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A GUNN-DIODE ACTIVE LEAKY-WAVE FREQUENCY SCANNING ANTENNA

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Abstract

A frequency tunable active leaky-wave scanning antenna using Gunn-diode voltage control oscillator (VCO) as source is developed. The frequency tuning controlled by changing either the varactor diode dc bias or the Gunn diode dc bias is demonstrated. The measured scanning angle of active antenna is close to 15 degree as the Gunn VCO frequency tuned from 12.58GHz to 12.98GHz. To excite the first higher order mode of the microstrip leaky-wave antenna is fed asymmetrically. The dominant mode excitation has been successfully suppressed by adding a sequence of covered wire in the middle line of the microstrip leaky wave antenna. This is a prototype of frequency scanning antenna using two terminal device, which can be easily scaled up to millimeter wave frequency region.

Key Words:

Ku-band, Voltage Controlled oscillator (VCO)

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I. Introduction

The existence of leaky modes on various open wave-guiding structure is well known. For conventional microstrip on isotropic substrates, the higher-order microstrip modes become leaky at lower frequency [1][2]. Generally, these higher-order modes have a different current distribution on the conducting strip and a field with the substrate from the usually current and field associated with the dominant mode, therefore such modes are usually not easily excited by a conventional feed. In practical application of leaky wave antenna, an asymmetrical feeding is always used. The propagation properties of microstrip line higher order modes were first studied by Ermert [3][4]. He used an accurate mode-matching method to find the propagation characteristics of the dominant mode and first two higher-order modes, but he failed to obtain real solutions near the cutoff of the higher-order modes. Oliner and Lee clarified the confusion of properties of microstrip line higher-order modes and divided the leakage modes into two forms, surface wave and space wave [6]. About the mode excited method, Menzel has proposed a successful method for the excitation of the microstrip line first higher-order mode [7]. He used an asymmetric feed arrangement with a sequence of transverse slits on the center of the microstrip line to suppress the microstrip line dominant mode.

Recently, there is a growing interest in linear antenna-array integration [8][9] using microstrip leaky-wave antenna as radiating elements. In 1996, C. K. Tzuang et al [8] proposed a design approach for an active-integrated antenna source module integrating a microstrip leaky-mode antenna at about 8GHz. Because the radiation main-beam of strip leaky wave antenna depends on the operating frequency, it can be used as a frequency-scanning antenna [10]. In 1997, Hu et al [11] demonstrate a X-band active frequency scanning leaky-wave antenna using HEMT VCO at X band. Although, the transistors can provide high-efficiency, high-power operations with low noise in the microwave frequency. However, it is difficult to extend the operating frequency of these transistors into the millimeter-wave band because of their inherent structure complexities. Therefore, two-terminal microwave diodes are the key devices for generation, amplification, and detection application in the millimeter-wave and submillimeter-wave bands.

The commonly used diode sources are Gunn diodes, the IMPATT (IMPact ionization Avalanche and Transit Time) diode, Tunnel diode, and RT (resonant Tunneling) diode, all of which directly convert a DC bias to RF power. They are natural oscillators. Furthermore, two-terminal devices have the advantages over HEMT such as higher f_{max}, simpler bias circuit, and they are suitable for monolithic millimeter-wave integration circuit. In this paper, an active frequency scanning microstrip leaky-wave active antenna prototype is demonstrated by composing a leaky-wave antenna with a Gunn diode Voltage control oscillator. This can be accomplished by using a varactor in the Gunn-diode-type VCO circuit. We can change the beam direction by either adjusting varactor dc bias or Gunn diode dc bias. Therefore, it can be used as a frequency-scanning antenna.

