Experiments on Injection Locking of Active Antenna Elements for Active Phased Arrays and Spatial Power Combiners

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Abstract—Two types of active antenna elements have been studied experimentally. One type uses a microstrip antenna with an active device mounted directly on the antenna. The other uses an active device coupled to a microstrip patch antenna through an aperture. Microstrip active antenna elements and two-element arrays have been demonstrated for both types of circuits. Injection locking of the antenna elements has been achieved through space and mutual coupling. The circuit Q factor was calculated based on the locking gain and the locking bandwidth. The power output from two elements has been successfully combined in free space with a combining efficiency of over 90 percent. For a single active antenna with a Gunn diode mounted directly on the patch, an electronic tuning range exceeding 9 percent has been achieved by varying the dc bias. The results should have many applications in low-cost active arrays, active transmitters, and spatial power combiners.

I. Introduction and Background

RECENT DEVELOPMENTS in solid-state devices and microwave/millimeter-wave integrated circuits have made it possible to combine the active devices with planar antennas to form active arrays. Many elements can be combined to build an active phased array or a spatial power combiner. These techniques allow monolithic implementation by fabricating both active devices and antennas on a single semiconductor substrate. The circuits can be made at low cost and should have many applications in radar, communication, and EW systems.

Two types of active array configurations have been investigated. The first type uses active devices mounted directly on planar antennas (shown in Fig. 1). The second type uses a transmit–receive (T/R) module mounted directly behind an antenna element (shown in Fig. 9). In these circuits, each element acts as a low-cost transmitter. Many of these elements can be combined to form a spatial power combiner or a quasi-optical power combiner.

Many power-combining approaches have been demonstrated in the microwave and millimeter-wave frequency range [1], [2]. Most of these techniques have serious limitations due to the moding and size problems. Consequently, the maximum number of devices that can be combined is limited. To overcome these problems, spatial or quasi-optical combiners have been proposed to combine the power in free space or in a Fabry–Perot resonator [3]. An active device mounted directly on a planar antenna forms a module for spatial or quasi-optical combiners. In order to achieve coherency and effective combining in free space, the modules will be injection locked to each other through mutual coupling or through an external master source.

This paper reports the design and measurements of a single active patch antenna with a Gunn diode oscillator integrated directly on the patch. The circuit forms an element for spatial or quasi-optical combiners. The output

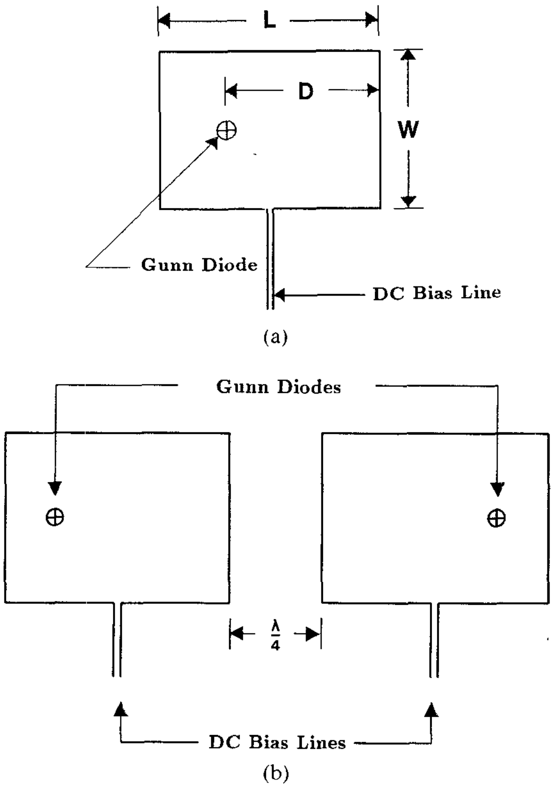

Fig. 1. (a) Single- and (b) two-element active antenna elements with devices mounted directly on antennas.

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power was found comparable to a waveguide circuit using the same Gunn diodes. The active antenna can be made tunable over a 9 percent bandwidth by varying the dc bias. This wider tuning range compared to a passive patch antenna is attributed to a lower loaded Q factor. The loaded Q factor was measured using spatial injection-locking techniques.

Two of these active antennas were successfully combined to form an array. Received output power was approximately doubled, indicating a combining efficiency of over 90 percent. Experimental results also showed that the array antenna pattern broke from a single beam into two separate beams as the dc bias voltage of one of the antennas was varied. This resulted in a tuning range of about 1 percent, which is lower than that of a single active patch antenna.

