Monolithic Millimeter-Wave IMPATT Oscillator and Active Antenna

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Abstract **—GaAs IMPATT diodes were monolithically integrated with a microstrip resonator and a loop antenna to produce a single-chip millimeter-wave transmitter module. Devices operating at 43.3 GHz produced 27 mW CW output power with 7.2 percent conversion efficiency. Linear arrays of such radiating elements were produced and radiation patterns were determined as a function of interelement spacing and element numbers. This monolithic oscillator chip was also directly coupled to and power combined in waveguides, producing an inexpensive millimeter-wave source.**

I. Introduction

GAAS IMPATT diodes are commonly used as power sources in solid-state millimeter-wave transmitters due to their unmatched power performance and efficiency. Conventionally, IMPATT's are used as discrete devices in hybrid circuits to maximize their output power. More recently, monolithic circuits containing IMPATT diodes have become available [1]–[3]. The capability of integrating IMPATT's with passive circuit elements on a single-chip now creates the possibilities of realizing more complex yet compact monolithic subsystems at frequencies extending into the millimeter-wave region. One example of such an integration is the fabrication of oscillators and radiating elements of a phased array system in a monolithic form. In such a system, each radiating element is fed by its own power source, eliminating the need for complex and often lossy power distribution networks. An other example is the integration of an oscillator with a waveguide feed. This makes a very inexpensive millimeter-wave source in contrast to the packaged devices, which require precisely machined cavities, or the conventional monolithic microstrip circuits, which require an expensive waveguide transition.

The devices described in this paper were realized using MOCVD prepared double-drift IMPATT structures. Both the IMPATT diode and the resonator/antenna circuits were produced on the top surface of a semi-insulating GaAs wafer. Via holes were used to ground one terminal of each diode. The radiating element, which also served as the resonator for a pair of diodes, was in the form of a microstrip loop antenna. The oscillation frequency and the radiation patterns were determined by the properties of on-chip circuitry. A study on the effect of substrate thickness on the oscillation frequency and device efficiency was conducted in an effort to optimize the oscillator performance. Radiation patterns of linear arrays of such radiating elements were determined as a function of interelement spacings and element numbers.

Although the monolithic circuit was primarily designed for direct radiation into free space, the possibility of coupling the output power into standard waveguides was also investigated. Conventionally, discrete IMPATT diodes are used in waveguide oscillator circuits to form power sources. In such arrangements, elaborate waveguide circuits are often required to ensure a single mode of operation. The monolithic IMPATT circuit described in this paper was also found to be suitable as an alternative to power sources in waveguides. Since the monolithic circuit contained matching circuits to oscillate the IMPATT diodes at the required frequency with desirable impedance levels, and the radiation pattern from the chip matched that of an open-ended waveguide, it could be interfaced with waveguides relatively easily. In fact, it was found that the power from the monolithic chip coupled very efficiently to the waveguide in some simple arrangements that did not require elaborate transition circuits.

II. Monolithic IMPATT Diode Fabrication

The IMPATT diode structures used in this study were of the flat-profile, double-drift type. All structures were grown by the metal organic chemical vapor deposition (MOCVD) technique. Dimethylzinc and silane in hydrogen carrier gases were used as the dopant gases for p- and n-type layers. To ensure monolithic circuit fabrication compatibility, epitaxial layers were grown on undoped LEC semi-insulating (SI) substrates. The n^+ and p^+ contact layers were doped to a level of 5×10^{18} and $1\times10^{19}\,cm^{-3}$, respectively. The doping concentrations and thicknesses of drift regions were typically $2\times10^{17}\,cm^{-3}$ and 0.25 μm, respectively.

