Submillimeter-Wave Polarimetric Compact Ranges for Scale-Model Radar Measurements

M. Coulombe[1], J. Waldman[1], R. Giles[1], A. Gatesman[1], T. Goyette[1], and W. Nixon[2]

[1]University of Mass. Lowell, Submillimeter-Wave Technology Lab., Lowell, MA 01854
[2]U.S. Army National Ground Intelligence Center, Charlottesville VA 22911

***Abstract* — Fully-polarimetric, wide-band compact radar ranges based on transceivers operating in the submillimeter-wave regime have been developed for obtaining radar measurements on scale models (nominally 1:16). These transceivers use fixed-tuned Schottky-diode mixers and varactor multiplier sources to obtain reasonably wide-band performance. Optically pumped gas lasers, combined with tunable microwave sideband generation in corner-cube-mounted Schottky diodes, have been implemented to extend the operating frequencies into the THz regime. A dielectric material fabrication and characterization capability has also been developed to fabricate custom anechoic materials for the ranges as well as scaled dielectric parts for the models and clutter scenes. The general approach to designing submillimeter-wave compact ranges and the particular details of systems operating at 524 GHz and 1.56 THz will presented in this paper.**

I. INTRODUCTION

As radar technology evolves, the availability of high quality radar cross section (RCS) data becomes essential for successful development of enhanced capabilities such as automatic target recognition (ATR). The type of data required for these programs include high-range-resolution (HRR) target profiles and synthetic aperture radar (SAR) images. The Submillimeter-Wave Technology Laboratory (STL) at UMass Lowell has developed several compact ranges which specialize in using scaled frequencies in the submillimeter regime to measure precisely scaled targets for obtaining full-scale target signatures. Scale factors used in these systems range from 1:10 through 1:200, while frequencies range from 160 GHz up to 3 THz.

The technique of using scale models and scaled frequencies to study electromagnetic scattering dates back to the 1940s [1]. The use of submillimeter-wave radiation for scale model measurements was first reported in the late 1970s and early 1980s [2]. These early systems were based on narrow-band, optically pumped, far-infrared (FIR) lasers, which are still used for frequencies above 700 GHz. STL has refined these early laser-based systems into high-performance, compact ranges capable of modeling the performance of modern radar systems at most popular radar bands. The laser-based systems have been augmented with Schottky diode sideband generators to provide a wide-band capability at THz frequencies [3].

At frequencies below about 700 GHz, a completely solid-state approach using varactor diode multipliers is used. This solid-state approach offers a low maintenance and compact alternative to the laser-based systems. Currently, systems at 160 GHz, 524 GHz [4], and 660 GHz have been developed at STL using this approach.

In the following sections, the details of the 524 GHz and 1.56 THz transceivers will be presented along with a description of the anechoic and scaled dielectric materials that have been developed for these frequencies, and a review of the various types of radar measurements that have been made.

II. COMPACT RANGE

A compact range configuration refers to a radar system in which a large collimating reflector antenna allows the simulation of a far-field measurement close to the antenna. A scale-model compact range extends this concept by using scaled wavelengths and models. For example, full-scale systems at X, Ka, and W-bands (10, 35, and 94 GHz) can be modeled for 1:16 scale using 160 GHz, 524 GHz, and 1.56 THz.

The typical compact range at STL, shown in figure 1, occupies a room 50' long by 25' wide and consists of four major functional components; the transceiver, the collimating reflector, the target and calibration positioner, and the data acquisition system.

