A Novel Two-Beam Scanning Active Leaky-Wave Antenna

Chien-Jen Wang, Christina F. Jou, and Jin-Jei Wu

***Abstract*— A novel two-beam scanning active leaky-wave antenna (LWA) has been developed. This LWA with a two-terminal feeding microstrip line structure is integrated with a varactor-tuned X-band high-electron mobility transistor (HEMT) voltage-controlled oscillator (VCO). The signal of the VCO is injected via a T-divider into the radiating element. To excite the first higher order mode, the designed antenna is fed asymmetrically at both ends of the microstrip line. Compared with single-terminal feeding leaky-wave antennas, this configuration offers the advantages of dual-direction and suppression of the reflected wave caused by the open end of the radiating element. The scanning angle is steered over a range of 24–46° for the right beam and 128–150° for the left beam. The Effective isotropic radiated power (EIRP) is calculated to be 17.5 and 16.67 dBm at 10.4 GHz, respectively. The measured return loss S_{11} is less than $-$10 dB in the range of 9–11.5 GHz. The transmission coefficient S_{21} indicates that the power radiates into the space.**

***Index Terms*— Leaky-wave antennas, microstrip transmission lines, printed antennas, scanning antennas.**

I. Introduction

Active integrated antennas [1] are widely used in applications such as the mobile system, the satellite communication, and the personal communication system (PCS). Recently, leaky-wave antennas (LWA's) have become popular and there is a growing interest in active leaky-wave antennas used as frequency-scanning elements [2], [3]. Leaky-wave antennas possess the advantages of low-profile, fabrication simplicity, easy matching, narrow beamwidth, and frequency-scanning capability. They are very suitable to be used as active integrated millimeter-wave antennas. Menzel [4] discovered a wider bandwidth phenomenon in microstrip leaky-wave antennas compared to resonator antennas, and Oliner [5] further derived the leaky-wave theory thoroughly. Several studies on leaky-wave antennas have been reported [6], [7].

As we know, leaky-wave antennas without using phase shifters have better beamscanning performance than other antennas such as the patch and the dipole. The propagation of the first higher order mode is operated in the radiation region where most of the guided power gives off in the form of the space wave. Because leaky-wave antennas have the traveling path, the space wave actually corresponds to the radiation at an angle. This angle changes with frequency, hence, the main beam can scan.

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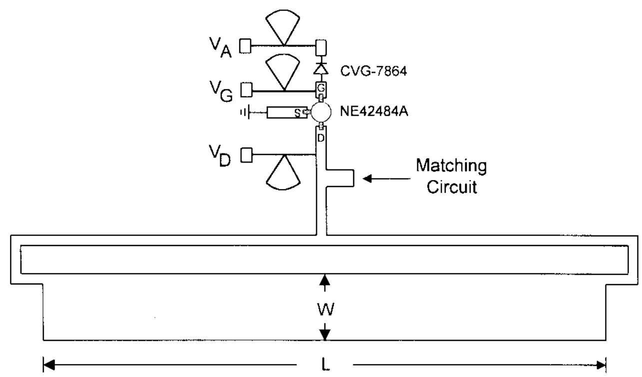

Fig. 1. Configuration of the active two-beam scanning leaky-wave antenna.

In this study, an active phase-shifterless two-beam scanning leaky-wave antenna is developed. A two-terminal feeding LWA is integrated with a varactor-tuned high-electron mobility transistor (HEMT) voltage-controlled oscillator (VCO) (see Fig. 1). The VCO frequencies are tuned by adjusting the varactor dc bias voltage to control the LWA two-beam scanning position. An advantage of our design is the suppression of the reflected wave coming from the open end of a finite-length leaky-wave antenna, although that can also be suppressed with a longer-length approach [4] or an array topology [8]. This two-port design can be thought to offer loads on both open ends of the antenna.

