Substrate Integrated Waveguide Based Compact Periodic Leaky-Wave Slot Antenna With Improved Beam Scanning using 〖TE〗 _10^y mode

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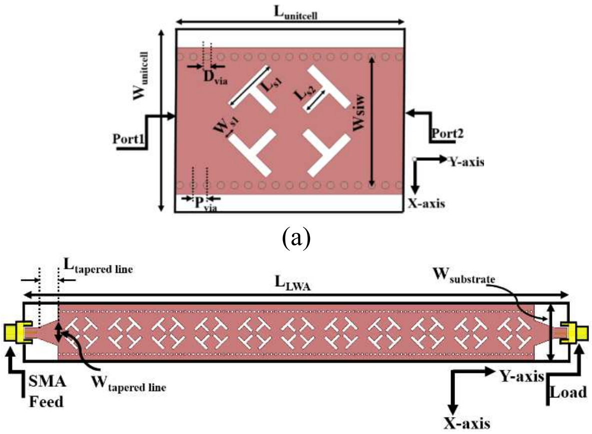
***Abstract*—In this work, leaky-wave radiation for wide and consistent beam scanning along with broadside radiation is proposed. Leaky-wave antenna (LWA) based on planar waveguide technology (substrate integrated waveguide) is designed using periodic loading of a new type of rectangular slot combination that is capable of beam scanning angle enhancement through broadside. This proposed compact leaky-wave antenna shows high impedance bandwidth of 37% and directive beam scanning in the leaky (fast) wave region $(n = -1)$ over the frequency band of 8.84 GHz to 12.9 GHz. The open stopband (OSB) problem is eliminated by combining four T-shape slots and rotating at $+45^0$ and -45^0 with respect to the longitudinal axis of the antenna for getting a better impedance matching. The scanning beam position changes from -74^0 to $+15^0$ while the frequency sweep from 8.84 GHz to 12.9 GHz, the return loss of the antenna is seen to be below -10 dB for the complete frequency band, with a minimum value of -50 dB. The characteristics of the designed prototype in the form of scattering parameters, radiation pattern, and gain are given.**

Keywords*—*beam scanning, dispersion diagram, open stopband (OSB), periodic leaky-wave antenna (PLWA)

I. Introduction

The development of modern wireless communication demands high-performance multi-standard antennas. These antennas must have a low profile, be lightweight, and be easy to integrate facility with other planar devices. One dimensional periodic leaky-wave antenna has the potential of fulfilling all the above advantages. A Leaky-wave antenna is a traveling wave (non-resonant) antenna, which has an opening along the length through which electromagnetic waves are coupled into free space. Due to periodic openings along the waveguide, complex wave generated, which travels with attenuated amplitude along the length of the guide. Change in phase velocity with frequency causes the radiated beam to scan with frequency [1]. Leaky-wave antenna using non-planar waveguide has its existence since 1940 [2]. But due to fabrication complexity, high cost, and is bulky in nature, leaky-wave antenna (LWA) using planar technology finds much attention. Planar LWAs gain huge attention in the late 70s, after Ermert [3] and W. Menzel [4]. Thereafter, A. A. Oliner gives significant analysis about the radiation characteristics of microstrip LWA [5]-[7]. Recently, planar waveguide or substrate integrated waveguide (SIW) based leaky-wave antennas are gaining close attention because of their significant advantages of wide beam scanning angle, low-cost manufacturing, easy integration, and low-profile [8]-[10]. Post wall waveguide/planar waveguide technology has been used by many researchers for designing several kinds of LWA, which has the potential of beam scanning from backfire to end-fire through broadside [12].



