WIDEBAND INTEGRATED VARACTOR - TUNABLE ACTIVE NOTCH ANTENNAS AND POWER COMBINERS*

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ABSTRACT

A Gunn device in a varactor tuned slotline-coplanar waveguide (CPW) resonator has been integrated with a planar, endfire notch antenna. The varactor provides more than 14 percent tuning bandwidth centered at 9.6 GHz with a power output of 14.5 ± 0.8 dBm. Wideband tunable quasi-optical power combiners have also been developed using these active elements.

I. INTRODUCTION

Active solid-state devices have been successfully integrated in resonant broadside radiating elements such as the microstrip patch antenna [1-4]. The microstrip patch antenna provides a resonant structure for the Gunn diode to oscillate, a ground plane suitable for efficient heat sinking, and an inexpensive method to create a microwave power source. However, the active patch antenna has exhibited very narrow tuning ranges with high cross-polarization levels, and wide power output deviations. Furthermore, the structure has inherent deficiencies for 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. Integration of the Gunn device in a varactor-tuned slotline-CPW resonator with a notch antenna provides a moderate and constant power output over a wide electronic tuning range. The notch antenna [5, 6] also has many desirable characteristics which include broad-impedance matching bandwidth, planar nature, and good reproducibility, as well as beamwidth design flexibility, relatively high gain and easy active element integration. This design allows the optimization of the antenna specifications (i.e. impedance, bandwidth, beamwidth) separate from the resonator requirements. The designer must merely match the circuits at the coupling point.

A Gunn diode [7] and an FET [8] have been integrated with a notch antenna. The active notch using the Gunn diode in a CPW resonator [7] exhibited a clean, stable bias-tuned signal from 9.2 to 9.47 GHz with a power output of 14.2 ± 1.5 dBm. For most applications, a low-cost method of providing a clean, stable signal with moderate power output over a wider electronic bandwidth is needed. The integration of a varactor in the oscillating circuit can greatly enhance the bandwidth and reduces output power deviation by maintaining a constant Gunn diode bias level. Previously, varactor tuning has been accomplished using waveguide and microstrip Gunn oscillators [9, 10]. However, no attempt has been made to introduce the varactor-tuned Gunn oscillator directly to the antenna.

This paper presents, for the first time, the novel integration of a Gunn diode in a varactor-tuned slotline-CPW resonator to a notch antenna. The circuit exhibits a tuning bandwidth from 8.9 to 10.2 GHz with an output power of 14.5 ± 0.8 dBm. This is equivalent to over 14% electronic tuning bandwidth. There are no mode jumps, the signal spectrum remains clean and very stable, and the output power variation is ± 0.8 dBm throughout the continuous electronic frequency tuning range. The spectral purity and tuning range are comparable to waveguide and microstrip oscillators. The circuit design was based on a transmission line model. The theoretical tuning range agrees very well with the measured 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 of two varactor-tuned active notch antenna elements, in a broadside configuration at a distance of $\lambda/4$ apart, has achieved over 70% combining efficiency throughout the tuning range. To the best of the author's knowledge, this is the first varactor tunable power combiner ever reported.

II. CIRCUIT DESIGN

Figure 1 shows the novel varactor tunable active notch antenna configuration. The circuit consists of a notch antenna fed by a varactor-tuned slotline-CPW resonator. A Gunn diode is placed in a heat-sink at one of the open ends of the resonator and a varactor at the other end.

The resonator is the essential design element for improved oscillations and stability. A coupled slotline-CPW resonator eases the integration of multiple DC-biased devices. The length of the resonator is approximately 0.5 λ. The notch antenna design was accomplished using slotline formulas. The slotline width was increased from the input impedance at the resonator coupling point to the free-space impedance as shown in Figure 2. The low dielectric constant of 2.3 allows efficient antenna radiation .

The circuit was optimized based on a transmission line model shown in Figure 2. The impedance seen by the Gunn diode $Z_{in}(V_v)$ is a function of the varactor voltage. Oscil-

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lation occurs when the real part of $Z_{in}(V_v)$ is less than the absolute value of the negative resistance of the Gunn diode. The frequency of oscillation occurs where the imaginary parts of $Z_{in}(V_v)$ and the Gunn diode cancel out. From this model, the theoretical tuning curve was calculated.