The second type of circuit configuration (shown in Fig. 9) uses a T/R module mounted directly behind an antenna element. Two commonly used feeding arrangements are the space-feed and corporate-feed techniques. Many T/R modules using FET's have been developed for these applications [4]–[6]. An aperture-coupled microstrip to patch antenna circuit is suitable to connect the T/R module to the antenna element. The circuit can also be used in spatial power combiners if the T/R module is replaced by an oscillator. The design is based upon an analysis using aperture coupling theory and an S-parameter matrix [7]. A two-element array was fabricated and tested at about 2.4 GHz. Injection locking through mutual coupling was demonstrated and good power-combining efficiency was achieved.

II. Patch Antenna with Active Device Mounted Directly on Antenna

Low-cost transmitters and power combiners can be made by mounting the active devices directly on antenna elements. Single-element microstrip active patch antennas have been reported by Thomas *et al.* [8] and Perkins [9] using Gunn and IMPATT diodes. Power combining using an open resonator has also been reported [10]. However, no attempt was made to injection lock two antenna elements through mutual or spatial coupling, to measure the Q factor, or to electronically tune the active antenna element. Furthermore, no attempt was made to combine the output power from two active antennas in free space.

Both the single patch antenna and the two-element array were constructed on Duroid 5870 substrate with a thickness of 1.524 mm. The circuits were designed at X-band using Gunn diodes and patch antennas. The circuit configurations are shown in Fig. 1.

The antenna dimensions were determined by equations given by James *et al.* [11]. The placement of the active device was chosen such that the device impedance was matched to the input impedance of the patch. The diode placement location D is given by

$$D = \frac{\lambda_g}{2\pi} \cos^{-1}\left[2 Z_{\text{in}} G_r \left(1 - \frac{G_m}{G_r}\right)\right]^{1/2} \tag{1}$$

where

G_r = radiation conductance,
G_m = mutual conductance of the two edges of the antenna,
D = distance from either antenna edge to the feed position,
Z_{in} = input impedance of the antenna at the diode location,
λ_g = guided wavelength.

For a rectangular patch with width $W = 0.3\lambda_0$ and length $L = \lambda_g/2 - 2\Delta l_{eo}$, G_r and G_m are given by James *et al.* [11]:

$$G_r = \left(\frac{W^2}{90\lambda_0^2}\right) \tag{2}$$

$$\frac{G_m}{G_r} = 0.32. \tag{3}$$

Here Δl_{eo} is the equivalent length to account for open-end fringing capacitance. The input impedance Z_{in} was set equal to the magnitude of the active device resistance, assumed to be 8 Ω [12].

The two-element active array is also shown in Fig. 1. Each element was designed to have the same dimensions as the single antenna. Two antenna elements were separated by one quarter of the guided wavelength. The Gunn diode is a packaged pill-type diode from M/A COM. It produced 10–25 mW of output power at 10 GHz in an optimized waveguide circuit.

III. Results for a Single Active Patch Antenna

To measure the power output from the active antenna, a standard horn antenna was used as a receiver. The active patch antenna has an output power P_o and a gain of G_1. A standard horn antenna with a gain of G_2 was placed a distance R away from the active antenna. The received power P_r can be measured using a power meter. The output power P_o can be calculated using the following equation:

$$P_o = P_r \left(\frac{4\pi R}{\lambda_0}\right)^2 \frac{1}{G_1 G_2}. \tag{4}$$

Here it is assumed that the two antennas are well aligned and matched, and the polarization loss is neglected.

For a single active patch antenna, the maximum output power is about 15 mW at 10.1 GHz. This power is calculated using (4) based on a 15.4 μW received power. The output power and frequency as a function of dc bias are shown in Fig. 2. A 3 dB tuning range of 839 MHz was achieved from 9.278 to 10.117 GHz. This tuning range is equivalent to a 9 percent bandwidth, which is much wider than that of a single passive patch.