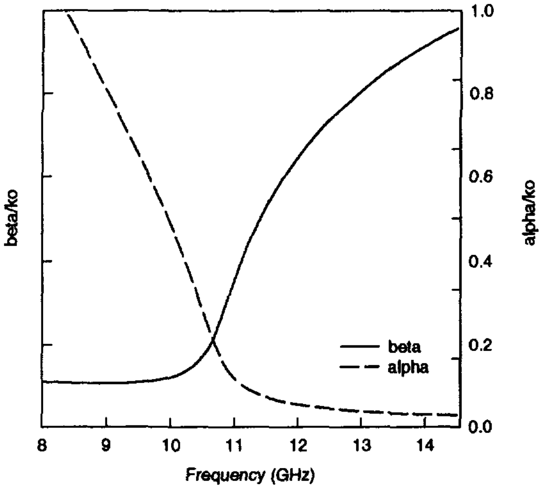

Fig. 1. Normalized complex propagation constant of the first higher mode for a particular microstrip leaky-wave antenna, where h=.508 mm, w = 8mm, and $\varepsilon_r = 2.2$. k_0 is the free-space wave number.

II. A Fixed Frequency Leaky-wave antenna Design

Because the dominant mode propagating in a microstrip is a slow wave, it cannot furnish a way to achieve a uniform leaky-wave antenna. Therefore, in contrast to the dominant mode's application, the first higher mode interests us. When the leakage modes leak into the air and the substrate around it, we call them space wave and surface wave. The space wave is our desired mode. But the dominant mode (surface mode) with zero cutoff frequency is often weakly excited. This is desirable since most electromagnetic energy will propagate in the intended direction rather than dissipating in the form of a surface wave on the dielectric layer outside the strip region. Therefore, if we suppress the more dissipating power caused by dominant mode or other modes, we can obtain more power at an intended direction on the air.

A. Dispersion Characteristic of the Leaky-Wave Active Antenna

In order to understand the radiation properties of such a microstrip leaky-wave antenna, we obtained its complex propagation constant β-jα of the first higher microstrip mode in its leaky range, where β is the phase constant, and α is the attenuation constant. The complex constant is obtained by employing rigorous (Wiener-Hopf) solution mentioned by Ref [9]. Fig.1 shows the variations of phase constant β and attenuation α as a function of frequency. The width of this leaky wave microstrip antenna design is 8 millimeter, the substrate dielectric constant 2.2 and substrate thickness 0.508milimeter. In our structure, the microstrip leaky-wave antenna is open at the top. For values of $\beta<k_0$, power will leaky into space and exist in a space wave form in addition to the surface wave. The space wave actually corresponds to radiation at some angle θ, the value of this angle changes with frequency. By using the approximate relationship $\theta m=Cos^{-1}(\beta/k_0)$ where θm is the angle of the beam maximum measured from the end fire direction, we can predict the main beam position.

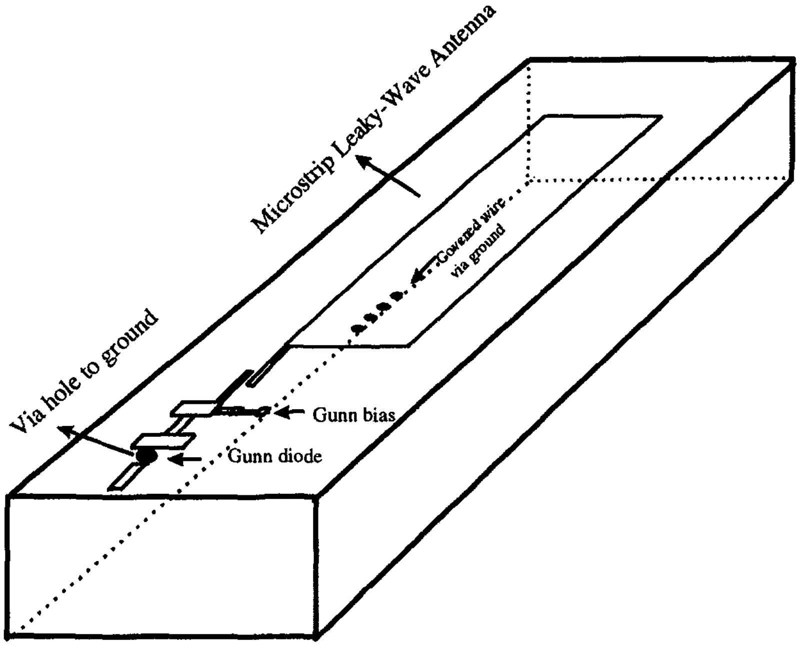

Fig. 2. Configuration of the asymmetric feeding active microstrip leaky-wave antenna designed at fixed 14.93GHz