II. Radiation Characteristics of the Leaky-Wave Antenna

The nature of leaky-wave antennas comes from the property of the first higher order mode in the microstrip line. Oliner [9] developed the leakage theory and presented several examples to illustrate its mechanisms, including radiation from waveguide discontinuities into the surface wave and the space wave. In the bond-mode region, the power releases in the form of the surface wave and the quasi-TEM wave; in the radiation region, the energy primarily gives off in the form of the space wave. Leaky-wave antennas are operated in the radiation region, and the normalized phase constant β/k_0 is less than one.

The geometry and coordinate system for the topology of this designed leaky-wave antenna are shown in Fig. 2. Each slot radiates the same field as the magnetic dipole [7], [10] with the equivalent magnetic current density $\boldsymbol{M}_{RS}$ for the

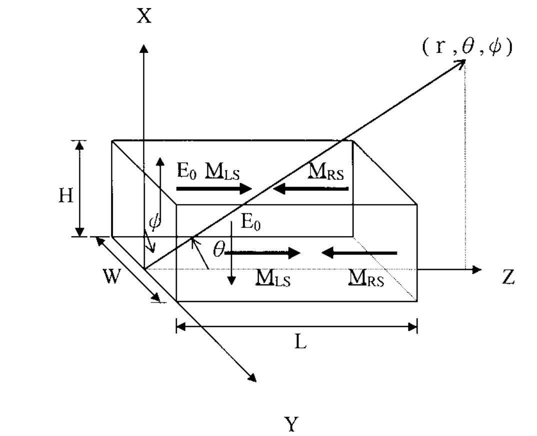

Fig. 2. The geometry and coordinate system for the topology of the two-beam scanning leaky-wave antenna.

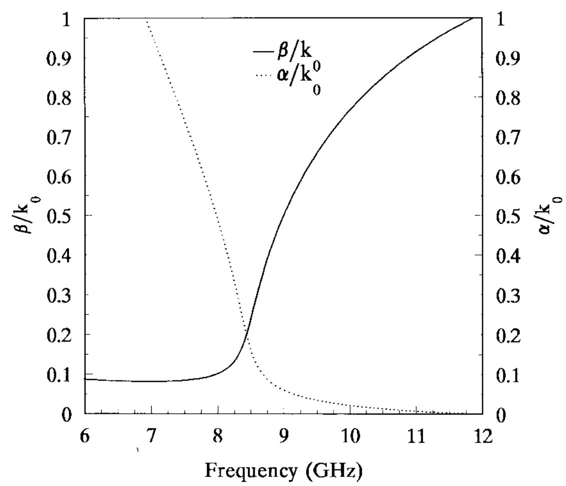

Fig. 3. Normalized complex propagation constants of the first higher mode for the particular microstrip leaky-wave antenna. $H = 0.508$ mm, $W = 11$ mm, and $\varepsilon_r = 2.2$. k_0 is the free-space wave number.

right injection and M_{LS} for the left injection. We employed a rigorous (Wiener–Hopf) solution [11] to find the normalized complex propagation constant $\beta/k_0 - j\alpha/k_0$ of the first higher order mode, where β/k_0 is the normalized phase constant and α/k_0 is the normalized attenuation constant. The variations in β/k_0 and α/k_0 with frequency are plotted in Fig. 3. Moreover, the elevation angle θ between the main-beam direction and the end-fire direction (the Z-axis direction) is calculated using $\theta = \cos^{-1}(\beta/k_0)$. Hence, the angle θ is a function of frequency.

