Development of an X-Band Coupled-Oscillator Transmit/Receive Phased Array

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The development of an 8.4 GHz (X-band) coupled-oscillator phased array employing full-duplex transmit and receive capability is described. Attractive features of phased arrays for deep-space communication include enabling high-data-rate communication and providing low-mass electronic beam steering. The coupled-oscillator phased-array concept seeks to reduce the cost and power consumption incurred in a conventional phased array by simplifying the beam-steering mechanism of the array. In this article, the overall system-level architecture of a full-duplex transmit and receive coupled-oscillator array is described, and the progress made in designing various specific components of a linear 1×7 coupled-oscillator array is also detailed.

I. Introduction

Phased arrays are of interest in deep-space applications where high-data-rate communication is desired. To better understand the attractive features of phased arrays for deep-space applications, we start by analyzing the equations that describe the link budget between two orbiting space assets. The carrier power-to-noise power ratio, C/N, at the input of each of the asset's receiver is given by

$$\frac{C}{N} = \frac{P_r}{kT_S B} \tag{1}$$

where P_r is the power at the receiver input delivered by the antenna, k is Boltzmann's constant, T_S is the system temperature of the receiver, and B is the intermediate frequency (IF) bandwidth of the receiver. The power at the receiver input, P_r, is given by

$$P_r = P_t G_t G_r \left[\frac{\lambda}{4\pi R}\right]^2 \tag{2}$$

where P_t is the transmitter power, G_t is the gain of the transmitting antenna, G_r is the gain of the receiving antenna, λ is the wavelength in the transmission medium, and R is the distance between the two assets [1]. We observe from Eqs. (1) and (2) that, in order to maintain the required C/N at the demodulator input

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with increasing distance (for fixed bandwidth and fixed receiver system temperature), the received power must be increased. As seen from Eq. (2), there are various options for how to increase P_r.

Let us assume at this point that one desires to employ solid-state amplifiers instead of tube amplifiers in the transmitter to achieve reduction in mass, hence imposing a limitation on the maximum transmitted power, P_t. Then, from Eq. (2), a further increase in the received power can be achieved by increasing the gain of the transmitting and receiving antennas. Increasing the gain of an antenna results in narrowing of the radiated beam; hence, the resulting beam needs to be scanned to achieve proper pointing. In a phased array, the transmitted power is divided among the N elements in the array, and spatial combining is employed to achieve the overall increase in received power. The phased-array concept allows us to employ solid-state amplifiers to achieve higher levels of transmitted power while also relaxing the requirements for the diplexers in each transmit/receive (T/R) module. Hence, whereas the diplexer in a single transponder feeding a high-gain antenna may have to be implemented using waveguides to withstand the transmit power level as well as to provide the necessary isolation between the transmitter and receiver, the diplexers in a phased array can be integrated within the T/R modules while employing microstrip or stripline transmission lines due to the reduced transmit power from each T/R module.

In a phased array, the radiated beam is steered electronically by inducing a progressive phase shift along the array elements (for the most part, there are phased arrays that employ both mechanical and electronic beam steering), hence resulting in reduced mass and increased scan speed when compared to a mechanically steered high-gain antenna. Conventional phased arrays employ phase shifters, vector modulators, or delay lines behind each array element to achieve the required phase progression along the array. Hence, the complexity of the phase-shifting network in conventional phased arrays increases with increasing array elements due to the control lines required for proper phasing of each element, thereby augmenting cost and power consumption of the array (since the onboard field-programmable gate array (FPGA) needs to control $2(M^2)$ phase shifters for an $M \times M$ planar array). In this article, the design of a coupled-oscillator phased array operating at 8.4 GHz (X-band) is discussed. In a coupled-oscillator phased array, low-power injection-locked oscillators are employed behind each array element, and beam steering is achieved by de-tuning the frequencies of the end injection-locked oscillators (perimeter oscillators in a planar array) [2–5]. The coupled-oscillator phased array seeks to reduce the cost and power consumption incurred in a conventional phased array by reducing the number of control lines needed in the beam-steering circuitry. In Section II of this article, the architecture for an X-band coupled-oscillator array designed to interface with the Electra radio is detailed. In Section III, the design of the T/R modules is discussed. Design details of the radiating aperture are given in Section IV, and an overall summary of the work is provided in Section V.