Fig. 2 shows a microstrip realization of a Ku band Gunn-diode frequency tunable leaky-wave antenna structure. It is composed of a Gunn diode oscillator and a microstrip leaky wave structure. In order to obtain the Gunn diode admittance, the method we used is to design a planar Gunn diode oscillator using microstrip line circuit. To design the antenna, the first important thing is to determine the exact Gunn diode admittance. The exactly equivalent circuit model of the Gunn diode is obtained by using the HP8563E spectrum analyzer to measure the exact oscillating frequency. The designed oscillator was using this admittance by utilizing a commercially available CAD tool HP-EEsof Libra. A couple line is used between oscillator and the microstrip leaky-wave structure to prevent the large reflected signal which might destroy the active device, and it also is part of the matching circuit. To excite the first higher order mode for better efficiency, the microstrip leaky-wave antenna is fed asymmetrically. A sequence of covered wire was inserted in the centerline of the antenna to suppress the propagation of the dominant mode [7] [11]. (whereas the longitudinal current would be zero for the first higher mode)

B. Radiation Pattern

The field equivalence principle is applied to derive the far field radiation pattern of the microstrip leaky-mode antenna. Fig.3 shows the model of the structure. The antenna consists of two slots, each of width w, length L, and height h. Each slot will radiate the same fields as a magnetic dipole with magnetic current density $\vec{M}_S = -n \times \vec{E}$ which can be assumed to be exponential decaying functions with an attenuation constant α and can be expressed as

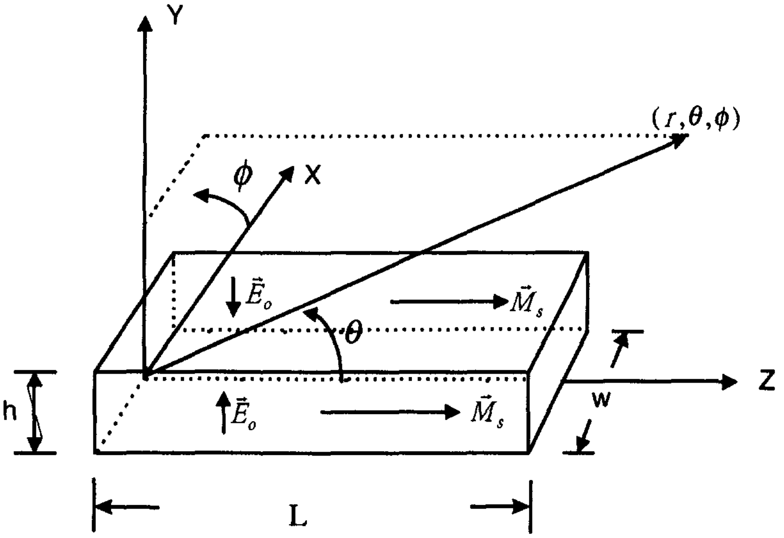

Fig. 3. Geometry and coordinate system for deriving the far-zone radiation pattern of a microstrip leaky-mode antenna

$$\vec{M}_S = \hat{z}\, E_0 e^{-j(\beta - j\alpha)z} \tag{1}$$

where E_0 is an arbitrary constant. The total field will be the sum of the two elements' array with each element representing one of the slots. Thus, the far-zone fields can be written as

$$E_r \cong E_\theta \cong 0$$

$$E_\phi \cong -jE_o \frac{khe^{-jkr}}{\pi r}\left\{\sin\theta\left[\frac{\sin(X)}{X}\right]\left[\frac{e^{ZL}-1}{Z}\right]\right\}\cdot\cos\left(\frac{kw\sin\theta\sin\phi}{2}\right) \tag{2}$$

where

$X = kh\sin\theta\cos\phi$

$Z = j(k\cos\theta - \beta) - \alpha$

and $k = 2\pi/\lambda$ are the wave number.

