Substrate Integrated Waveguide Based One Dimensional Leaky-Wave Antenna with Enhanced Scanning Range and Consistent Gain Characteristics

Ravi Anand
Dept. of Electronics and Communication Engineering
National Institute of Technology, Rourkela
Rourkela, India
ravi.ravi.anand@gmail.com

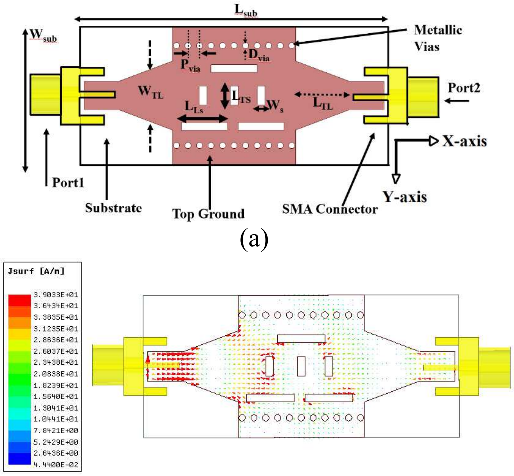
Sudipta Maity
Dept. of Electronics and Communication Engineering
National Institute of Technology, Rourkela
Rourkela, India
sdpt123maity@gmail.com

***Abstract*—In this paper, a new approach of designing single layer Substrate Integrated waveguide (SIW) based planar leaky-wave antenna for X-band (8-12 GHz) application is presented. The beam scanning range of the final prototype is found to be $85^o(-60^o$ to $25^o)$. This design consists of a new type of unit cell, which is the combination of three transverse and three longitudinal rectangular slots. These slots are arranged periodically. The periodic loading of these slots incorporates capacitive coupling, which is further responsible for a wide range of scanning. The designed antenna is showing a high impedance bandwidth of 40% (9.74-14.63 GHz) and a directive beam in the leaky-wave region. The most challenging task for a leaky-wave antenna is continuous beam scanning from the backward-to-forward with a broadside radiation patterns. In this paper, the designed LWA achieves this task with a significant reduction in side lobe level (SLL) and cross-polarization. The final prototype with directive beam and stable gain characteristic in the desired frequency band is designed. It is found from the radiation pattern that SLL for all the frequency is below -15 dB and cross polarization level of -18 dB. A thorough analysis of dispersion diagram of the unit cell and radiation characteristics using fundamental TE_{10} mode of SIW is conducted using a full-wave EM-simulator.**

Keywords— beam scanning, dispersion diagram, leaky-wave antenna (LWA), open stopband (OSB), substrate integrated waveguide

I. INTRODUCTION

For more than forty years compact flat antennas are the subject of interest for many researchers and engineers. These types of antennae generally are of low cost and easy to fabricate, which can be suitable for integration with other microwave circuits. Also, due to its low profile and planar, it can be placed on different shapes of bodies. With the advancement of wireless communication, the requirement of high efficiency with multi-standard antennas gains high attention. Leaky-Wave antenna (LWA) is one of the most popular candidates satisfying the above requirements. In 1978, W. Menzel introduced a planar non-resonant antenna (Travelling wave antenna) capable of frequency scanning [1], which is further explained more elaborately by A. A. Oliner in 1986 [2]. A leaky-wave antenna continuously radiates along its length as the wave progress. Due to the periodic openings, the modified waveguide supports complex (leaky) wave with attenuation along the length of the guide [3]. LWA can be designed for both backward-to-forward scanning using $n = -1$ space harmonic [4]. Periodic LWA suffers from a problem of open band stop at broadside where its radiation characteristics deteriorate [5]. A quarter-wave transformer, or alternatively a matching stub, is introduced into the unit cell of the antenna, which is capable of suppressing the open stopband at the broadside [6]. These antennas have high potential features of beam-scanning with the frequency change. They also have many features like a simple feeding structure for reducing the design complexity. Due to these, they can be used for the application in satellite and missile systems.