III. CIRCUIT PERFORMANCE

The circuit was fabricated on a 60 mil (1.524 mm) thick RT-Duroid 5870 substrate. To test the passive circuit, an SMA connector was soldered on to the notch and the mesurements were performed 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 tested in an anechoic chamber to determine its radiating characteristics and gain. The relative gains of the passive notch antenna measured at 9.0, 9.6, and 10.2 GHz were 8.0, 8.2, 9.0 dBi, respectively. The gain is needed to determine the active notch output power from the Friis Transmission Equation [11].

A Gunn diode and a varactor diode from M/A COM were then integrated into the resonator. Figure 3 shows the theoretical and experimental frequency as a function of varactor tuning voltage. The theoretical tuning curve was derived from the equivalent circuit shown in Figure 2. The agreement between the theory and experiment is very good. A frequency tuning range of 8.9 to 10.2 GHz was achieved for varactor voltages of 0 to 30 volts. This 1.3 GHz tuning is equivalent to over 14% electronic tuning bandwidth. The experimental power output and frequency vs. varactor voltage of the active notch antenna for a Gunn bias of 13.5 volts is shown in Figure 4. There are no mode jumps and the signal spectrum remains clean and very stable, with an output power variation of $\pm$ 0.8 dBm throughout the frequency tuning range. The E and H-field patterns as well as the cross-polarization patterns are shown in Figure 5 for the active varactor-tunable slotline-CPW notch antenna at 10.2 GHz.

IV. POWER COMBINING

Quasi-optical or spatial power combiners [12 - 15] 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 ($\lambda/4$ at 9.6 GHz) separation. To achieve efficient power-combining, the active notch antenna elements were injection-locked 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. Figure 6 shows the powers of each active notch antenna separately and in combination. The power combining efficiency is defined by

$$\text{Efficiency} = \left[\frac{P_{\text{combiner}}}{P_1 + P_2}\right] \times (100)\% \qquad (1)$$

where

$$\begin{aligned} P_1 &= \text{Power of active notch \# 1.} \\ P_2 &= \text{Power of active notch \# 2.} \\ P_{\text{combiner}} &= \text{Power of injection} - \text{locked,} \\ &\quad \text{power} - \text{combined signal.} \end{aligned}$$

All power calculations were based on the Friis Transmission Equation [11]. The increase in gain of the notch and the array beam sharpening has been included in the calculation. Over 70% combining efficiency was observed throughout the varactor tuning range. The H - plane field pattern is shown in Figure 7. To the best of our knowledge, these results represent the first varactor-tunable power combiner over a wide tuning range reported in literature.

V. CONCLUSIONS

An active varactor-tuned coupled slotline-CPW notch antenna and power combiner have been developed with wide frequency tuning range in X-band. The signal spectrum remains clean and very stable with nearly constant power output throughout the electronic tuning range. These results offer a simple, lightweight, low-cost, reproducible, and truly planar active wideband tunable source for many microwave applications. The wide electronic tuning range is useful for frequency modulated communication links, radar and electronic warfare applications.

VI. ACKNOWLEDGEMENTS

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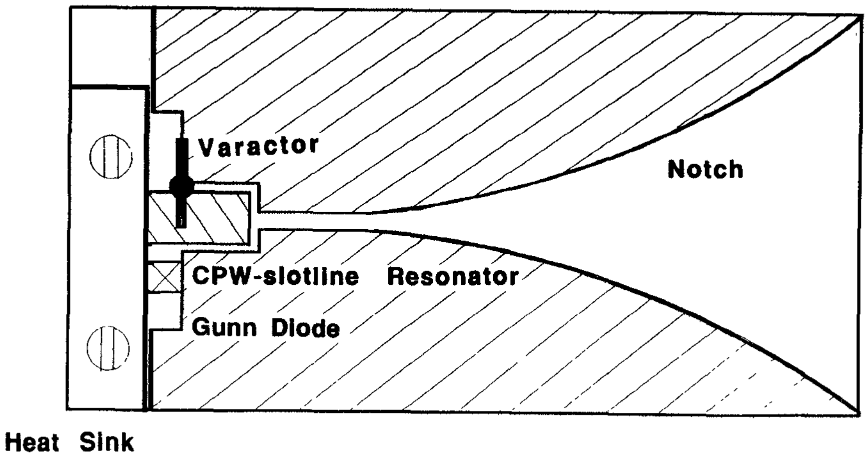