In the fabrication of monolithic diodes, a self-aligned contact metallization scheme was used to minimize the device series resistance. This technique is similar to the self-aligned emitter–base contact fabrication technique for heterojunction bipolar transistors (HBT's) [4]. Briefly, 5-μm-diameter top contacts of IMPATT diodes were es-

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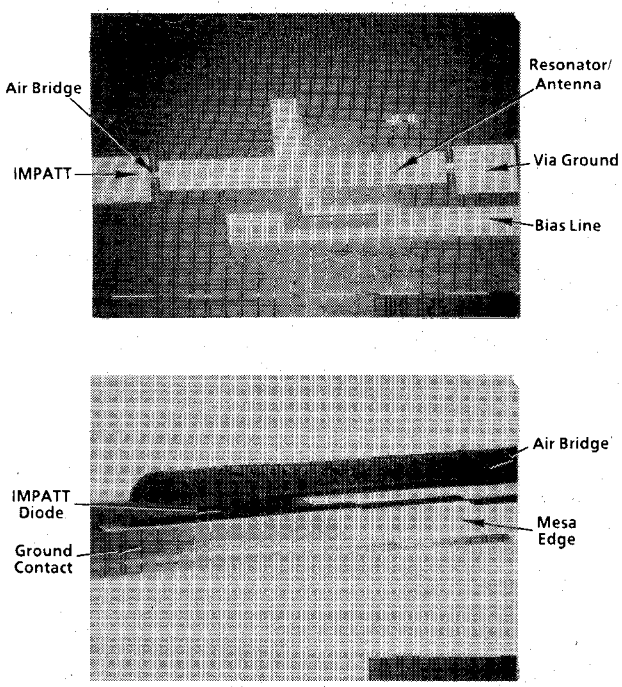

Fig. 1. SEM picture of active antenna circuits.

tablished by photolithography and lift-off techniques. Ti–Pt–Au was used as the contact metal. BCl_3 reactive ion etching (RIE) was then used to isolate devices by removing p^+, p, and n layers. All devices were connected to each other at this stage with the n^+ bottom contact layer. Since this RIE step produced no undercut, the device area was precisely defined. A controlled amount of undercut was, however, introduced in a subsequent chemical etch so that the top metal could be used as a mask for the definition of the bottom contact metal. AuGe/Ni metallization was used as the bottom contact. Miniature air bridges were used to connect the top contacts of each device to the resonator/antenna circuit. An SEM picture of the air bridge connection is shown in Fig. 1.

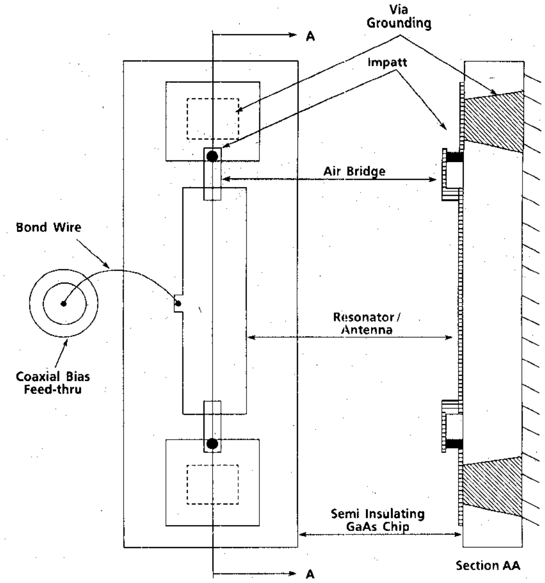

Fig. 2. A schematic drawing of the monolithic resonator/antenna structure.

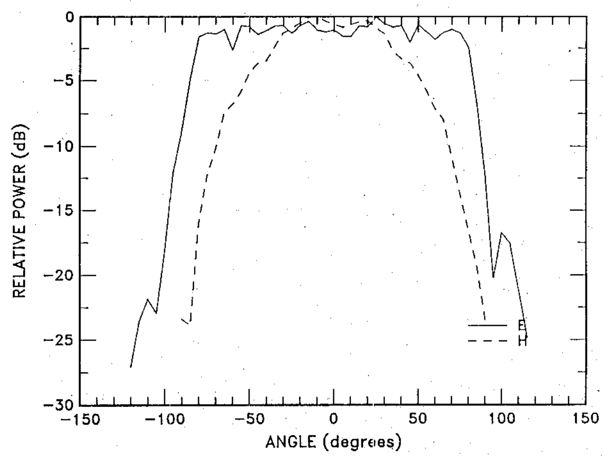

Fig. 3. Radiation pattern of a single-element monolithic active antenna at 48.5 GHz.