(a)

(b)

Fig. 1. (a) The design of unit cell for complete beam scanning (b) the surface current distribution of the proposed antenna unit cell

Recently, the designing of a LWA system for high-frequency range has gained a huge pace after the proposal of planar millimeter and microwave waveguide commonly known as substrate integrated waveguide (SIW). Due to its excellent features like high Q-factor, low-loss, easy to fabricate and highpower handling capability antenna systems are developing for high microwave and millimeter-wave frequencies [7]-[9]. For the achievement of a broader scanning range this laminated waveguide structure is in frequent use in recent years. Leakage from the periodic gaps of vias [10], using a long slot [11], array of inclined slots [12], half mode characteristics with array of transverse slots [13] are most commonly used for leaky wave radiation. Due to the high directive beam and high-frequency scanning capability LWA using SIW have gained high attention for microwave and millimeter wave range [14].

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

$L_{unit\ cell}$	W_{sub}	L_{Ts}	W_{Ts}	L_{Ls}	W_{ls}	D_{via}	P_{via}	$P_{unitcell}$
16	18	3	1	4	1	0.8	1.6	20

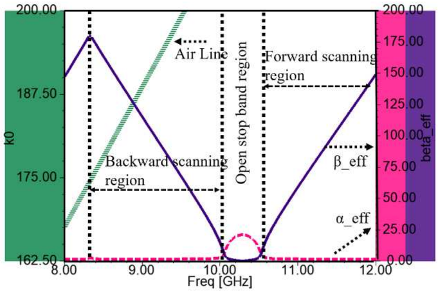
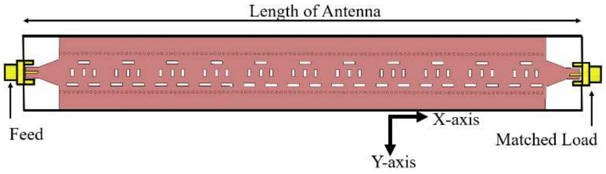


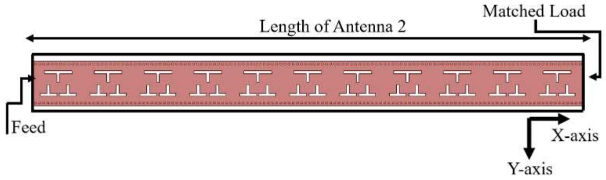
Fig. 2. Dispersion diagram of the unit cell

With all these many more periodic LWA based on SIW has been proposed for forward beam scanning [15], multi-standard application [16]. There is also one class where LWA uses the composite right / left-handed properties of the unit cell to scan completely through broadside [18]-[21].

To overcome the problem of broadside scanning, we propose a very simple and novel designed LWA using a planar waveguide structure, which is further loaded with six rectangular slots. Those slots are arranged in the transverse and longitudinal directions. The longitudinal slots are arranged periodically for adding capacitive loading. The capacitive loading of slots however cannot eliminate the problem of OSB. Therefore, additional longitudinal slots are incorporated for providing inductive loading. These combined slots configurations are creating a balanced condition for continuous forward-to-backward scanning through broadside. This newly designed SIW-based LWA can scan forward-to-backward through broadside. Although dispersion characteristics are showing good results for complete scanning the SLL and cross-polarization are significantly high. These problems are reduced by designing another prototype of LWA.



(a)



(b)

Fig. 3. Complete schematic of (a) LWA 1 (b) LWA 2

II. LEAKY-WAVE ANTENNA DESIGN AND ANALYSIS

A. Unit cell and leaky mode analysis

The basic building block of any LWA is designing a unit cell. The design of the unit cell using a planar waveguide is shown in Fig. 1(a). The detailed dimensions of the unit cell are shown in Table 1. In this design, the substrate is chosen Rogers RT/duroid5880 ($\varepsilon_r = 2.2$ and $tan\delta = 0.0009$). After this, both the top and the bottom surfaces are coated with copper and metallic vias on both sides along the structure as the perfect electric wall with via diameter ($D_{via} = 0.8mm$) and pitch ($p_{via} = 1.6mm$). In this unit cell, six rectangular slots are loaded symmetrically. The height (L_{Ts}) and width (w_s) of the transverse slots are kept identical for additional change of phase. After this full-wave analysis of the unit cell is performed using EM simulator ANSYS HFSS 18.0.1.