The E-plane antenna patterns for several bias voltages are shown in Fig. 3. This shows a beam width of 90°. The large peak present at −60° is most likely due to radiation

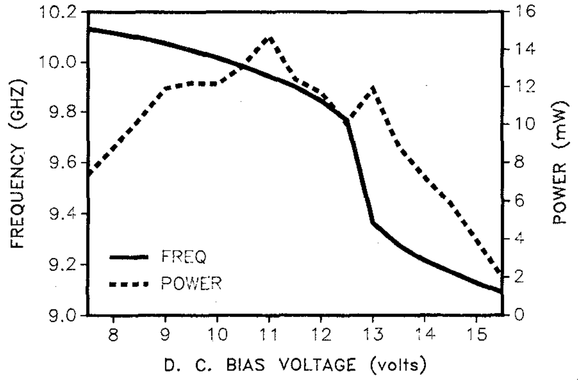


Fig. 2. Output power as a function of frequency and bias voltage for a single active antenna.

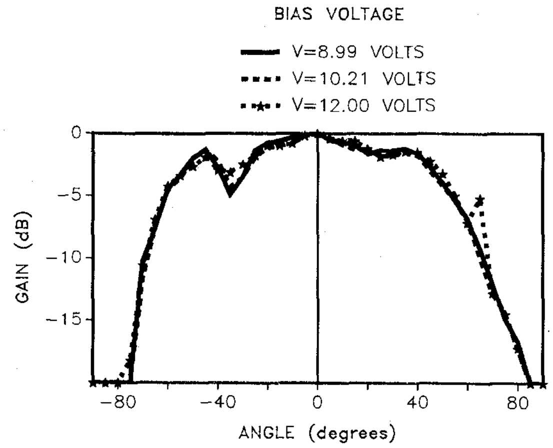


Fig. 3. *E*-plane antenna patterns for several different bias voltage levels for a single active antenna.

from the dc bias line that is required to bias the Gunn diode. The plot also shows that the pattern changes very little as the bias voltage (and thus the frequency and power) is varied.

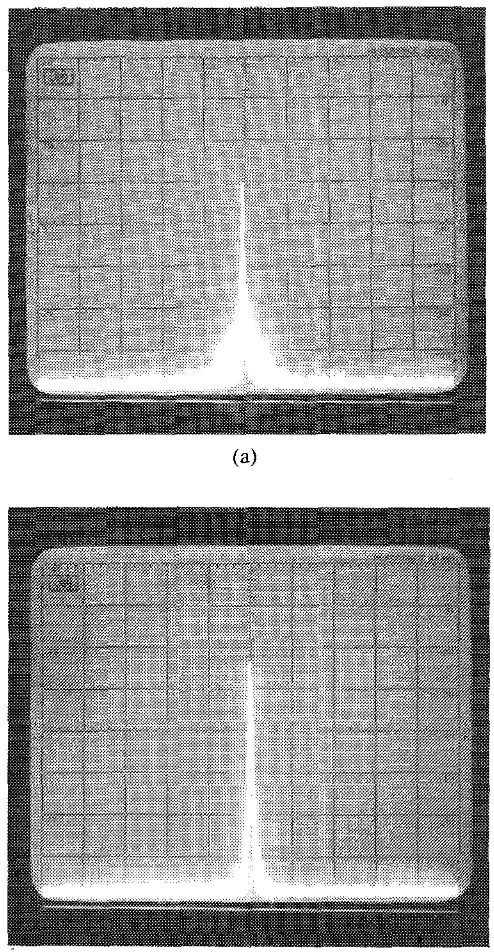
The single patch antenna can be injection locked by an external signal incident on the patch. Fig. 4 shows the frequency spectrum before and after the injection locking. The frequency stabilization and the noise suppression provided by injection locking are evident. Fig. 5 shows the injection-locking bandwidth versus locking gain (which is defined as P_o/P_i). The external Q can be found from Adler [13]:

$$Q_e = \frac{2f_o}{\Delta f}\sqrt{\frac{P_i}{P_o}} \tag{5}$$

where

Q_e = external Q factor,
f_o = operating frequency,
Δf = injection-lock bandwidth,
P_i = injection-lock signal power,
P_o = free-running oscillator power.

For the results shown in Fig. 5, the external Q value is about 20. This low Q value explains why a wider tuning range was achieved for a single active patch antenna. The



(a)

(b)

Fig. 4. Signal spectra (a) before and (b) after the injection locking. Vertical: 10 dB/div. Horizontal: 500 kHz/Div. Center frequency: 9.967 GHz.

