600 GHz Imaging Radar with 2 cm Range Resolution

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Abstract — **We report the first submillimeter-wave imaging system that has radar ranging capabilities. By frequency-modulating the K-band synthesizers of a single-pixel 630 GHz scanning vector imager and applying a distortion compensation technique in software, we have achieved a range resolution of approximately 2 cm for targets at a range of several meters. Relief images of test objects obtained with our system demonstrate that three-dimensional THz imaging of scanned targets is feasible using a room temperature, all solid-state approach.**

Index Terms — **Submillimeter wave imaging, FMCW chirp radar, submillimeter wave radar, radar imaging, THz radar.**

I. Introduction

Imaging systems at millimeter and submillimeter wavelengths are actively being developed in response to the demand for new capabilities in surveillance and concealed weapons detection [1-4]. Strong molecular responses to THz radiation is also a driver for this technology, with applications in biomedicine and Earth and planetary science [5]. While THz imaging technology has primarily focused on acquiring two-dimensional camera-like representations of a scene, additional utility would come from a fully three-dimensional imager with high range resolution.

In this paper we describe how a 630 GHz single-pixel scanned imager was modified to achieve a range resolution of about 2 cm at 4 m range. The approach is to adapt the frequency-modulated continuous-wave (FMCW) radar technique to an existing imaging system [6], chirping the coherent illumination beam over a bandwidth of 8 GHz and performing signal post-processing to reduce waveform distortion effects. Our results represent the first time, to our knowledge, that a non-laser radar has been operated above 300 GHz. We expect that in addition to enhancing THz imager capabilities, the technology described here could impact conventional high-resolution radar applications of target detection and tracking, automotive anti-collision systems, and atmospheric remote sensing.

II. Measurement System

The submillimeter radar is a modified version of the vector imager system described in [6] and shown in Figure 1. To measure signals reflected from a test target, a beamsplitter was added to co-align the transmit and receive beams through a 20 cm diameter Teflon Fresnel lens. This lens focuses the beams from the transmitter and receiver feedhorns down to a spot size of ~1 cm at a range of 4 m, where a small mirror is used as a test target.

While the lateral cross-range resolution of a radar/imager is determined primarily by the lens diameter and the target distance, the range resolution has a theoretical limit determined by the bandwidth of the transmitted signal. In the FMCW radar technique [7], the transmit waveform needs to be smoothly chirped in frequency over a wide span (bandwidth) ΔF of ~15 GHz to reach ~1 cm-scale resolution. Achieving a smooth chirp appears incompatible with the vector imager of Fig. 1 because the two Micro Lambda Wireless MLSL synthesizers have a minimum step size of 125 kHz (corresponding to 9 MHz after multiplication). However, we found that continuous and highly linear chirps can be generated by frequency modulating the synthesizers' 10 MHz reference input with an Agilent 33220A arbitrary waveform generator. The MLSL synthesizers have a loop bandwidth of only ~10 Hz, so in order to maintain phase lock the chirp rate needs to be kept quite low. Through experimentation we found that the maximum possible chirp rate is 20 GHz per second.

To preserve the phase noise-canceling characteristic of the vector measurement system, it was necessary to feed the same swept reference signal to both synthesizers. Because of the different multiplication factors in the RF and LO synthesizers, some chirp is still present in the 1st IF (450 MHz) signal. As a result, the chirp span is limited by the 437.21 MHz bandpass filter in the noise cancellation stage, which has a 3 dB bandwidth of 8 MHz and a rejection of over 100 dB at 9 MHz beyond the band edges. This limits the maximum final transmit FMCW bandwidth to about 8 GHz.

After downconverting to the final IF frequency of ~66 kHz, the deramped signal was recovered using a Measurement Computing PCI-DAS6034 card in place of the lock-in amplifier described in [6]. Digital signal processing of the IF signal, such as range compression using the fast Fourier transform (FFT) algorithm, was implemented using Labview and Matlab software.

