FET Active Slotline Notch Antennas for Quasi-Optical Power Combining

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Abstract—**A new active antenna structure with applications in quasi-optical power combining is described. The active antenna combines a slotline FET oscillator with a notch antenna. The new structure was successfully used to create both E-plane and H-plane linear arrays as well as a 2-D array. Preliminary results of radiation patterns and the power combining efficiencies of the arrays are discussed.**

I. Introduction

Because of their small size, low operating voltage, and high efficiency, solid-state devices are desirable for use as microwave and millimeter-wave power sources. However, when compared with tube devices, solid-state devices provide very low power. To achieve high output power from solid-state sources, the output signal from many devices must be combined [1].

Many different techniques exist for combining the power from solid-state sources. One of the methods is quasi-optical (or spatial) power combining [2]–[8]. Quasi-optical power combining relies on arrays of individual oscillating elements, each of which radiates into free space. The oscillating elements are placed close to each other so that they will couple and will all oscillate at the same frequency. The total power radiated is the sum of the power radiated from all of the individual oscillating elements.

Many different structures can be used for the oscillating elements. Active microstrip patch oscillators using both Gunn diodes and FETs have been reported [3],[5]–[9]. However, microstrip patch antennas have a low impedance matching bandwidth and are difficult to integrate with solid-state devices at high millimeter-wave frequencies.

Notch antennas based on the Vivaldi antenna as described by Gibson [10] offer a good alternative to microstrip patch antennas. Notch antennas have a wide impedance matching bandwidth and allow for easy integration with solid-state devices. Notch antennas in a linear array were connected to oscillators to form a phased array [11]. Also, a notch antenna has been successfully combined with a Gunn and a varactor diode to create an electronically tunable active antenna [12].

An FET is desirable as a solid-state power source because of its low noise and its high efficiency. Previously, an FET was combined with a notch antenna for use as a receiver [13].

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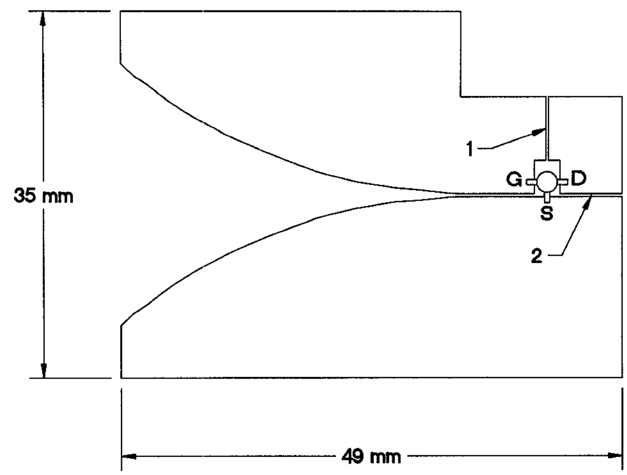

Fig. 1. FET active notch antenna circuit layout.

This paper reports a new circuit structure for an FET active notch antenna which is suitable for use in quasi-optical power combining.

II. Design and Performance of Single Element

The layout of the FET active notch antenna is shown in Fig. 1. The circuit was etched on 60 mil thick Duroid 5870 substrate. The substrate's low dielectric constant of $\varepsilon_r = 2.3$ allows for efficient radiation from the notch antenna. The transistor used was an Avantek ATF26836 general purpose GaAs FET.

In order for the circuit to oscillate, there must be feedback from the FET's drain to its gate. The slotline labeled 1 in Fig. 1 provides the required feedback. Changing the length and width of this line alters the amount of feedback and can be used to control the frequency of oscillation. The operating frequency of the circuit was varied from 5 to 8 GHz using this technique.

A piece of copper tape measuring 1 cm by 2 cm was placed on the reverse side of the substrate opposite the slotline labeled 2 in Fig. 1. The tape creates a capacitance which acts like a short circuit on the slotline. Moving the tape shifts the position of the short along the slotline, thus altering the impedance and the behavior of the circuit. The circuit can be finely tuned by changing the position of the tape.

The spectrum produced by the circuit was very clean. The center of oscillation was 6.98 GHz. Changing the drain bias voltage level on the power supply resulted in a 2% bias tuning bandwidth.