The transceiver produces a transmit signal centered at the desired scaled frequency and tunable over a scaled bandwidth (BW). This transmit radiation is coupled out as an expanding spherical-wave beam which propagates 6.3m out to the main collimating antenna mirror. The transmit beam at this point is about 0.68m in diameter (-3dB). The radiation is collimated by the reflector and propagates downrange to the target, located approximately 10m from the reflector. The target is therefore illuminated with a beam having a very flat phase front and a Guassian

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
2002		**00-00-2002 to 00-00-2002**

4. TITLE AND SUBTITLE	
Submillimeter-Wave Polarimetric Compact Ranges for Scale-Model Radar Measurements	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Massachusetts Lowell,Submillimeter-Wave Technology Laboratory,175 Cabot Street,Lowell,MA,01854**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**		**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

amplitude profile constant over most of the target. Backscattered radiation from the target retraces the transmit path to the receiver where the backscattered signal is down-converted through several mixer stages to the final IF where DSP instrumentation records the amplitude and phase at each transmit frequency.

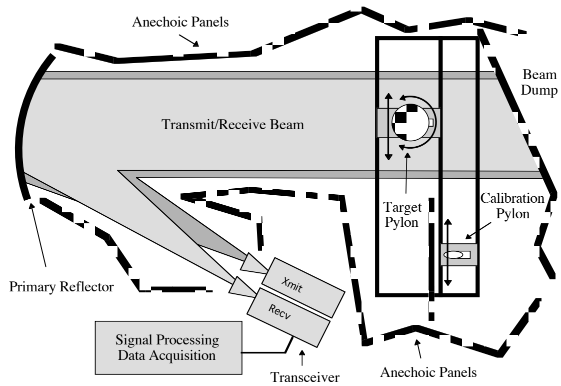


Fig. 1. Typical compact-range room configuration.

The compact range antenna is a 1.5m diameter, 6.3m focal length, CNC machined, hand finished, aluminum mirror. The mirror edge is rolled to control edge-diffracted radiation. The mirror has an optical finish, greatly aiding in the alignment of the system as well as testing of the antenna using optical techniques.

The target stage allows for automatic placement of the target and calibration pylons into the range as well as orientation of the calibration objects. Phase, amplitude, and polarization calibration of the system is accomplished with measurements of two calibration objects, a flat disk and a dihedral corner reflector measured at two seam orientations, (90° i.e. horizontal, and 67.5°). A software technique [5] then calculates a correction matrix, calibrating the system and improving the cross-polarization rejection ratio from –30dB to –60dB. The systems' excellent polarimetric performance allows accurate transformation of the H and V pol data into other polarization states(e.g., circular or other linear states).

To minimize backscatter from the compact range chamber as well as interactions between the target and chamber, the internal walls are covered with a custom fabricated, wedge-style, anechoic material [6] designed at STL and optimized for submillimeter-wave operation at 160 GHz, 500 GHz and 1.5 THz. Available in either iron-oxide loaded silicone 2'x2' sheets (designated FIRAM™-160 and FIRAM™-500) or carbon-loaded polyethylene 4''x4'' interlocking tiles (TERASORB™-500 and TERASORB™-1500) [7], these materials provide a 40 dB reduction in specular reflectivity with greater than 80 dB performance levels at non-specular angles. The anechoic is mounted onto large movable panels that allow maximum exploitation of the material's non-specular performance characteristics in the reduction of backscatter and target-chamber interactions, as well as the deflection of unwanted stray radiation to appropriate areas of the chamber.

III. SOLID-STATE 524 GHZ TRANSCEIVER

The 524 GHz compact range is based on a fully polarimetric transceiver [8] using a dual frequency, step-tunable, X-band, source driving four X48 multiplier chains. The transceiver consists of the frequency synthesizer/converter, the transmit multiplier chain, the receive multiplier chain/mixer, the IF converter and I/Q demodulator. As shown in figure 2.

