A Seven-Element, Modular, Coupled-Oscillator-Based Agile Beam Receiver

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The design, fabrication, and testing of a coupled-oscillator-based agile beam receiver are described. The receiver uses the Cao–York concept of deriving local oscillator (LO) signals from an array of mutually injection-locked oscillators. These LOs allow downconversion of a received 7.167-GHz (X-band) signal to ultra-high frequency (UHF) for intermediate frequency (IF) combining. The concept involves frequency doubling each 3.372-GHz oscillator signal, mixing each resulting 6.744-GHz LO signal with a corresponding 7.167-GHz signal received by each element in the antenna aperture, and then combining the resulting 422.5-MHz IF signals. As suggested by Cao and York, the receive beam is steered by detuning the end oscillators of the array. Antenna range measurements of the circularly polarized response of the receiver as a function of incidence angle and beam position are presented.

I. Introduction

Some years ago, Cao and York [1] suggested that an agile beam receiver could be designed based on the concept of mutually injection-locked oscillators. In this concept, each of the oscillators provides a local oscillator (LO) signal that is mixed with a corresponding radio frequency (RF) signal received by each of the elements in the aperture. The resulting intermediate frequency (IF) signals are combined, producing the receive antenna gain. The most significant advantage of this approach is the simplicity of the beam-steering system. When a signal is obliquely incident on the aperture of the array, a linear phase progression is produced in the RF signals received by the elements across the aperture. The LO signals must have a linear progression in phase, which cancels that of the RF signals so that, upon mixing, the IF signals produced will be rendered co-phasal for in-phase combining. Thus, the slope of the phase progression in the LO signals determines the direction of the receive beam. Now, this slope is very simply controlled by the tuning of the perimeter oscillator of the array (end oscillators in the case of a linear array). Moreover, it has been shown that the necessary tuning is constant along the edges of the array and antisymmetric across the array. Thus, the beam may be positioned anywhere in the field of view by means of two degrees of freedom controlled by two independent bias voltages that tune the perimeter voltage-controlled oscillators (VCOs).

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[1] Flight Communications Systems Section.

The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

The above concept has been previously demonstrated in a laboratory benchtop experiment in which the incident wave was simulated using a 16-way power divider because the array had no receiving aperture [2]. Here, we report the design, fabrication, and testing of a complete agile beam receiver with an aperture consisting of 7 circularly polarized patch elements. Unlike previous arrays, a degree of modularity was introduced into this design. The final testing of the receiver was carried out at a far-field antenna range where receive patterns were measured for a number of beam positions while the aperture phase was monitored and controlled. A LabVIEW™ software program was written to monitor the array phase and control beam steering.[2]

II. Detailed Description of the Array

The Cao–York coupled-oscillator receive array concept requires the use of N oscillators in an N-element array. (Each array element requires its own oscillator that is coupled to oscillators of adjacent array elements to achieve beam steering.) Hence, to reduce the power consumption of the receive array, we adopted a low-power, low-Q oscillator design developed by Clemson University [3]. The low-Q oscillator design allows for increased locking range and thereby reduced tuning sensitivity of injection-locked oscillators. The Clemson oscillator design requires less than 5 mW of dc power, while typical commercial monolithic microwave integrated circuit (MMIC) VCOs require about 200 mW, which becomes impractical for large receive arrays. Figure 1(a) shows a receive array element module, and Fig. 1(b) shows an expanded view of the coupled-oscillator section.

The low-Q oscillator design does result in increased phase noise of an uncoupled oscillator; however, the phase noise of the ensemble frequency decreases as oscillators are coupled and injection-locked. Furthermore, the phase noise of the ensemble frequency can be further reduced by injection-locking the center element's coupled oscillator to an external quiet oscillator. The path for external injection-locking (coupled to the gate of the oscillator) is seen in Fig. 1(b).

When the outputs of two oscillators are coupled properly and the oscillators are tuned to the same resonant frequency, the oscillators will mutually injection-lock. Then if one oscillator is tuned away from the frequency of the other, a phase difference between the output signals is induced [4]. However, the maximum phase difference attainable is 90 deg, beyond which the oscillators lose lock and oscillate independently, producing a characteristic multiline spectrum. If an array is designed with aperture elements spaced a half-wavelength apart, this maximum phase difference will result in a maximum beam-steering angle of 30 deg from broadside (normal to the array plane). This maximum steering angle can be increased by means of frequency multiplication, as described by York and Itoh [5]. In our array, we used frequency doubling to enhance the steering range. Thus, our oscillators were designed to operate at 3.372 GHz, and the outputs were frequency doubled to 6.744 GHz. The received RF signal was at 7.167 GHz, resulting in a 422.5-MHz IF signal for the stripline combiner. This yields a theoretical limit of 90 deg of beam steering from normal, which was, of course, not obtained in practice both because of difficulty in maintaining lock near the edge of the locking frequency range due to non-uniformity in the array components and because of element pattern and edge effects in the array aperture.

The overall board layout of the array, including the stripline IF combiner, is shown in Fig. 2 together with photographs of the actual board with the modules attached and an enlargement of two of the modules and the small coupling board between them. Figure 3 shows a photograph of an actual module with the cover removed to show the contents. Directional couplers are placed along each coupling line inside the module to sample the signal for phase diagnostic purposes. The signal samples are fed to a phase comparator chip that produces a voltage, indicative of phase difference, which is processed by the

[2] Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

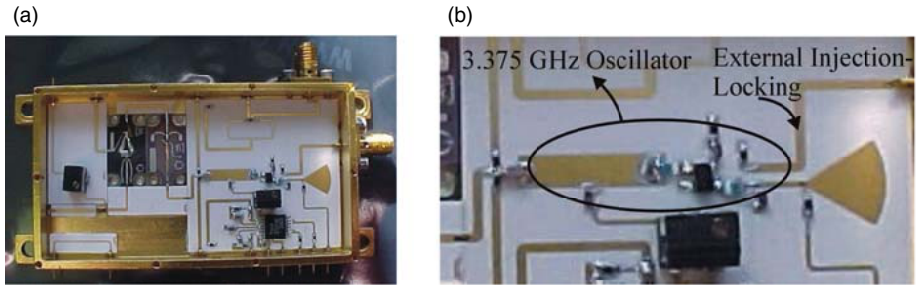


Fig. 1. Photographs of (a) the receive array element module and (b) an expanded view of the 3.375-GHz coupled oscillator.