The H-plane normalized radiation patterns derived from (2) are plotted in Fig.4 for operating frequencies at 12.58 GHz and 12.98 GHz.

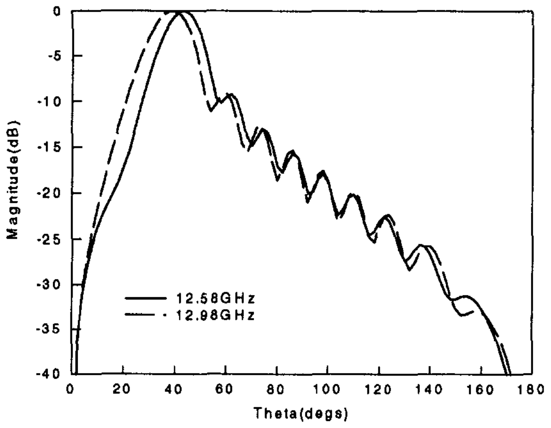

Fig.4. Theoretical H-plane (y-z plane) radiation patterns of the microstrip leaky-wave antenna for two different frequencies.

C. Power Radiation

The output power P_0 was calculated using the Friss transmission equation:

$$P_o = P_r\left(\frac{4\pi R}{\lambda_0}\right)^2 \frac{1}{G_o G_r}$$

where

P_r = Power received.

P_o = Power transmitted from the active leaky-wave antenna.

λ_o = Wave length in free space.

R = Antenna separation.

G_t = Gain of the transmit antenna.

G_r = Gain of the receive antenna.

If the active antenna gain is unknown, the Equivalent Isotropic Radiation Power (EIRP) defined below should be used.

$$EIRP = P_r\left(\frac{4\pi R}{\lambda_0}\right)^2 \frac{1}{G_r}$$

Figure 5 shows the measured H-plane radiation pattern at 14.93GHz which agrees well with the prediction data.

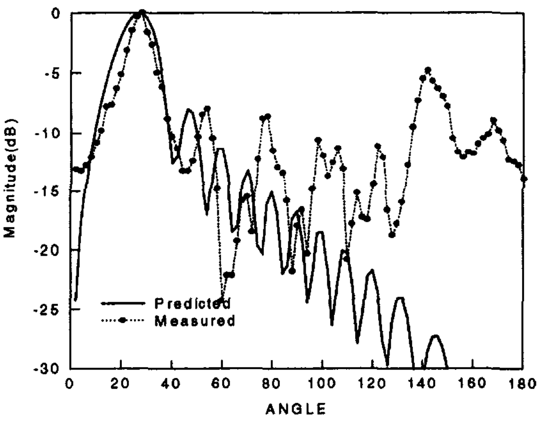

Fig. 5. The H-plane radiation pattern of the asymmetrically feeding active leaky-wave antenna measured at 14.93GHz