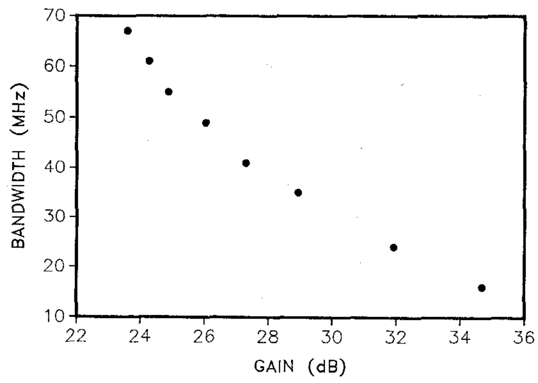


Fig. 5. Injection-locking bandwidth as a function of locking gain.

Q factor measured here compares favorably with those previously reported for microstrip oscillators [14], [15].

IV. Results for Two-Element Active Array

The two active devices in the two-element array will injection lock each other through mutual coupling. Injection locking may also be obtained by the use of an external source.

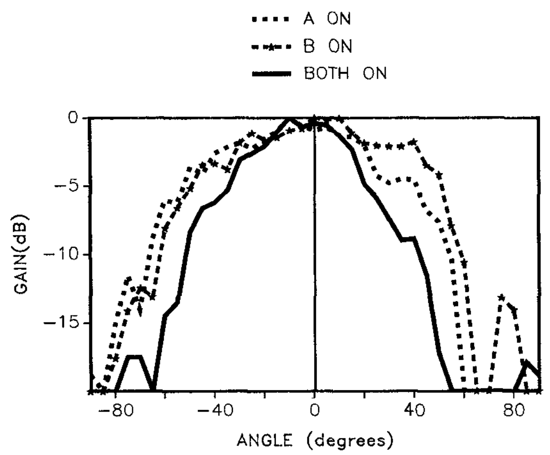


Fig. 6. Measured E-plane power pattern for a two-element array.

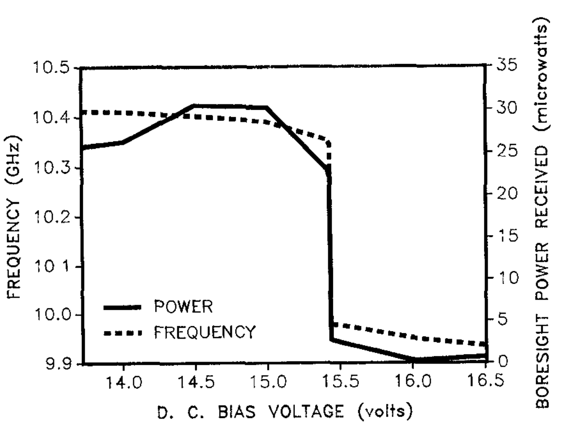


Fig. 7. Frequency and received power as a function of bias voltage of one diode.

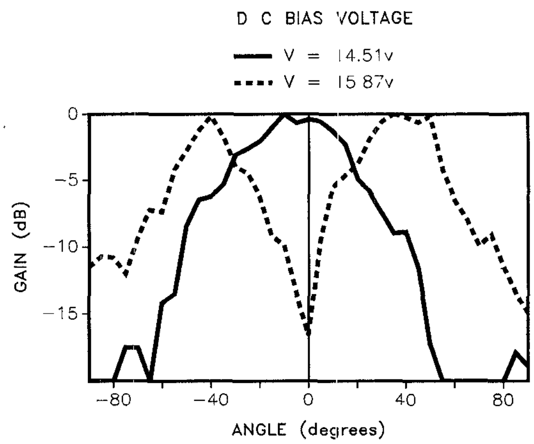


Fig. 8. Pattern broken up above 15.45 V.