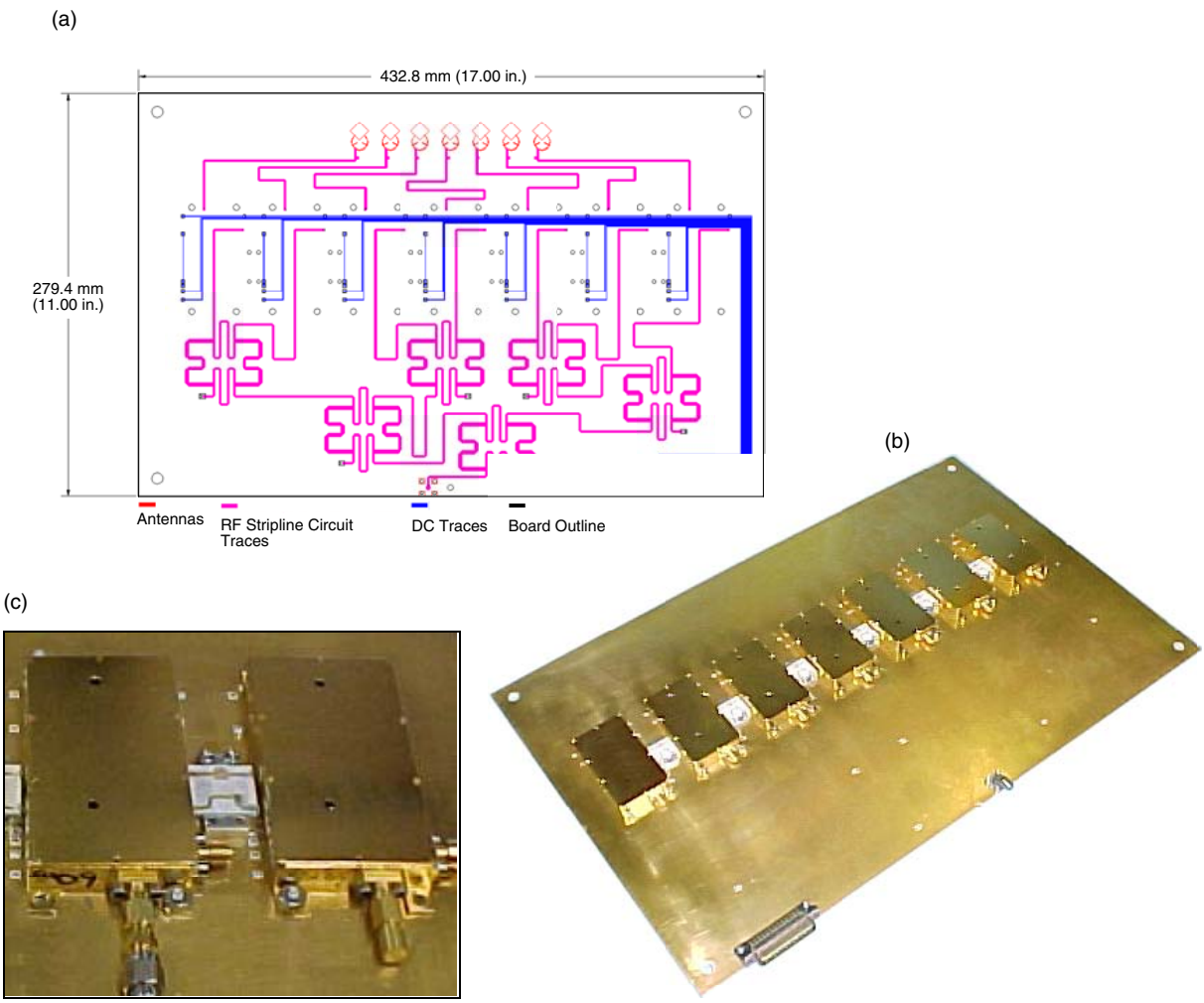


Fig. 2. The 1 x 7 oscillator array: (a) board layout, (b) assembled board, and (c) detail of two coupled modules.

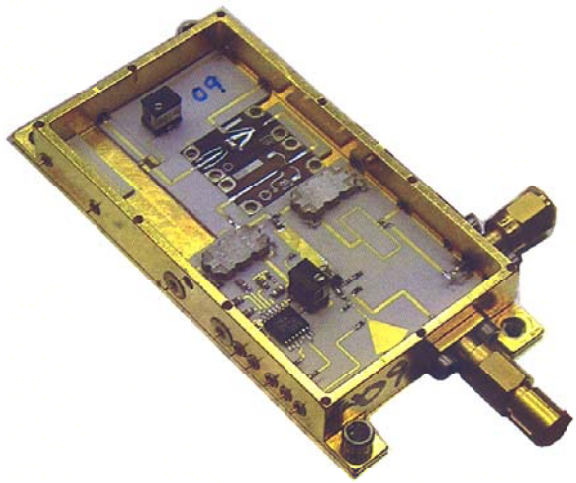


Fig. 3. Photograph of an actual unit with the cover removed.

LabVIEW™ program for display of the aperture phase distribution. Details of this diagnostic system are described in Section III. The array aperture elements shown in the board layout in Fig. 2(a) are on the underside of the multilayer board and will be described in Section IV.

