A Heterodyne-Scan Phased-Array Antenna

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Abstract— **A new phased-array antenna system concept for narrow-band frequency beam steering is introduced. The phase shift between neighboring antennas in the array is controlled by changing the frequency of the signal traveling along fixed delay lines in a series feed network. Diode mixers are added before each antenna to convert the frequency of the control signal to a constant radiating frequency. A complete transmit system, using microstrip patch antennas, was built on a 4 $\times$ 6 in^2 printed circuit board for an X-band demonstration. As the control frequency was swept from 15.1 to 18.4 GHz, the beam was steered from -52 to $+46$ degrees with the peak power density variation of 5 dB, mainly due to nonuniform mixer conversion loss at different control frequencies.**

Index Terms— **Beam steering, heterodyne-scan, phased array antenna.**

I. Introduction

Radio frequency (RF) analog beamforming networks provide the baseline for most phased-array antenna systems used in a variety of radar and communications applications. These networks generally require individual phase shifters for each radiating element [1]. As an alternative, simple series-fed frequency-scan arrays provide beam steering with virtually no phase shifter components, except fixed delay lines [2]. However, most practical systems require the radiating frequency to be kept fixed as the beam angle is steered. This can be achieved by inserting heterodyne mixers before each antenna in the frequency-scan array. In the mid 1950's, Huggins invented a substitute for the phase shifter by using a fixed delay line sandwiched by two frequency mixers [3]. Subsequently, achieving element phase control in the array through heterodyning was introduced [4] and demonstrated in a four-element feed circuit [5]. However, a complete phased-array system with an RF feed network integrated with antennas using solid-state frequency mixers has not been demonstrated. In this letter, we present the first successful heterodyne-scan phased-array antenna system operating at X-band.

II. System Design

The heterodyne-scan phased-array antenna system consists of antenna elements, solid-state mixers, and feed networks for two external signals [Fig. 1(a)]. The amount of phase difference for the signals delivered to any two neighboring antennas in the array can be controlled by changing the frequency of the signal propagating on the fixed delay lines in the control network. The series-fed control network also contains power couplers for tapping portions of the control signal power and delivering them to the frequency mixers. The LO signal pumps the mixers through a parallel power

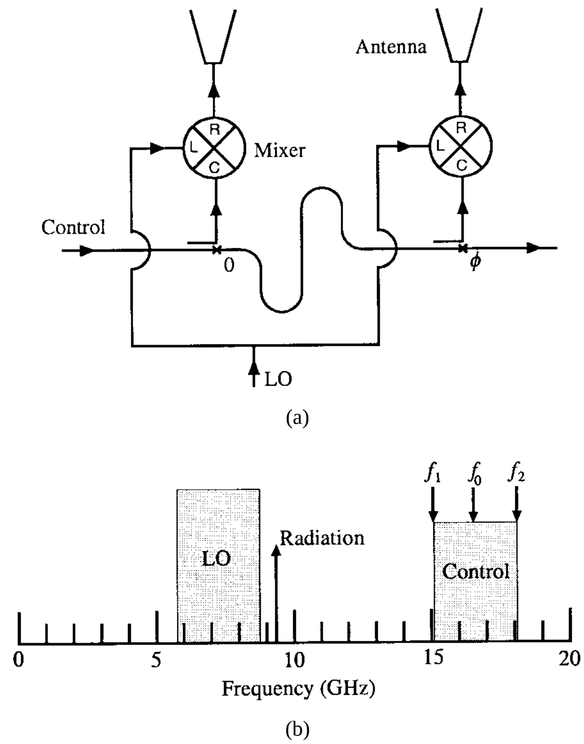

Fig. 1. (a) Heterodyne-scan transmit phased array antenna diagram and (b) frequency bands allocated for the two external input frequencies and the output radiating frequency.

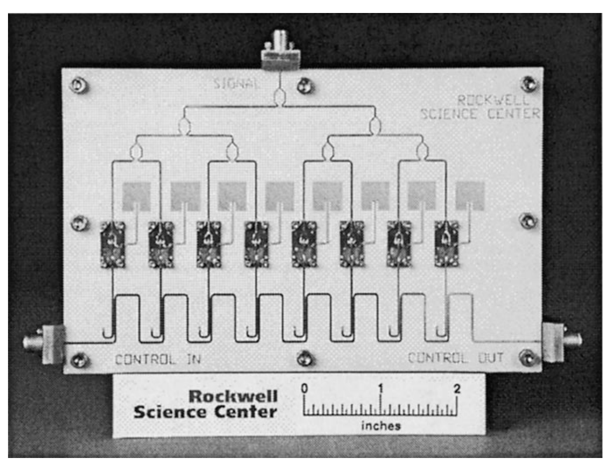

Fig. 2. Complete X-band phased-array antenna system. The LO signal activates eight surface mount mixers from the top while the control signal passes through the series feed network from the left before reaching the 50-Ω termination on the right side.