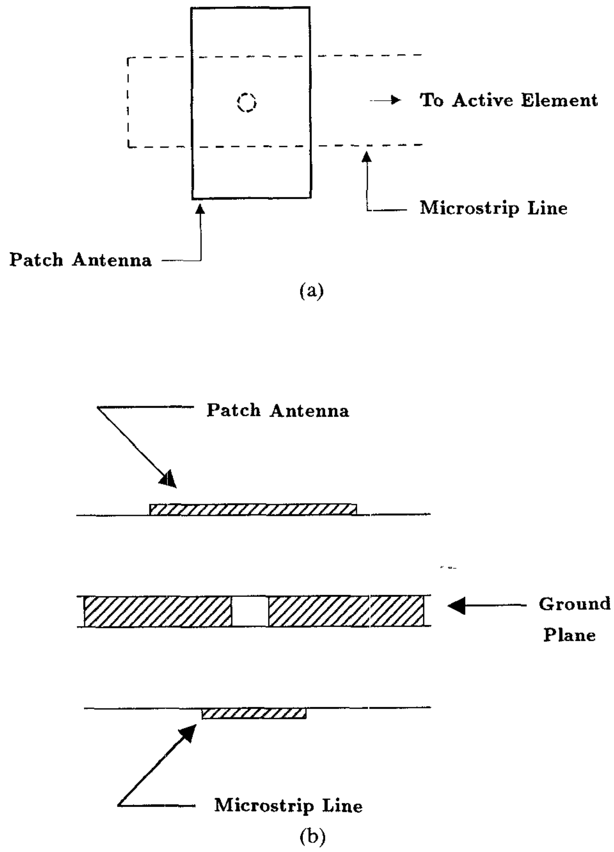


Fig. 9. Aperture-coupled microstrip to patch antenna circuit for active array (a) Top view. (b) Cross-sectional view.

The measured E-plane pattern for the array is shown in Fig. 6 Also shown are the patterns with either antenna "off." It can be seen that when both antennas are "on," the beam width is narrower and the gain is thus higher. The patterns were normalized to the peak radiation power. The bias to either diode was optimized individually to achieve the maximum output power. The received boresight power and frequency as a function of dc bias on one diode are given in Fig. 7. An output power level of 30 mW was achieved at 10.42 GHz. The power was calculated by using (4) with a two-element array antenna gain. This output power level is about twice that from a single patch active antenna. This demonstrates good combining efficiency. It can be seen that the boresight power and the operation frequency of the array experience a severe drop at a bias voltage of 15.45 V. To investigate this phenomenon, antenna patterns were made for bias voltages above and below 15.45 V. These results are shown in Fig. 8. It was found that the radiation pattern broke from a single beam into two separate beams above this bias voltage. The useful electronic tuning range is about 1 percent due to the breakup phenomenon. It is believed that this breakup is caused by the loss of phase lock. This phenomenon should not pose any serious problem in practical applications for narrow-band systems. A similar breakup phenomenon has recently been reported by Stephan and Young [16] for a different type of circuit.

V. Aperture-Coupled Patch Antenna Circuits

One practical difficulty with active arrays using T/R modules is in isolating the input and output signals and maintaining the stability of the array. Another problem is maintaining unidirective radiation and avoiding spurious radiation from feed lines.

To overcome these problems, a two-sided substrate circuit has been proposed [17]. As shown in Fig. 9, the active circuits, which include the oscillators, amplifiers, and phase

TABLE I
DIMENSIONS FOR TWO APERTURE-COUPLED ANTENNAS

parameter (mm)	Patch A	Patch B
antenna width	29.5	29.5
antenna length	39.5	39.0
aperture size	10.25	10.0
line length	50.0	50.0
stub length	19.0	19.0

Edge separation between elements is 19.5 mm.

shifters, are located on the bottom side of the ground plane. The antenna elements are located on the top side of the ground plane. The ground plane provides a good heat sink for the active devices. The coupling between the two layers is accomplished by circular apertures in the ground plane. The ground plane separates the radiating aperture from the feed network, eliminating the possibility of spurious signal radiation from the source. Because of the good isolation between the radiating antenna and active device, the antenna and active circuits can be optimized separately. Furthermore, since two substrates are used, one can use a low-dielectric-constant substrate for the antennas to increase the efficiency, and a high-dielectric-constant substrate (such as GaAs) for the active circuitry. These features have made aperture-coupled patch antenna circuits a very attractive structure for active array applications.

The design of the aperture-coupled patch antenna was based on the analysis reported by Gao and Chang [7]. A six-port network was used to model the coupling circuit based on the aperture-coupling theory and an S-parameter matrix. The input impedance as a function of frequency can be calculated using this analysis.

The spacing between the elements is a prime consideration in the design of the array and is chosen based upon the coupling requirement for injection locking. For the structure considered here, one antenna is to be connected to a sweeper, and the other to a free-running oscillator. The free-running oscillator will be injection locked to the sweeper signal through mutual coupling. The coupling between antennas was designed at 20 dB (thus providing 20 dB of injection-locking gain). Using the data from Jedlicka, Poe, and Carver [18], and assuming E-plane antenna coupling, it can be seen that 20 dB coupling corresponds to a one-quarter-wavelength edge separation.