Transmitter power and LO power for the heterodyne receiver are derived from custom W-band MMIC power

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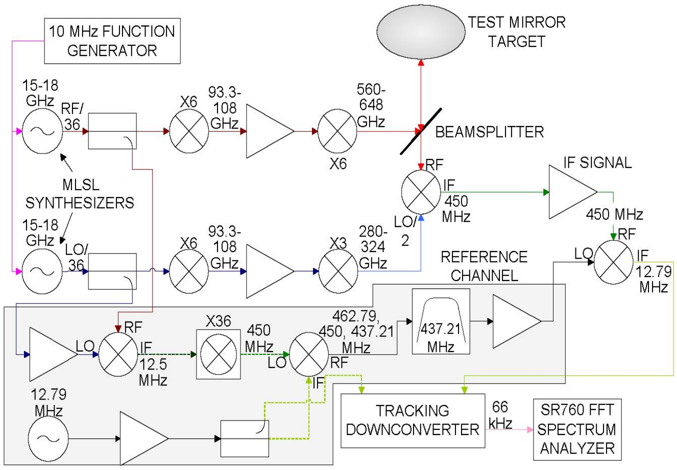

Fig. 1. Block diagram of measurement system.

amplifier modules and frequency multiplier chains consisting of doublers and triplers. These components have been described elsewhere [6]. In order to maximize output power, the 200, 300 and 600 GHz multipliers are all operated at their optimum safe operating bias and input power levels. Because the gain of the 100 GHz power amplifiers feeding the multipliers varies widely with frequency, a lookup table is used to adjust the supply voltage to the amplifiers at every operating frequency. To protect the multipliers from damage in the event of the synthesizers unlocking from the chirped 10 MHz reference, a software control loop was written to shut down the amplifier power supply in the event of an unexpected unlock event.

The power transmitted by the multiplier chain's feedhorn is only ~50 μW at 630 GHz, and the system noise temperature referred to the receiver mixer input is ~300,000 K. These values reflect the use of unoptimized submillimeter Schottky diode blocks, and they pose a limitation on the achievable SNR. We expect that much higher transmit powers and much lower noise temperatures can be attained using state-of-the-art component substitutions.

III. Results

In FMCW radar, range information is encoded in the spectral content of the final IF signal. In particular, a target at a range R will appear as a peak in the IF spectrum at a frequency

$$f_{IF} = f_0 + \frac{2KR}{c} \qquad (1)$$

where f_0 is the final IF center frequency of 66.24 kHz, K is the chirp rate, and c is the speed of light.

To test the basic functionality of our radar, a 5 cm mirror was positioned at a range of 4.4 m and aligned with the transceiver beam. The FMCW ramp spans 8 GHz over a duration of 0.5 s, which gives a chirp rate of K = 16 GHz/s and a pulse repetition frequency (PRF) of 1 Hz for the round-trip ramp up and down. The resulting IF spectrum is shown in Figure 2a. The reflected signal from the mirror appears as two peaks located at ± 497 Hz from the IF center frequency of 66.24 kHz, and the innermost spikes represent reflected power from the beamsplitter and Fresnel lens. The two symmetric peaks from the mirror arise from the positive and negative slopes of the transmit frequency ramp during the pulse repetition interval (PRI). Using Eq. (1) for a range of 4.4 m, the expected target location is ± 470 Hz, which is very close to the values observed in Fig. 2a.