Manuscript received September 3, 1999; revised October 13, 1999.

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Publisher Item Identifier S 1051-8207(99)10297-6.

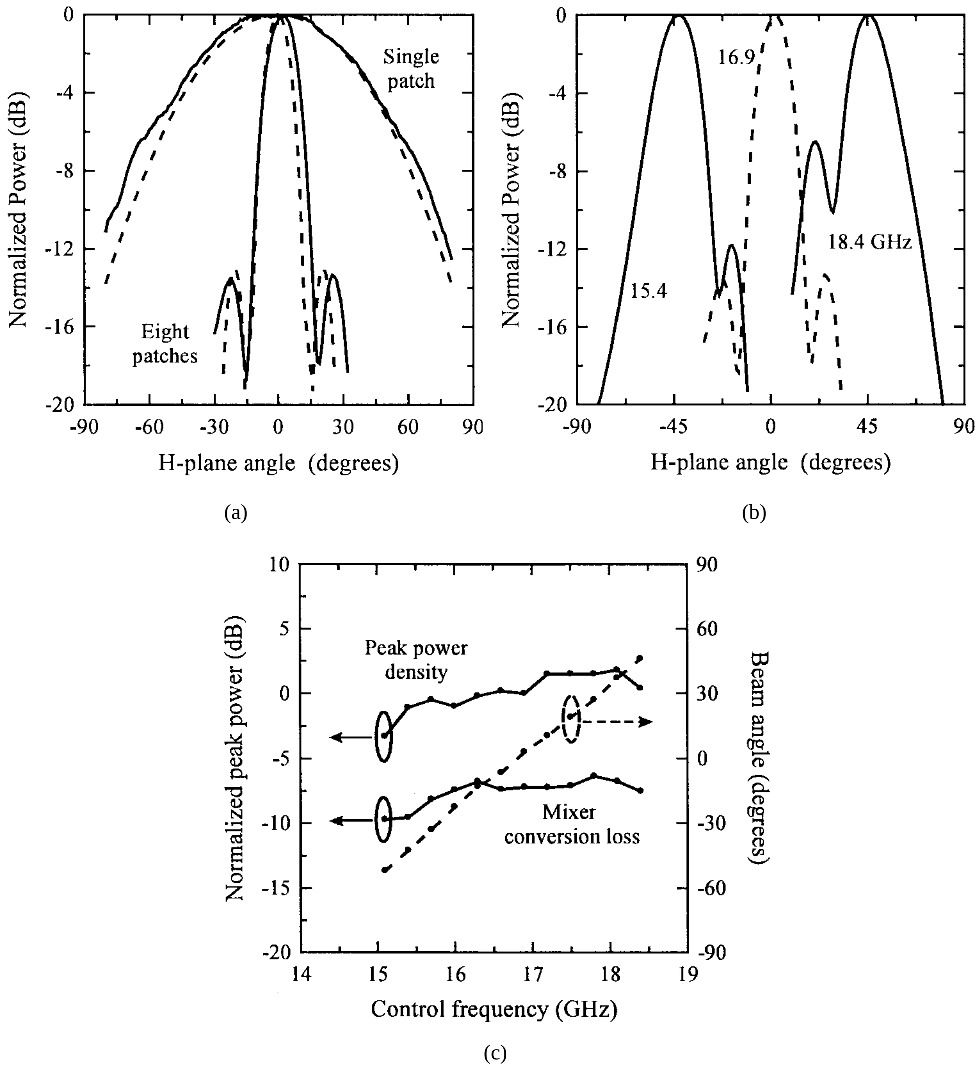

Fig. 3. (a) Theory (dashed) and measurement (solid) of the H-plane patterns for the single patch and the eight-element patch array. All eight patches were excited with the same amplitude in the Ensemble simulation. (b) The H-plane patterns when the beam was steered to -42 (15.4 GHz) and $+46°$ (18.4 GHz). (c) Performance summary for the phased array.

divider network while its frequency is compensated to keep the radiating signal at a fixed frequency. The information signal is modulated onto the LO channel to reduce the beam squint associated with the frequency modulation in most frequency-scan arrays.

