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Small Size Dielectric Image Linebased Leaky Wave Antenna with 3 H-Shaped Patches

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Abstract—A small size dielectric image line (DIL)-based leaky wave antenna (LWA) is proposed in this paper. Three H-shaped patches as radiation elements are periodically printed on top surface of DIL, which generates infinite higher order space harmonics, and the proposed antenna works at the first order mode. The H-shaped unit cell has high attenuation constant, which leads to power leaking quickly. So high radiation efficiency can be realized with only 3 unit cells. Simultaneously, the open stopband (OSB) is suppressed using H-shaped unit cells to get high efficiency at broadside. The working principle of the proposed antenna is analyzed, and the numerical results validate the theory analysis. Over the operating band ($11.5 \sim 14.6$ GHz), the proposed antenna covers 71° from -41° to 30° (including the broadside) with stable gain (8.7 dBi ~ 10.6 dBi) varying less than 2 dBi. A prototype is fabricated and measured, which has good agreement with simulation results.

1. INTRODUCTION

Since the first LWA consisting of a slotted rectangular waveguide was proposed in 1940s [1], LWAs have received much attention in microwave and millimeters wave field. LWAs have high performances, such as wide impedance band, simple feeding network, high directivity, and frequency beam-scanning property. Compared with phased array antennas [2, 3], LWAs have a simple structure and low price and have been widely applied in radar systems, wireless communication systems, and surveillance systems.

LWAs can be broadly classified into uniform LWA and periodic LWA [4]. A uniform LWA has a uniform guiding structure along the length or a periodic structure with a period much less than a wavelength, which generally works at the fundamental mode of a fast-wave guiding structure (like metallic waveguide and substrate integrated waveguide) [5, 6] Radiation beams of the uniform LWA only cover the forward region above the cutoff (broadside). The periodic LWA is always based on a

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slow-wave guiding structure (like microstrip line, SSPP line and DIL) whose fundamental mode is slow wave [7, 8]. Infinite space harmonics are generated by periodical units along the length of the guiding structure, some of which are in the fast-wave region.

Some recent developments of LWAs have been reported to realized continuous beam scanning from backward region to forward region [9–12]. The composite righ/left-handed (CRLH) LWA is a good way to continuously scan through the broadside [9, 10]. When the CRLH unit is in the balance condition, the OSB of the CRLH LWA can be closed, so beam of the CRLH LWA can be directed at the broadside without degradation. Another good way is to use metamaterials [11, 12]. A ferrite LWA proposed in [11] is a waveguide having an open side filled with an exotic material (ferrite). When the ferrite is biased, multiple modes exist depending on the frequency. The ferrite LWA scans from the backward region to forward region over 5.85 GHz $\sim$ 6.07 GHz. The ferrite LWA has no issue of the OSB because of the uniform structure. A Dirac LWA at terahertz having continuous beam scanning is proposed [12], whose leaky-wave radiates from the interface of a photonic crystal with a Dirac-type dispersion and air. Periodic LWA is able to scan from backward to forward. However, if there is no precautions taken, an OSB effect always occurs at broadside, which leads to very low radiation efficiency over the broadside frequency. A feasible approach to overcome OSB is by utilizing asymmetric unit cell. The OSB at broadside is depressed efficiently by a pair of asymmetry cross-slots that have a quarter of guided wavelength [13]. Asymmetrically modulated Goubau LWAs are proposed to improve the radiation efficiency at broadside [14], which are two kinds of unit cells asymmetrically modulated along transversed and longitudinal directions, respectively.

However, all these designs indicated above have relatively long lengths. When the attenuation constant of the periodic unit cell of periodic LWA is low, the length of the antenna should be long enough in order to realize high efficiency, which will enlarge the antenna size. In this paper, a DIL-based LWA with 3 H-shaped patches is proposed. The proposed antenna has high attenuation constant, which can ensure more than 90% power radiation with only 3 unit cells. The length of the antenna is short about $2.3 \times \lambda$ (λ is the wavelength in the free space at the broadside frequency). The basic guiding wave structure of the proposed antenna is DIL in [15], which is a slow-wave structure. By introducing a periodic set of H-shaped patches, the LWA can operate at $n = -1$ space harmonics in the fast-wave region. The working performance is good with wide scanning region continuously from the backward to the forward. And the peak gain is stable with 1.9 dBi variation.

