Broadband Electronically Tunable Planar Active Radiating Elements and Spatial Power Combiners Using Notch Antennas*

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***Abstract*—A Gunn device has been integrated with two types of active planar notch antennas. The first type uses a coplanar waveguide (CPW) resonator and a stepped-notch antenna with bias tuning to achieve a bandwidth of 275 MHz centered at 9.33 GHz with a power output of 14.2 ± 1.5 dBm. The second type uses a CPW resonator with a varactor for frequency tuning to achieve a bandwidth of over 1.3 GHz centered at 9.6 GHz with a power output of 14.5 ± 0.8 dBm. This is equivalent to over 14% electronic tuning bandwidth. Both configurations exhibit a very clean and stable output signal. A theoretical circuit model was developed to facilitate the design. The model agrees well with experimental results. Injection-locking experiments on the second configuration show a locking gain of 30 dB with a locking bandwidth of 30 MHz at 10.2 GHz. Power combining experiments of two varactor-tuned CPW active notch antenna elements in a broadside configuration have achieved well over 70% combining efficiency throughout the wide tuning range. The circuits have advantages of small size, low cost, and excellent performance.**

I. Introduction

Considerable effort has been directed toward the development of microwave and millimeter-wave hybrid and monolithic integrated circuits. Recent developments have made it possible to combine active devices with planar antennas to create active radiating elements or active quasi-optical transmitters. Due to the power limitations of active solid-state radiating elements, quasi-optical and spatial power combining techniques have been used by [1]–[6]. The general power combining techniques have been reviewed in [6]. The spatial power combining techniques create a single, coherent and higher-power signal from many low-power radiating sources. Furthermore, spatial or quasi-optical power combining is not limited by size or moding problems and allows the combination of a greater number of active radiating elements.

The microstrip patch antenna has been used for an active, planar, integrated, low-cost radiating element [1], [2], [7]–[10]. The microstrip patch antenna provides a resonant structure for the Gunn diode to oscillate, a ground plane for efficient heat sinking, and an inexpensive method to create a microwave source. However, the active patch antenna has exhibited very narrow tuning ranges with high cross-polarization levels, and wide power output deviations. Futhermore, the structure has inherent deficiencies for active millimeter-wave operation due to its small patch dimensions, and it does not allow easy integration of other solid-state devices, such as the varactor, for wideband electronic frequency tuning. Previously, varactor tuning has been accomplished using waveguide and microstrip Gunn oscillators [11], [12], but no attempt has been made to integrate the varactor-tuned Gunn oscillator directly into the antenna. An alternative approach for active element integration can be accomplished by using the notch antenna.

The notch antenna has many desirable characteristics which include broad impedance matching bandwidth and planar nature, as well as good reproducibility, and ease of integration to passive and active devices. Furthermore, the length of the notch can be increased to create a travelling-wave antenna like the linear-tapered slot antenna (LTSA) [13]. The main design parameter of the notch antenna is the flare of the slot as given by the exponentially-tapered Vivaldi antenna [14]. Other important work has been reported in the characteristics of the antenna impedance and radiation [15]–[17]. The flexibility of this type of antenna makes it ideal for many diverse applications.

An FET has been integrated with a notch antenna [18] using slotline and CPW to create a 20 GHz receiver front-end. No other attempt has been made to use the advantages of the notch for an active quasi-optical transmitter. This paper presents two novel configurations for the integration of a Gunn oscillator to a notch antenna:

1) Biased-tuned Gunn oscillator in the CPW resonator using a stepped-notch antenna. The notch is coupled to the center of a CPW resonator which is physically perpendicular to the slotline.

2) Varactor-tuned Gunn oscillator in a CPW resonator using a smooth-tapered notch antenna. The notch is coupled to one end of a CPW resonator which is physically in colinear to the slotline.

The first configuration exhibits a clean, stable bias-tuned signal from 9.2 to 9.47 GHz with a power output of 14.2 ± 1.5 dBm. However, bias tuning creates a wide deviation in power output and the resonator orientation

Manuscript received November 29, 1990; revised September 18, 1991. This work was supported in part by the U.S. Army Research Office.
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IEEE Log Number 9104775.
*Patent pending.

may introduce a strong cross-polarization component. For most active antenna applications, a low-cost method of providing a clean, stable signal with moderate and constant power output over a wider electronic tuning bandwidth is needed. This can be accomplished by introducing a varactor in the oscillating circuit. The second configuration, with varactor tuning, exhibits a tuning bandwidth from 8.9 and 10.2 GHz with an output power of 14.5 ± 0.8 dBm. The spectral purity and tuning range are comparable to state-of-the-art results achieved in waveguide and microstrip oscillators. The theoretical tuning curve obtained from a circuit model agrees fairly well with experimental results.