Figure 1. The circuit configuration of a varactor - tuned active notch antenna

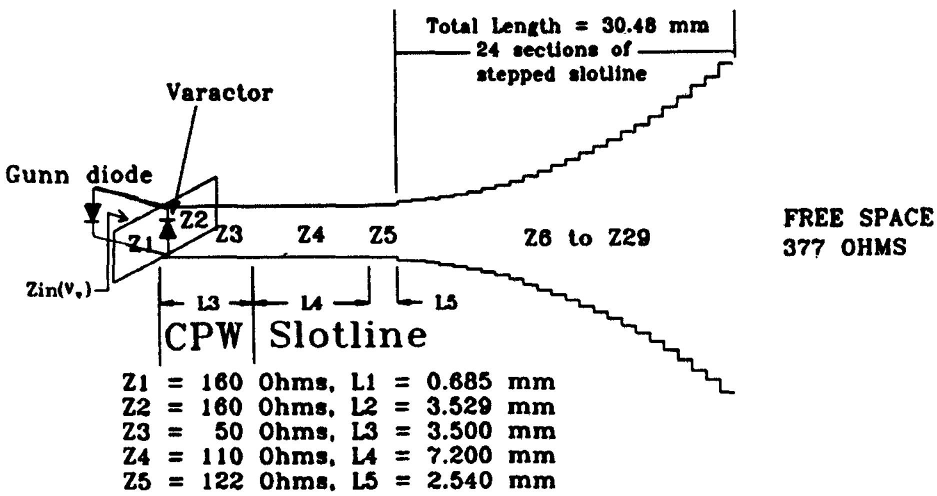

Figure 2. Equivalent circuit for theoretical analysis

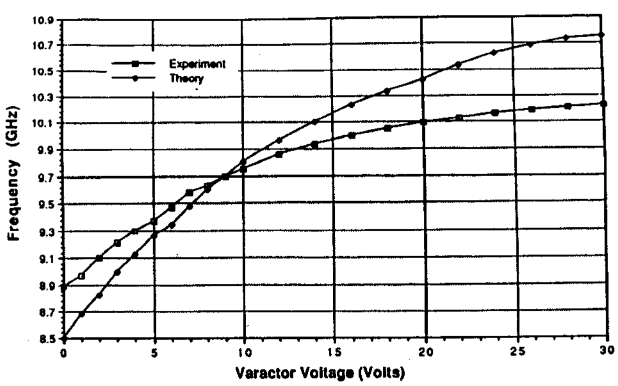

Figure 3. Comparison of theoretical and experimental oscillating frequency

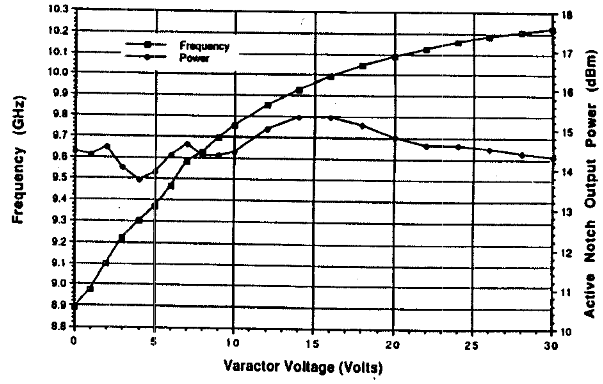

Figure 4. Output power and frequency versus varactor voltage