2. ANTENNA DESIGN

2.1. Antenna Configuration

The structure of the proposed antenna is described in Fig. 1, which is a periodic LWA based on DIL with small size 3 H-shaped patches periodically printed on the top surface of the DIL to realize leaky-wave radiation. The period of H-shaped units is P. Two SMA connectors are connected at two ends of the proposed antenna. One is for excitation input, and the other is loaded with matching impendence. The size of the big ground is $L \times W$. The width and thickness of the dielectric line are W_1 and H_1, and the relative permittivity ε_r of the dielectric line is 10.2. The feeding network is a truncated microstrip line with two capacitive gaps and two inductive metal strips to improve the impendence matching. a and b are the tapered length and width of the truncated microstrip line, respectively. Widths of gap and metal strip are g and s, respectively.

2.2. Operation Mechanism Analysis

The dominant mode of DIL is in slow wave region where no wave radiates even though the structure is open. The proposed antenna is a DIL-based periodic LWA with a set of the H-shaped patches periodically printed on the top surface of the DIL along the transmitting direction (z-axial). Therefore, according to Bloch-Floquet theory, infinite space harmonics are generated, and the phase constant of the nth order space harmonic is given by [13]

$$\beta_n = \beta_0 + \frac{2n\pi}{P} \tag{1}$$

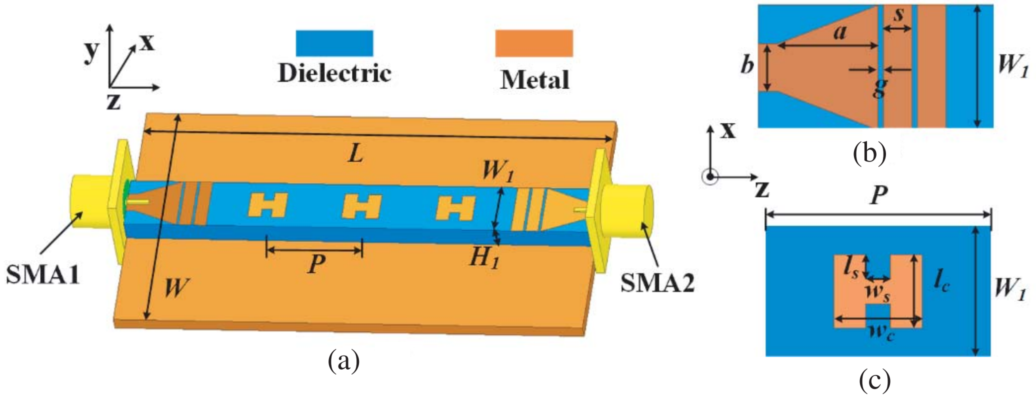

Figure 1. Configuration of the proposed antenna. (a) The overall structure. (b) The feeding network. (c) The H-shaped patch. $L = 54.15$ mm, $W = 40$ mm, $W_1 = 6.25$ mm, $H_1 = 2.52$ mm, $P = 10.75$ mm, $w_c = 4.2$ mm, $l_c = 3.5$ mm, $w_s = 1.2$ mm, $l_s = 1$ mm, $a = 5$ mm, $b = 2.4$ mm, $g = 0.3$ mm, $s = 1.5$ mm.

where β_0 and β_n are the phase constants for the fundamental and nth order space harmonics, respectively. n is an integer.

The dispersion diagram of a unit cell is shown in Fig. 2. The dominate mode β_0 of the DIL is in the slow-wave region. Because of introducing discontinuous units with a certain period, the first space harmonic ($n = -1$) is in the fast-wave region where the power can radiate out in the free space. At 12.9 GHz (f_A), the beam of the proposed antenna directs on the broadside ($\beta_{-1} = 0$). Before 12.9 GHz, the beam scans in the backward ($\beta_{-1} < 0$). After 12.9 GHz, the beam scans in the forward ($\beta_{-1} > 0$).