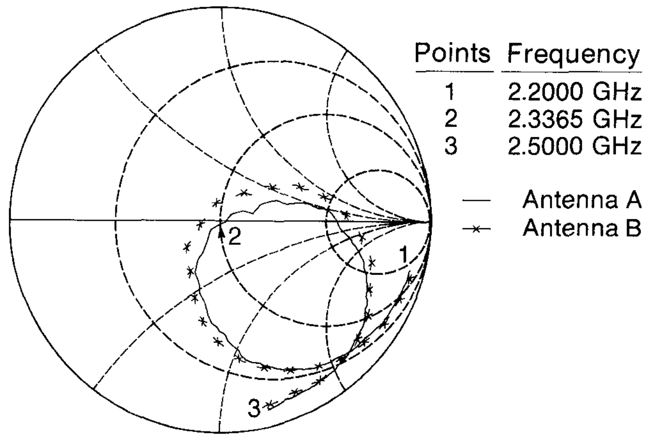


Fig. 10. Input impedance measurements on the two antennas using an HP 8510 network analyzer.

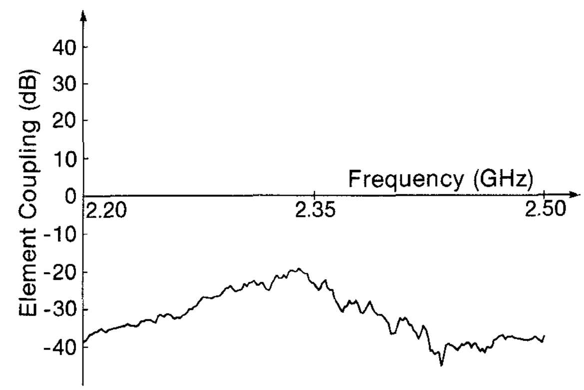


Fig. 11. Mutual coupling between two aperture-coupled antennas.

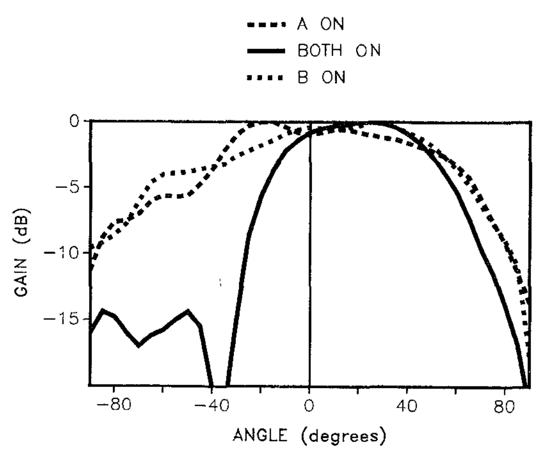


Fig. 12. E-plane power pattern of a two-element aperture-coupled active array.

VI. TWO-ELEMENT ACTIVE ARRAY USING APERTURE-COUPLED PATCH ANTENNAS

To demonstrate the concept, a two-element active array was designed and built on Duroid 5870 substrate operating at around 2.36 GHz. The dimensions for the two aperture-coupled antennas are given in Table I.

Smith charts showing the input impedance for the two antennas are given in Fig. 10. It can be seen that the two antennas have similar impedance characteristics and resonate at almost the same frequency. The coupling between antenna elements was also measured and is given in Fig. 11. It can be seen that maximum coupling is about 19.4 dB, very close to the desired value of 20 dB. The antenna bandwidth was also measured. The bandwidth for an input $VSWR$ of less than 2.0 is 28.5 MHz for one antenna and 31.5 MHz for the other.

The antenna pattern and injection-locking bandwidth were measured in an anechoic chamber. One antenna was connected to a sweeper and the other to a free-running oscillator. The oscillator was a transistor oscillator manufactured by EMF Systems Inc. The sweeper was used to

