewidth of all the radiated tones is less than 2 Hz. In later sections, a phase-noise reduction technique is introduced that can compensate the phase noise degradation caused by frequency multiplication.

III. EXPERIMENTAL SETUP

A 130-nm SiGe BiCMOS picosecond pulse radiator based on PIN diode reverse recovery [6] is used as the radiating source. In this experiment, the repetition rate of the radiating pulses is set at 5.5 GHz, which results in a frequency comb with 5.5 GHz spacing between adjacent tones.

Due to the high dielectric constant of silicon substrate, the radiation of the on-chip antenna is coupled to the substrate modes. Hence, a hemispherical silicon lens is placed on the back of the chip to eliminate the substrate modes and increase the total radiation efficiency.

Fig. 2 shows a diagram of the measurement setup. Off-axis parabolic mirrors were used to collimate the THz radiation at the transmitter and focus it on the horn antenna at the receiver. A rigid plane mirror was used to direct the collimated beam and pick up the mechanical sound vibrations from the speaker. Precise alignment is essential to maximize the received THz power. The alignment was performed with the aid of a visible light laser. A 1-mW visible laser was used to precisely align the pulse radiator chip and mirrors. On the receiver side, a VDI Spectrum Analyzer Extender (SAX) in
conjunction with a Keysight PXA N9030A signal analyzer was used to down-convert the received tones, which are in 320-500-GHz range. To recover the micro-Doppler side tones, AM/FM analog demodulation was performed using Keysight N9063A application.

Subtle vibrations generate low-power side tones that can fall below the skirt caused by the phase noise of the carrier. Considering the phase noise deterioration due to frequency multiplication in the THz radiator and the VDI SAX, the overall sensitivity of the system is reduced significantly. Therefore, the summation of the uncorrelated phase noises of the radiated tones and the LO signal poses the main challenge for capturing the micro-Doppler signature of weak vibrations. In order to tackle this problem, the measurement setup in Fig. 3 is proposed. By splitting the power of the signal generator, the phase noise of the LO and the radiated tones remain correlated, thereby mitigating the phase noise degradation of the radiated tones. The VDI SAX module consists of a \( \times 36 \) multiplier which converts the 5.5 GHz input to 396 GHz LO. By feeding the same input to the pulse radiator chip, the tones at 401.5 and 390.5 GHz are down-converted to the IF of 5.5 GHz as shown in Fig. 4. Due to the correlation of the phase noise of the chip and VDI SAX, the phase noise degradation due to frequency multiplication is compensated. As a result, the sensitivity of the system is significantly improved, which enables the detection of weaker vibrations. The measurement setup is shown in Fig. 5.

**IV. MEASUREMENT RESULTS**

In the first experiment, a 42-sec music track and a 30-sec chirp audio signal (50 to 700 Hz) were played via a speaker in proximity of the plane mirror (Fig. 2, Fig. 3). The sound was recovered at the receiver from the micro-Doppler signatures of the plane mirror. To avoid loss of information, the recovered sound must preserve the main frequency components of the original sound waves. Fig. 6 shows that fundamental frequency components of the recovered sound follow the original chirp sound. Additionally, in Fig. 7, the spectrogram of both the original music track and the reconstructed version are shown. It is explicit that the main frequency components in the spectrogram of the original track match with those in the recovered sound. It is evident that using this measurement setup, any arbitrary audio signal can be recovered from the vibrations.

To demonstrate the frequency modulation of the carrier tone, single frequency tones at 270 Hz, 400 Hz, 600 Hz, and 750 Hz were produced by the speaker. Two separate
measurements for the same amount of vibration (same displacement) were performed using the measurement setups of Fig. 2 (without phase noise suppression) and Fig. 3 (with phase noise suppression). The received tones after down-conversion are shown in Fig. 8. It can be seen that using the measurement setup of Fig. 3, the noise floor of the received tone has decreased by at least 20 dB for frequency offsets below 200 Hz and by 15 dB for frequency offsets below 1 kHz. For 270-Hz and 400-Hz audio tones, the FM side tones can be seen around the carrier frequency with the spacing set by the frequency of the sound vibration as predicted by the analysis in section II. As observed in Fig. 8, the coupling of the power lines and non-linearity of the system cause spurious tones at 60 Hz and its harmonics, thereby limiting the sensitivity of the system at these frequencies.

V. CONCLUSION

This paper demonstrates a non-contact based vibrometry at THz frequencies. An experimental setup was designed and utilized to retrieve sound waves using micro-Doppler effect. The micro-Doppler signature of a scattering surface was recorded using a THz carrier tone generated by a low-power custom-designed THz pulse radiator chip. Due to high modulation depth, which is achieved by using THz carrier tones, and by suppressing the phase noise, the sensitivity of the system is significantly improved, thus enabling the detection of weak micro-Doppler signatures. Additionally, narrow spectral line-width of the tones and suppressed phase noise enables detection of vibrations with frequencies as low as 5 Hz.

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REFERENCES