III. The Phase Diagnostic and Array Control System

The computer phase diagnostic and control system was designed to provide control of the oscillator tuning and to graphically display a representation of the phase distribution across the array. The phase measurements are done at 3.372 GHz—that is, prior to frequency doubling. The basic block diagram of the system is shown in Fig. 4, with module detail shown in Fig. 3(a). Here a sample of the signal from a given oscillator is obtained by a directional coupler as the signal enters the coupling network. This signal is compared with a similarly obtained signal from an adjacent oscillator using an Analog Devices AD8302 phase comparator integrated circuit (IC). One of the input lines to the phase comparator is intentionally made 90 deg longer than the other. This places the 0-deg phase difference in the center of the comparator output voltage curve, making it possible to measure almost the full ±90-deg phase difference between oscillators. The output voltage from each comparator is fed by means of a multipin connector to a National Instruments data acquisition card in a personal computer (PC) and processed by means of a virtual instrument programmed in LabVIEW™ to provide a graph of the phase distribution. The phase is referenced to the center oscillator, and the phase of the other oscillators is obtained by integrating the phase differences indicated by the phase comparators. The resulting display is shown in Fig. 5.

The VCO frequency of each module is set by tuning its 2-V to 5-V tuning bias by means of an Analog Devices AD5235 10-bit programmable digital potentiometer. The serial digital input/output (SDIO) command and clock data come from the computer. A multiplexer (MUX) IC allows each digital potentiometer to be addressed and set independently. The VCO range is 3 V, and the VCO adjustment step size is approximately 3 mV. This provides an accurate and repeatable means of setting the free-running frequency of each oscillator.

IV. The Receive Aperture Design

The receive aperture consists of 7 microstrip patch elements, each fed by means of a microstrip power divider that induces the proper phase relation between the two feed points on each patch to produce circular polarization. The square patches are rotated 45 deg to reduce mutual coupling.

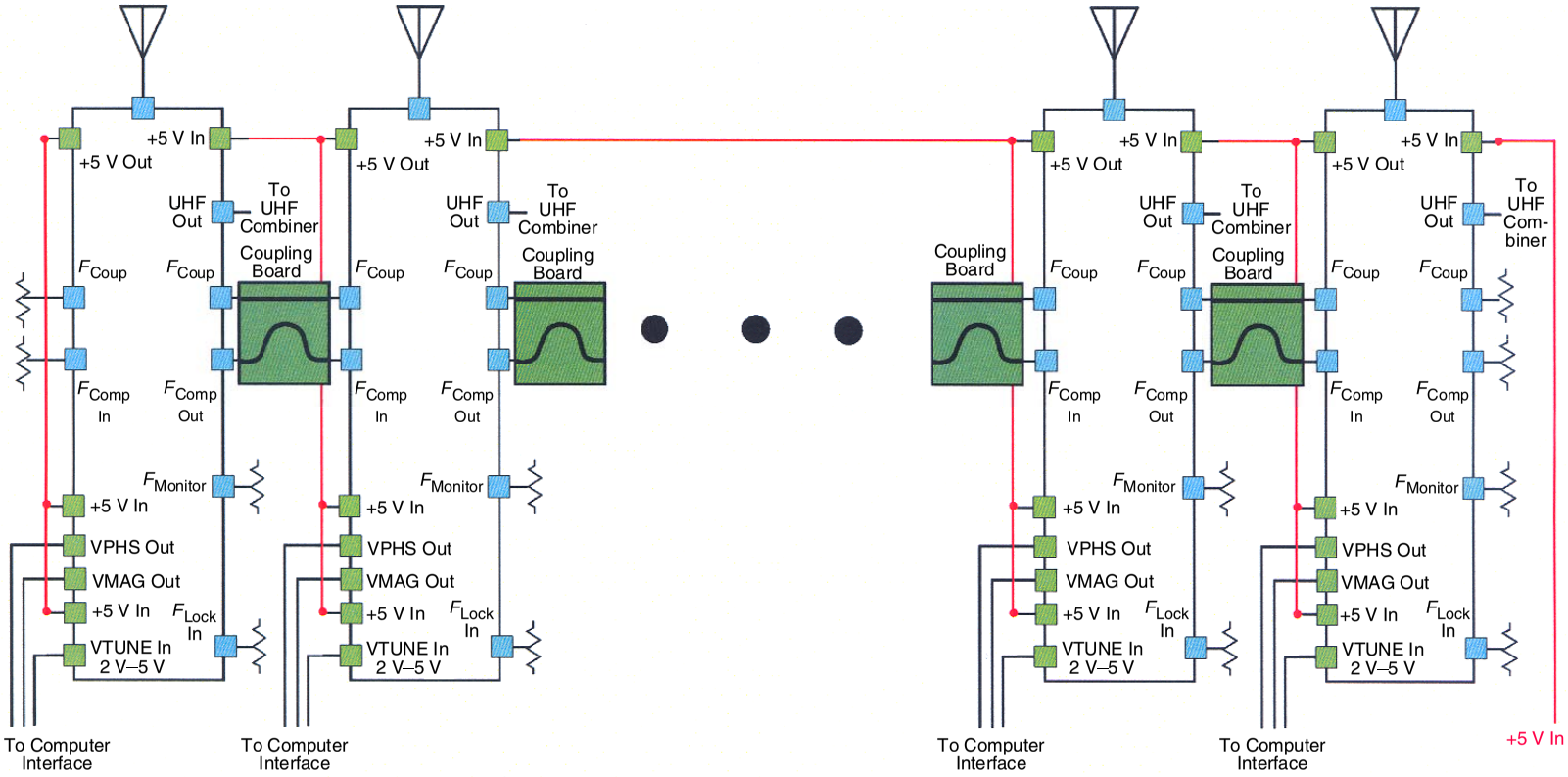


Fig. 4. The 1 x 7 oscillator array block diagram.