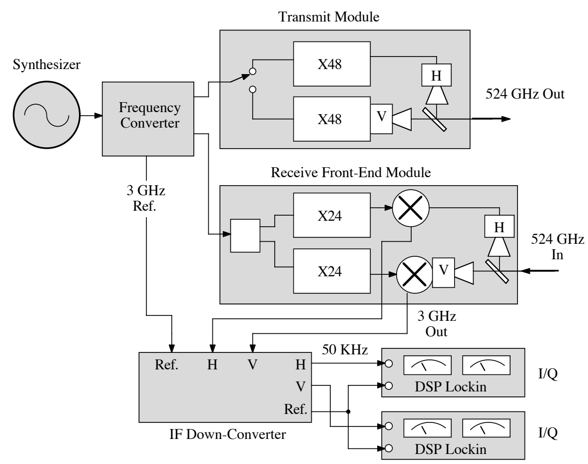


Fig. 2. The 524 GHz transceiver block diagram.

The frequency synthesizer/converter module generates three principal frequencies; the transmit multiplier chain drive signal, the receive multiplier chain drive signal, and the IF frequency/phase reference. Because of the X48 multiplication factor, very good spectral purity is extremely important. To achieve these frequencies, the 10.83 GHz synthesizer center frequency is shifted up by 62.5 MHz (3.0 GHz/48) using an up-converter, filter, and down-converter sequence. This dual conversion allows for a very wide sweep range with suppression of spurious tones, without the need of slow, complex tunable filters. The 62.5 MHz difference, after X48 multiplication, results ultimately in the 3 GHz first IF product. The 62.5 MHz oscillator is also directly multiplied by X48 to generate a 3 GHz reference which is down-converted in the IF chain along with the receive signals.

The design of the transceiver requires a controlled frequency sweep in which several thousand samples per second are measured with a stringent requirement for frequency and phase accuracy. This requirement favors frequency multiplication over phase-locked tunable source techniques. The multiplier chains are configured as a transmit module and a receive module, as shown in figures 2 and 3.

The transmit multiplier chain consists of an amplified quadrupler followed by two additional varactor doublers and a tripler to achieve 200 μW at the desired 524 GHz center frequency. Each final tripler has an integral diagonal horn that radiates a 12° beam. A small lens located very near the horn's aperture reduces the beam angle to 6°. A wire grid diplexes the H and V channels and cleans up the polarization, reducing the cross-polarization rejection ratio to >30 dB.

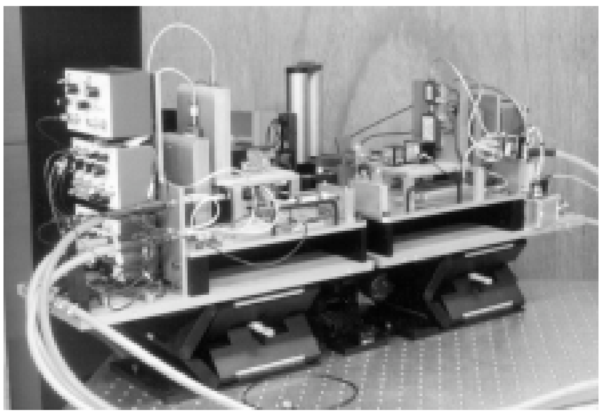
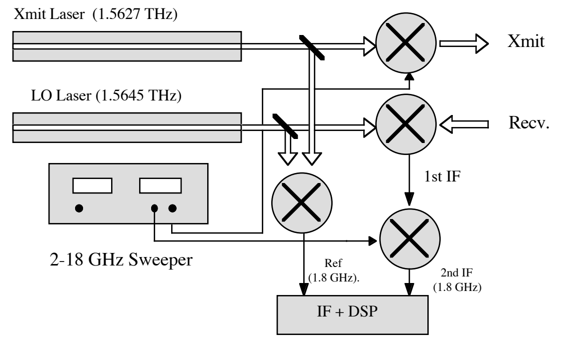


Fig. 3. Rear view of the 524 GHz transceiver modules (receiver on left, transmitter on right).