Injection-locking experiments were also conducted showing a locking gain of 30 dB with a locking bandwidth of 30 MHz at 10.2 GHz. Power combining experiments of two varactor-tuned active notch antenna elements, in a broadside configuration at a distance of 8 mm ($\lambda/4$ at 9.6 GHz) apart, have achieved well over 70% combining efficiency throughout the tuning range with a maximum of 129.2% at 9.7 GHz. To the best of the authors' knowledge, this is the first varactor tunable power combiner ever reported.

The circuits offer many advantages of low cost, simplicity, small size, wide electronic tuning range, good stability, and excellent performance. Although Gunn and varactor diodes were used here, other active devices can also be used. Due to their planar nature, these circuits are amenable to monolithic implementation and offer many applications in radar, communications, and electronic warfare systems.

II. The Active CPW Stepped-Notch Antenna

Fig. 1 shows the active CPW stepped-notch antenna configuration. The circuit consists of a stepped-notch antenna coupled to a CPW resonator via slotline. A Gunn diode is placed in a heat-sink at the open terminals of the resonator. The notch is formed by many step transformers which match the slotline impedance to free space.

The resonator is the essential design element for improved oscillation and stability. Considering the planar nature, Q-factor, and ease of integration with active devices, CPW was chosen for the resonator. The CPW slots were designed to be 0.3 mm with a 3.5 mm separation. This arrangement provides a 50 Ω characteristic impedance and mates well with the 3.5 mm cap of the Gunn diode. The length of the resonator is about 0.5λ at 10 GHz. A DC block was incorporated at the shorted end for biasing purposes. The circuit is mounted on an L-shaped metal block which serves as a heat-sink and holder.

The notch antenna design was accomplished by using cascading slotlines which act as impedance transformers from the coupling point to free space. The low dielectric constant of 2.3 allows efficient antenna radiation. The input impedance of the notch was matched to the resonator at the coupling point.

Matching from free space to the resonator was optimized using a transmission line equivalent circuit model. The lengths of the transformer sections were optimized for minimum return-loss throughout X-band. The circuit was fabricated on a 60 mil thick, RT-Duroid 5870 substrate. To test the passive circuit, an SMA connector was soldered on to the CPW resonator and the measurements were performed on an HP-8510 Network Analyzer. The stepped-notch antenna gain was measured at 9.3 and 9.6 GHz and found to be 7.1 and 7.7 dBi, respectively. Integration of an active device may change the antenna efficiency and introduce degenerate modes at the oscillating frequency. However, one can use this method to approximate the oscillator power output. The gain measurements were used to calculate the oscillator power output with the Friis transmission equation:

$$P_t = P_r\left(\frac{4\pi R}{\lambda}\right)^2\left(\frac{1}{G_{ot}G_{or}}\right) \tag{1}$$

where

P_r = Power received.
P_t = Power transmitted from the active notch antenna.
λ = Wavelength of operation.
R = Antenna range length.
G_{ot} = Gain of the transmit antenna.
G_{or} = Gain of the receive antenna.

A Gunn device from M/A COM was integrated with the stepped-notch antenna. This Gunn diode produces 72 mW in an optimized waveguide circuit. The bias voltage vs. frequency and power output is shown in Fig. 2.

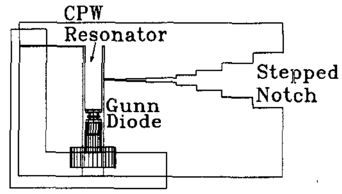


Fig. 1. CPW Stepped-notch antenna circuit configuration.