III. Monolithic Resonator/Antenna Design

The resonator/antenna circuit consisted of a section of a 125-μm-wide microstrip line typically produced on a 100-μm-thick SI GaAs substrate. (The substrate thickness was varied in some experiments as described below.) As shown in Fig. 2, the resonator/antenna circuit is placed between two IMPATT diodes, 30 μm away from each end. The total length of the microstrip line was chosen to be equal to one half of a wavelength at the frequency of oscillation, taking into account all the loading effects of the diodes, air bridges, and via ground terminals. The resonator and the diode dimensions were chosen by considering the optimum radiation resistance of the resulting circuit as well as the optimum impedance matching of the active devices.

The diodes were subjected to the diodes via coaxial feed from the back of the ground plane. A bond wire was used to connect the center of the resonator to the coaxial feed, as shown in Fig 2. This type of dc biasing was found to be best suited for these devices from a stability point of view. When the bond wire was attached closer to the ends of the resonator (i.e., closer to the active devices), the oscillation frequency was shifted lower and under large-signal conditions instabilities were observed. These instabilities were associated with the interaction of the bias line and the RF circuits. In general, longer bias wires (larger inductance) were found to cause the least instability. Bias wire attached to the center of the resonator usually resulted in oscillators with clean frequency spectra, even under large-signal operation.

The radiation pattern for a single oscillator/antenna is shown in Fig. 3. The radiation pattern closely resembles that of a half square loop antenna placed close to the ground plane [5], [6]. As seen in Fig. 3, the E field is omnidirectional whereas the H plane has some gain due to the finite separation of the image in the ground plane. To measure the power radiated from the active antenna a more direct approach was taken. All the radiated power

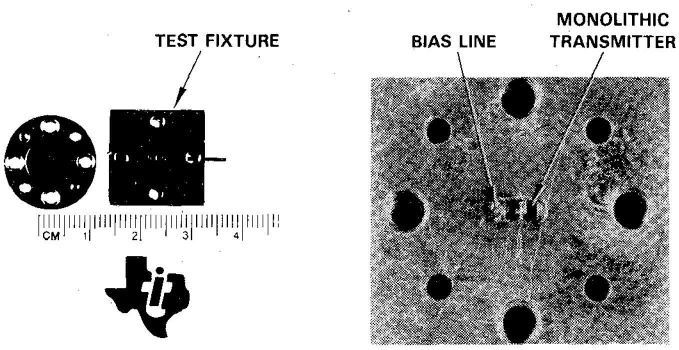

Fig. 4. A single-element oscillator/antenna structure mounted on the backshort of a waveguide test fixture.

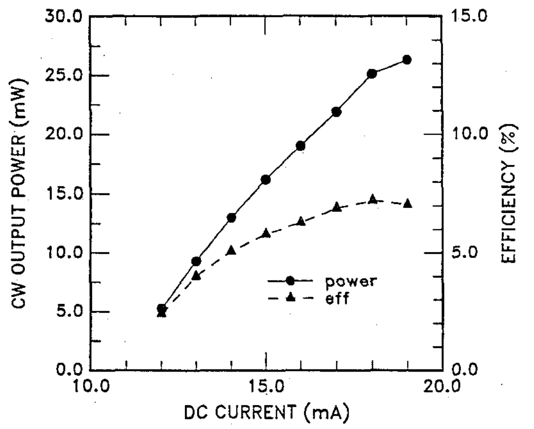

Fig. 5. Output characteristics of a single-element oscillator measured in waveguide at 43.3 GHz.