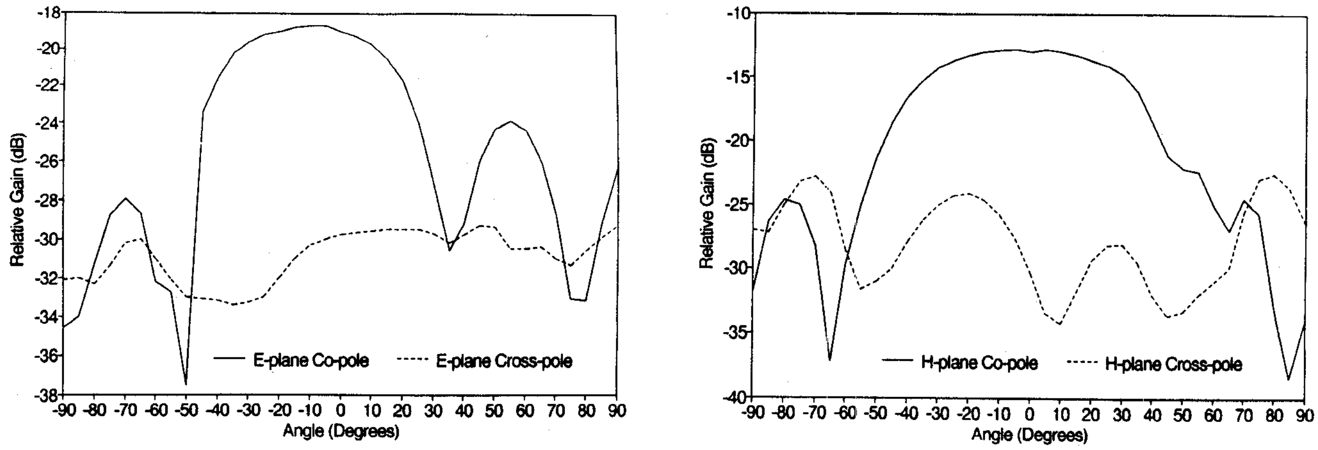

Figure 5. The E- and H- plane field patterns of the active varactor - tuned notch antenna

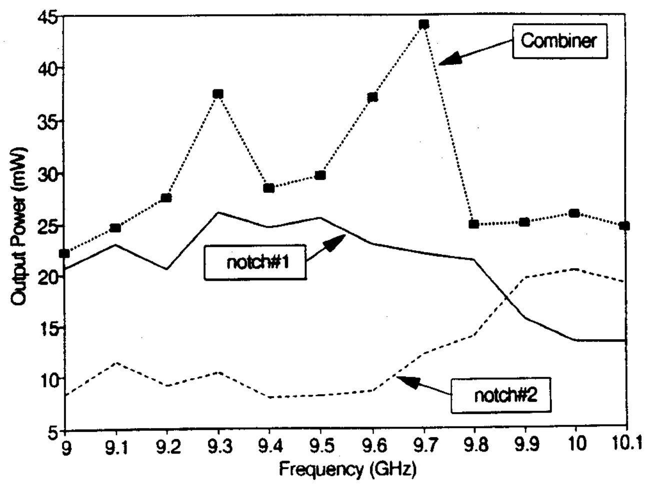

Figure 6. Output power P_1, P_2 and P_{combiner} versus frequency

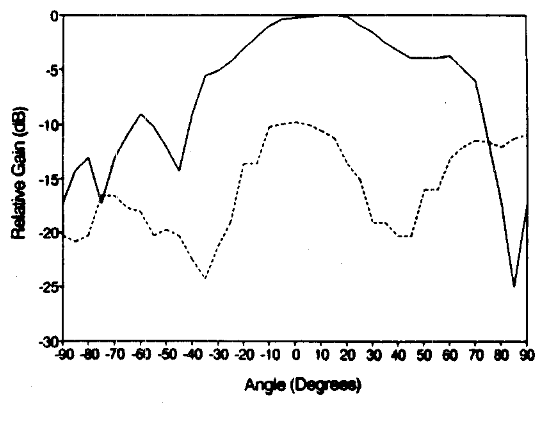

Figure 7. H- plane field pattern of the combiner at 9.6 GHz