(a)

(b)

Fig. 1. Designed geometry of (a) unit cell of the proposed LWA (b) complete LWA with feed

For example, in [11], vias are arranged periodically to excite leaky modes. J. Liu *et al* uses TE_{10} mode of SIW and incorporate transverse slots [12] and H-type slots [13] for broadside to forward end-fire beam scanning. Some other PLWA based on SIW technology has been proposed for the broader angle of scanning with enhanced gain characteristics [14]. There are many more LWA antennae showing circular polarization [15] and multiband operation [16]-[17] using SIW technology. Radiation in LWA occurs due to the first-order space harmonics $(n = -1)$ [5], which allows one single beam to scan from backfired to end fired continuous scanning with frequency. Recent advancement in metamaterial transmission line has further accelerated research in this area. In [18], polarization-agile antenna application is proposed based on a combination of SIW and composite right/left-handed (CRLH) transmission lines. Another CRLH inspired planar waveguide-based LWA is proposed for circular polarization [20]. In above all the cases, the problem of high insertion loss, design complexity, and open stop band effects still prevails. Due to these reasons, the antennas which find widespread application in space satellite and imaging, with compact size and high efficiency, still need to be realized.

Another very important point to be taken care of while designing an efficient LWA is symmetric beam scanning through the broadside. In [24], using reconfigurable partially reflecting surface (PRS) continuous beam scanning of $-15^o\ to +15^o$ is proposed. In 2012 by using a centre feed Fabry Perot LWA is proposed for electronic beam scanning from $-25^o\ to +25^o$ angle [25]. Another technique of achieving symmetric scanning has been proposed in [26], where the author has used the interdigital capacitor for designing composite right/left-handed leaky-wave antenna for consistent beam scanning range of $-70^o\ to +70^o$.

TABLE I. DETAILED DIMENSIONS OF UNIT CELL (IN MM)

$L_{unit\ cell}$	$W_{unitcell}$	L_{S1}	W_S	L_{S2}	D_{via}	P_{via}	W_{SIW}
16	20	6	0.8	3.3	0.8	1.6	14

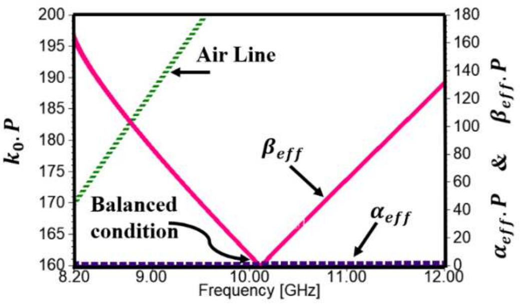


Fig. 2. Dispersion curve of the designed unit cell

With the aim of consistent beam scanning from backfire to forward end-fire along with the broadside, we have designed an LWA by using a novel slot configuration. Here we have taken four longitudinal and four transverse slots. These slots are then rotated with respect to the axis of the planar waveguide. These eight slots look like four T-shaped $+45^0$ and -45^0 rotated slots, having the potential of a wide range of beam scanning. In this work, periodic loading of slots in the substrate integrated waveguide environment is proposed. Using this novel slot combination, we have tried to eliminate the open stopband (OSB) problem and achieve a wide range of beam scanning through the broadside without gain deterioration. The proposed radiator has large impedance bandwidth and the main directive beam, which scans over a wide range of angles with the frequency. This antenna uses a very simple microstrip feeding technique. After going through the open literature, we found that this kind of slot-loaded periodic leaky-wave antenna (PLWA) is the first one in this class.

In this paper, we have proposed a novel design and analysis of one-dimensional periodic loaded slot LWA based on SIW technology. Here, we have tried to eliminate the problem of open stopband by optimizing the dimensions of slot, period of the unit cell, and position of slots on the top layer of the planar waveguide. The unit cell of the proposed antenna contains four T-shaped rotated slots. These slots are designed near center frequency to perturb the surface current. This will lead to a small leakage constant and a high directive beam. Thereafter slots position and period of a unit cell are so well optimized that it matching between each unit cell is achieved. This complete matching between all unit cells leads to the elimination of the OSB problem. By optimizing the slot dimension and position as well as the period of the unit cell, a balanced condition is achieved for complete beam scanning from backward-to-forward direction through broadside. In the class of narrow beam antenna, using this type of combined slot is the first one. Dispersion analysis of designed unit cell and radiation behavior of the designed periodically loaded slot leaky-wave antenna is investigated with the help of a full-wave electromagnetic simulator. After this the proposed LWA will be fabricated and testing will be conducted for experimental validation in our laboratory. We will further elaborate more properties of the designed antenna by incorporating side lobe level, cross-polarization level, and surface current density. Thereafter, we will give the comparison chart in the form of state-of-art of some of the studied literature in this paper already with our designed LWA prototype.