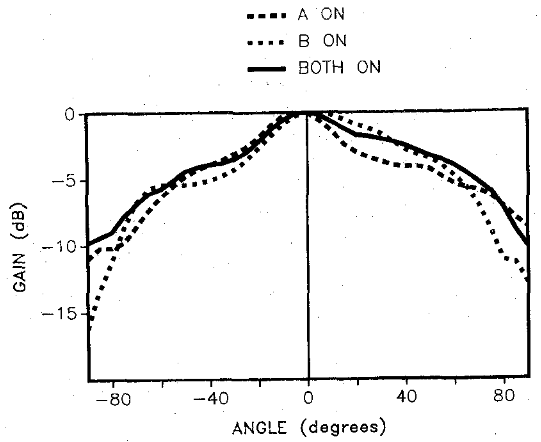
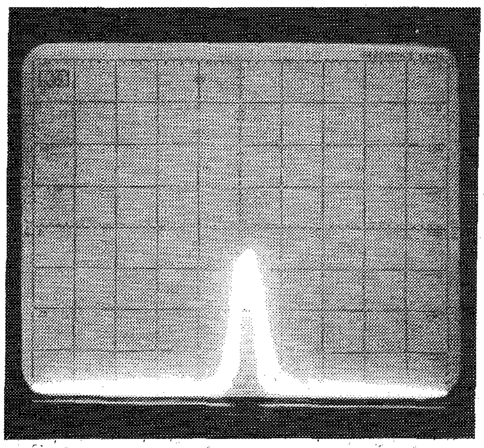
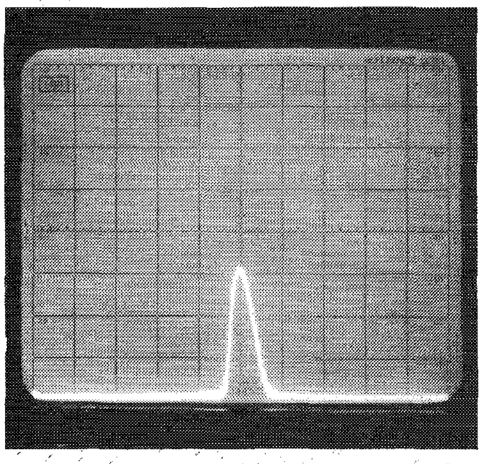


Fig. 13. H-plane pattern of a two-element aperture-coupled active array.



(a)



(b)

Fig. 14. Oscillator spectra (a) before and (b) after injection locking. Vertical: 10 dB/div. Horizontal: 100 kHz/div. Center frequency: 2.384 GHz.

injection lock the free-running oscillator by mutual coupling.

Fig. 12 shows the E-plane pattern of the active array when only the sweeper is "on," when only the oscillator is "on," and when both sources are "on." When one of the sources was disengaged, a 3 dB beam width of about 90° was measured. This beam width was reduced to 65° when both sources were "on." Furthermore, the power with both sources operating was about 2 dB higher than the power with any single source operating. This shows that the array is exhibiting good power-combining properties. With both sources on, the main lobe is centered at roughly 25°. This off-center condition is due to the different lengths of the transmission lines used to connect antennas and sources. A phase difference thus exists between the two sources. This difference can be adjusted and overcome by the use of a transmission line section or phase shifter.

Fig. 13 shows the H-plane pattern of the array. It can be seen that no matter which sources are operating, the antenna pattern remains relatively unchanged. This is to be expected since the antennas are arranged for E-plane coupling. Very little H-plane coupling can be expected. The antenna H-plane beam width was about 120°.

The injection locking through mutual coupling was also demonstrated. Fig. 14 shows the oscillator spectra before and after the injection locking. It can be seen that injection locking has a dramatic effect in reducing oscillator noise. The locking bandwidth was measured to be 2.15 MHz. Assuming an injection-locking gain of 20 dB, the locking bandwidth corresponds to an external Q factor of 217. The narrow locking bandwidth and high Q factor are believed to be due to the high-Q transistor oscillator.

VII. Conclusions

Two types of active antenna elements have been investigated. The first type uses active devices directly mounted on the antennas. The second type uses an aperture-coupled microstrip to patch antenna circuit which can be used to accommodate a transmit–receive module. A two-element array was built and demonstrated in both cases. Injection locking was achieved by using either mutual coupling or an external master source. Good power-combining efficiency was achieved for both circuits. An electronic tuning range of over 9 percent was achieved for the single active antenna element and of about 1 percent for a two-element array.

Acknowledgment

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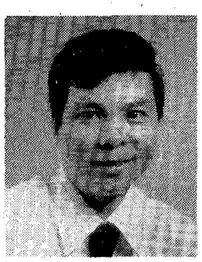

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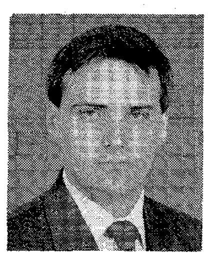

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