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 oscillator module. Devices operating at 43.3 GHz produced 27 mW cw output power with 7.2% conversion efficiency. Linear arrays of such radiating elements were produced and radiation patterns were determined as a function of inter-element spacings and element numbers. This monolithic oscillator chip was also directly coupled to waveguide producing an inexpensive millimeter-wave source.

INTRODUCTION

GaAs IMPATT diodes are commonly used as the power source in solid state millimeter-wave transmitters due to their unmatched power performance and efficiency. Conventionally, IMPATTs are used as discrete devices in hybrid circuits to maximize their output. More recently, monolithic circuits containing IMPATT diodes have also become available (1,2). The capability of integrating IMPATTs with passive circuit elements on a single-chip creates the possibilities of realizing more complex yet compact monolithic subsystems at frequencies extending into the mm-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 a complex and lossy power distribution network. Another example is incorporating an oscillator with a waveguide feed. This makes a very inexpensive millimeter-wave source unlike the packaged devices that require precisely machined cavities or the conventional monolithic microstrip circuits that 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 the 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. Linear arrays of such radiating elements were produced and radiation patterns were determined as a function of inter element spacings and element numbers. This monolithic oscillator was also coupled to waveguide using several configurations.

MONOLITHIC IMPATT DIODE FABRICATION

The IMPATT diode structures used in this study were of flat -profile, double-drift type. All structures were grown by Metal Organic Chemical Vapor Deposition (MOCVD) technique. Dimethylzinc and silane in hydrogen carrier gasses were used as the dopant gasses for p- and n-type layers. To assure 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 5E18 and 1E19 cm^{-3}, respectively. The doping concentrations and thicknesses of drift regions were typically 2E17 cm^{-3} and 0.2 - 0.3 µm, respectively.

In the fabrication of the 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) reported earlier (3). Only a brief description is therefore given here. After establishing 5 µm diameter top contacts (Ti-Pt-Au) for each diode by photolithography and lift off techniques, reactive ion etching (RIE) in BCl_3 gas was used to isolate devices. Since RIE produces no undercut, the device area was controlled precisely. 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 Figure 1.

MONOLITHIC OSCILLATOR/ANTENNA DESIGN

The resonator/antenna circuit consisted of a section of a 125 µm wide microstrip line produced on a 100 µm thick SI GaAs substrate. As shown in Figure 2, the resonator/antenna resonant circuit is placed between two IMPATT diodes, 30 µm away from each end. The air bridge connections were 10 µm in width and 3 µm in height. The total length of the microstrip line was chosen to be equal to half a wavelength at the frequency of oscillation, taking into account all the loading effects of the diodes, air bridges, and via ground terminal.

The radiation pattern for the oscillator/antenna is shown in Figure 3. The radiation pattern closely resembles that of a half square loop antenna placed close to the ground plane (4,5). As seen in Figure 3, the E-field is omni-directional whereas the H-field 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 from the chip was coupled into a waveguide and the power was measured in the waveguide set-up. This approach was preferred due to its simplicity and accuracy over the method of integrating the radiated power (6).

Completed wafers were separated into 1.25 x 0.75 mm chips by sawing. Each chip was soldered onto fixtures similar to that shown in Figure 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 back short. The power radiated 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. Tuning by means of an E-H tuner did not improve the output power which indicated that the device matched very well to the waveguide structure. Biasing was best achieved by bringing a coax perpendicular to the ground plane and bonding a 25 µm diameter wire to the center of the resonator as shown in Figure 2. This bond wire did not seem to affect the oscillator or the radiation properties if attached to the center of the resonator where a null exists in the electric field. Several different impedance coaxial feeds were tried out but none of them seemed to have rf leakage problems or out of band resonances.