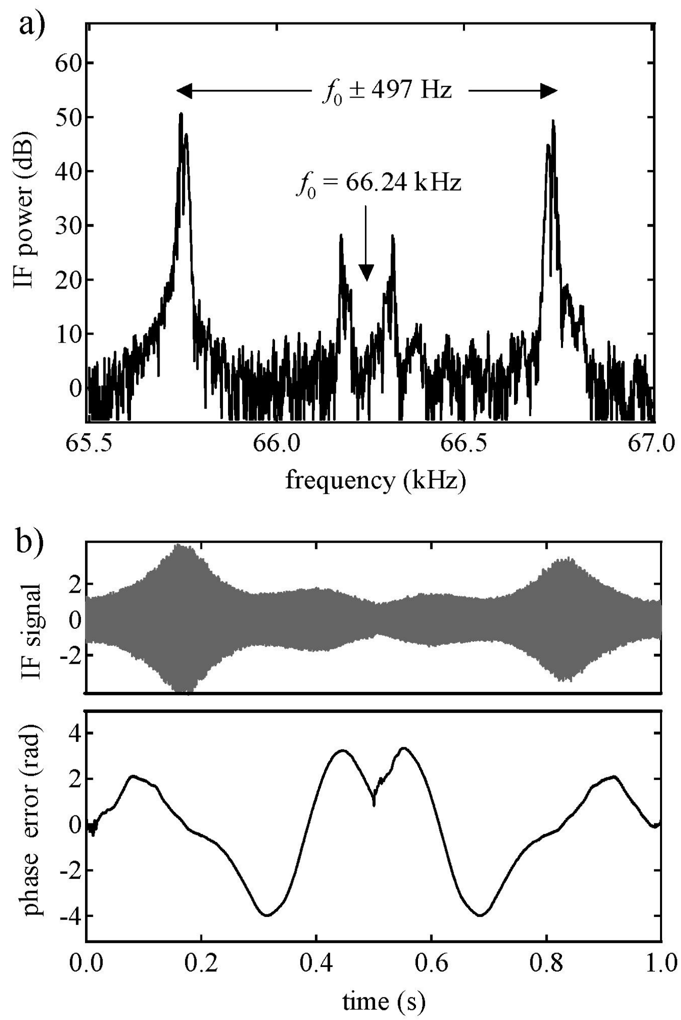

Fig. 2. a): Raw spectrum of radar IF signal for a mirror target at 4.4 m range. The symmetry about the IF center frequency comes from ramping up and down in the FMCW waveform, and the structure at close range is due to the lens and beamsplitter. b): Raw IF signal envelope (top) and phase error from a constant slope (bottom) versus time. This AM and FM deviation is responsible for the broadened point-target response.

The discrepancy of 27 Hz is probably a result of a residual electrical path difference in the transmit and receive channels. To show this, we measured the position of the mirror peak in the IF spectrum as a function of the mirror position for ranges

between 1.5 and 4.5 m. As expected, a linear dependence was observed as shown in Figure 3. The maximum error from a linear fit is less than 1%, and extrapolating to zero range gives an offset of 20 Hz in the IF signal. This is consistent with the 27 Hz difference in the absolute range signal for the 4.4 m

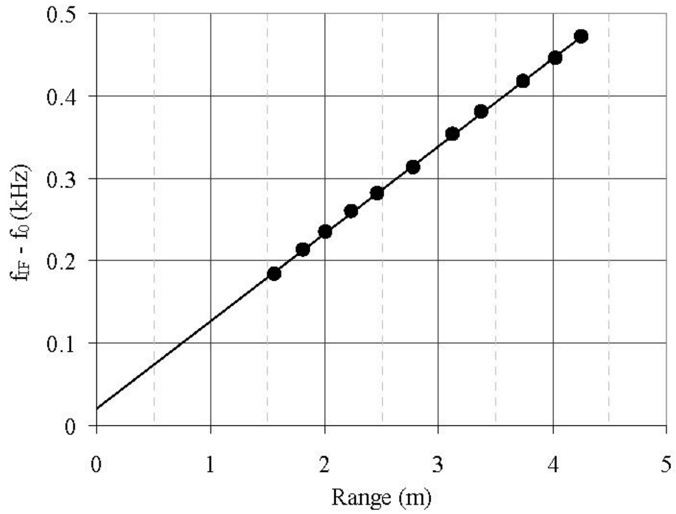

Figure 3. Measured IF frequency as a function of target mirror distance. The x-intercept of 20 Hz corresponds to an electrical path length difference of 15 cm in the transmit and receive channels.

target to within the distance measurement uncertainties.