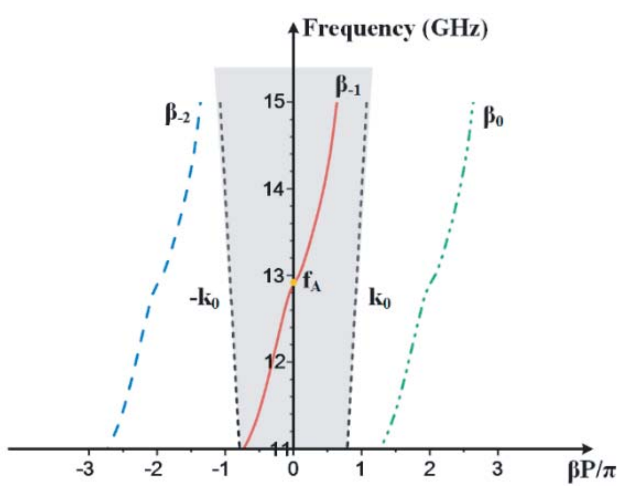

Figure 2. Dispersion diagram of the unit cell.

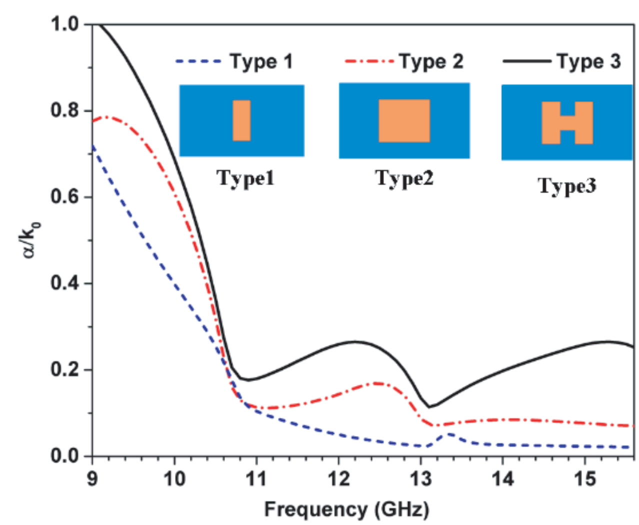

Figure 3. Normalized leakage rate.

The beam direction of LWA is connected with the rate of the phase constant in guiding structure and the wavenumber k_0 in free space. The proposed antenna works at $n = -1$ order mode. The phase constant β_{-1} of the $n = -1$ space harmonic can be derived by phase constant β_0 of the fundamental mode and the period p of unit cells from formula (1). So the beam direction of the proposed antenna is determined by the phase constant β_0 of the fundamental harmonics and the period p.

$$\theta = \arcsin\left(\frac{\beta_{-1}}{k_0}\right) = \arcsin\left(\frac{\beta_0}{k_0} - \frac{2\pi}{pk_0}\right) \tag{2}$$

where θ is the beam direction with respect to y-axis. When the size of the DIL is fixed, the broadside beam at a frequency point of interest will be obtained by changing the period p of unit cells.

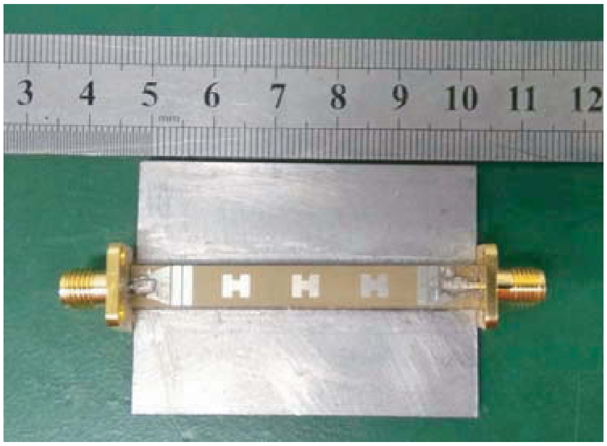

Figure 4. Photo of the proposed antenna.