II. Coupled-Oscillator Phased-Array Architecture

In this section, the overall system-level architecture for an X-band coupled-oscillator phased array is discussed. Various system-level architectures were investigated for the design of a linear seven-element X-band coupled-oscillator phased array (scalable to a planar array) with full-duplex capability. A phased array operating in full-duplex mode and employing a single radiating aperture to transmit and receive at two different frequencies must be capable of generating independent phase progressions along the transmit and receive paths for coincident pointing of the radiated beams. Therefore, an architecture employing two sets of coupled oscillators was selected; one set of coupled oscillators induces the proper phase shift along the transmit path while the other set of coupled oscillators induces the proper phase shift along the receive path. In a conventional phased array, two sets of phase shifters would be required behind each array element to enable full-duplex capability. Therefore, an $M \times M$ conventional phased array requires $2(M^2)$ phase shifters to be controlled by an onboard FPGA chip. In the coupled-oscillator architecture, although two sets of coupled oscillators are employed, only 16 control lines would be required, independent of array size, to achieve beam steering. Furthermore, since the perimeter oscillators are tuned anti-symmetrically about the array center, the FPGA would be required to provide only a small fixed number of tuning voltages independent of array size.

Figure 1 illustrates the components internal and external to each T/R module in the array. Array beam steering is achieved by means of the two sets of 4.0-GHz coupled oscillators. The frequencies