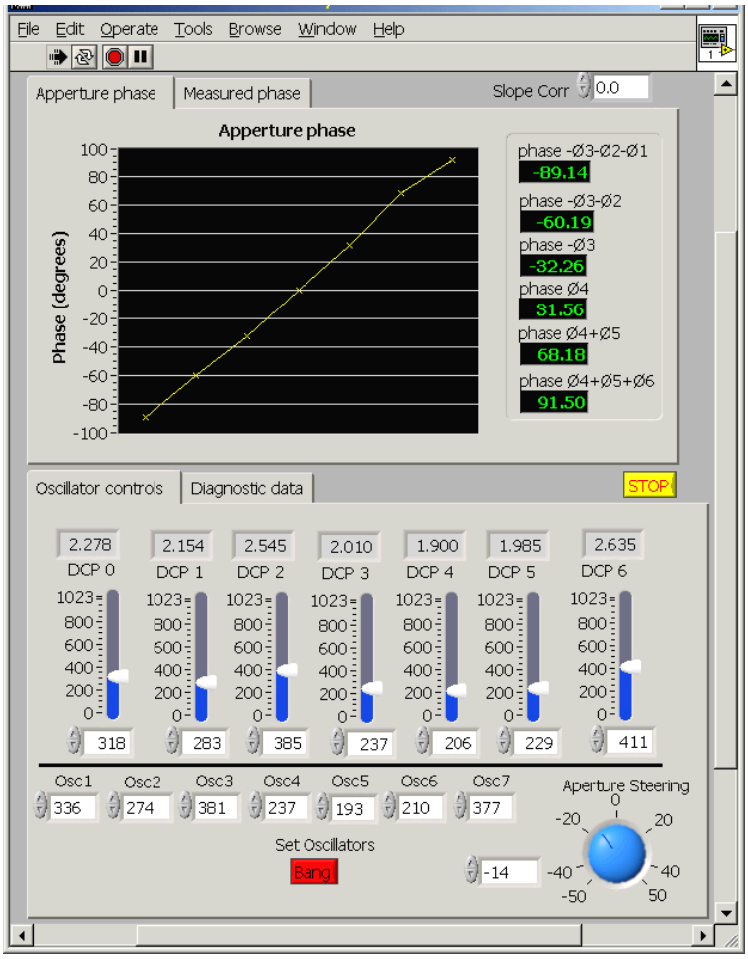


Fig. 5. Computer display of array phase distribution.

A single microstrip patch element, shown in Fig. 6, was designed using Ansoft Designer. The stubs were used for impedance matching. The return loss for a single patch at the design frequency of 7.167 GHz was an acceptable 16.3 dB, and the bandwidth was approximately 230 MHz, or roughly 3.2 percent. The gain was about 4.5 dB, and the axial ratio about 0.6 dB.

When this element was placed in its depicted orientation in a 7-element array, it was found that mutual coupling caused unacceptable degradation in the active return losses of some central elements—as high as 8 dB in the worst case. In an attempt to minimize the mutual coupling, the elements were rotated by 45 deg, as shown in Fig. 7. This resulted in a much better active input reflection coefficient in the array environment (and by chance, actually better than the single element by itself). The calculated active reflection coefficients for various scan angles at 7.167 GHz are given in Table 1, which shows a good match out to scan angles close to 40 deg.

The calculated patterns for the 7-element array at 0-deg and 30-deg scan angles are shown in Fig. 8, which shows a gain of 12.3 dB at a 0-deg scan angle and a 0.8-dB scan loss at a 30-deg scan. Figure 9 shows the calculated axial ratios at the same angles, which are 0.6 dB and 0.5 dB at 0-deg and 30-deg scan angles, respectively.

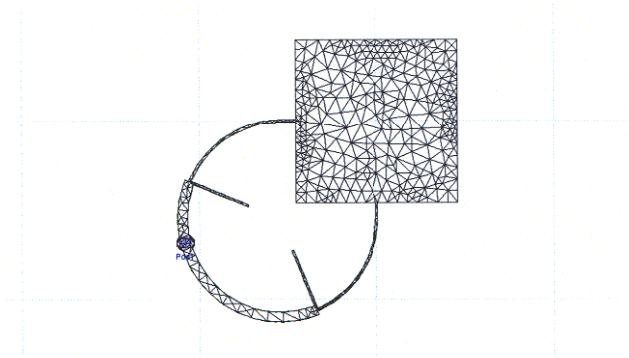


Fig. 6. Single element. Relative permittivity of the substrate is 4.5 and substrate thickness is 1.27 mm (50 mils).

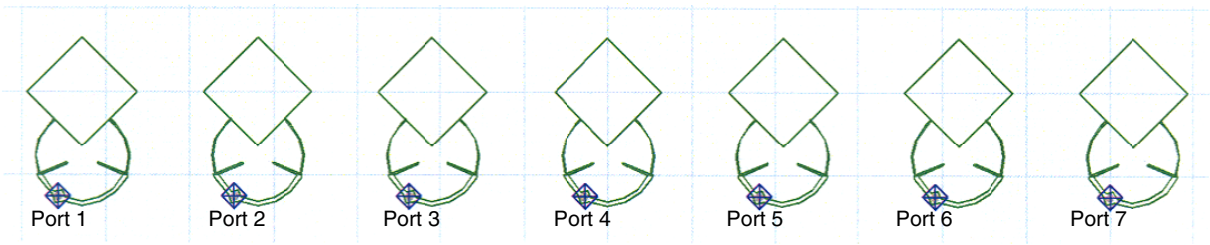


Fig. 7. The 1 x 7 circularly polarized array. Relative permittivity of the substrate is 4.5 and substrate thickness is 1.27 mm (50 mils).