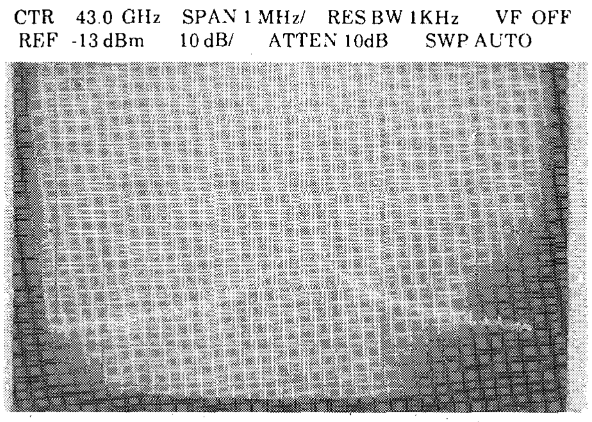

Fig. 6. Frequency spectrum of the single-element oscillator/antenna structure.

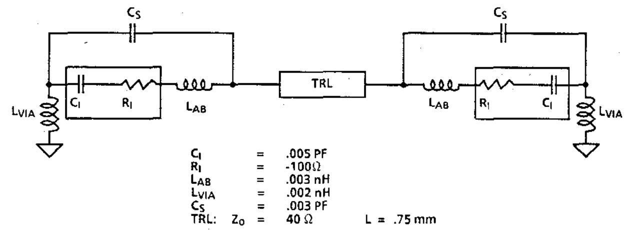

Fig. 7. Equivalent circuit for the IMPATT resonator/antenna structure.

from the chip was coupled into a waveguide and the power was measured in the waveguide setup. This approach was preferred owing to its simplicity and accuracy over the method of integrating the radiated power [7]. For these tests, each chip, measuring 1.25 mm × 0.75 mm, was soldered onto fixtures as shown in Fig. 4. The output power and frequency information was obtained in waveguide circuits by attaching the fixture to the end of a waveguide section so that the ground plate for the chip also became a backshort. The power radiating from the monolithic chip coupled to the waveguide efficiently in this arrangement since the radiation pattern of a single element transmitter is very similar to the radiation pattern of an open-ended waveguide. Therefore no additional tuning or transition circuits were needed. Typical output characteristics of a device operating at 43.3 GHz are shown in Fig. 5. CW output power of 27 mW was achieved at this frequency with 7.2 percent efficiency. This efficiency compares favorably with the 10 percent efficiency obtained with nonradiating monolithic circuits using the same IMPATT structure. This result indicates that the oscillator/antenna structure is operating efficiently both as an oscillator and as a radiator. The oscillator performance is basically maintained in this radiating structure due to the fact that the oscillator circuit still has a reasonably high Q value for a monolithic circuit. This is evident from the frequency spectrum of the radiated signal for a free-running oscillator, as shown in Fig 6.

Typical devices were fabricated using air bridges to connect to the IMPATT diodes as shown in Fig. 1. Devices with silicon nitride overlay bridges were also made to improve the device yield. When silicon nitride was used under the bridge, C_s (in the equivalent circuit shown in Fig. 7) was higher than in the case with air bridges. This capacitance added to the effective lenght of the resonator and thus made the circuit oscillate at a lower frequency. Similar devices processed simultaneously but with different bridges oscillated at 49 GHz when air bridges were used and at 44 GHz when silicon nitride overlay bridges were used.