II. LEAKY-WAVE ANTENNA ANALYSIS AND DESIGN

A. Unit cell analysis

The complete characteristics of the LWA antenna can be predicted by analysing the dispersion graph of a unit cell. The unit cell of the proposed PLWA is shown in Fig. 1 (a), and the complete schematic of the proposed antenna with forward to backward through broadside scanning capability is shown in Fig. 1 (b). The periodic leaky-wave antenna consists of a series of unit cells with a period of 16 mm. Due to the periodic loading of the planar guide phase constant (β_{yn}) varies from left-handed region to right-handed region with the change in frequency.

First, we have designed a planar waveguide commonly known as SIW. For this, first, we choose the substrate Rogers RT/duroid5880 ($\varepsilon_r = 2.2\ and\ tan\delta = 0.0009$). After this, both the top and the bottom surfaces are coated with metallic copper and arrays of metallic vias ($D_{via} = 0.8mm\ and\ P_{via} = 1.6mm$) on both sides along with the structure as the perfect electric wall with via diameter ($D_{via} = 0.8mm$) and pitch ($p_{via} = 1.6mm$). A tapered microstrip line is used to feed the designed transmission line so that it works in TE_{10} mode. After that, for a wide range of scanning, we have loaded four T-shaped slots. These slots are tilted and dimensionally optimized to get perfect impedance matching with the balanced condition at the centre frequency of 10 GHz for X-band (8 GHz-12 GHz). The optimized dimension of the unit cell is presented in Table. 1.

For a leaky-wave generation, the propagation constant along its aperture must be complex in nature $\left(k_{yn} = \beta_{yn} + j\alpha_y\right)$ [22]. The propagation constant of conventional periodically loaded leaky-wave antenna for n^{th} harmonics is given by [24]:

$$k_{yn} = \beta_y + \frac{2n\pi}{p} \tag{1}$$

where, k_y is the wavenumber of the dominant mode, n represents the n^{th} space harmonics and p denote the periodicity of the unit cell.

In this proposed designed leaky (fast) wave $\left(\beta_{yn} < k_0\right)$ is excited by periodic disturbance of fields/currents along the length of the planar guide. The complex leaky-wave contribute forward radiation $\left(\beta_y > 0\right)$ and backward radiation $\left(\beta_{yn} < 0\right)$. For a periodic LWA, the direction of the main beam for first-order space harmonics $(n = -1)$ i.e., Fast wave region $\left(-k_0 < \beta_{yn} < k_0\right)$is calculated by using the following relation [22]:

$$\theta(f) = sin^{-1}\left(\frac{\beta_y(f)}{k_0(f)}\right) \tag{2}$$

where θ is the angle from the longitudinal axis and k_0 denote the free space wavenumber at the designed frequency.

The dispersion (phase constant with frequency) and leakage (alpha with frequency) characteristics of the designed unit cell are shown in Fig. 2. This dispersion diagram is plotted using simulated results of scattering parameters using the following equations [21].

$$\beta_{eff} = \left(\frac{1}{p}\right)\left|Im\left(cosh^{-1}\left(\frac{1 - S_{11}S_{22} + S_{21}S_{12}}{2S_{21}}\right)\right)\right| \tag{3}$$

$$\alpha_{eff} = \left(\frac{1}{p}\right)\left|Re\left(cosh^{-1}\left(\frac{1 - S_{11}S_{22} + S_{21}S_{12}}{2S_{21}}\right)\right)\right| \tag{4}$$

The balanced condition of zero phase constant is found at 10.16 GHz. The airline $\left(k_0 = \omega\sqrt{\mu_0\varepsilon_0}\right)$ is shown with the dashed line. The backward radiation ranges from 8.84 GHz to 10.1 GHz, whereas the forward radiation starts from 10.16 GHz to 12.9 GHz. The complete dispersion diagram of the unit cell is separated into three different regions: region 1 ($f < 8.84\ GHz$) is left-handed guided wave region, and region 3 ($f > 12.9\ GHz$) right-handed guided wave region. Region 2 ($8.84\ GHz < f < 12.9\ GHz$) the leaky-wave region with ($\beta < 0$) defines backfire radiation and ($\beta > 0$) defines forward radiation. The transition region ($\beta = 0$) occurs at the centre frequency of 10.16 GHz.