The receiver uses two additional multiplier chains to generate the LO for the two primary diode mixers. In most respects, the receiver module is identical to the transmitter except the last doubler and tripler are replaced with a tripler followed by a 2^{nd} harmonic mixer. The received 524 GHz signal is split into its two linear polarized components (H,V) using a wire-grid beam splitter. Each component is then coupled through separate lenses and horns into the mixers and down-converted to a pair of 3 GHz IF signals. The receiver NEP is about $4x10^{-19}$ W/Hz. The H, V, and reference IF signals are amplified and further down-converted to 50 KHz. DSP techniques are used to recover the I&Q signals from the three 50 KHz signals.

IV. HYBRID 1.5 THZ LASER TRANSCEIVER

The 1.56 THz transceiver, shown in Fig. 4, is functionally similar to the 524 GHz system but instead of using a multiplier chain, a 10-18 GHz microwave sweeper is mixed with a fixed 1.56 THz, 50 mW laser in two corner-cube-mounted diode mixers [9]. This generates approximately 5 μWatts of tunable sidebands, which are used for the H and V pol transmit signals. A second laser, offset in frequency by about 1.8 GHz, is used as the LO signal for a second diode mixer, configured as the receiver. The two lasers are also mixed with each other in a third mixer to generate the IF phase reference. Hi-purity Si etalons are used to optically filter the unshifted laser radiation from the transmit signal. The sidebands are then



spatially filtered to produce a clean gaussian-shaped beam.

Fig 4. Simplified diagram of 1.56 Hz Laser Transceiver.

Similar to the 524 GHz system, the received signal and reference are down-converted and fed to DSP instrumentation for complex demodulation. The unwanted (upper) sideband is electronically filtered in the receiver using frequency-shifted, asymmetric down-conversion.. The laser-sideband technique produces adequate power up to at least 3 THz, well above the current useful-power, upper frequency limit of 700 GHz for solid-state approaches.

V. DIELECTRIC MATERIALS

In order to acquire accurate radar signatures, the non-metallic scale model components (radomes, tires, fiberglass, fabrics, etc.) are fabricated from dielectrically scaled materials. In addition, targets are placed on ground planes modeling both the roughness and dielectric constant of common battlefield environments (sand, soil, trees, asphalt, etc.). A materials program at STL [6,7,10] assures that each measurement scene (target and environment) is dielectrically correct. Proper modeling of the target and environment dielectric behavior is necessary to optimally exploit signatures for ATR efforts, programming of smart munitions/weapons, testing of predictive codes, etc.

Electromagnetic modeling the radar frequency behavior of dielectric materials at submillimeter wavelengths requires that the dielectric constant of the scale model component equal the dielectric constant of the corresponding full-scale component. After the non-metallic materials of the vehicle and terrain of interest have been identified, the radar dielectric properties are measured on a microwave network analyzer, or when available, taken from the literature. Creating a material with identical submillimeter-wave properties is accomplished by exploiting the vast array of urethanes, epoxies, paints, and silicone-based materials available. When necessary, these materials can be loaded with powdered agents (silicon, carbon, aluminum, copper, stainless steel, etc.) to achieve a close match to the full-scale, complex dielectric constant.

STL has used dielectric scaling and model building technology to establish a library of more than 100 high-fidelity scale model tactical targets, as well as rough and smooth ground terrain, in support of its radar signature measurement programs.

VI. MEASUREMENTS

Data from targets measured in the compact ranges are typically processed into total radar cross-section (TRCS) plots, HRR profiles, and Inverse SAR (ISAR) images. Since the systems are very stable, a sequence of ISAR images taken at different depression angles can be further processed into 3D ISAR

To obtain measurements, a scale model target is mounted either in free-space or on a scaled dielectric ground-plane. The typical target is measured over a compete 360° aspect spin in increments between 0.1 and 0.01 degrees. At each aspect angle, the frequency is swept over the desired bandwidth while measuring the amplitude and phase. The sweep is transformed to the time domain using a DFT. Software range gating reduces this large data array to the desired target extent.