Another factor studied was the effect of the semi-insulating GaAs substrate thickness on the circuit perfor-

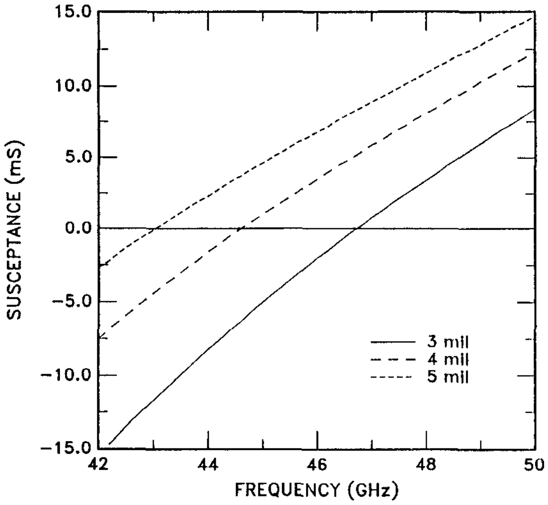

Fig. 8. Computed susceptance of monolithic IMPATT active antenna circuits as a function of substrate thickness.

TABLE I
EFFECT OF SUBSTRATE THICKNESS ON OUTPUT CHARACTERISTICS OF MONOLITHIC ACTIVE ANTENNA CIRCUITS

Substrate Thickness (μm)	Oscillation Frequency (GHz)		Output Power (mW)	Efficiency (%)
	Experimental	Computed		
75	46.2	46.8	14.1	3.2
100	44.1	44.6	19.0	4.7
125	43.3	43.0	26.3	7.1

mance. Thinner substrates were desirable to reduce the device thermal resistance since the diodes were located on the top surface of the wafer. It was also expected that thinner substrates would yield higher Q resonators to enhance the coupling between the resonator and the diodes. The disadvantage of a thinner substrate was that the antenna radiation efficiency would be lower. In an experiment, all circuits were produced simultaneously on a wafer but the wafer was later cut into several pieces and each piece was lapped separately to obtain substrates of different thickness. Monolithic circuits with substrate thickesses of 75, 100, and 125 μm were investigated in this experiment. Several circuits from each lot were tested and the average values of oscillation frequency, output power, and efficiency were determined. Table I shows these results as a function of substrate thickness. Also shown in this table are the computed values of the oscillation frequencies. To estimate the oscillation frequency, the equivalent circuit of Fig. 7 was used. This equivalent circuit was derived from the physical dimensions of the monolithic circuit elements and the measured (1 MHz) diode capacitance. The resonator susceptance was computed for each substrate thickness and the results are plotted in Fig. 8 The oscillation frequency is obtained when the resonator susceptance becomes equal to zero. These computed results show that the effect of reducing substrate thickness is to increase the oscillation frequency, in agreement with the experimental results. Referring back to the results in Table I, a change of 50 μm in the substrate thickness produced and average of 2 GHz change in frequency. This change in frequency was relatively small compared with the change in the output power and efficiency of devices. The device output power increased from 14.1 mW to 26.3 mW as the substrate thickness was increased from 75 μm to 125 μm. This increase in output power occurred despite the fact that devices on 75 μm substrates had 20 percent lower thermal resistances than those on 125 μm substrates. The increase in output power was therefore due to the increase in the device efficiency. As seen in Table I, the device efficiency more than doubled by increasing the substrate thickness from 75 μm to 125 μm. These experiments point out that, for this circuit design, the IMPATT diodes are operating in a more optimum loading condition when the substrate thickness in increased. The other explanation is that the circuit efficiency is improved. Precisely which of these mechanisms is more responsible for this output power increase is not clear at present.

IV. COUPLING AND POWER COMBINING IN WAVEGUIDES

The active antenna structure described above could easily be coupled to a waveguide since its radiation impedance was very similar to that of an open-ended waveguide (or a slot in the waveguide wall). this was evident in the radiation pattern of the active antenna shown in Fig. 3. Coupling has been achieved to a waveguide by placing the device on the backshort, as shown in Fig. 4. Tuning by means of an $E-H$ tuner did not improve the maximum available output power from the chip, indicating that the circuit matched very well to the waveguide structure. Biasing was best achieved by bringing a coaxial line through the ground plane and bonding a 25-μm-diameter wire to the center of the resonator as shown in Fig. 2. This bond wire did not seem to affect the oscillator or radiation properties of the monolithic chip if attached to the center of the resonator. To determine the influence of coaxial bias feed-through on power coupling, various impedance coaxial lines were tried but none of them produce RF leakage or out-of-band resonances.