Typical output characteristics of a device operating at 43.3 GHz is shown in Figure 5. Cw output power of 27 mW was achieved at this frequency with 7.2% efficiency. This efficiency compares favorably with the 10% efficiency obtained with non-radiating monolithic circuits using the same IMPATT structure. This result indicates that the oscillator/antenna structure 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 Figure 6. This method of coupling the IMPATT circuit to waveguide was effectively a very inexpensive way to produce millimeter-wave waveguide oscillators. Although the power produced by the current chips was only of the

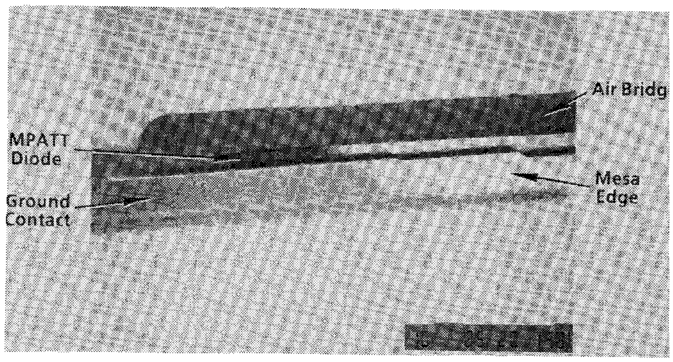

Figure 1. SEM Picture of the air-bridge connecting the IMPATT Device.

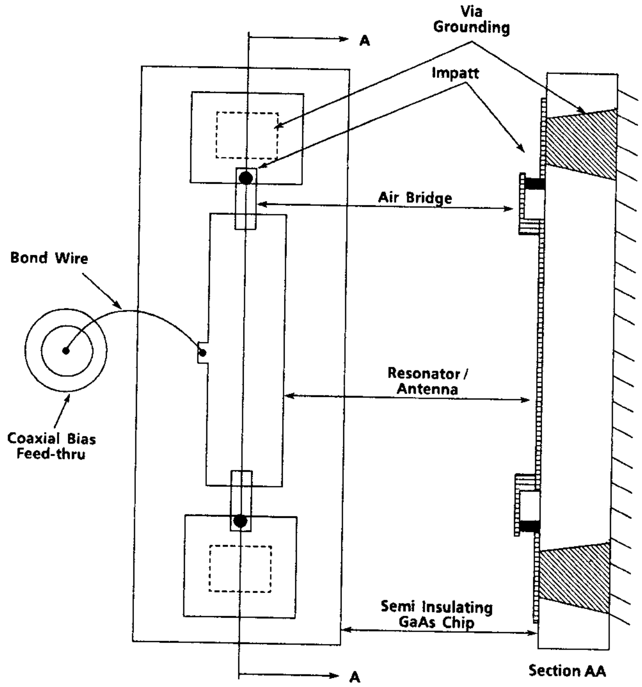

Figure 2. Schematic of the monolithic resonator/ antenna structure.

order of a few milliwatts, devices using the same circuit concept and larger IMPATT diodes could produce comparable power to conventional circuits.

MONOLITHIC ACTIVE ANTENNA ARRAY

The operation of an antenna array using active elements was governed by two factors. These were a) the antenna array configurations and b) the phase locking behavior of the oscillators. Looking into the design from an antenna array point of view, single radiating beams were obtained when the radiating elements were placed close to half wavelength apart in free-space. On the other hand, the radiating elements needed to be in phase for broad side beam forming. A constant phase shift between adjacent elements could be used to shift the beam off the broad side axis. With these design considerations an optimum array design required the placement of radiating elements approximately half a wavelength apart in free space, while locking elements in phase.

Two mechanisms could be used to injection lock oscillators of an array. These were injection locking by radiation coupling between elements and locking by means of a transmission line between the elements. The former option was undesirable for several reasons. Injection locking due to mutual free-space coupling resulted in 180° phase shift between the adjacent elements of the array that were placed half a wavelength apart. This would essentially produce two radiation lobes with a null in the broad side which was undesirable for most applications. To achieve in-phase operation, elements needed to be placed one wavelength apart in free-space. This however produced three beams. The other consideration of this option was that the coupling between elements was weaker due to larger separation. To insure injection locking of all elements, oscillators with Q values lower than the ones described in the previous section were required.