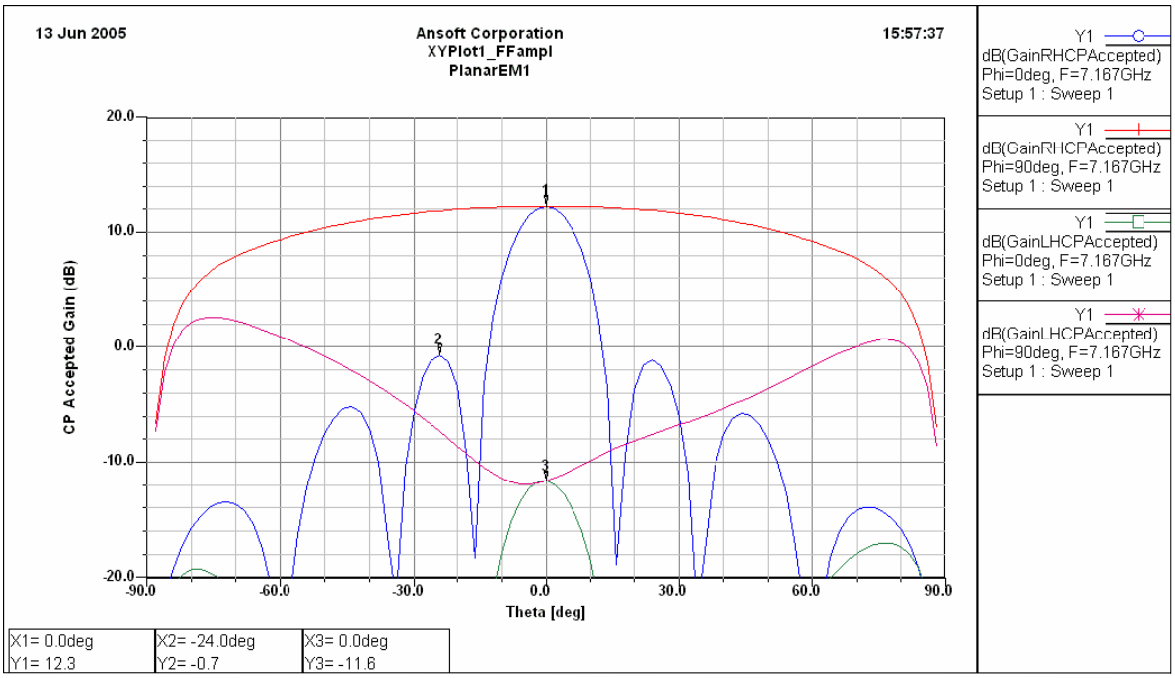
Table 1. Active input reflection coefficients for various scan angles at 7.167 GHz.

Input $\lvert S_{NN}\rvert$, dB	0-deg scan	10-deg scan	20-deg scan	30-deg scan	40-deg scan
S_{11}	−21.8	−19.1	−16.8	−14.2	−12.8
S_{22}	−23.6	−31.9	−27.4	−16.5	−12.9
S_{33}	−26.5	−24.4	−22.3	−20.6	−15.0
S_{44}	−24.5	−26.0	−21.9	−20.2	−15.5
S_{55}	−26.3	−28.0	−27.1	−17.6	−14.0
S_{66}	−23.9	−23.4	−20.2	−16.3	−12.9
S_{77}	−21.5	−24.2	−20.9	−19.3	−15.7

V. The Receive Pattern of the Array

Measurement of this antenna requires rather non-standard use of the measurement range. The range receiver requires a reference signal coherent with that transmitted to the receive antenna to achieve lock and an injection signal to stabilize the receive oscillator array and render it coherent with the range receiver reference. This was accomplished using two frequency synthesizers, one at the IF frequency of 422.5 MHz and one at the oscillator array ensemble frequency of 3.372 GHz, as shown in Fig. 10. The two synthesizers were synchronized by using a 10-MHz reference signal from the 3.372-GHz synthesizer to phase lock the

(a)



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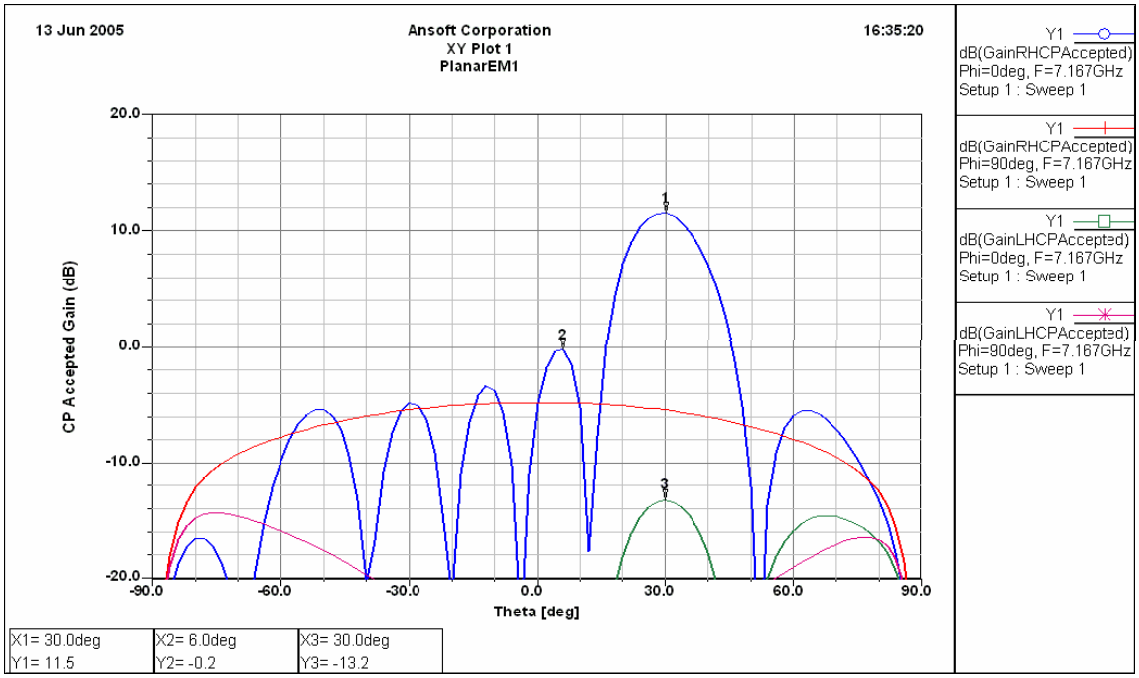
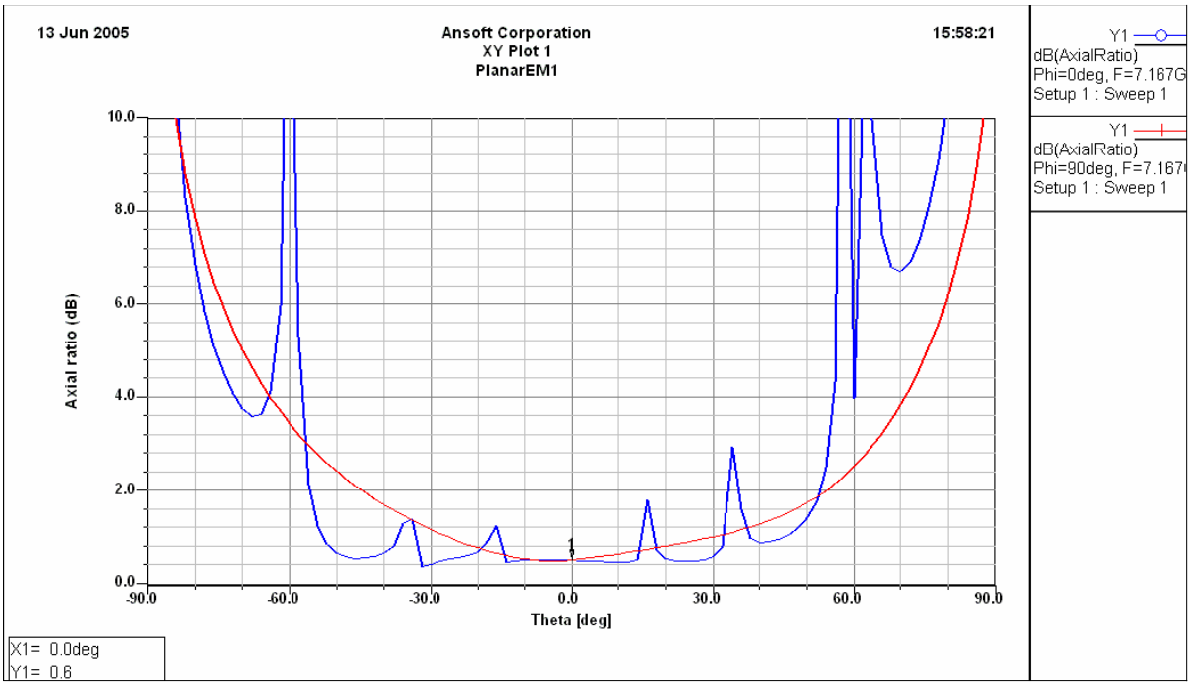