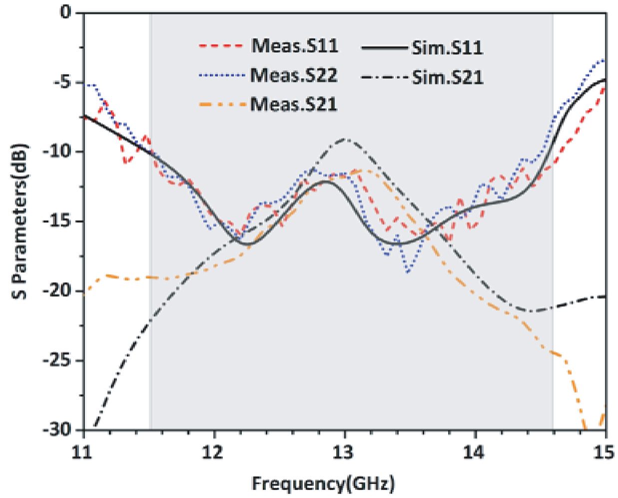

Figure 5. Measured and simulated S parameter.

Figure 3 shows the normalized leakage rates for 3 types of unit cells. The power of LWA is leaked from discontinuous units. The parameter of the attenuation constant α represents the power radiation situation of LWA. So, the attenuation constant of the proposed antenna in relation to the size and shape of the unit is analyzed. The attenuation constant is increased by expanding size of the radiation element from comparison between the trip unit (Type1) and the rectangular patch unit (Type2). Two slots are cut in the patch of Type2 to form an H-shaped patch of Type3, in which the attenuation constant is improved obviously.

3. ANTENNA DESIGN AND SIMULATION RESULTS

The proposed antenna is simulated with commercial software HFSS, then manufactured and measured. A photo of the proposed antenna is in Fig. 4. The proposed antenna is a small size DIL-based LWA with 3 H-shaped patches periodically printed on the top surface of DIL. The simulated and measured S parameters of the proposed antenna are described in Fig. 5. The structure of the proposed antenna is totally symmetrical on the z-axis. Over the working frequency from 11.5 GHz to 14.6 GHz, the return loss is less than -10 dB, and the measured results have good agreement with the simulated ones. The band around 13 GHz is obviously raised due to the OSB effect, but it is still less than -10 dB. The simulated and measured S_{21} are less than -8 dB and -11 dB.

The normalized radiation patterns of the proposed antenna are shown in Fig. 6. The beam scans from -41° at 11.5 GHz to 30° at 14.6 GHz, including the broadside direction at 13 GHz. The measured results are in agreement with the simulated ones. As shown in Fig. 7, the peak gains over the working frequency band are stable from 8.7 dBi to 10.6 dBi. However, the measured results are a little lower than the simulated ones because of the dielectric attenuation, manufacture tolerance, and test tolerance. The scanning angles of the proposed antenna calculated by Eq. (2), simulated by HFSS, and measured in the microwave anechoic chamber are also given in Fig. 7. The scanning angles calculated by HFSS and formula (2) are overall coincident with each other. The measured results have good agreement with the simulated ones, which testify the theory analysis.

Table 1 illustrates the comparison between the proposed DIL-based LWA and previous works. [16] is a DIL LWA application in millimeter. The novelty of antenna is that it is able to avoid OSB phenomenon at broadside by using pairs of copper discs at 90° phase quadrature. However, it has really long length and low efficiency. A wide scanning region DIL LWA is proposed with about 8.6λ [17], and an aperture-coupled microstrip array antenna fed by DIL is proposed in [18]. The antenna can only operate at forward region. Because of the radiation element of the antenna is a rectangular patch, the length of the antenna is relatively short with 6.3λ. The proposed antenna has the smallest length with

Table 1. Comparison between proposed antenna and previous works.