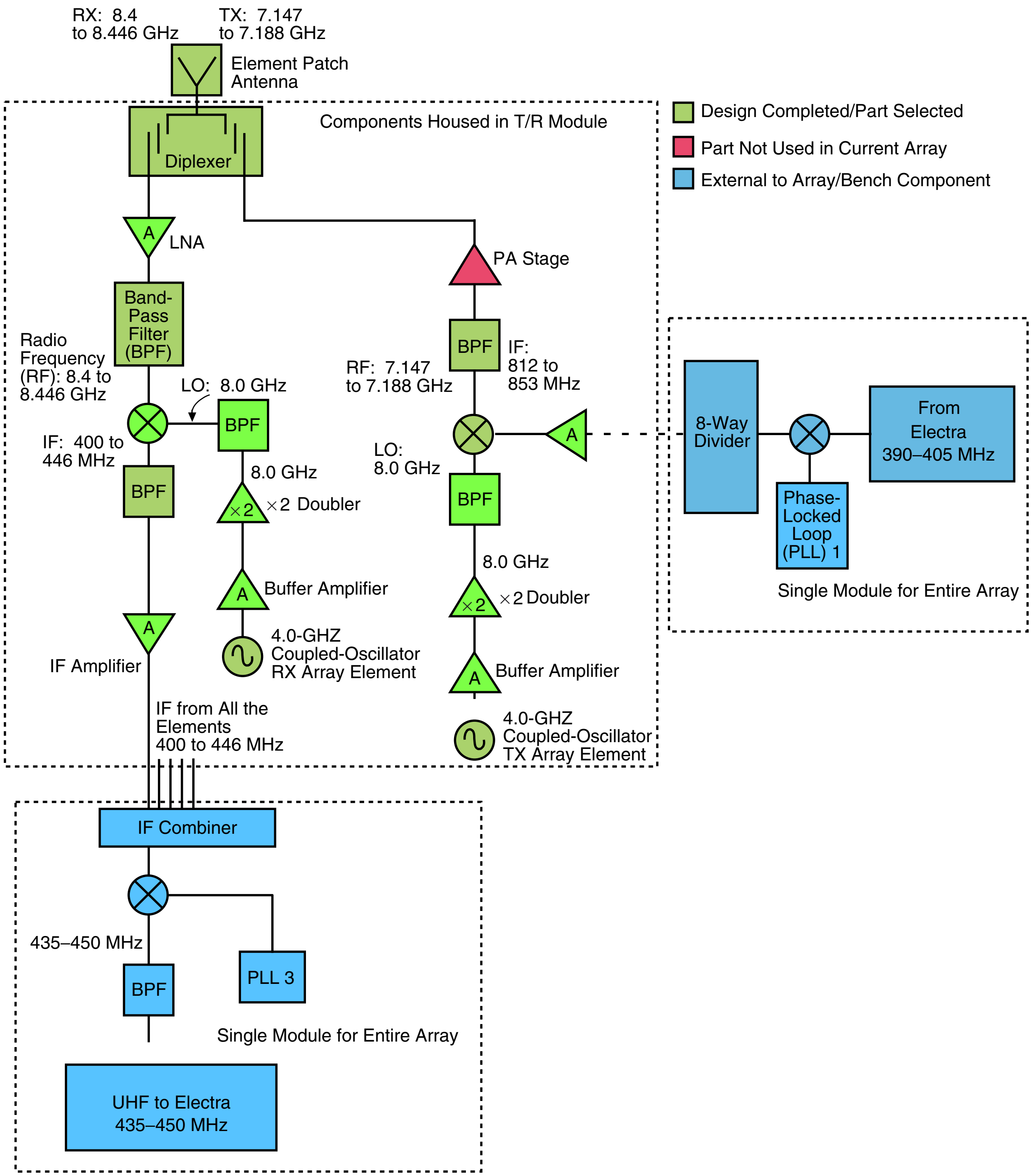

Fig. 1. System-level architecture of breadboard X-band coupled-oscillator phased-array element with transmit and receive capability and full-duplex operation.

of the coupled oscillators in the transmit and receive paths were chosen to be the same for redundancy in the breadboard array; these frequencies could be changed to avoid interfering local oscillator (LO) frequencies between the transmit and receive paths as well as to prevent injection-locking of oscillators in the transmit path with oscillators in the receive paths. Each T/R module in the array has its own diplexer (implemented in stripline transmission lines) and provides adequate isolation between the transmit and receive paths (spatial power combining relaxes the output power from each T/R module, hence enabling the use of stripline diplexers). The received signal from each array element is downconverted to an ultra-high frequency (UHF) compatible with the Electra radio along with the proper beam-steering phasing provided by an 8.0-GHz LO signal derived from the set of coupled oscillators in the receive path. In addition, the LO also imposes the proper beam-steering phase. Buffer amplifiers follow the oscillators to prevent pulling of the oscillators by subsequent stages. Frequency doublers are employed to increase inter-element phase shift and thereby increase the maximum achievable scan angle. The downconverted UHF signal feeds into an amplifier and IF combiner (external to the T/R module) for power combining.

The transmit path of each array element consists of a modulated signal from the Electra radio that is upconverted for transmission at X-band. Upconversion is achieved by mixing the modulated signal from the Electra radio with the frequency-doubled output from the set of coupled oscillators in the transmit path. Hence, proper phasing for beam steering along the transmit path is provided by the frequency-doubled output of the coupled oscillator feeding the LO for upconversion. The design of the power amplifier (PA) stage was beyond the scope of this work and was therefore omitted. The X-band transmit and receive frequencies were chosen so that the array would be able to communicate with a transmit-only coupled-oscillator phased array (transmitting at 8.4 GHz) being developed under the Mars Technology Program.

III. Design of the Coupled Oscillators and T/R Module Layout

The design of a linear 7-element coupled-oscillator array was pursued as an incremental step toward the development of a planar 49-element array. In this section, the design of the T/R module circuitry, specifically the design of the coupled oscillators, is discussed; details on how to implement a scalable planar coupled-oscillator array employing T/R modules will be discussed in a future article.

The first step in the design of the array electronics was to breadboard and characterize a set of five 4.0-GHz coupled oscillators designed using the approach in [6]. An expanded view of the coupled oscillators is provided in Fig. 2. Figure 3 illustrates the measured tuning curves of the oscillators; it is seen that the tuning curves are close to linear around 4.0 GHz. The design of low-Q oscillators resulted in increased locking range (measured locking range >84 MHz); increased locking range between the coupled oscillators results in decreased beam-steering sensitivity. The low-Q oscillator design does result in increased phase noise from each oscillator when uncoupled; however, the phase noise of the oscillators at the ensemble frequency decreases as the oscillators are injection-locked in the array. The overall phase noise of the coupled oscillators can be further reduced by externally injection-locking the center element to an external source [7].