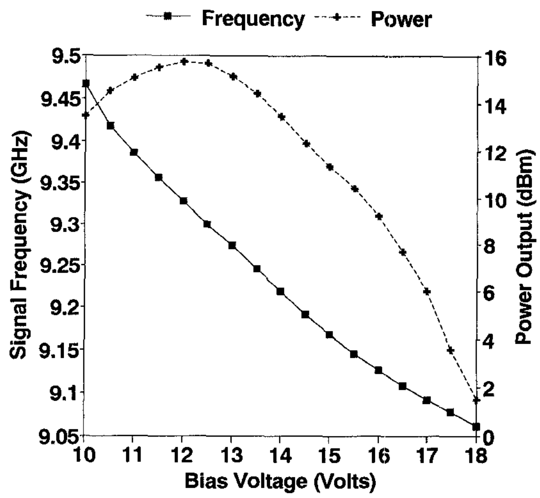


Fig. 2. Frequency and power output versus bias voltage of the active CPW stepped-notch antenna.

The 3 dB bias-tuning bandwidth was 275 MHz centered at 9.33 GHz with a maximum power output of 37.5 mW at 9.328 GHz.

III. The Varactor-Tunable CPW Active Notch Antenna

Fig. 3(a) shows the varactor-tunable CPW active notch antenna configuration. The circuit consists of a notch antenna integrated with a varactor-tuned CPW resonator. The notch antenna couples to the resonator via slotline. A Gunn and a varactor diode are placed at either end of the CPW resonator. This arrangement provides strong coupling between the Gunn diode and the varactor diode for increased tuning bandwidth.

The CPW resonator allows multiple dc-biased devices to be integrated due to its inherent dc blocks used for separate biasing. The input impedance of the antenna was matched at the coupling point with the resonator and the flare of the notch antenna was modified from the stepped to a smooth taper for improved bandwidth performance.

A theoretical model was developed to facilitate the design. The equivalent circuit can be represented as shown in Fig. 3(b). The modeling of the CPW junction is based on reference [19]. Neglecting the junction discontinuity effects, the transformer ratio n is set equal to 1. The flare of the notch antenna was approximated by 24 sections of slotlines of different widths and impedances. The equivalent circuits of the Gunn and varactor diodes used for calculations are shown in Fig. 4. The diode parasitics for the Gunn and varactor are given by the vendor. The following conditions were used to determine the oscillating frequencies at various varactor bias levels:

$$|\mathrm{Re}\,(Z_{\mathrm{diode}})| \geq |\mathrm{Re}\,(Z_{\mathrm{circuit}})| \tag{2}$$

$$\mathrm{Im}\,(Z_{\mathrm{diode}}) + \mathrm{Im}\,(Z_{\mathrm{circuit}}) = 0 \tag{3}$$

where Re (Z_{diode}) is assumed to be $-8\ \Omega$ [20] and the oscillations occur when condition 1 is satisfied. The oscillating frequencies are found from condition 2.

The overall dimensions of the circuit board are 1 × 2 inches. The circuit was etched on a 60 mil thick RT-Duroid 5870 substrate. To test the passive circuit, a coaxial connection was soldered on to the notch and measured on an HP-8510 Network Analyzer. The measured SWR was less than 2 : 1 throughout the *X*-band range (8–12.4 GHz). The passive notch was then tested in an anechoic chamber for the field patterns and relative gain. The relative gain (G_o) of the passive notch antenna measured at 9.0, 9.6, and 10.2 GHz were 8.0, 8.2, and 9.0 dBi, respectively. The gain was later used in (1) to determine the active notch output power.

A Gunn and varactor diode from M/A COM were integrated into the resonator and coupled to the notch antenna via slotline. This Gunn diode (MA49106) produces 80 mW in an optimized waveguide circuit while the varactor (MA46602F) is rated for 1.6 pF at 0 V. Theoretical results were calculated using the circuit model shown in Fig. 3(b) and (2) and (3). Fig. 5 shows the theoretical tuning curve obtained for varying varactor bias levels from 0 to 30 V. Experimental results are shown in the same figure for comparison. Considering the large deviation of active device modelling parameters, the theoretical model agrees fairly well with the experimental results. A frequency tuning range of 8.9 to 10.2 GHz was achieved for varactor voltages of 0 to 30 V. This is equivalent to over 14% electronic tuning bandwidth. There are no mode jumps and the signal spectrum remains clean and very stable, with an output power variation of ±0.8 dBm throughout the frequency tuning range. The spectrum of the received signal from the varactor-tunable notch antenna is comparable to the spectrum of the active stepped-notch. The *E* and *H*-field patterns as well as the cross-