The use of microstrip line on GaAs to injection lock all oscillators were found to be more desirable for the present study. The slow wave properties of a transmission line produced on GaAs allowed us to place the radiating elements at a distance of close to half a wavelength apart in free space while injection locking the oscillators in phase. This essentially meets the ideal array conditions discussed earlier. The other advantage of coupling elements with a microstrip line was that the coupling strength could be adjusted by the characteristic impedance of the line. For the present work we used the coupling lines also as a part of the dc bias network. A schematic of the one dimensional array using active antennas is shown in Figure 7.

The optimum spacing between elements was determined in a series of experiments using a two element array. Since the wavelength in a GaAs microstrip was about 1/3 of the free-space wavelength, for in-phase operation oscillators were placed about one third of a wavelength apart. Injection locking of the array elements was readily achieved in this configuration as evidenced by the measured frequency spectrum which was identical to that shown in Figure 6. The radiation patterns for 1, 2, and 3 element arrays operating in-phase are shown in Figure 8. The beam sharpening obtained for 2 and 3 elements is appropriate for elements spaced 1/3 of a wavelength apart. 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 Figure 8 since for the one-dimensional array studied here, the radiation patterns have been observed to be the same as that of a single element (see Figure 3). It can be expected that a sharpening of the E-field pattern will also result in two-dimensional arrays.

Studies are underway to determine the radiation patterns, beam steering capabilities, and injection locking properties of one and two dimensional arrays of monolithic IMPATT transmitting elements. These studies will lead to totally monolithic active antenna arrays for millimeter-wave frequencies.

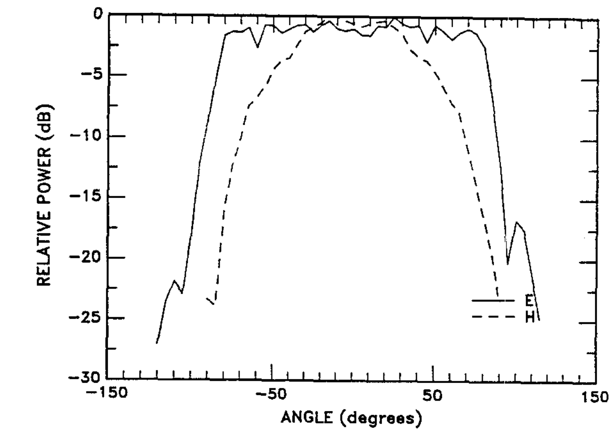

Figure 3. Radiation pattern of a single element monolithic active antenna at 48.5 GHz.

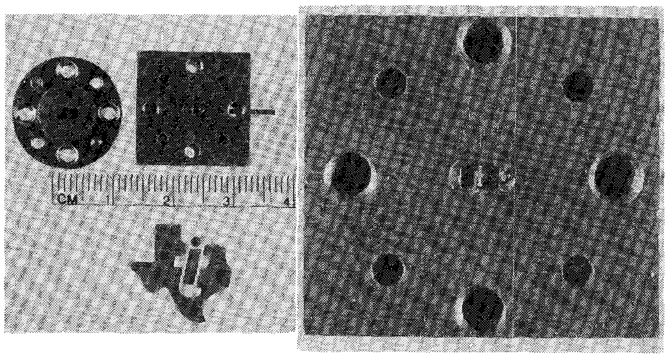

Figure 4. A single element oscillator/antenna structure mounted on the back short of a waveguide test fixture.

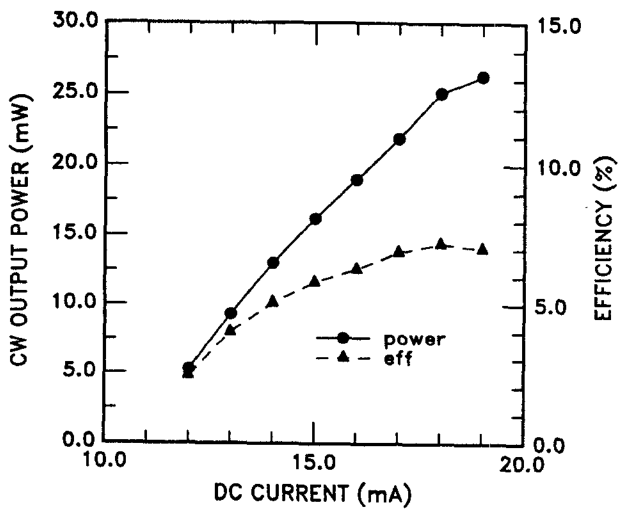

Figure 5. Output characteristics of a single element oscillator measured in waveguide at 43.3 GHz.