Commercial parts were selected for components such as the low-noise amplifier (LNA), mixers, and frequency doublers. The components in the receive path were designed/selected to achieve a noise figure of less than 4 dB, based upon the link budget of a mission similar to that of Mars Reconnaissance Orbiter (MRO) in its Mars science orbit using an Electra transceiver.[2] An X-band diplexer, operating at 7.1 GHz and 8.4 GHz, was designed using stripline transmission lines and designed to exhibit a maximum insertion loss of 1.8 dB over the passband. Figure 4 illustrates the X-band diplexer modeled using

[2] S. Stride, J. Venkatesan, R. Pogorzelski, and O. Quintero, *X-band Coupled Oscillator Tx/Rx Phased Array*, JPL Preliminary Requirements Document, JPL Interoffice Memorandum 337-SLS-20070427-040 (internal document), Jet Propulsion Laboratory, Pasadena, California, July 2006.

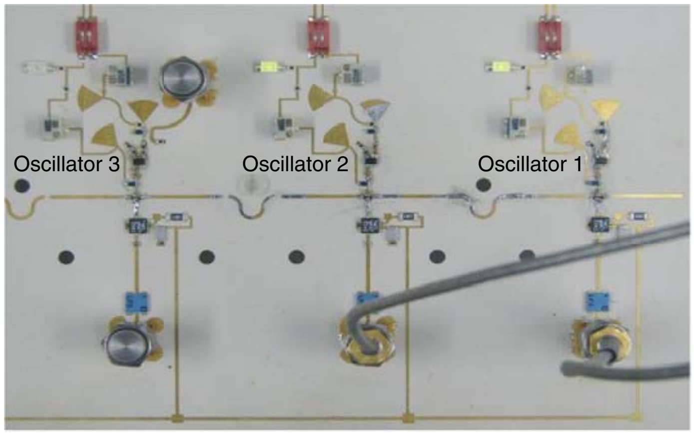

Fig. 2. Expanded view of 4.0-GHz breadboard coupled oscillators (expanded view of three of the five coupled oscillators).

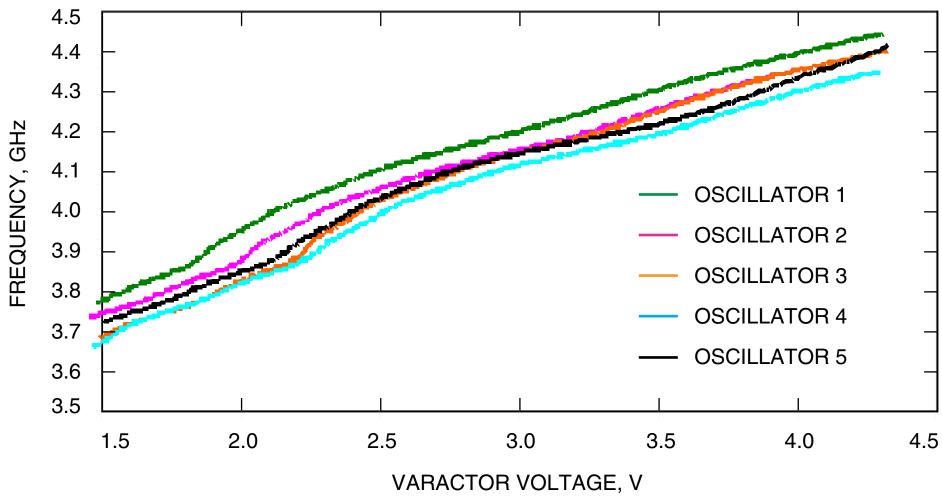

Fig. 3. Measured frequency tuning curves for individual oscillators in the five-element coupled-oscillator breadboard illustrated in Fig. 2.

Ansoft's Designer;[3] numerical results are illustrated in Fig. 5. Numerical results predicted a maximum insertion loss of 1.2 dB over the passband and greater than 60-dB isolation between the transmit and receive paths. Figure 6(a) is a cross-section drawing of the multi-layer T/R module board, and Fig. 6(b) shows the layout of the T/R module board. The T/R modules were designed to plug onto the array panel board by means of micro-miniature board connectors (MMBX).

[3] 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.