It is known that a long periodic structure can support n number of space harmonics [3], which arises due to the n number of periods. The leaky-wave radiation in PLWA (Periodic Leaky-Wave Antenna) originates due $n = -1$ space harmonics, whereas the dominant mode supports slow-wave $\beta > k_0$ [14]. These first-order harmonics provide one single main beam which can radiate from backward to forward direction. The most important relation between phase constant and period of the structure is given by [14]

$$\beta_n = \beta_0 + 2\frac{n\pi}{d} \qquad (1)$$

where, d represents the period and β_0, is related to the fundamental mode phase constant. As we know from [14] for generating a single main beam $n = -1$ space harmonic is needed, so as fast wave ($\beta_n < k_0$) is generated.

In periodic LWA the main beam direction is given by

$$\theta_m(\omega) \approx sin^{-1}\left(\frac{\beta_{-1}(\omega)}{k_0(\omega)}\right) \qquad (2)$$

where, θ_m is the maximum radiation angle measured in the broadside direction [14].

The effective attenuation (α_{eff}) and effective propagation constant $(\beta_{eff})$of the designed unit cell are plotted using the following equations [26].

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

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

where, p is the period of the unit cell.

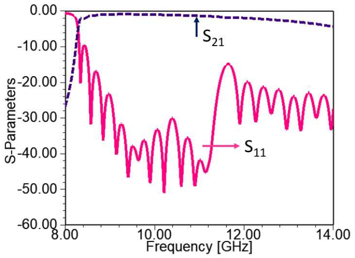
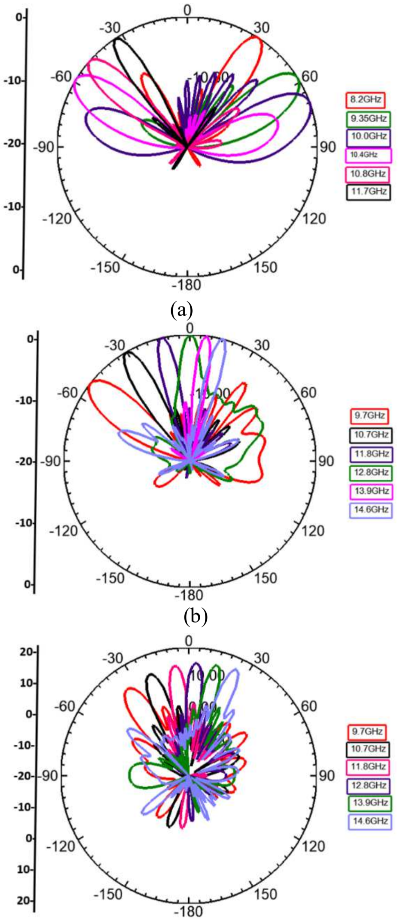


Fig. 4. Simulated reflection and transmission coefficient vs frequency



(a)

(b)

(c)

Fig. 5. Normalized radiation pattern of (a) LWA 1 and (b) LWA 2 (c) E-Plane radiation pattern showing a consistent gain of 15 dB in the operating range.

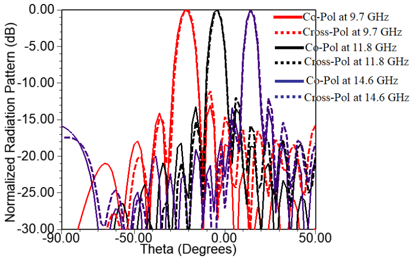


Fig. 6. Simulated normalized radiation (co and cross) pattern of the proposed LWA2