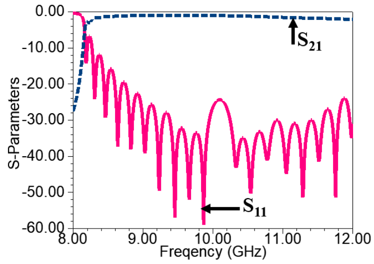


Fig. 3. Scattering parameters of proposed LWA versus frequency

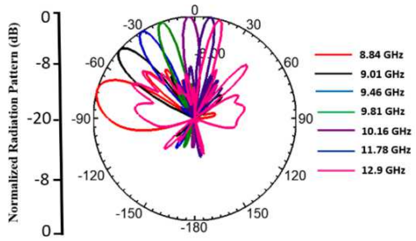


Fig. 4. Normalized H-plane radiation pattern (in dB) of the proposed LWA

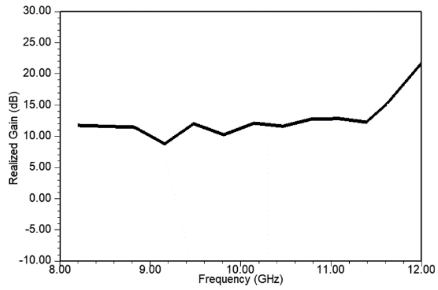


Fig. 5. Realized gain and directivity versus frequency

The leakage constant (α) of the unit cell is negligibly small throughout the operating range (8.4 GHz to 11.74 GHz). The periodic loading of the slots is mainly responsible for a wide range of scanning by introducing phase delay in this designed planar waveguide.

B. Scattering Parameters

The simulated scattering parameters in the form of reflection coefficients ($|S_{11}|$) and transmission coefficient ($|S_{21}|$) versus frequency are shown in Fig. 3. We can observe that in the complete operating band $|S_{11}|$ peaks at 10.16 GHz. Although we are getting a peak at transition frequency (10.16 GHz), we achieve broadside radiation.

C. Radiation pattern

The radiation characteristics of tilted T-shaped slots loaded PLWA prototype is presented in Fig. 4. The main radiating beam scan continuously from -75^0 $(at\ 8.84\ GHz)$ to $+15^0$ $(at\ 12.9\ GHz)$ along with broadside radiation $(at\ 10.16\ GHz)$. The simulated beam scanning range is found to be 90^0 in the complete operating band of frequency in the H-plane $(y - z\ plane)$. In this paper we didn't achieve symmetric beam scanning through broadside $(\theta = 0^o)$. This we can accomplish by using two techniques first, by incorporating asymmetry in the unit cell design so that we can independently control the distributed capacitances and inductances along the leaky-wave structure, and second by modulating the reactance's of the leaky line.

D. Realized gain

The realized gain as a function of the frequency of the designed periodically loaded slot leaky-wave antenna is shown in Fig. 5 for the complete operating band (8.84 GHz to 12.9 GHz). The peak realized gain of the designed antenna is 21 dB with a gain variation of 8 dB between 11.95 GHz and 11.38 GHz. This variation in gain should be minimized for stable gain characteristics.

III. CONCLUSION

In this work, a novel slot-loaded periodic leaky-wave antenna (PLWA) having potential of continuous full space beam scanning from left hand to right hand through broadside is presented. The proposed leaky-wave antenna uses TE_{10} mode of SIW. The proposed antenna has been realized by four T-shaped tilted slots on the top layer of the substrate. The overall antenna is compact in shape with continuous beam scanning $(from -74^0\ to +15^0)$ of 89^0 through broadside in the H-plane (y-z plane) when the operating frequency changes from 8.84 GHz to 12.9 GHz. The open stopband effect is completely eliminated by designing a compact slot-loaded unit cell. The advantages of the newly designed antenna prototype in terms of scanning range, gain characteristics over the wide range of frequency is highly significant. Our designed antenna is compact in size and broad bandwidth of 37% as compared with the recently designed PLWA using transverse and longitudinal slots. We will definitely elaborate this work with new acceptable and more detailed results very soon.

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