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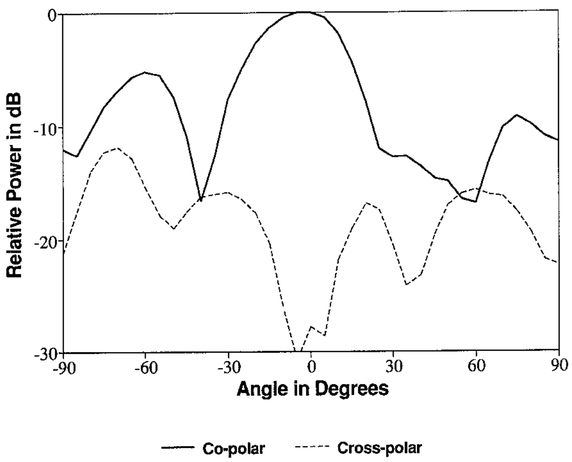
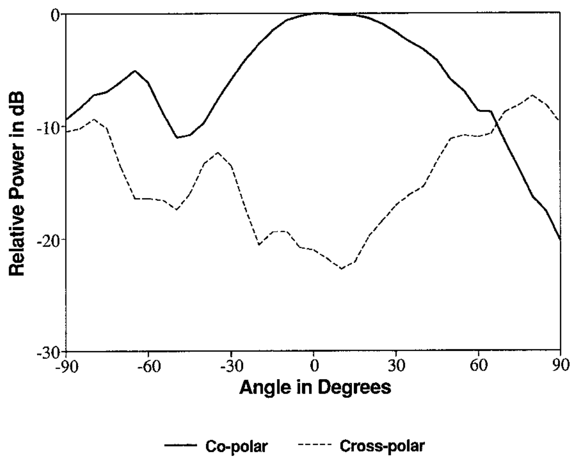


(a)



(b)

Fig. 2. Radiation patterns for a single element. (a) E-plane. (b) H-plane.

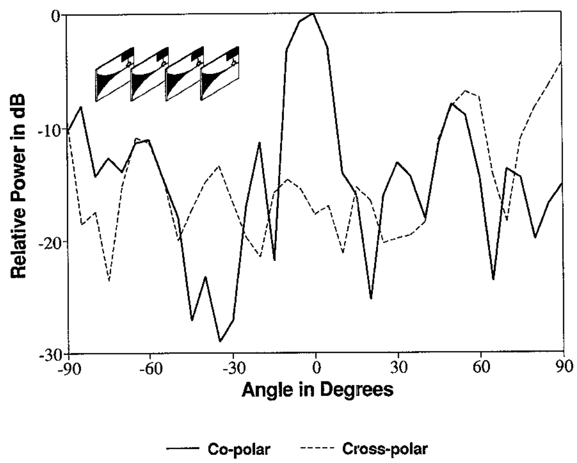


Fig. 3. H-plane radiation pattern for a four element H-plane linear array.

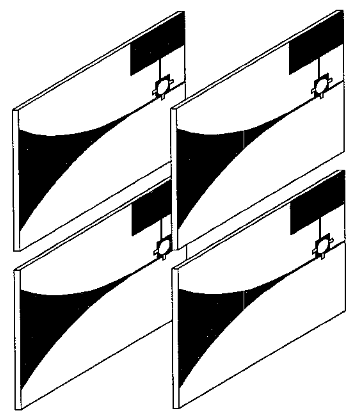


Fig. 4. Arrangement of circuits in 2 × 2 array.

To determine the output power produced by a circuit, a standard gain horn antenna was placed a fixed distance away from the antenna. The power received by the horn was then measured using a power meter. The transmitted power can be calculated from the Friis transmission formula as described in [7], [12]. The gain of the passive notch antenna was measured to be 7 dB. The power transmitted by the active notch antenna was determined to be 8.9 mW with a 7.4% DC-to-RF conversion efficiency.

The E-plane and H-plane radiation patterns of the active antenna were determined by measuring the received power as a function of the angle. The results are shown in Fig. 2(a) and 2(b). The E-plane had a half-power beamwidth of 40°, while the H-plane had a half-power beamwidth of 65°. Crosspolarization levels were low in both planes.

For an active antenna to be useful as an oscillating element in quasi-optical power combining, it must be possible to injection lock the circuit to an external signal. The active notch antenna was successfully injection locked to the output signal from a sweep oscillator. For a locking gain of 26 dB, a 16 MHz locking bandwidth was achieved. The quality factor for the active notch antenna was determined to be 44.9 using an equation from [14].