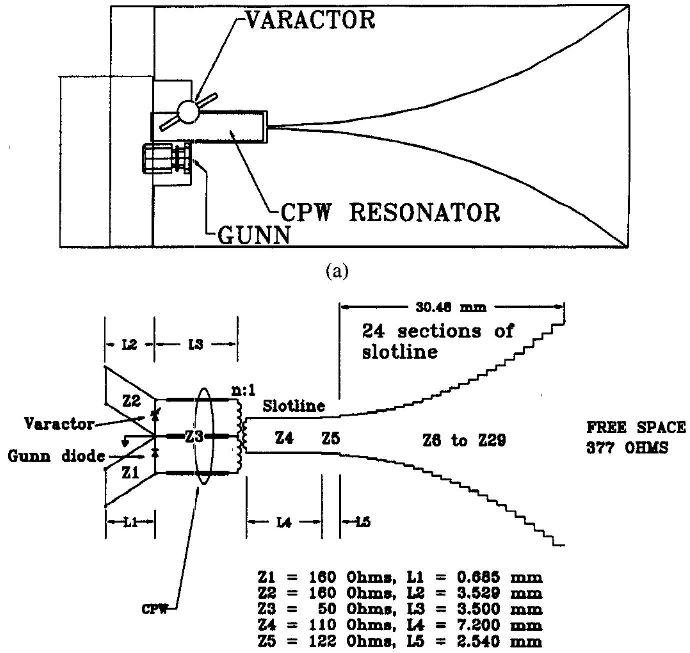


Fig. 3. The varactor-tunable CPW notch antenna. (a) Circuit configuration. (b) Equivalent circuit.

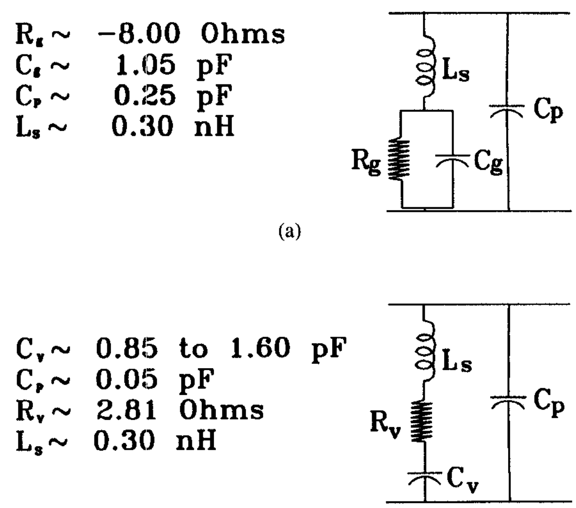
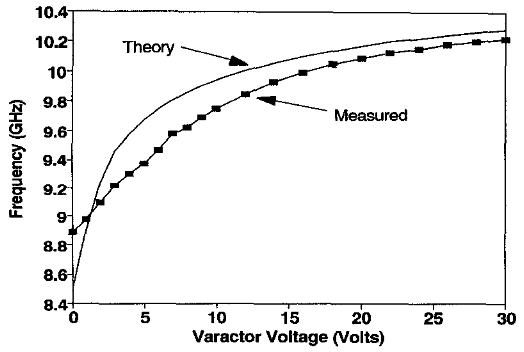
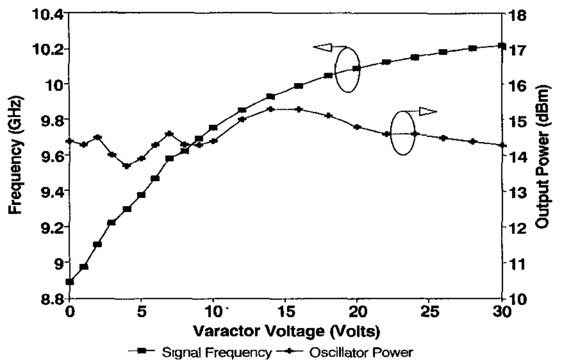


Fig. 4. Device Equivalent Circuits. (a) Gunn diode. (b) Varactor diode.