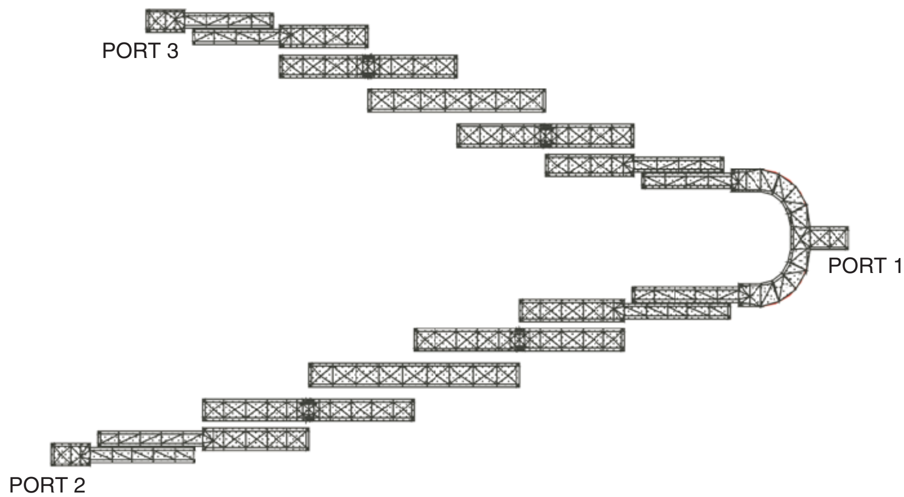

Fig. 4. X-band diplexer modeled and meshed in Designer.

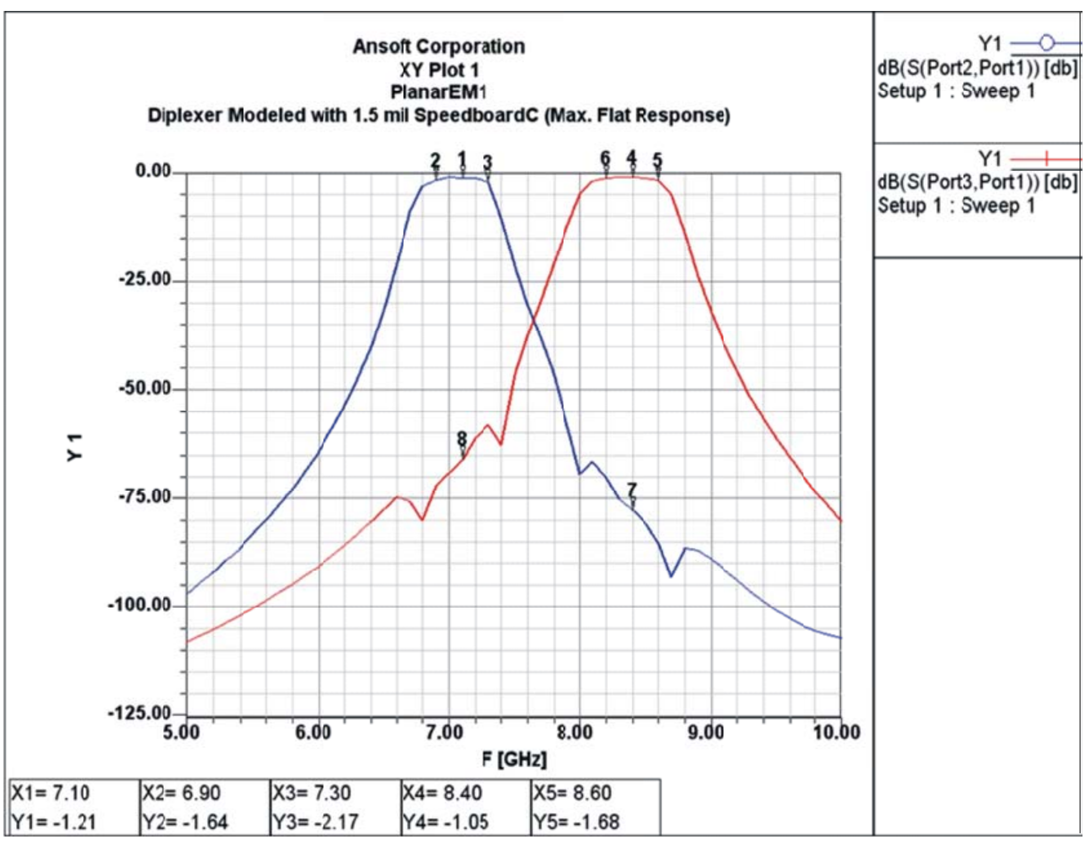

Fig. 5. Plot of the diplexer frequency response computed using Designer for the diplexer in Fig. 4.