Using the far-field equivalence principle, we derive the radiation pattern of the two-terminal feeding leaky-wave antenna. Under the far-field condition, the equivalent magnetic current densities $\boldsymbol{M}_{RS}$ and $\boldsymbol{M}_{LS}$ are expressed as

$$\boldsymbol{M}_{RS} = \boldsymbol{Z}E_0 e^{-j(\beta - j\alpha)z}$$
$$\boldsymbol{M}_{LS} = \boldsymbol{Z}E_0 e^{j(\beta - j\alpha)z}$$

where E_0 is the arbitrary constant. According to the geometric configuration of the microstrip leaky-wave antenna in Fig. 2, the far-zone electric fields of the right beam are determined using the following:

$$E_r \cong E_\theta \cong 0$$
$$E_\phi = -jE_0 \frac{kHe^{jkr}}{\pi r} \left\{ \sin\theta \left[\frac{\sin(X)}{X} \right] \left[\frac{e^{ZL} - 1}{Z} \right] \right\} \cdot \cos\left(\frac{kW \sin\theta \sin\phi}{2} \right) \quad (1)$$

where the wave number $k = (2\pi/\lambda)$

$$X = kH \sin\theta \cos\phi,$$
$$Z = j(k\cos\theta - \beta) - \alpha.$$

The width W, height H, and length L are dimensions of the leaky-wave antenna. The equation of E_ϕ assumes that there is no reflection from the open end of the waveguide and that the total radiated power leaks in the form of the space wave only. We can derive the far-field electric fields of the left beam in the similar way. The theoretical radiation pattern of the two-beam leaky-wave antenna is then determined by applying the superposition of two electric fields.

III. Design of the Two-Beam Scanning Leaky-Wave Antenna

The design of an X-band active two-beam scanning leaky-wave antenna is presented as follows. As shown schematically in Fig. 1, the unit consists of an HEMT VCO, a matching circuit and a microstrip two-terminal feeding leaky-wave antenna. The HEMT VCO, acting as an active source, is designed by using the negative-resistance method and a commercially available CAD tool HP-EEsof Libra. The RT/Duriod substrate used has the thickness of 0.635 mm and the dielectric constant of $\varepsilon_r = 2.2$. The NE42484A low-noise GaAs HEMT is used as an oscillator device. An ALPHA CVG 7864 GaAs package varactor is used as the tuning varactor for this VCO. The capacitance for the tuning voltage from 1 to 11 V approximately ranges from 11 pF to 0.3 pF according to the data sheet.

The matching circuit is required for the VCO to match the input impedance of the leaky-wave antenna. The operating frequency varies continuously within the tuning range of the VCO. A simple T-type power divider provides the equal power, where each half of the VCO power is injected into the feeding terminal of the antenna.

To excite the first higher order mode within the operating range of frequency, this microstrip leaky-wave antenna is fed asymmetrically and the width W and length L of the radiating element are empirically chosen to be 11 mm and 15 cm, respectively. In this way, the normalized phase constant β/k_0 is less than one and most of the radiating energy leaks in the form of the space wave.

IV. Theoretical and Experimental Results

The measurement setup is shown in Fig. 4. An HP8563E spectrum analyzer and an X-band standard-gain horn antenna with a gain of 16 dB at 10 GHz are used to determine the

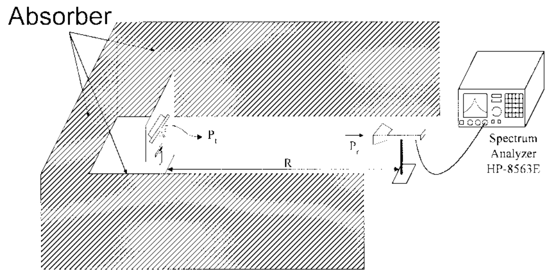

Fig. 4. The measurement setup in this experiment for the active two-beam scanning leaky-wave antenna.