Ref.	Band (GHz)	Length ($\lambda = C/f$)	Angle (deg)	Max Gain (dBi)	Total Efficiency $(1 - \lvert S_{11}\rvert - \lvert S_{21}\rvert) \times 100\%$
[16]	$60 \sim 75$	23.9λ	$-10° \sim 15°$	–	50%
[17]	$11.8 \sim 17$	8.6λ	$-65° \sim 25°$	$9.9 \sim 15.5$	–
[18]	$9.76 \sim 10.65$	6.3λ	$-25° \sim -5°$	13.5 @10.55 GHz	–
Pro.	**$11.5 \sim 14.6$**	**2.3λ**	**$-41° \sim 30°$**	**$8.7 \sim 10.6$**	**84%**

high efficiency and is capable of continuous scanning from backward region to forward region. Moreover, the realized gain of the proposed antenna keeps stably varying less than 2 dBi.

4. CONCLUSION

In this paper, a small size DIL-based LWA with 3 H-shaped patches is proposed. The dominate mode of the DIL is perturbed by infinite space harmonics generated by 3 H-shaped patches periodically printed on the top surface of the DIL with a big ground. The proposed antenna works with $n = -1$ order mode in the fast-wave region. The length of the proposed antenna is about $2.3 \times \lambda$ at 13 GHz. The H-shaped radiation element has high attenuation constant, which leads to high efficiency with only 3 unit cells. The antenna has good radiation performance with wide scanning region and stable gain. Over the working band, the beam of the proposed antenna can scan from the backward with $-41°$ at 11.5 GHz, to the forward with $30°$ at 14.6 GHz, including the broadside at 13.3 GHz. The peak gain over the working band has small variation from 8.7 dBi to 10.6 dBi. The antenna is easy to design. The size is small, and the structure is simple.

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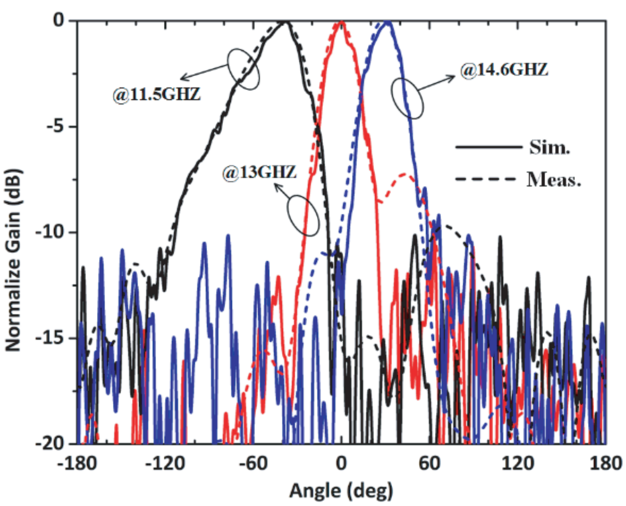

Figure 6. Measured and simulated normalized radiation patterns.

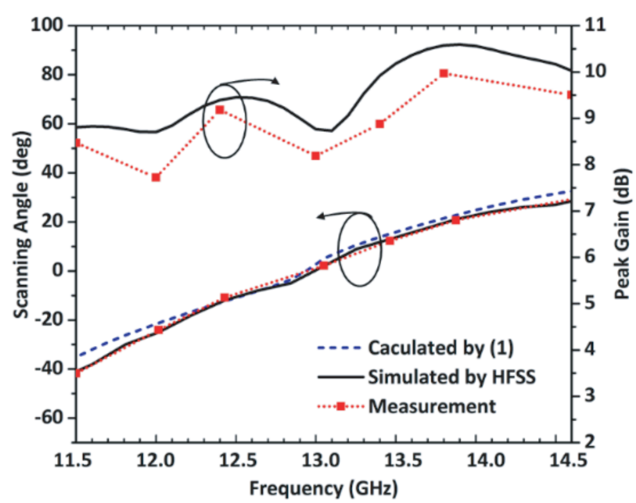

Figure 7. Peak gain and scanning angle with frequency variation.

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