Coupling to the waveguide could also be achieved by placing the monolithic chip on the waveguide walls in the same position where a radiating half-wavelength slot would be placed [8]. This has been experimentally verified and the output power from the device was found to be the same for several different positions on the waveguide wall. Placing the device on the backshort was the easiest to manufacture, however, since a split-block fixture was not needed. This was effectively a very inexpensive way to produce millimeter-wave waveguide oscillators. Although the power produced by the current chips was only of the order of a few mW, larger IMPATT diodes in similar circuits can be used to achieve output powers similar to IMPATT's in conventional circuits.

Another way of achieving higher output power is by combining the output power of several monolithic chips.

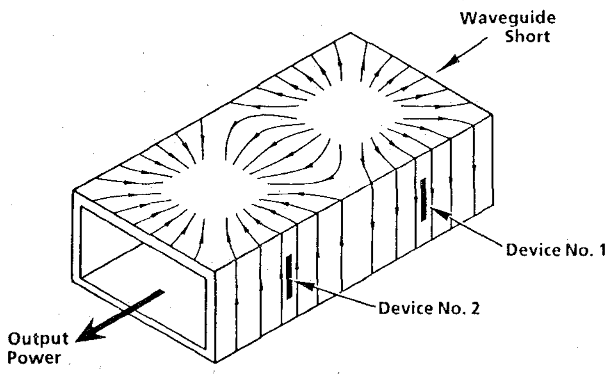

Fig. 9. The flow of surface currents in the walls of a rectangular waveguide excited with a TE_{10} mode, and the location of monolithic IMPATT circuits.

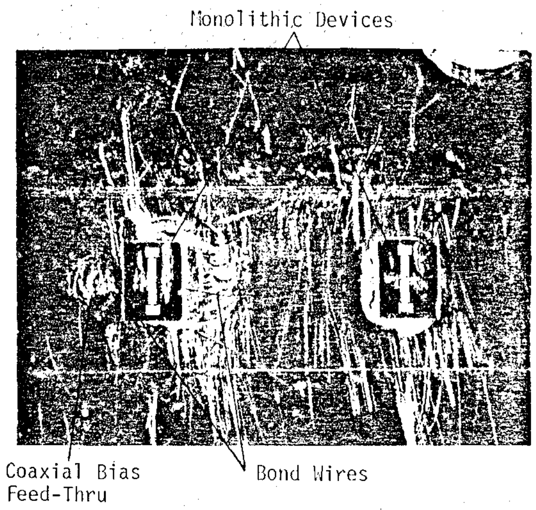

Fig. 10. Photograph of two power combined monolithic devices on the waveguide sidewall.

This could be accomplished in free space (as will be described in the next section) or in waveguides. Since the circuits were fabricated monolithically, variations in performance between circuits were minimal. This reproducible feature allowed power combining of several chips with relative ease. In the waveguide combiner scheme, monolithic chips were placed on the waveguide wall at locations where radiating slots would have been placed in a waveguide slot array. As shown Fig. 9, the monolithic chips were placed on the sidewalls of the waveguide with the E plane of the monolithic circuit aligned parallel to the direction of the surface currents in the sidewalls. The second monolithic chip was placed half a wavelength away from the first chip so that they were 180° apart. Fig. 10 shows a picture of the two-chip arrangement on the waveguide wall. A bias feed-through was provided by the use of a miniature coaxial line, as shown in this figure. The bias line entered the sidewall of the waveguide very close to one of the chips. The second chip was biased from the same bias supply by connecting the centers of the resonators to each other using a 25-μm-diameter bond wire. Tests were conducted in a WR-22 waveguide.