The 3 dB peak widths of the mirror signals in Fig. 2a are ~20 Hz, substantially broader than the bandwidth-limited value of 2·PRF = 2 Hz. In other words, the radar's range resolution is about 10 times worse than the bandwidth-limited value of

$$\Delta R = \frac{c}{2\Delta F}. \qquad (2)$$

The broadening we observe arises from the effects of unwanted amplitude and frequency modulation (AM and FM) of the transmitted waveform. These AM and FM distortions are generated in the radar/imager electronics, and they can be measured using the IF signal of the mirror target of Fig. 2a. In Fig. 2b, the raw IF signal during a single PRI is plotted in the top panel, showing an AM variation of nearly 15 dB. The FM error can be quantified by using a Hilbert transform to obtain the time series of the IF signal's phase, and then removing a constant slope to obtain the phase deviation. The bottom panel of Fig. 2b shows that the phase deviation is several radians during a PRI. Together, these distortions result in the broadening of the single-mirror (point-like target) response of Fig. 2a.

Fortunately, the AM and FM distortions of Fig. 2b are highly reproducible, and therefore their deleterious effects can be undone in signal processing. In other words, the range spectrum of some target configuration can be "focused" by compensating the IF signal's amplitude and phase deviations by the amounts shown in Fig. 2b before the FFT compression step.

The results of this compensation procedure for the case of two closely spaced point-like targets are shown in Figure 4. The two mirrors consist of a small 2.6 cm mirror positioned in front of the same 5 cm mirror of Fig. 2, so that approximately equal power is reflected from each surface. The range difference of the two mirrors is 4.4 cm. The red dashed curve in Fig. 4 shows the raw, unprocessed IF signal spectrum coming from the two mirrors. Its width of ~20 Hz is too broad to resolve the two mirrors because a range separation of 4.4 cm corresponds to an IF frequency difference of 4.7 Hz. But by implementing the AM/FM compensation scheme using the calibrated single-mirror data of Fig. 2b, the new IF spectrum becomes very well focused. This is shown as the black curve in Fig. 4, where two maxima are clearly visible with a dip of 15 dB between them. Indeed, the 3 dB width of each peak is about 2 Hz, consistent with a 2 cm bandwidth-limited range resolution of the 8 GHz FMCW radar measurement.

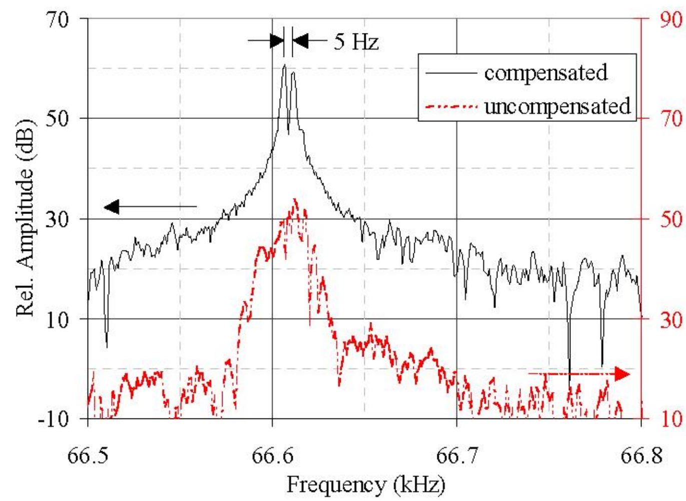

Figure 4. Red trace: raw IF spectrum of two target mirrors displaced by 4.4 cm from one another. Black: compensated spectrum after accounting for the AM and FM distortion calibrated in Fig. 2b. With a resolution of 2 cm, the radar can easily distinguish the two targets.