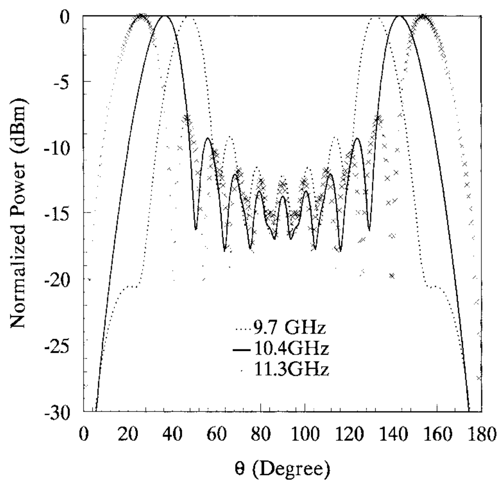

Fig. 5. The theoretical radiation patterns (X-Z plane) of the active two-beam scanning leaky-wave antenna at 9.7, 10.4, and 11.3 GHz.

received power. By adjusting the varactor's bias voltage of the HEMT VCO, the operating frequency can be continuously varied from 9.7 to 11.3 GHz. Using the Friis transmission equation we lump the antenna and oscillator properties into the effective isotropic radiated power (EIRP), as defined in the following [12]:

$$\mathrm{EIRP} \equiv P_t G_t = \frac{P_r}{G_r}\left(\frac{4\pi R}{\lambda_0}\right)^2 \tag{2}$$

where

- P_t the transmitted power from the active leaky-wave antenna;
- P_r the received power of the standard-gain horn antenna;
- G_t the gain of the leaky-wave antenna;
- G_r the gain of the horn antenna;
- R the distance between the horn antenna and the leaky-wave antenna;
- λ_0 the wavelength in the free space.

Under the far-field condition, two measured EIRP levels of 17.5 dBm for the right beam and 16.67 dBm for the left beam are obtained at 10.4 GHz.

The theoretical radiation patterns (see Fig. 5) for this two-beam scanning leaky-wave antenna is determined by taking the data in Fig. 2 into (1). The calculated angles for the right beam are 46.3, 34.3, and 21°, and those for the left beam are 133.7, 145.7, and 159° at three frequencies of 9.7, 10.4, and 11.3 GHz, respectively. Fig. 6 demonstrates a comparison of the theoretical and the measured radiation patterns for this microstrip two-beam leaky-wave antenna operated at 10.4 GHz.

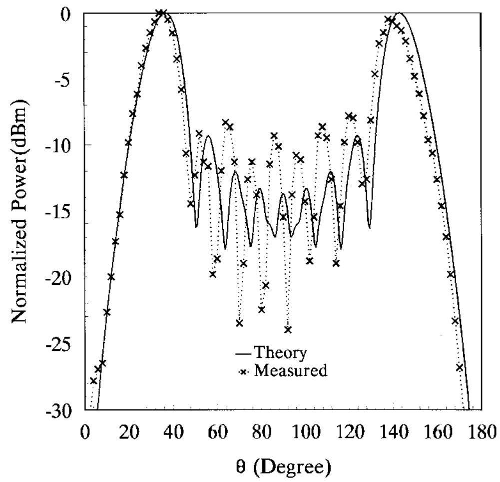

Fig. 6. A comparison of the theoretical and the measured radiation patterns for this microstrip two-beam leaky-wave antenna operated at 10.4 GHz.

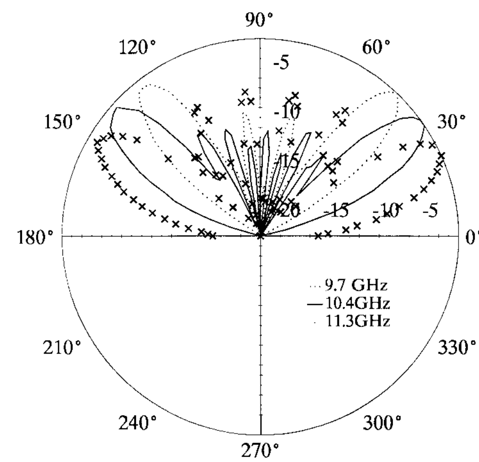

Fig. 7. The measured polar radiation patterns (X-Z plane) of the active two-beam scanning leaky-wave antenna at 9.7, 10.4, and 11.3 GHz.