Table II shows the results of devices operating individually and together. When operating together, devices produced more output power than the sum of the output powers of each device operating individually. In other words, instead of the power increasing by 3 dB, it increased by 4.9 dB. This increase in output power of combined oscillators is probably caused by the more favorable impedance matching achieved in the presence of an injection signal for each oscillator.

TABLE II
PERFORMANCE OF SINGLE AND MULTIPLE DIODES IN A WAVEGUIDE

Device	Voltage (V)	Current (mA)	Power (dBm)	Frequency (GHz)
No. 1	16.2	13	1.0	43.11
No. 2	16.2	14	1.4	43.09
Both	16.2	28	6.1	43.28

V. MONOLITHIC ACTIVE ANTENNA ARRAY

The operation of an antenna array using active elements is governed by two main factors. These are 1) the antenna array configuration and 2) the phase locking behavior of oscillators. Looking into the design from an antenna array point of view, single radiating beams are obtained when the radiating elements are placed close to half a wavelength apart in free space. On the other hand, the radiating elements need to be in phase for broadside beam forming. A constant phase shift between adjacent elements can be used to shift the beam off the broadside axis. With these design considerations it is evident that an optimum array requires that the radiating elements be placed approximately half a wavelength apart in free space, while locking all elements in phase.

Two mechanisms can be used to injection lock the monolithic IMPATT oscillators in an array. These are 1) injection locking by radiation coupling between elements and 2) locking by means of a transmission line between the elements. The former option is undesirable for several reasons. Injection locking due to mutual free-space coupling results in a 180° phase shift between adjacent elements of the array placed $\lambda/2$ apart. This essentally produces two radiation lobes with a null in the broadside. To achieve an in-phase operation, elements must be placed a full wavelength apart. This, however, produces three main lobes. Further, in this configuration the coupling between elements is weaker, resulting in much narrower locking bandwidths.

The use of microstrip lines on GaAs was found to be an effective way to injection lock all oscillators. The slow wave properties of a transmission line produced on GaAs made it possible to place the radiating elements at a distance of less than half a wavelength in free space while injection locking the oscillators in phase. This essentially met the ideal array conditions discussed earlier. The other advantage of synchronizing radiating elements with a microstrip line was that the coupling strength could be adjusted by the characteristic impedance of the line. As

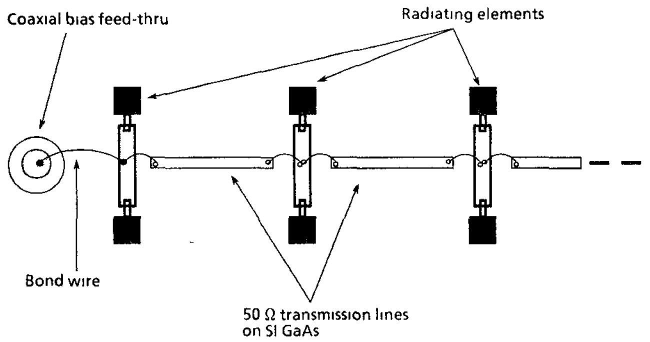

Fig. 11. A schematic drawing of the one-dimensional array arrangement.

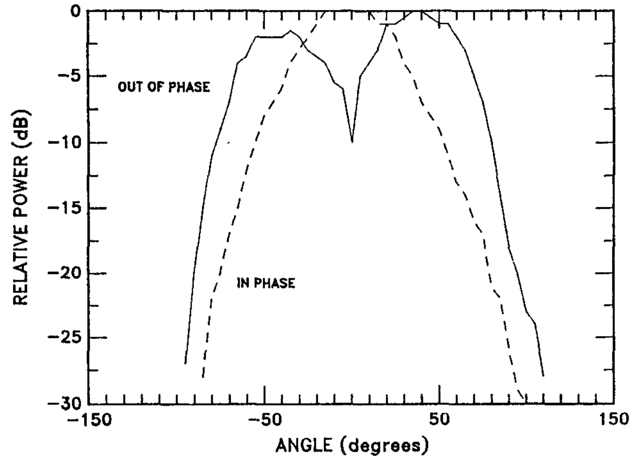

Fig. 12. *H*-field radiation patterns of a two-element array operating in and out of phase at 43 GHz.

shown in the schematic drawing of a one-dimensional array using active antennas (Fig. 11), the coupling line was also used as the dc bias line between elements.