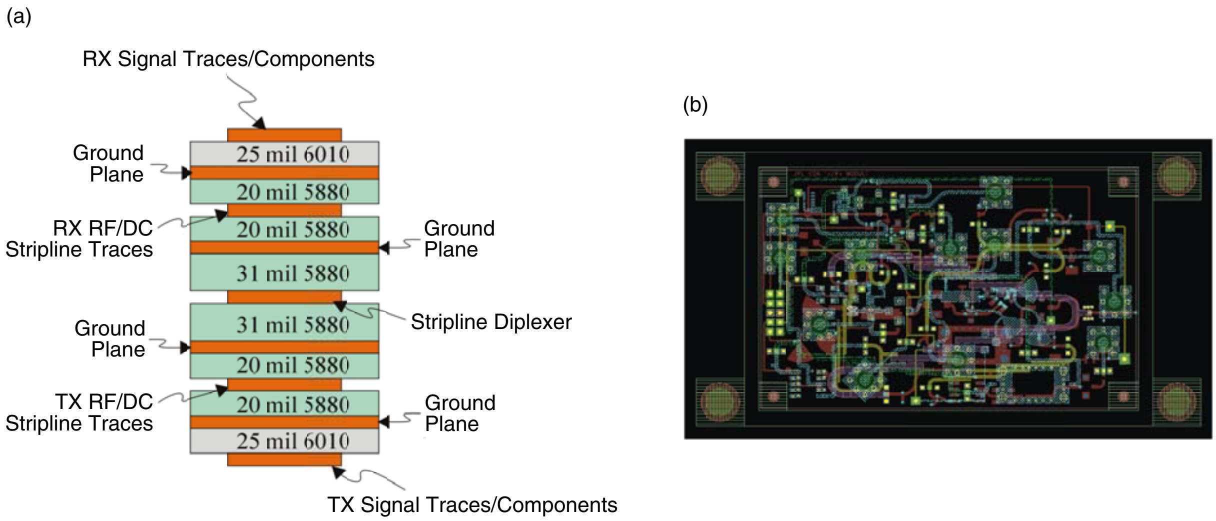

Fig. 6. T/R module board: (a) illustration of a cross section of the multi-layer T/R module board (ground connections not illustrated) and (b) actual layout of the T/R module board with all layers visible.

IV. Design of the Radiating Aperture

In this section, the design of the radiating aperture for the breadboard 7-element coupled oscillator array is discussed. It was desired to have a single radiating aperture (array of patches due to their low profile) that would cover the transmit and receive frequencies at X-band. Also, it was desired that the array radiate right-hand circularly polarized (RHCP) waves. Hence, with the above specifications, the patch antennas in the array could be designed as dual-band patch antennas or broadband patch antennas covering the 7.147-GHz to 7.188-GHz and 8.4-GHz to 8.446-GHz bands. Post-fabrication tuning issues with dual-band patch antennas as well as an improved axial ratio of broadband stacked patches led to the design of broadband stacked microstrip patches for the radiating aperture of the array.

Figure 7(a) illustrates the cross section of the array panel with the details of the stacked microstrip patches labeled. The lower patch was designed on a 1.27-mm-thick Rogers 6010 substrate, and the upper patch was designed as an inverted patch on a 0.254-mm-thick Rogers 4003 substrate. The upper and lower patches were separated by a 2.54-mm Astroquartz honeycomb substrate; the honeycomb substrate allows reduction of mass of the array while providing a mechanically rigid backplane for the array panel. The lower patch antennas were fed using broadband stripline hybrids to excite the desired circular polarization. The broadband nature of the array feed is illustrated in Fig. 7(b), where the computed active impedance of each patch feed is plotted on the Smith chart. Computed antenna patterns for the 7-element patch array are presented in Fig. 8, where broadside and scanned patterns at ± 30 deg are plotted at 7.1 GHz and 8.4 GHz.

