A High-Resolution Imaging Radar at 580 GHz

K. B. Cooper, *Member, IEEE*, R. J. Dengler, *Member, IEEE*, G. Chattopadhyay, *Senior Member, IEEE*,
E. Schlecht, *Member, IEEE*, J. Gill, A. Skalare, *Member, IEEE*, I. Mehdi, *Senior Member, IEEE*, and
P. H. Siegel, *Fellow, IEEE*

***Abstract*—We have developed a high-resolution imaging radar at 580 GHz. Coherent illumination in the 576–589 GHz range and phase-sensitive detection are implemented in an all-solid-state design based on Schottky diode sensors and sources. By employing the frequency-modulated continuous wave (FMCW) radar technique, we achieve centimeter-scale range resolution while utilizing fractional bandwidths of less than 3%. Our high operating frequencies also permit centimeter-scale cross-range resolution at several-meter standoff distances without large apertures. Scanning of a single-pixel transceiver enables targets to be rapidly mapped in three dimensions, and here we apply this technology to the detection of concealed objects on persons.**

***Index Terms*—Frequency-modulated continuous wave (FMCW), submillimeter radar, terahertz (THz) imaging, terahertz (THz) radar.**

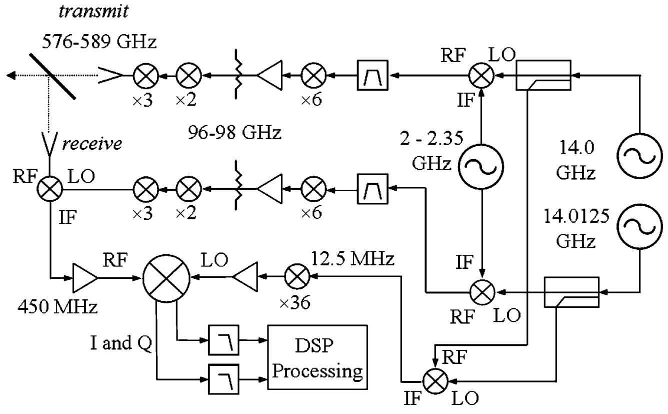

Fig. 1. Block diagram of 600 GHz radar imager.

I. INTRODUCTION

RECENT Progress in terahertz (THz) technology, as well as the demand for new surveillance capabilities, has led to the development of prototype submillimeter imagers capable of detecting weapons concealed within clothing or packages [1]–[4]. Imaging in the THz regime is attractive because wavelengths in the range 100 μm $< \lambda <$0.5 mm are short enough to provide high resolution with modest apertures, yet long enough to penetrate materials such as cloth or cardboard. However, current approaches to THz imaging do not yet meet all of the real-world and often conflicting requirements of standoff range, portability, high speed, penetrability, target identification, and cost.

For example, while active THz imaging systems using high-power coherent illumination and ultra-low-noise heterodyne detection show great promise, they often face operational drawbacks such as requiring cryogenic detectors or bulky laser sources. A more fundamental difficulty with coherent active imaging is that by relying on a single frequency, target recognition is reliant on an object's contrast and brightness which, in turn, are highly sensitive to incidence angle of radiation, clutter signal from the foreground or background, and interference and speckle effects.

Here we describe a room temperature, all-solid-state active submillimeter imager that is designed to overcome these limitations by utilizing the swept-frequency FMCW radar technique to map a target in three dimensions. Our radar is currently able to distinguish targets with centimeter-scale resolution in both range and cross-range, and the images we obtain indicate that radar capability may emerge as a key component of active THz imagers.

II. MEASUREMENT SYSTEM

The block diagram of the submillimeter radar is shown in Fig. 1. The system evolved from a tunable, continuous-wave (CW) 600 GHz vector imager system described in [4]. The radar's key components, custom-built for a different application at the Jet Propulsion Laboratory, are the Schottky-diode multipliers generating transmit powers of 0.3–0.4 mW over 575–595 GHz [5] and a balanced fundamental mixer exhibiting a DSB noise temperature of ~4000 K over the same range [6]. Also notable in our design is that residual phase-wander between the locked RF and LO K-band source synthesizers is canceled at an intermediate 450 MHz IF stage before final conversion to baseband by an IQ mixer.

To implement the FMCW chirp, we use a 2–4 GHz low-phase-noise YIG synthesizer (Teledyne Microwave) with a tuning bandwidth of 5 kHz, typically ramping over 350 MHz (subsequently multiplied by 36 to 12.6 GHz) in 50 ms. The chirp signal is upconverted onto the CW synthesizers' signals before multiplication, and deramping of the FMCW waveform occurs at the 600 GHz receiver mixer. While high multiplication factors should be generally avoided in FMCW radar systems to minimize the impact of phase noise in the transmitted signal, in this case the short standoff ranges

Manuscript received May 29, 2007; revised August 22, 2007. This work was supported by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration, by a contract to the California Institute of Technology, Division of Biology, and by the Naval Explosive Ordnance Disposal Technology Division [with funding provided by the DoD Physical Security Equipment Action Group (PSEAG)].