The optimum spacing between elements was determined experimentally with the use of a two-element array. Since the wavelength in a GaAs microstrip is about 1/3 the free-space wavelength, radiating elements were placed about $\lambda/3$ and $\lambda/6$ apart for in-phase and out-of-phase operations, respectively. The radiation patterns of such a two-element array operating in and out of phase are shown in Fig. 12. Injection locking of the array elements was readily achieved in this configuration, as evidenced by the measured frequency spectrum, which was identical to the one shown in Fig. 6. The radiation patterns for one-, two-, and three-element arrays operating in phase are shown in Fig. 13. These radiation patterns clearly showed the success of fabricating monolithic active arrays where the phase between adjacent elements was controlled. The radiation patterns for the *E* plane are not shown in Fig. 13 since, for the one-dimensional array studied here, it was the same as that obtained with a single element radiator (see Fig. 3). It is expected that a similar narrowing of the *E* field pattern will be obtained in a two-dimensional array.

Studies are under way to determine the radiation patterns, beam steering capabilities, and injection locking properties of one- and two-dimensional arrays of mono-

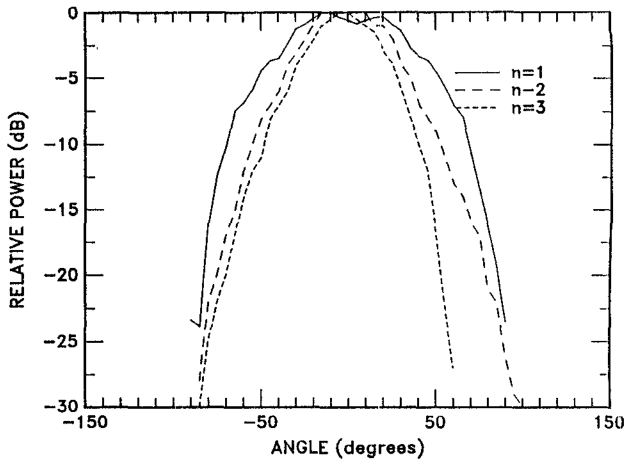

Fig. 13. *H*-field radiation patterns of one-, two-, and three-element arrays operating at 43 GHz.

lithic IMPATT transmitting elements. These studies will lead to totally monolithic active antenna arrays for millimeter-wave frequencies.

VI. Conclusions

A monolithic IMPATT fabrication technique was developed to integrate active devices and radiating elements on the same surface of a GaAs substrate. Since the IMPATT diode resonator also acted as the radiating element, the oscillator was automatically matched to the antenna properties, eliminating antenna feed mismatch losses. Single devices operating at 43.3 GHz produced 27 mW of CW output power with a 7.2 percent conversion efficiency. A study of the effect of substrate thickness of oscillation frequency and efficiency was conducted. Power combining of the oscillators in waveguide was achieved using two monolithic elements. Linear arrays of such radiating elements were also produced and radiation patterns were determined as a function of interelement spacings and element numbers. It is concluded that the monolithic millimeter-wave IMPATT diodes can be used in more complex circuits than has hitherto been possible. Totally active antenna arrays with beam-steering capabilities are within the reach of monolithic technology.

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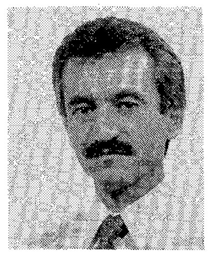

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