Three-dimensional images obtained using this system are shown in Fig. 5. To raster scan the beam over the target, a large flat mirror mounted to a 2-axis rotation stage was placed in front of the Teflon lens. Although images of sufficient quality could be obtained with this system as seen in Fig. 5a, the signal-to-noise ratio had to be improved in order to obtain imagery of human test subjects in a reasonable amount of time (minutes as opposed to hours). This was done by replacing the subharmonic mixer with a fundamentally pumped balanced mixer [9], yielding a system noise temperature of 6,500 K. Because this mixer and accompanying LO chain were designed for a lower frequency, the images of Fig. 5b were obtained at a center frequency of 585 GHz. The chirp rate was also increased from 16 GHz/s to 80 GHz/s by replacing the

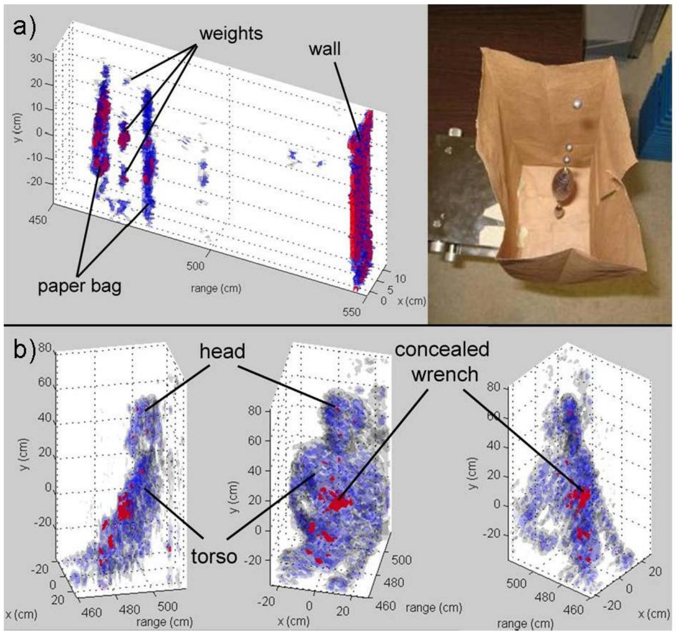

Figure 5. a): Three-dimensional image of fishing weights suspended inside a paper bag. In additional to the metallic weights, both the front & back sides of the bag are visible as well as the wall behind the bag. b): 3D image of human subject holding a wrench underneath clothing. A fundamental balanced mixer and improved chirp generation scheme were used to obtain these images.

synthesizer reference modulation scheme with a sweeping VCO, mixers and sideband filters to generate the base microwave RF and LO signals.

The radar/imager described here is capable of impressive range resolution, but we expect that this emerging technology can be readily improved in several ways. The system noise temperature was reduced by nearly two orders of magnitude by replacing the receiver's subharmonic mixer with a fundamental balanced mixer. An alternative approach would be to simply replace the subharmonic mixer with one that has been optimized to the available LO power. Likewise, the transmitter chain's multipliers can be optimized to increase the radar's output power to the mW level.

For scanned 3D imaging applications, it will be very helpful to further increase the PRF by building a custom chirped source that is fast, linear, and wideband. These requirements are conflicting because of the tradeoff between speed and phase noise, but such systems have already been developed for specialized FMCW radars [8]. Indeed, phase noise and chirp nonlinearities in submillimeter radars will likely pose severe constraints as target distances increase and clutter and multipath signals appear [7]. Nonetheless, the results presented here suggest that the component technology and signal processing algorithms are advanced enough to make submillimeter radar viable.

IV. Conclusion

A submillimeter FMCW radar system suitable for three-dimensional imaging has been demonstrated at 630 GHz. Despite the narrowband limitations of using an IF system designed for CW imaging applications, range resolution of ~2 cm was achieved by ramping the transmit signal over a bandwidth of 8 GHz in 0.5 s. Attaining this high resolution required a simple software compensation for removing pre-calibrated AM and FM nonidealities in the chirp waveform. These results demonstrate the feasibility of high-resolution submillimeter FMCW radar based on an all solid-state approach, and they point to a clear direction of how to improve performance by lowering noise and increasing speed and bandwidth. We believe that a submillimeter radar designed for sub-cm resolution and video-rate acquisition will be possible with only evolutionary improvements over the system described here.

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