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SIW Based Leaky-Wave Antenna Supporting Wide Range of Beam Scanning through Broadside

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***Abstract*— In this letter, a substrate integrated waveguide (SIW) based leaky wave antenna with wide beam scanning is presented to mitigate open stopband (OSB). The unit cell of this proposed antenna consists of a longitudinal slot and a post placed oppositely offset from the center line. By introducing inductive post along with longitudinal slot in each unit cell, the open stopband is suppressed resulting continuous beam scanning. An equivalent circuit of the proposed unit cell is developed to explain impedance matching technique used here to suppress OSB. Dispersion diagram is also used to analyze this seamless scanning. This antenna can scan from -49^0 to +69^0 through broadside because of wide impedance matching. Finally, the antenna is prototyped and experimentally verified. Measured results are in accord with simulated results. This antenna provides maximum gain of 14.2dBi and low level of cross-polarization.**

***Index Terms*— SIW, leaky wave antenna, open stopband, impedance matching, and wide beam-scanning.**

I. Introduction

LEAKY-wave antenna (LWA) is a traveling wave antenna, which permits to leak electromagnetic wave along its structure. The most important feature of this type of antenna is the scanning capability without requirement of any complex feeding network, unlike a phased array antenna. These antennas are used for beam scanning, direction-of-arrival estimation, collision avoidance, and indoor communications, etc. LWAs can be realized in substrate integrated waveguide (SIW) structure. SIW based LWA provides several advantages such as low loss, easy to fabricate, high-power handling capabilities and narrow beam-width. Because of these advantages, SIW-based LWAs have got considerable attention to the researchers recently [1].

SIW based LWA may be classified into two groups according to their structure: uniform (quasi-uniform) and periodic. Uniform LWAs support fast wave compared to free space wave, hence phase constant (β) of a fast wave is less than that of free space (k_0). This type of antenna can scan only either in forward $(\beta<k_0)$ or backward $(-k_0<\beta)$ direction. In other types of LWAs periodic discontinuity is created in SIW structure which can generate infinite number of space waves [1]. The wave corresponds to $\beta_n<k_0$ is a fast wave and leaks the electromagnetic wave through the periodic discontinuity. This periodically modulated LWAs can scan in both forward and backward direction but no broadside radiation which is known as open stop-band (OSB) problem [2]. This OSB problem occurs due to two oppositely directed spatial harmonics with same amplitude causes degradation of the radiation pattern in broad side [3]. The techniques used for OSB suppression in periodic LWAs are impedance matching [4], [5], [6], [7], [8] reflection-cancelation [9], use of asymmetric unit cell [6], [10], use of ridged structure [10] etc. Seamless scanning is also achieved using dielectric image line (DIL) fed by slots [11]. But DIL structures are usually used for high frequency applications. Some other LWAs are capable to scan backward to forward, known as composite right/left-handed (CRLH) underbalanced or matched unit cell. But CRLH based LWAs have a problem of random dispersive behavior on cutoff [12]. Apart from the OSB suppression, beam scanning range is also a vital concern in LWA design. In all the above reported LWAs the OSB problem has been resolved but failed to achieve good impedance bandwidth resulting a common problem of limited beam scanning range.

In this letter, a periodic SIW based LWA supporting wide beam scanning is proposed with suppressed OSB and sufficient gain in whole operating range. Unit cell of this antenna consists of a longitudinal slot and an inductive post. Combination of post and slot is also exploited in [7], [8] to suppress OSB but with limited beam scanning. In [7] impedance matching is achieved by placing the slot quarter wavelength apart from posts. This condition cannot be fulfilled for a band of frequencies limiting the impedance bandwidth and scanning range. In [8] post and slot both are placed at the same side of the center line of SIW. This reduces the degree of freedom in locating the post resulting limited impedance bandwidth and beam scanning range. The slot and post in the proposed unit cell are placed oppositely offset from the center line. An array containing 19 such unit cells is designed to radiate seamlessly from backward to forward with the change in frequency. Impedance matching technique is exploited here to suppress open stop-band (OSB).

II. Proposed Structure And Dimension

In a SIW structure, the substrate is cladded with conductor on top and bottom sides to form a waveguide, together with two rows of metallic vias at edges. The thickness and the width of the SIW are h and w respectively. The vias with diameter d are placed periodically separated by distance s. A 3-D perspective including top view of the proposed antenna is shown in Fig. 1. All the dimensions mentioned in Fig. 1 are tabulated in Table I. EM simulator HFSS is used carefully for optimization of all the dimensions to achieve enhanced beam scanning with low cross-polarization level. The substrate used here is RO4350 (ε_r=3.66 and $tan\delta$=0.004).