K. B. Cooper, R. J. Dengler, G. Chattopadhyay, E. Schlecht, J. Gill, A. Skalare, and I. Medhi are with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA (e-mail: e-mail: ken.b.cooper@ipl.nasa.gov).

P. H. Siegel is with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA. He is also with the Department of Biology, California Institute of Technology, Pasadena, CA 91125 USA (e-mail: phs@caltech.edu).

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Digital Object Identifier 10.1109/LMWC.2007.912049

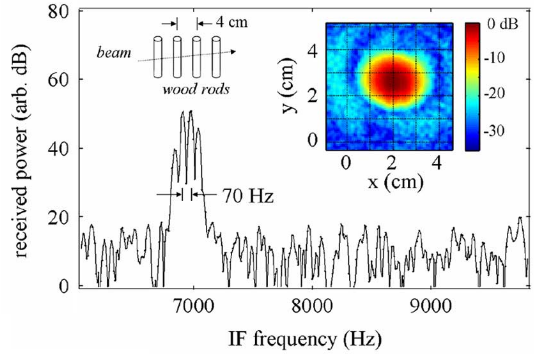

Fig. 2. Demonstration of cm-scale range resolution using a target of four balsa wood rods with 4 cm spacing. Inset: Cross-range beam profile at 4 m standoff showing a 3 dB full width of ~1 cm.

produce a phase noise floor that lies below the thermal noise except for the brightest, mirror-like specular targets.

The submillimeter power is transmitted first through a silicon wafer beamsplitter and then a plano-convex Teflon lens with a diameter of 20 cm. This lens focuses the THz beam to a spot size of ~1 cm at a standoff range of 4 m. To achieve scanned images, a flat mirror on a two-axis rotational stage deflects the beam in the desired direction. For the images reported here, the typical acquisition time is 100 ms per pixel (50 ms ramp up and down).

In FMCW radar, Fourier processing of the final IF signal yields a power spectrum where a target at range R appears at a frequency given by $f_{\mathrm{IF}} = 2KR/c$, where K (Hz/s) is the chirp rate and c the speed of light. For our chirp rate of 250 MHz/ms, targets at 4 m standoff distances yield frequencies around 7 kHz. After amplification and anti-alias filtering, we typically digitize the baseband I and Q channels at a 40 kHz sampling rate and 16-b resolution.

Before windowing and processing via fast Fourier transform, we find it necessary to phase modulate the complex-valued digitized signals to undo the effects of FMCW ramp nonlinearity. This method is described in [7], and we now believe that the nonlinearity is introduced, in large part, by the power dependence of the submillimeter components' phase response over the chirp bandwidth. This conclusion is based on the pronounced sensitivity of the ramp's nonquadratic phase deviation on small attenuation changes at the W-band stages prior to the final multiplication steps. However, because the chirp nonlinearity is very stable over time, near-optimal range resolution is achieved without recalibration over periods of days.

III. RESULTS

The 3-D resolution capabilities of the submillimeter radar imager are demonstrated in Fig. 2. In the inset, a 101 × 101-pixel scan is shown of the range-gated return power from a 0.3 cm gold-plated bead suspended by sewing thread at 4 m range. The two-way beam profile exhibits a 3 dB full beam width of about 1 cm, with sidelobes down by 25 dB at 2.5 cm offset from the beam center.

The range resolution, on the other hand, has a theoretical limit given by $\Delta r_o = c/2\Delta F$, where ΔF is the chirp bandwidth. Our chirp bandwidth of 12.6 GHz gives $\Delta r_o = 1.2$ cm. While this bandwidth is very large by conventional FMCW standards, it is only 2.5% of the carrier frequency at these submillimeter wavelengths. The small fractional bandwidth, by not imposing difficult tradeoffs at the component level, is one of great advantages of operating at submillimeter frequencies.

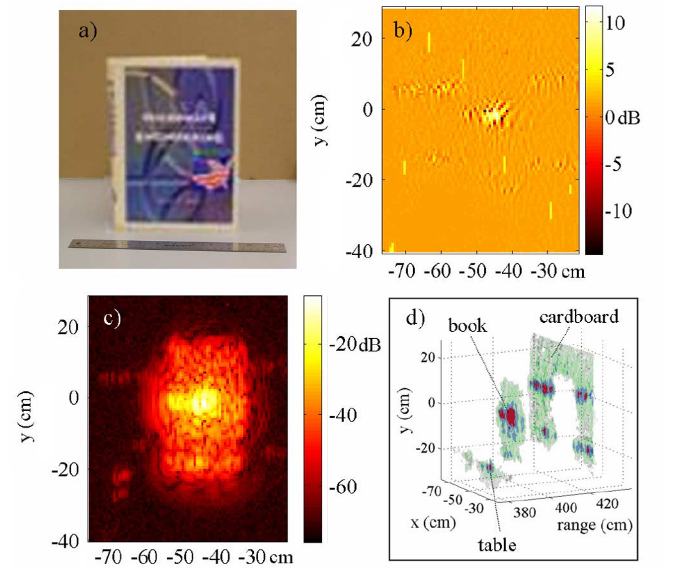

Fig. 3. (a) Photograph of target scenario: a textbook in front of a cardboard background at 4 m standoff range. The foot-long ruler was absent during the scans of (b)-(d). (b) 2-D image obtained by scanning the imager in CW mode at 585 GHz. (c) In contrast to (b), the book becomes visible when using FMCW radar and range-gating around the book only. (d) 3-D reconstruction shows the book and its shadow on the cardboard background.