V. Conclusions

Design aspects of a linear 7-element (scalable to a planar 49-element) coupled-oscillator phased array with transmit and receive capability have been discussed in this article. Various system-level architectures for the phased array were studied, and the resulting architecture employing two sets of coupled oscillators (one for the transmit path and one for the receive path) was detailed in this article. The array electronics were designed to be housed in T/R modules that could be plugged onto the array panel by means of MMBX connectors. A single radiating aperture, consisting of an array of broadband stacked microstrip patches, was designed to cover the 8.4-GHz and 7.1-GHz X-band transmit and receive frequencies. Future work on this topic would consist of fabrication and testing of the arrays to demonstrate the feasibility of employing coupled-oscillator phased arrays for full-duplex communication.

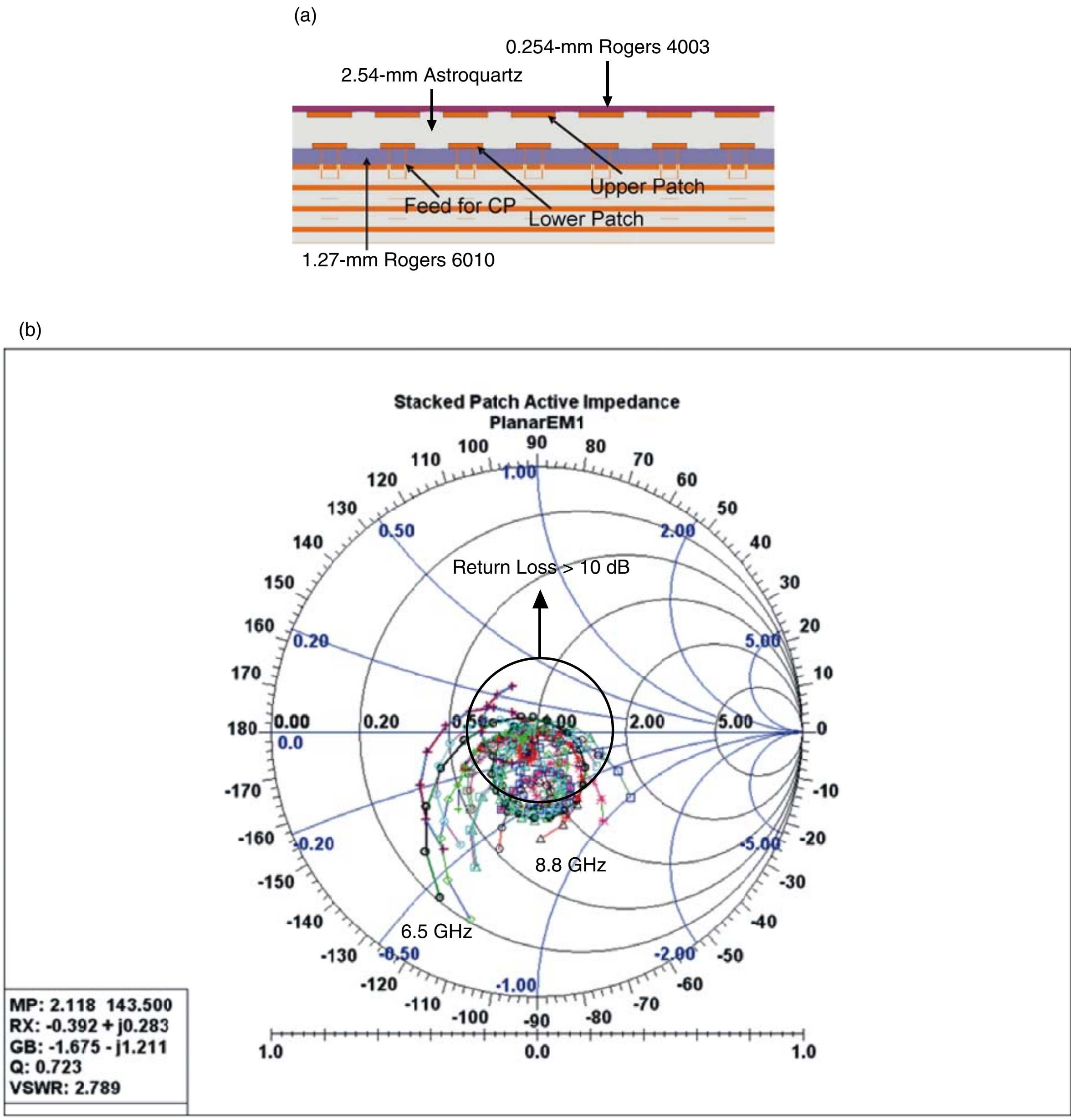

Fig. 7. Seven-element broadband stacked patch array (a) cross section and (b) active input impedance computed using Designer.