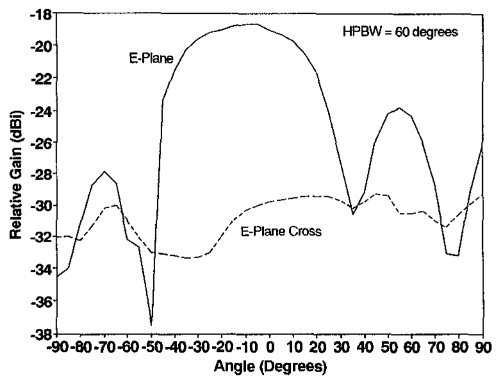


(a)

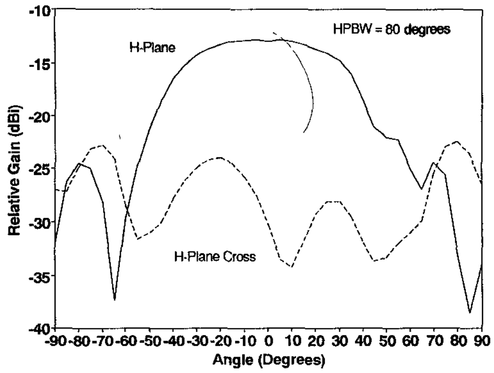


(b)

Fig. 5. Active varactor-tunable CPW notch antenna results. (a) The theoretical and experimental varactor tuning frequency versus voltage (b) The experimental power output of the active varactor-tunable CPW notch antenna.



(a)



(b)

Fig. 6. Field patterns of the active varactor-tunable CPW notch antenna at 10.2 GHz. (a) *E*-plane pattern and cross-polarization measurements. (b) *H*-plane pattern and cross-polarization measurements.

polarization patterns are shown in Fig. 6 for the varactor-tunable active notch antenna at 10.2 GHz. The back radiation remains below −10 dB throughout the tuning bandwidth.

IV Injection-Locking and Power-Combining Experiments

Injection-locking experiments with an external HP-8690B Sweep Oscillator source were performed to determine the locking-gain and locking-bandwidth of the active notch antenna configuration. The test measurement set-up is shown in Fig. 7. Equation (1) was used to determine the P_i from P_t and P_o from P_r. Injection-locking experiments were performed throughout the electronic tuning range. The locking-gain (P_o/P_i) vs. locking bandwidth (ΔF) results are shown in Fig. 8 and they are comparable to previous patch antenna experiments [1]. A locking gain of 30 dB with a locking bandwidth of 30 MHz was obtained at 10.2 GHz. The Q-factor of the circuit is found to be 21.5 and can be calculated with [21]

$$Q_e = \frac{2F_o}{\Delta F}\sqrt{\frac{P_i}{P_o}} \tag{4}$$

The locking gain in dB is defined as

$$G_L = 10 \log \frac{P_o}{P_i} \tag{5}$$

where

Q_e = External Q-factor.
F_o = Operating frequency.
ΔF = Injection-locking bandwidth.
P_i = Injection-lock signal power.
P_o = Free-running oscillator power.

Quasi-optical combiners using Fabry–Perot resonators and spatial power combiners have the potential of combining many solid-state devices at millimeter-wave frequencies. To demonstrate the feasibility of the spatial power combiner, two notch antennas were set up in a broadside array at 8 mm separation. To achieve efficient power-combining, the active notch antenna elements must injection-lock to each other through mutual coupling. Power combining experiments of two injection-locked, varactor-tuned active notch antennas were conducted throughout the electronic tuning range at 100 MHz increments. The power combining efficiency is defined by

$$\text{Efficiency} = \left(\frac{P_{\text{combiner}}}{P_1 + P_2}\right) \times (100)\% \tag{6}$$

where

P_1 = Power of active notch #1 (Use $G_{ot} = G_o$, G_o is the antenna gain of a single passive notch antenna).
P_2 = Power of active notch #2 (Use $G_{ot} = G_o$).
P_{combiner} = Power of injection-locked, power-combined signal (Use $G_{ot} = 2G_o$).

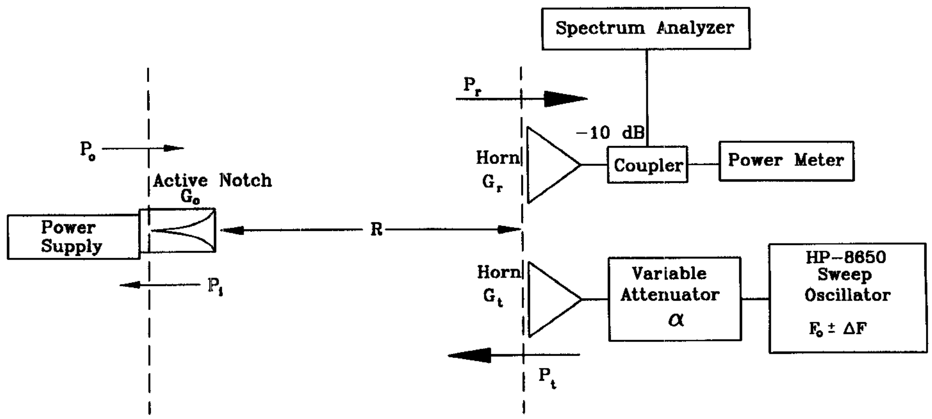


Fig. 7. The measurement set-up for injection-locking experiments using an external source.