Fig. 7 plots the measured two-beam scanning radiation patterns for this antenna at three frequencies. The main beams swing up from the end-fire direction (the Z-axis). Notes that at 9.7, 10.4, and 11.3 GHz the measured scanning angles for the right beam are 46, 34, and 24°; meanwhile, the measured angles for the left beam are 128, 140, and 150°, respectively. The total measured scanning angle of 22° for a single beam (in Fig. 7) is close to the theoretical angle of 25.3° (in Fig. 5). The discrepancy of 3.3° may be attributed to the finite length of the leaky-wave antenna.

The return loss S_{11} and transmission coefficient S_{21} of this two-terminal feeding leaky-wave antenna are measured (see Fig. 8) by using an HP8720C network analyzer. The S_{11} is approximately less than -10 dB in the range of 9.5–11.5 GHz. The transmission coefficient S_{21} indicates that the injected power leaks into space. The relative power absorbed (RPA $= 1-|S_{11}|^2-|S_{21}|^2$) in Fig. 8 demonstrates the power efficiency of this antenna. Fig. 9 presents the measured scanning angles of this active two-beam scanning leaky-wave antenna.

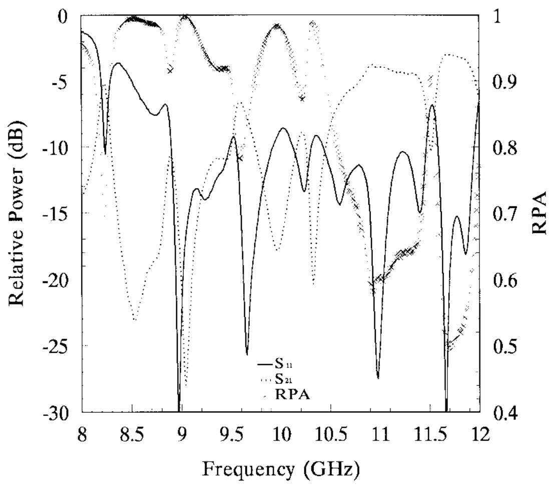

Fig. 8. The measured S parameters and the RPA of the microstrip two-beam scanning leaky-wave antenna.

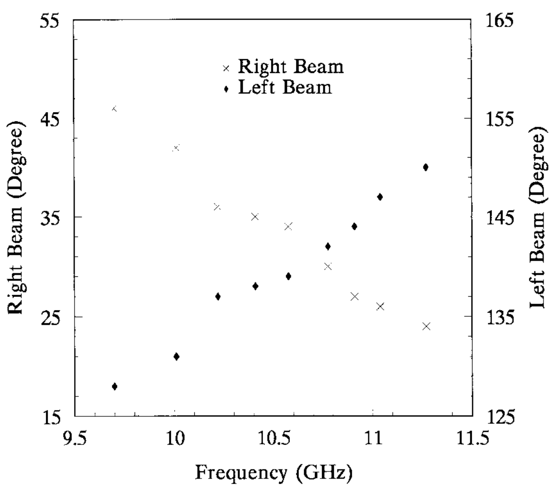

Fig. 9. The measured scanning angles of the active two-beam scanning leaky-wave antenna for different frequencies.

V. Conclusion

A design of a novel two-beam scanning active leaky-wave antenna is proposed and developed. We successfully employ a two-terminal feeding topology to create a dual-beam radiation pattern. With adjusting the bias voltage of the varactor and the frequency of the HEMT VCO, the main beam is controlled. The scanning angle can be steered over a range of 24–46° for the right beam and 128–150° for the left beam. This designed antenna exhibits the properties of large bandwidth and double scanning angle and will be a suitable candidate for applications of the mobile communication and the satellite communication. The circuit can also be easily implemented into a monolithic leaky-wave array module.

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