(a) (b) (c)

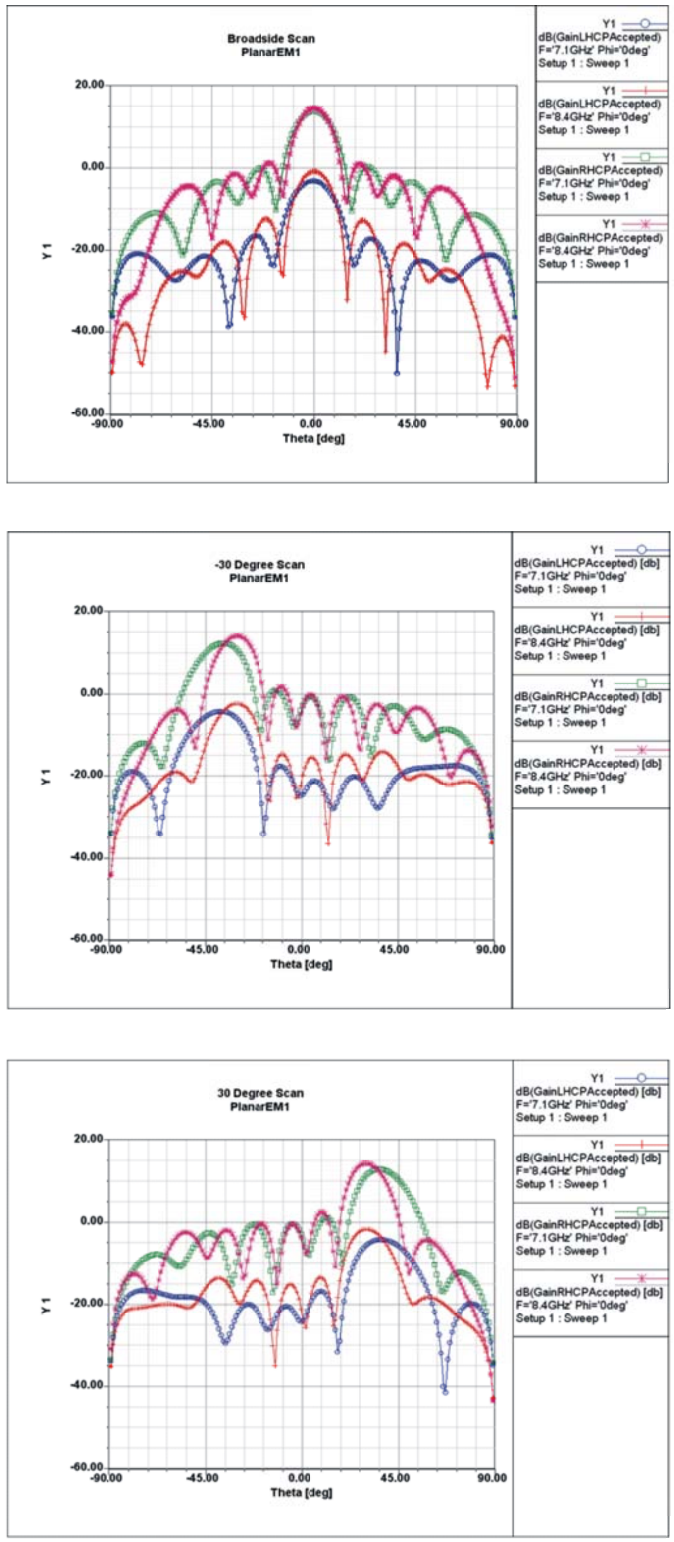

Fig. 8. Antenna patterns computed using Designer for the array in Fig. 7 when (a) radiating at broadside, (b) steered –30 deg from broadside, and (c) steered +30 deg from broadside.

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