Fig. 8. Calculated far-zone patterns for a 1 x 7 circularly polarized array at scan angles of (a) 0 deg and (b) 30 deg.

(a)



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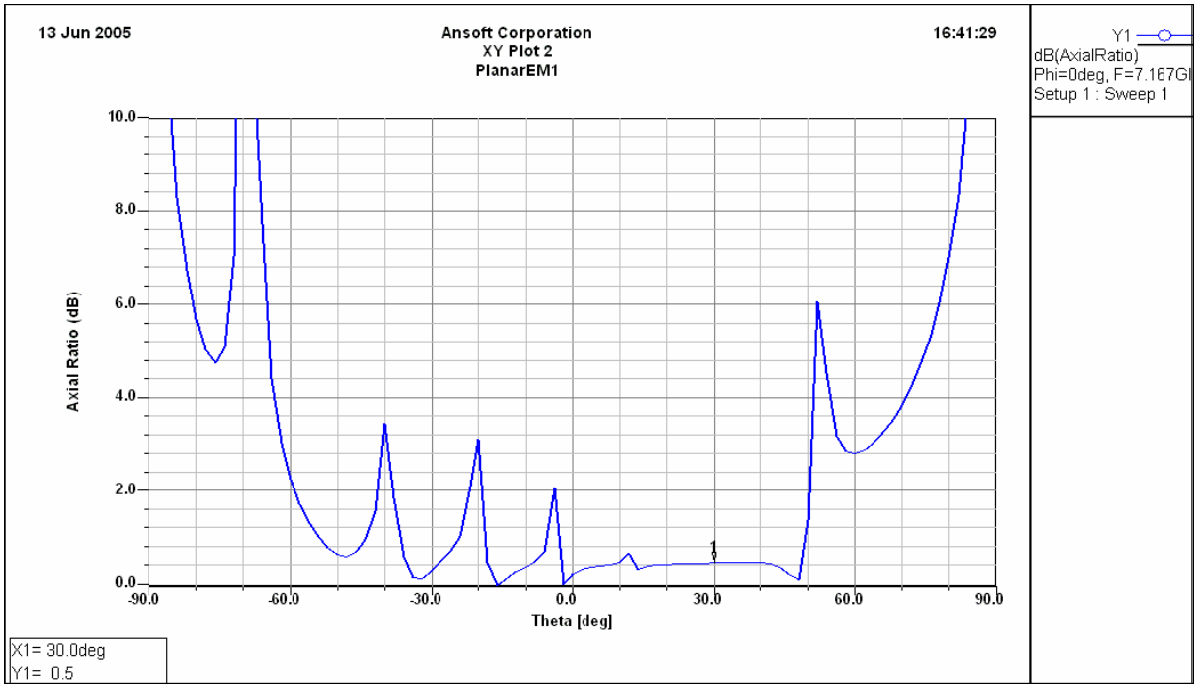

Fig. 9. Calculated far-zone axial ratios for a 1 x 7 circularly polarized array at scan angles of (a) 0 deg and (b) 30 deg.

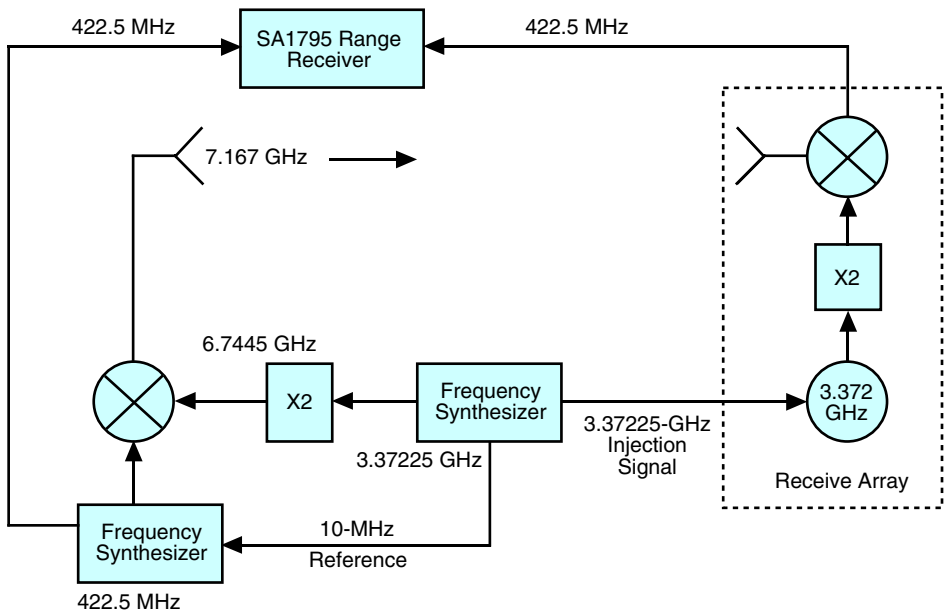

Fig. 10. Block diagram of the antenna range measurement setup.