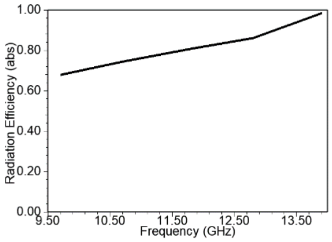


Fig. 7. LW Antenna 2 Efficiency versus frequency

B. *Dispersion Analysis and Antenna Optimization*

The dispersion diagram of the slot-loaded planar waveguide is shown in Fig. 2. From the dispersion diagram, it is very clear that one radiation band is achieved in which forward-to-backward scanning is possible with one-stop band at the center frequency ($at\ 10\ GHz$). This OSB problem can be eliminated by properly optimizing the slot dimensions and period of the unit cell, so that perfect impedance matching can be achieved. Here we have used first the longitudinal slots in both sections of the SIW centerline. These alone cannot mitigate the OSB problem, therefore a group of three additional transverse slots is added for achieving the balanced condition by providing additional inductance in the unit cell. To achieve continuous beam scanning, no bandgap should present in the dispersion diagram. From Fig. 2, we can also see a sudden rise in the effective attenuation at the center frequency. Hence in our next design of LWA 2 as shown in Fig. 3 (b), we have very finely optimized all the parameters to eliminate this problem and achieve continuous beam scanning from backward-to-forward through broadside.

TABLE II. COMPARISION OF SIW-BASED LWA AND PROPOSED ANTENNA

Antenna Structure	**Antenna Type**	**Broadside Gain**	**Gain variation**	**Scanning Angle**
[16]	HW-MLWA	No Beam	2.5, 3.4, and 3.1	30^o to 64^o -75^o to -18^o $-19^o$to -4^o
[23]	SIW	10.6 dBi	3.9 dBi	-31.5^o to 17.1^o -34.3^o to 20^o
[24]	SIW	Not Mention	Not Mention	Not Mention
[25]	SIW	No Beam	Not Mention	Near broadside to Near endfire
Proposd Antenna	SIW	15 dBi	2 dB	-60^0 to $+25^0$

III. RESULTS AND DISCUSSION

A. *Scattering Parameters*

The simulated scattering parameters are shown in Fig. 4. The simulated return loss $|S_{11}|$ is below -10 dB in the complete frequency range, with a minimum value of -50 dB. The transmission coefficient $|S_{21}|$ of the designed prototype is high throughout the designed frequency range and becomes < -2 dB at the center frequency. This is due to the OSB problem seen in the dispersion diagram of Fig. 2. Therefore, we have proposed another design of LWA 2. The S-parameters as shown in Fig. 4 are for LWA 2.

B. Radiation characteristics and efficiency

The simulated radiation pattern of the proposed LWA is shown in Fig. 5. Initially with the LWA 1 design we get forward beam scanning from $(-60^0 \text{ at } 8.20GHz \text{ to} -30^0 \text{ at } 9.01GHz)$ and backward scanning from $(+30^0 \text{ at } 9.35GHz \text{ to} +75^0 \text{ at } 11.74GHz)$ as shown in Fig. 5 (a), here we did not achieve broadside radiation due to OSB (Open Stop Band) situation. Therefore, we have designed another LWA 2 geometry and finally receive continuous beam scanning from $(-60^0 \text{ at } 9.74GHz \text{ to} -25^0 \text{ at } 14.63GHz)$ as shown in Fig. 5 (b). From the simulated radiation pattern shown in Fig. 5 (c), we found that the LWA 2 has consistent gain characteristics of 15 dB in the desired frequency of operation. It is found from Fig. 7 that the radiation efficiency varies from 70% to 85% while the main beam of antenna changes its direction.

IV. CONCLUSIONS

In this paper, a new design method for SIW based LWA is proposed. This antenna is applicable for X-band applications. It is reliable for continuous beam scanning from the backward-to-forward direction with increasing frequency. It is found that with the designed LWA 1, the OSB problem remains in the LWA 1. But after optimizing the feed dimensions which we have used in the design and position of periods, the new antenna starts radiating in a broadside direction also. The second antenna shows cross polarization level of -18 dB and slight variation in antenna gain while beam scanning with frequency. This improved the scanning ability of antenna wile keeping the gain consistent in the desired frequency range. The complete simulated results are justifying the proposed LWA is highly efficient for complete beam scanning in various satellite and missiles system.

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