III. Frequency scanning active leaky-mode antenna

Figure 6 shows the microstrip realization of a varactor-tuned frequency-scanning active leaky-wave antenna structure. The circuit is designed and fabricated on RT/Duroid substrate with a dielectric constant of 2.2 and thickness of 20 mils. C&K W2420 Gunn diode is used. A varactor ALPHA DKV3803 was used as the tuning varactor, which has a capacitance of 2 pF at 18 V. The field measurement is done under the far field condition. For a varactor tuning voltage from 8 V to 14 V, the active leaky-wave antenna exhibits a tuning bandwidth from 12.58 to 12.98 GHz when Gunn diode is biased at 7.84 Volts with a current of 120mA. The variation of frequency and effective radiation power (EIRP) of leaky wave antenna with VCO as a function of varactor bias is shown in Fig.7. The EIRP of this active antenna is about 43 dBm ±2 dBm throughout the frequency tuning range at a distance of 68.5cm from the horn to the antenna. Figure 8 , 9, 10 show the experimental and the theoretical results of the H-plane pattern for operating frequency at 12.58 GHz, 12.78 GHz and 12.98 GHz respectively. We can see from Fig. 8, 9, 10 that as the operating frequency is higher, the direction of main beam swings up close to z-axis. This phenomena can be referred to Fig.2 where it shows that the attenuation constant decrease as the operating frequency increases, resulting in the observed narrower beam width in Fig. 11. The differences in the power level of main beam are caused mainly by the varied microstrip leaky-wave antenna impedance as function of frequency.

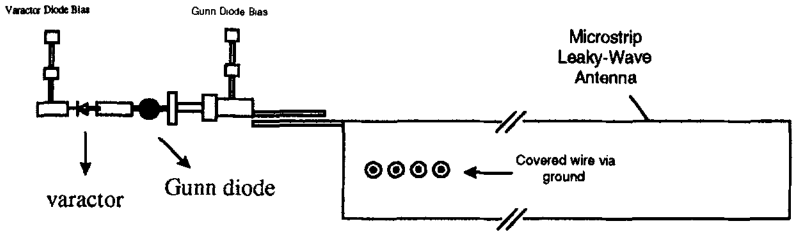

Fig. 6. Configuration of the varactor-tuned frequency-scanning active leaky-wave antenna.

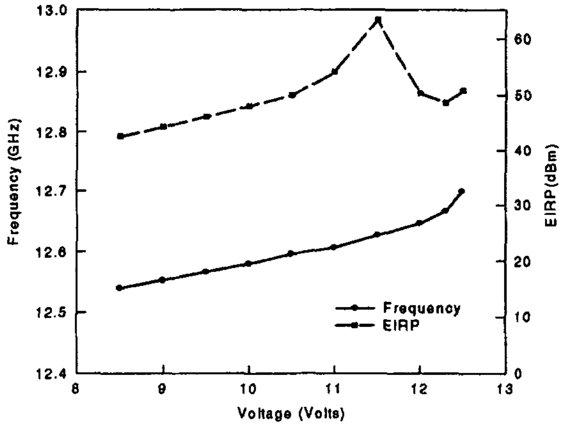

Fig. 7. The frequency tuning and effective radiation power (EIRP) variation of Gunn VCO leaky wave antenna as a function of varactor bias voltage.

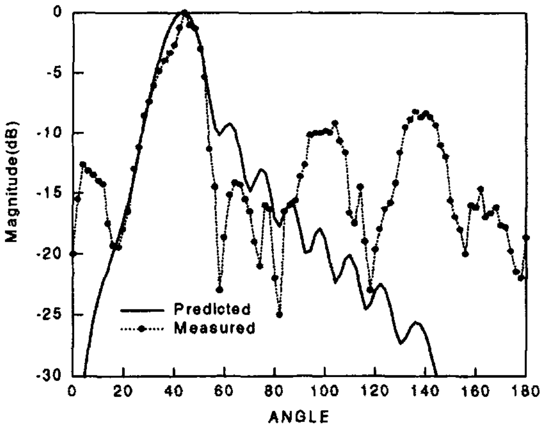

Fig. 8. The H-plane radiation pattern of the asymmetric feeding active leaky-wave antenna measured at 12.58 GHz.