422.5-MHz synthesizer. The output of the 3.372-GHz synthesizer was frequency doubled and then mixed with the signal from the 422.5-MHz synthesizer to form the 7.167-GHz X-band transmit signal. As mentioned above, the 3.372-GHz synthesizer was also used to injection-lock the center element of the receive oscillator array. The 422.5-MHz synthesizer also provided the reference signal for the range receiver. Inside the agile beam receiver, the 3.372-GHz oscillator outputs were frequency doubled (to enhance their phase excursion) and mixed with the received 7.167-GHz signal, downconverting it to the 422.5-MHz IF, which was measured by the range receiver.

The receive array mounted on the range positioner is shown in Fig. 11. All but the aperture of the array was covered with microwave-absorbing material to help mitigate excitation of parallel plate modes between the ground planes of the multilayer circuit board (vias were also used). In order to balance the amplitude distribution among the elements, each oscillator was turned on individually while the array was illuminated and the IF output of the combiner was measured. Then the gain of the low-noise amplifier (LNA) in each module was adjusted to produce equal results at the combiner output. The phase distribution was then set using the virtual instrument, and an azimuthal pattern cut was measured and recorded. Two representative patterns are shown in Fig. 12, an unscanned (on-axis) beam and a beam scanned 23 deg from normal to the array.

By tuning the end oscillators of the array, the phase slope across the array was changed in 10-deg-per-oscillator increments, as shown in the virtual instrument displays in Fig. 13. The corresponding measured far-field patterns are shown in Fig. 13(a). Note that the actual beam peak did not move as far as one would infer from the phase slope. Some of this may be due to the rather small number of array elements. Figure 14 shows the beam scanned in the opposite direction. The increase in the peak gain is an anomaly, but resources did not permit determination of its cause.

Fig. 11. The receive array on the range positioner.

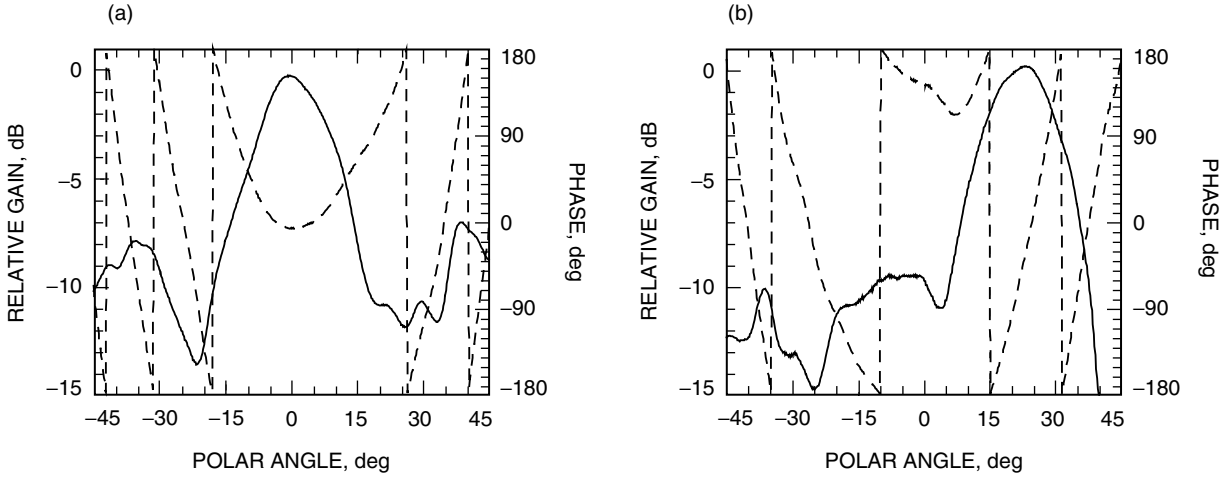

Fig. 12. Representative measured antenna patterns showing beams (a) on axis and (b) scanned to +23 deg.

VI. Concluding Summary

The design, fabrication, and evaluation of a seven-element, circularly polarized, agile beam receiver have been presented. The receiver used frequency doubling to enhance the beam-scanning range. For diagnostic purposes, the phase distribution across the oscillator array was derived from the outputs of phase comparators comparing signal samples from pairs of adjacent oscillators. The receive aperture consisted of seven circularly polarized patch elements. The patterns of the normal beam and several scanned beams were measured on an antenna range by illuminating the array in circular polarization with an X-band circular corrugated horn. Absorbing material was suitably placed to mitigate excitation of parallel plate modes between the ground planes of the multilayer board. The beamwidth and scan angles were consistent with theoretical values, but the side-lobe level was unexpectedly high, possibly due to non-uniformity in the IF amplitude distribution at the input to the IF combiner.