CONCLUSIONS

A monolithic IMPATT fabrication technique was developed to integrate active devices and radiating elements on the same surface of a SI GaAs substrate. Since the IMPATT diode resonator also acted as the radiating element, the oscillator was automatically matched to the antenna properties so that antenna feed mismatch losses were eliminated. Devices operating at 43.3 GHz produced 26 mW cw output power with 7.1% conversion efficiency. The oscillation frequency and the radiation patterns were determined by the properties of on-chip circuitry. This monolithic oscillator was also coupled to waveguide using several configurations. A low cost oscillator fabrication technology has been demonstrated. Linear arrays of such radiating elements were produced and radiation patterns were determined as a function of inter-element spacings and element numbers. It is concluded that the monolithic mm-wave IMPATT diodes can be used in more complex circuits than hitherto been possible. A totally monolithic active antenna arrays with beam steering capabilities are within the reach of the monolithic technology.

ACKNOWLEDGEMENTS

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CTR 43.0 GHz SPAN 1 MHz/ RES BW 1KHz VF OFF
REF -13 dBm 10 dB/ ATTEN 10dB SWP AUTO

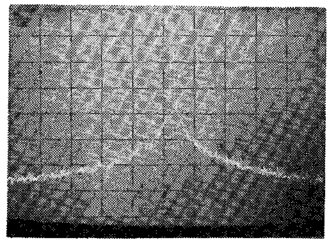

Figure 6. Frequency spectrum of the single element oscillator/antenna structure.

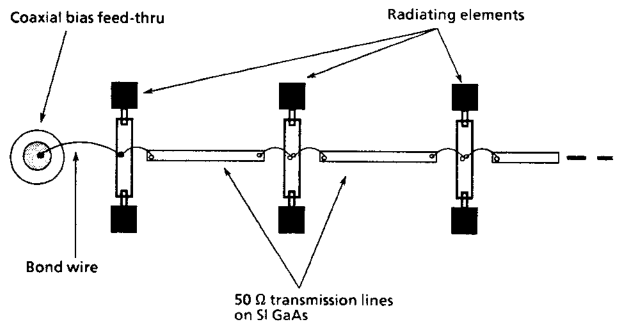

Figure 7. A schematic drawing of the one dimensional array arrangement.

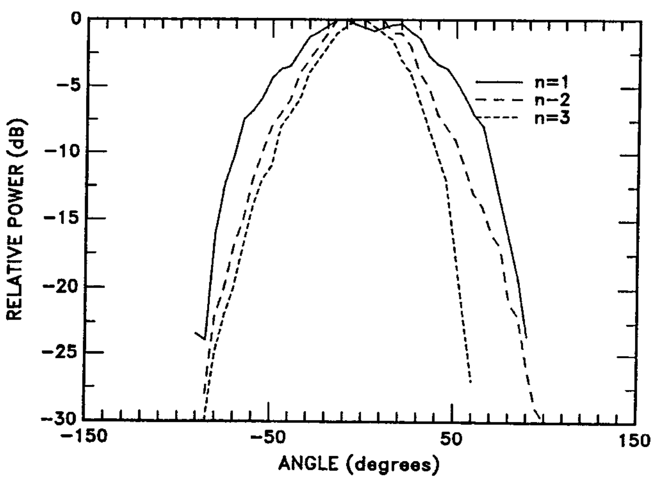

Figure 8. H-field radiation patterns of 1, 2, and 3 element arrays operating at 43 GHz.