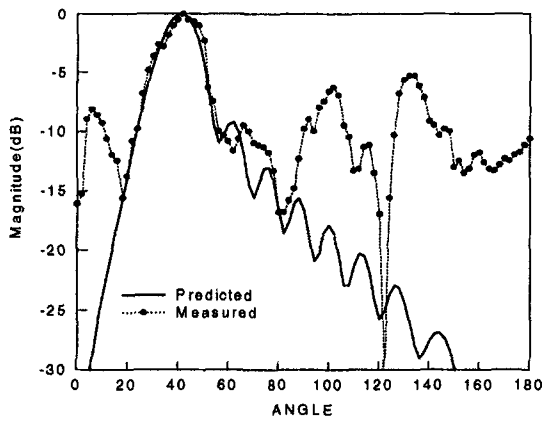

Fig. 9. The H-plane radiation pattern of the asymmetric feeding active leaky-wave antenna measured at 12.78 GHz.

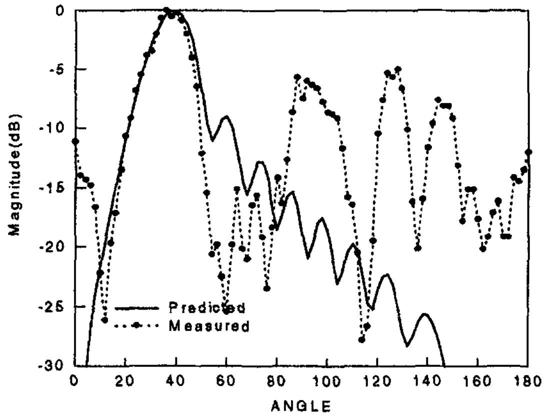

Fig. 10. The H-plane radiation pattern of the asymmetric feeding active leaky-wave antenna measured at 12.98 GHz.

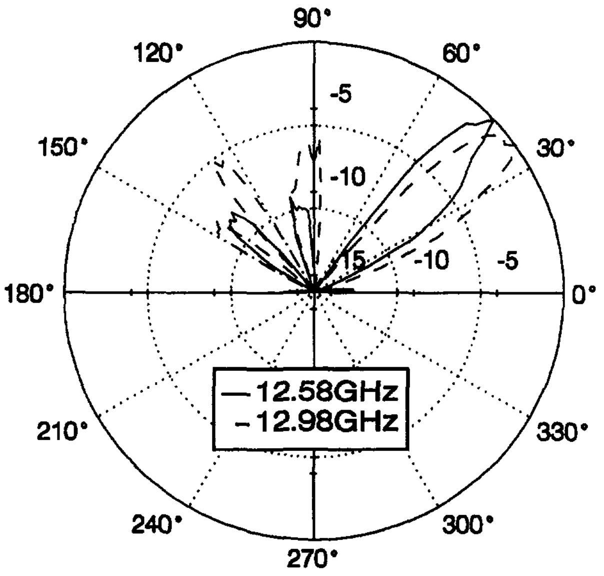

Fig. 11. H-plane (y-z plane) frequency scanned radiation patterns with polar chart.

IV. Conclusions

A asymmetrically feeding Gunn diode active leaky-wave frequency scanning antenna has been developed. This is a prototype of frequency scanning antenna using two terminal device, which is demonstrated in Ku band. By tuning the varactor DC bias, beam-scanning control of close to 15° is achieved. The measured beam-scanning angle agrees well with the predicted data. The operating frequency and tuning bandwidth are mainly limited by the device performance of the Gunn diode and varactor diode. In our active leaky-wave antenna, the first higher order mode can be successfully excited by asymmetrically feeding. The present results of Gunn-diode-type frequency scanning antenna show that it can be easily scale up to operate in the millimeter wave region by using two-terminal devices, such as Gunn diode, IMPATT diode, tunnel diode and resonant tunneling diode etc.... The circuit offers a small, simple, light weight, low cost frequency tunable source for many application. And as the frequency increases, it can be easily implemented for monolithic circuit integration. According to these achievement of single frequency scanning antenna, the goal of two-dimensional scanning array may attain.

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