The delay length of the control network is chosen to obtain zero phase shift across the array for broadside radiation at the center control frequency, f_0

$$\phi f_0/f_{\rm rad} = 2n\pi \qquad (1)$$

where $f_{\rm rad}$ is the radiation frequency, n is an integer, and ϕ is the phase shift for the delay line at the radiating frequency. The delay lines also have to produce sufficient phase change to steer the beam over the required angle at the upper and lower limit of the control frequency band, f_2 and f_1

$$\phi(f_2 - f_1)/f_{\rm rad} = \Delta\phi \qquad (2)$$

where $\Delta\phi$ is the required change in the phase shift between signals applied to two neighboring antennas. For 90° beam steering from an array with antenna separation distance of a half-wavelength, $\Delta\phi$ needs to be approximately 260°. The frequency bands should be carefully chosen for the following reasons [Fig. 1(b)]. Any of the frequencies used in the system should not overlap with each other, and the mixer should produce reasonable performance at the selected control and LO frequencies. A careful choice of the frequency range for the control signal is also necessary to minimize the delay line length and thus the circuit size. For our system, the radiation frequency and the delay line length were chosen to be 9.3 GHz and 2.24 $\lambda_{\rm rad}$ with a control frequency band of 15.1 to 18.1 GHz.

III. Measurements

The complete phased-array system was built on a 4 × 6 in^2, 10-mil-thick Duroid RO3003 substrate with a dielectric constant of 3.0 (Fig. 2). The system uses eight 9.4-mm square patch antennas spaced at 16 mm, about a half free-space wavelength at 9.3 GHz. These patches were designed to resonate at 9.3 GHz with a 3-dB radiation beamwidth of 80°. The inset feeds provide good antenna impedance matching without external tuning circuits. The different components in the system were connected using 50-Ω microstrip lines. The control feed network includes eight pairs of power-couplers and delay-lines. Measurement on a single pair showed −10 to −12 dB of coupled power and approximately 1.5 dB of insertion loss. The LO feed network uses a simple 1-to-8 Wilkinson power divider tree with 100-Ω chip resistors terminating the isolation ports. Commercial broadband diode mixers in a microstrip package (Magnum Microwave MM94MS-6) were mounted on the substrate and combine control and LO to deliver the radiation signal to each patch antenna. When driven with 10 dBm of LO power, a single mixer showed varying control-to-radiation conversion loss of 6.4–9.7 dB at the fixed radiation frequency of 9.3 GHz. The isolation of LO-to-radiation and control-to-radiation were both better than 20 dB.

The broadside radiation pattern of the phased array at 9.3 GHz was measured with a control frequency of 16.9 GHz, slightly higher than the design frequency of 16.6 GHz, and compared with the pattern of the single patch antenna in Fig. 3(a). The array pattern showing −14 dB side lobes matches well with the pattern predicted by an electromagnetic simulator, Ensemble [6]. This indicates that all eight elements were radiating effectively. Fig. 3(b) shows the array patterns when the beam was directed to −42 and +46 degrees for control frequencies of 15.4 and 18.4 GHz, respectively. The theory does predict an increase in side lobe level by 4 dB at a 46° angle off broadside. However, the 7.5-dB increase in the measured side lobe for the 46° case suggests some of the mixers in the array may not be functioning as well as the others at higher control frequencies. As the control frequency is swept from 15.1 to 18.4 GHz, the radiation beam was steered from −52 to +46 degrees with a fluctuation in peak power density of roughly 5 dB, much more than the 1 dB predicted by the Ensemble simulation. This variation may be explained by the nonuniform mixer conversion loss evident in Fig. 3(c).

IV. Conclusion

A compact low-cost one-dimensional transmit phased-array system operating with two external microwave signals has been built to demonstrate better than 90° of continuous beam steering at a fixed radiating frequency of 9.3 GHz. The steered beams display reasonable radiation patterns that match well with theory. In our current system, only a small percentage of the input control power radiates because the diode mixers have conversion loss close to 10 dB. Using active devices to fabricate mixers and attaching amplifiers in the antenna feed could provide a solution for a more efficient high-power transmit system.

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