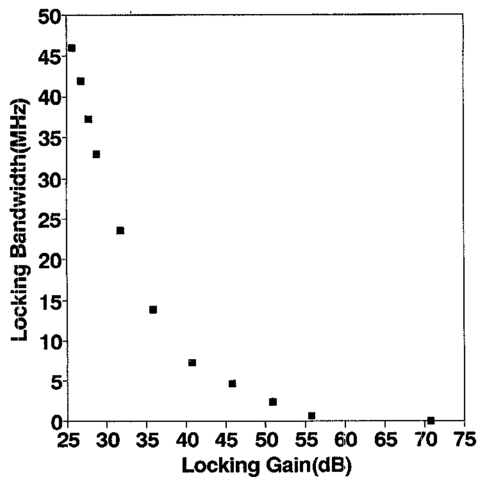


Fig. 8. The injection locking-gain versus locking-bandwidth at 10.2 GHz.

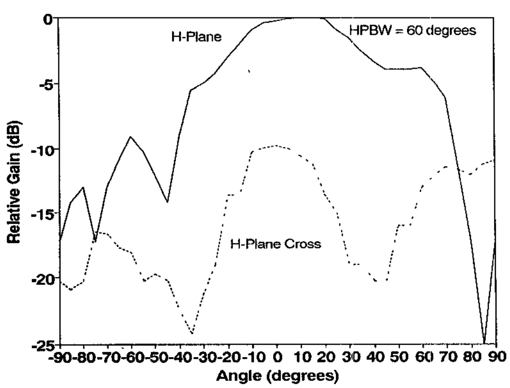


Fig. 9. The H-plane and cross-polarization meausurements of two mutually-coupled injection-locked, power combined active notch antennas at 9.6 GHz.

All power calculations are calculated from (1). For the P_1 and P_2 calculations, the gain of a single passive antenna was used for the transmitting active antenna gain G_{ot}. For the P_{combiner} calculations, the array gain was assumed to have twice the gain of a single passive antenna. The power combining efficiencies measured at 9.4, 9.7, and 10 GHz were 90.0, 129.2, and 75.0%, respectively. The combining efficiency of over 100% at certain frequencies can be attributed to improved impedance matching in two mutually-coupled oscillators as compared to a single oscillator which is not fully optimized. Similar results have been reported by another power combiner [22]. The H-plane field pattern and cross-polarization measurements at 9.6 GHz are shown in Fig. 9 for the combiner. The 3 dB beamwidth of the array was 53 degrees compared to 78 degrees for a single element. To the best of our knowledge, these results represent the first wideband varactor-tunable power combiner reported in literature.

V. Conclusion

The Gunn device has been integrated with a stepped-notch antenna using a CPW resonator. The configuration was modified to incorporate a varactor diode and form a varactor-turned active antenna element. Over 14% electronic tuning range was achieved with a fairly constant power output. Two of these varactor-tuned active antenna elements were successfully injection-locked to each other via mutual coupling and power combined throughout the wide electronic tuning range with over 70% combining efficiency.

These circuits offer a small, simple, lightweight, low-cost, reproducible, and truly planar active wideband tunable source for many microwave applications. Using these elements in planar arrays with injection-locking and power combining techniques will enable higher power levels. The wide varactor tuning range should prove useful for frequency modulated communication links, radar, and electronic warfare applications. The circuits are amenable to monolithic circuit integration for mass production and should have many applications in frequency-agile transmitters at microwave and millimeter-wave bands.

Acknowledgment

The authors would like to thank Mr. R. C. Waits for his instruction and use of the fabrication facilities. The authors would also like to thank Mr. J. C. McCleary and Mr. K. A. Hummer for many valuable discussions and suggestions.

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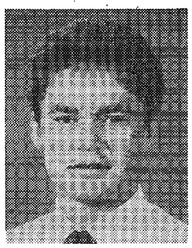

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