The median or center-frequency power of each frequency sweep can be plotted as a function of look angle to create a TRCS plot. This data format can be used to estimate a target's probability of detection by a radar system. The individual HRR profiles are often used for target identification algorithms. By grouping a set of sequential frequency sweeps over a small aspect range and applying a 2D FFT, a 2D ISAR image of the target can be generated.

The ISAR images can be further processed as a function of aspect and depression angles to create 3D tomographic image volumes to determine scattering centers with 3D coordinates. This type of 3D data can be useful input for seeker simulations where scattered waveforms can be synthesized to study seeker servo loop behavior when approaching a target. Examples of STL’s scale-model data are available at { HYPERLINK "http://stl.uml.edu" }.

VII. CONCLUSION

Fully-polarimetric compact ranges operating at submillimeter wavelengths for the purposes of making scale-model radar measurements have been described. Transceivers operating from 160 GHz and extending to several THz have been designed using diode multipliers and mixers combined with conventional microwave hardware and, for THz operation, a hybrid laser system. Recent advances in diode fabrication, multiplier, amplifier and mixer technology [11], should permit the extension of power, frequency, and bandwidth performance.

REFERENCES

[1] G. Sinclair, "Theory of models of electromagnetic Systems" *Proc. IRE*, Vol. 36, No. 11, Nov. 1948, pp.1364-1370.

[2] J. Waldman, H. R. Fetterman, W. D. Goodhue, T. G. Bryant, and D. H. Temme: "Submillimeter modeling of millimeter radar systems", *Proc. SPIE*, Vol 259 , p 152 (1980) .

[3] T. M. Goyette, J. C. Dickinson, J. Waldman, W. E. Nixon, and S. Carter, " Fully polarimetric W-band ISAR imagery of scale-model tactical targets Using a 1.56 THz Compact Range", *Proc. SPIE*, Vol 4382, p 229, (2001).

[4] M. J. Coulombe, T. Horgan, J. Waldman, G. Szatkowski and W. Nixon, " A 524 GHz polarimetric compact range for scale model RCS measurements", Proceedings of the 21st Annual Symposium of the Antenna Measurements and Techniques Association, p 118, October 1999, Monterey CA.

[5] T. J. Chen, T. H. Chu and F. C. Chen., "A new calibration algorithm of wide-band polarimetric measurement system*", IEEE Trans. of Antennas and Propagation*, Vol. 39, No. 8, August 1991

[6] R. H. Giles, A. Gatesman, J. Fitz-Gerald, S. Fisk and J. Waldman., "Tailoring artificial dielectric materials at terahertz frequencies", *Proc. of Fourth Int. Symp. of Space THz Technology*, Los Angeles, CA, 1993.

[7] R. H. Giles, T. Horgan, and J. Waldman, "Silicone-based wedged-surface radiation absorbing material", U.S. Patent Number 5,260,513, November 1993.

[8] N. R. Erickson., "A 500 GHz transmitter/receiver system for phase/magnitude measurements*", IEEE MTT-S Digest*, Vol. 2, pp 1149-1152, June 1992

[9] W.C.B. Peatman, P.A.D. Wood, D. Porterfield, and T.W. Crowe, "A quarter-micron GaAs Schotky barrier diode with high video responsivity at 118 um," *Appl. Phys. Lett*. 61 (3), pp. 294-296, 20 July 1992.

[10] A. J. Gatesman, T. M. Goyette, J. C. Dickinson, J. Waldman, J. Neilson, and W. E. Nixon, “Physical scale modeling the millimeter-wave backscattering behavior of ground clutter", *Proc SPIE*, Vol. 4370, (2001).

[11] D. S. Kurtz, J. L. Hesler, T. W. Crowe, R. M. Weikle, "Millimeter-wave sideband generation using varactor phase modulators," *IEEE Microwave and Guided Wave Letters*, Vol. 11, No. 6, pp. 245-7, June 2000