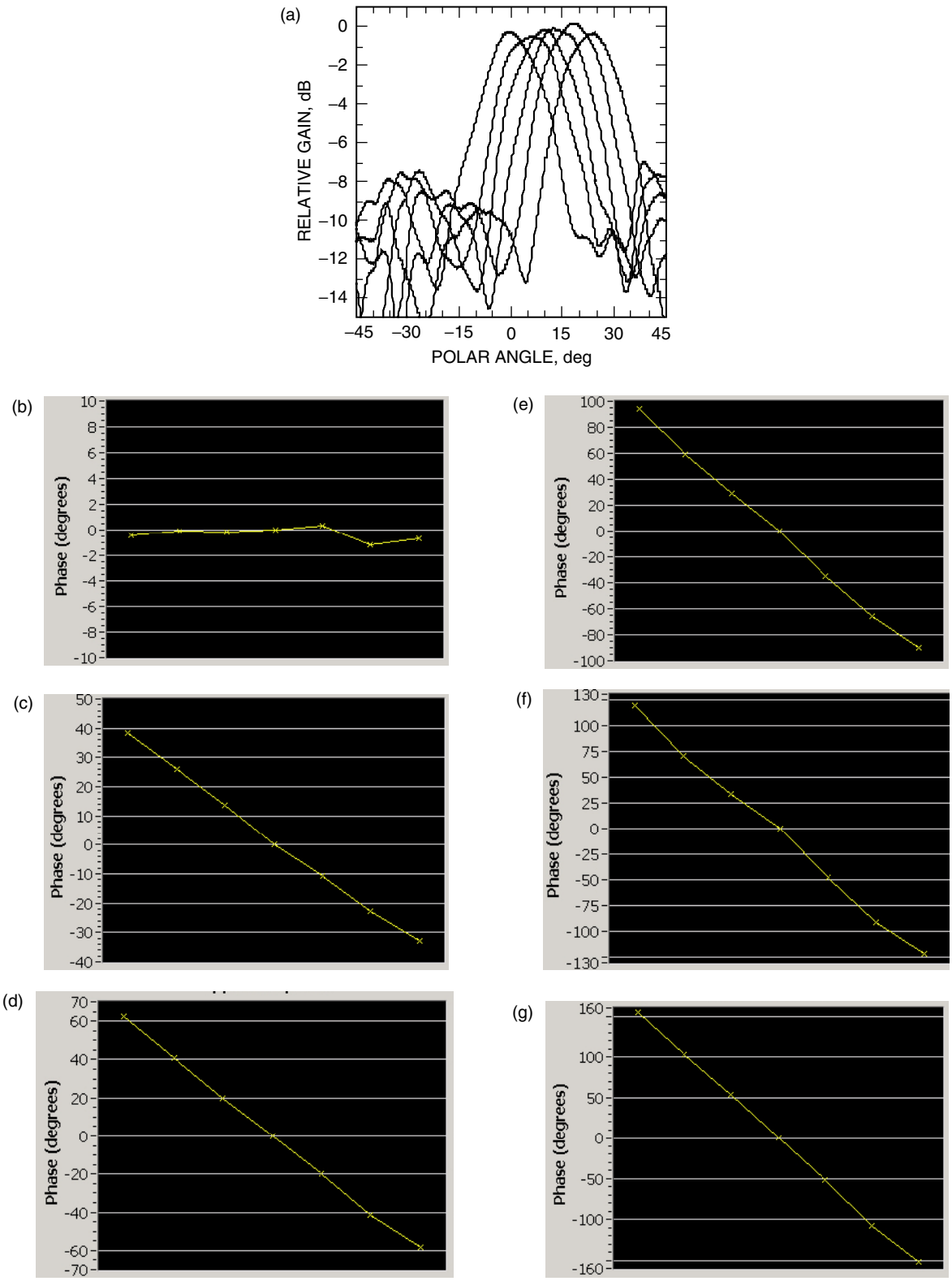

Fig. 13. A sequence of scanned beams (a) with the corresponding phase distribution as displayed by the phase diagnostic system: (b) 0 deg, (c) 8.5 deg, (d) 13 deg, (e) 20.6 deg, (f) 29 deg, and (g) 34 deg.

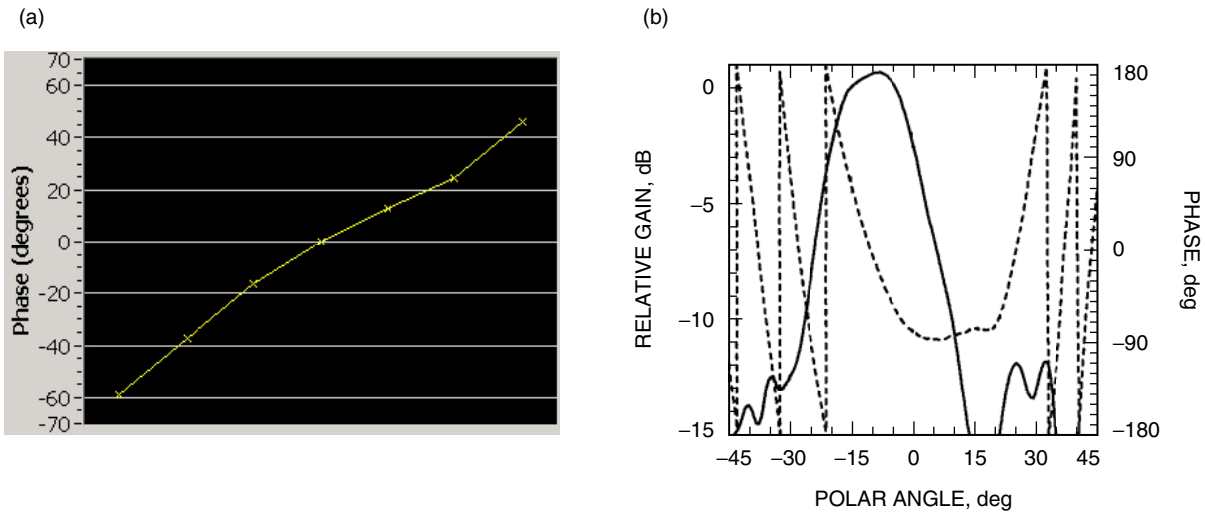

Fig. 14. Beam scanned to a negative angle: (a) phase distribution and (b) scanned far-zone beam pattern.

Acknowledgments

Thanks are due Robert J. Beckon of JPL for help with the LabVIEW™ code, Cosme Chavez of JPL for help with the measurements, Alex Peralta of JPL for help with assembly, and Dean Allen of JPL for machining the mounting fixture for the range measurements.

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