In practice, the radar range resolution will be somewhat degraded because of nonlinearities in the chirp waveform and windowing after digitization. In Fig. 2, we demonstrate the range resolution of our radar by showing the IF spectrum of a grid of four parallel 1/4-in diameter balsa wood rods placed along the direction that the beam travels. The rod spacing is 4 cm, and each rod is clearly visible in the spectrum as one of four distinct peaks at frequencies separated by 70 Hz $\times c/2K = 4.2$ cm. This value is consistent with the 4 cm rod spacing after taking into account uncertainties from the angle of intersection between the beam and the grid and the rod thickness. The measured 3 dB peak widths of 30 Hz correspond to an experimental range resolution of 1.8 cm.

To demonstrate the benefit of using range information in active submillimeter imaging, Fig. 3 contrasts images obtained with and without radar capability. The scenario for these data is shown in the photograph of Fig. 3(a), where a textbook is propped up on a table in front of a cardboard background. The image in Fig. 3(b) was obtained using the system of Fig. 1 in CW mode at 585 GHz; no chirping or FMCW processing was used. The book's outline is completely invisible, with the only suggestion of its presence coming from a strong glint near the image center. Instead, most of the received power comes from the backscattering from the beamsplitter and the Teflon lens (which has no antireflective coating). In addition, the clutter signal reflected by the cardboard background is indistinguishable from the book's reflection.

On the other hand, Fig. 3(c) shows an image of the identical scenario except now using the radar imager in its FMCW mode.

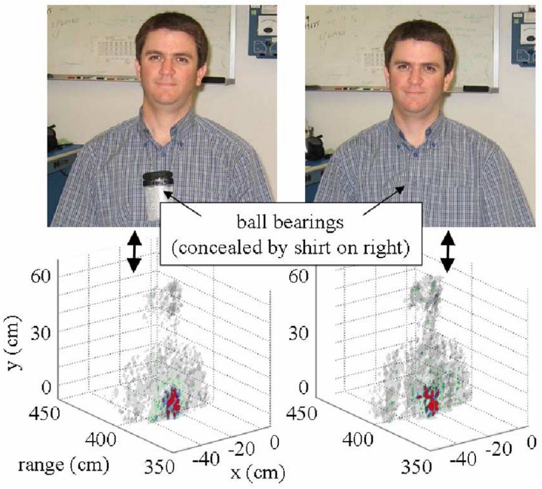

Fig. 4. Photographs (top) and 3-D THz radar imager reconstructions (bottom) of a person. On the left, the subject is wearing an exposed plastic container filled with ball bearings. On the right, the same filled container is concealed underneath his shirt.

The image (81 × 101 pixels acquired in about 15 min) was obtained by range-gating the total returned power over a depth of about 50 cm centered around book only. This serves to exclude clutter signals from both the optics and the cardboard. With a dynamic range of nearly 70 dB, the book is now clearly visible even though the physical clutter environment is identical to that of Fig. 3(b).

The range information can also be used to construct a 3-D map of the target using a straightforward peak-finding routine. This is shown in Fig. 3(d), with the book casting a distinct shadow on the cardboard background, and with a line of strong near-specular reflection continuing across the entire scene. Such 3-D imagery is more naturally interpreted by human observers, indicating how the range dimension of submillimeter imagery might be of great benefit to threat identification with lower probability of false alarms.

To assess the potential of THz radar imaging for the detection of concealed weapons, the 3-D scans of Fig. 4 were made. Two scenarios are illustrated: on the left, a plastic container filled with ball bearings (to mimic shrapnel) was hung around the subject's neck and over his shirt, while on the right, the same container was hung beneath the shirt. Each 50 × 50-pixel THz image was obtained in approximately 5 min, and as in Fig. 3, the chirp bandwidth and center frequency were 12.6 and 585 GHz.

The results of Fig. 4 show that bright targets such as ball bearings are easily detectable using submillimeter radar imagery, even when they are concealed by clothing. In addition, the ability to three-dimensionally represent the scene helps to clarify the image interpretation because clutter signals from the foreground and background are gated away. As range (and cross-range) resolution is improved further, as we expect them to be, we anticipate that the 3-D contours of small concealed objects (e.g., guns) will become visible as well. We also point out that unlike thermal THz imaging, the detectability of the targets in this case does not require any solar illumination or temperature differentials. Finally, because this submillimeter radar imager uses proven solid-state device technology, we are optimistic that future use of multipixel receivers, as well as optimizing the system optics and power, will permit 3-D imagery to be captured in real-time at standoff ranges of many meters.

ACKNOWLEDGMENT

The authors wish to thank Dr. J. Ward, JPL, for providing the 600-GHz sources.

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