III. Linear Arrays

Four of the notch antenna circuits were placed next to each other to create an H-plane linear array. A drawing of the array is shown in the inset of Figure 3. The spacing between the elements of the array was one wavelength. A 5 mm thick piece of plexiglass with $\varepsilon_r = 2.6$ was placed a half of a wavelength in front of the array. The plexiglass provided a slight feedback to the array which increased the mutual coupling and aided in injection locking the elements.

To determine the combining efficiency of the array, the power transmitted by each element and by the active array was calculated in a method similar to the single element. When oscillating elements such as these are placed in an array, the antenna gain of the array is increased by a factor approximately equal to the number of elements in the array. Thus, the antenna gain for this array is four times the antenna gain of a single element. The combining efficiency can be calculated using

$$\eta = \left(\frac{P_{\text{array}}}{P_1 + P_2 + P_3 + P_4} \right) \times 100\% . \tag{1}$$

The combining efficiency for the four element H-plane array was measured to be 93%.

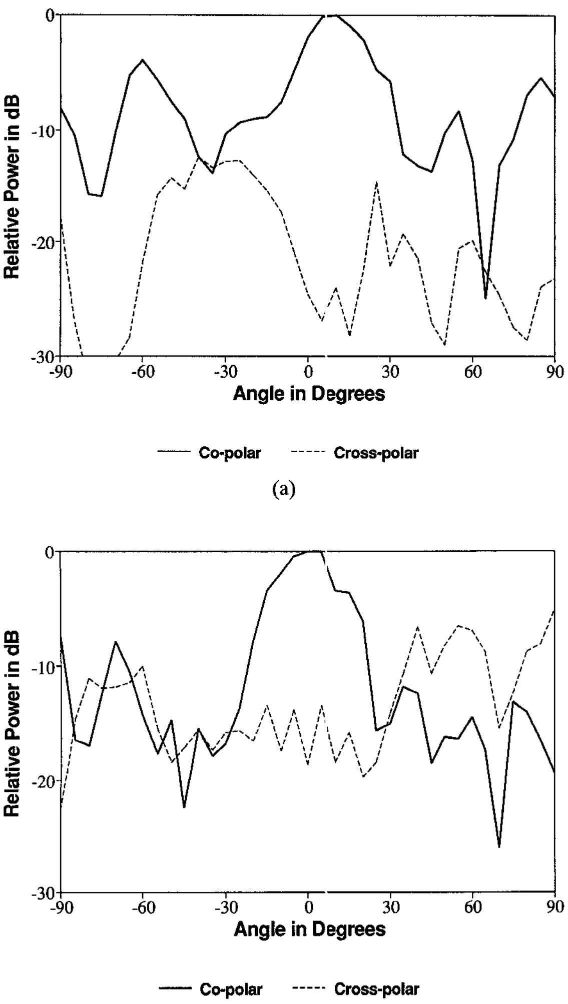


Fig. 5. Radiation patterns for 2 × 2 array. (a) E-plane. (b) H-plane.

Since the elements are aligned in the H-plane, the E-plane pattern of the array should have little change from the E-plane pattern of single element. The H-plane pattern of the array was substantially narrowed to 15° as shown in Fig. 3. This sharpening of the beam reflects the increased antenna gain of the array.

The four elements were then stacked vertically to create an E-plane linear array. The distance between the elements was one wavelength from centerline to centerline. A piece of plexiglass was again placed a half wavelength in front of the array to facilitate injection locking between the elements. The power radiated by the E-plane array combined with 83% efficiency. In this case, the E-plane pattern was narrow with a beamwidth of 15° resulting from the increased antenna gain of the array. The H-plane pattern was relatively unchanged.

IV. 2-D Array

The four elements were next placed into a 2-D 2 × 2 array. The arrangement of the elements is shown in Fig. 4. The elements were placed one wavelength apart in both directions, with a piece of plexiglass placed a half wavelength in front of the array. The combining efficiency of the 2-D array was 72%.

Fig. 5(a) and 5(b) show the preliminary results of the E-plane and H-plane patterns of the 2-D array. The beamwidth of the E-plane pattern was 25°, and the beamwidth of the H-plane pattern was 25°. Sharpening of the beam occurred in both planes because the array spanned two dimensions. The beams were not as sharp as the four element linear arrays because there were only two elements in each direction.

V. Conclusions

A new kind of active antenna circuit has been developed. The circuit combines the advantages of both the FET oscillator and the notch antenna. Both 1-D and 2-D arrays of injection locked elements were demonstrated with good power combining efficiencies. This circuit should find many applications as a quasi-optical power source.

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