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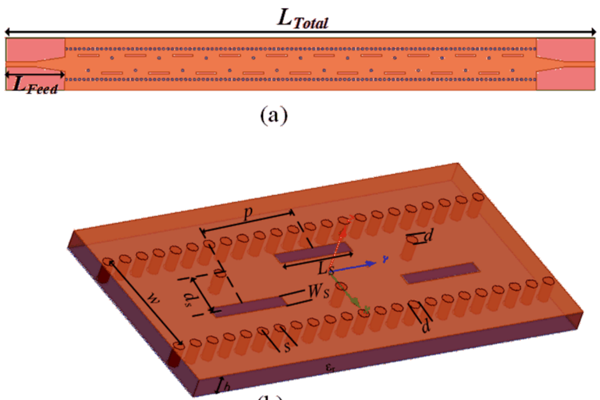

Fig. 1. Configuration of proposed SIW periodic leaky-wave structure (a) top view (b) 3-D view.

III. Unit Cell And Equivalent Circuit

A. Proposed Unit Cell Structure

SIW based unit cell contains an inductive post and a longitudinal slot which are placed oppositely offset from the center of SIW. Longitudinal slot and post provide capacitive

TABLE I
PARAMETERS OF PROPOSED LWA

Parameter	Value (mm)	Parameter	Value (mm)
w	10.5	d_s	5.1
p	8	S	1.4
d	0.8	L_{Total}	200
h	0.762	L_{Feed}	20
w_s	0.45	L_s	7

and inductive effect respectively. Thus combining these two impedance matching is achieved.

The longitudinal slots on top metallic plate are placed away from the center to perturb the surface current for radiation. The unit cell with slot and post radiates backward to forward through broadside. Main lobe direction changes with frequency. The frequency at which antenna radiates at broadside direction can be predicted from unit cell dispersion diagram. In general, main beam direction of n^{th} space harmonic is given by [1]

$$\theta_n \approx \sin^{-1}\left(\frac{\beta_n}{k_0}\right) = \sin^{-1}\left(\frac{\beta_0 + 2n\pi/p}{k_0}\right) \tag{1}$$

where β_n and k_0 are the phase constant for n^{th} space harmonic and free space wavenumber respectively. For fast waves $|\beta_n| < k_0$ and in this region antenna would radiate. The value of radiation angle θ_n would be negative, zero, and positive indicating backward, broadside and forward radiation, respectively. Here this seamless scanning is possible because of impedance matching which is explained in the following section with the help of the equivalent circuit and dispersion diagram.

B. Equivalent Circuit and Dispersion Analysis

A unit cell with periodicity p=16mm and all other relevant dimension as mention in Table I is considered. Unit cell containing a longitudinal slot only on the top metal plane can be represented by equivalent T- network [13] as shown in Fig.

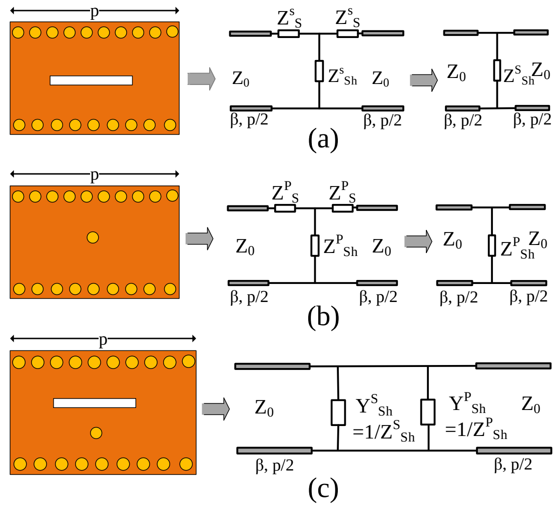

Fig. 2. Equivalent circuit of (a) unit cell with longitudinal slot (b) post in unit cell (c) proposed matched unit cell.

2(a). Further, a unit cell consists of post only can also be represented by an equivalent T-network as shown in Fig. 2(b). The network components, normalized series impedance, $Z^i{}_S$ and shunt impedance, $Z^i{}_{Sh}$ used in equivalent T-network can be found from the following equations [13].

$$Z^i{}_s = \frac{(1 + S_{11} - S_{21})}{(1 - S_{11} + S_{21})} \tag{2}$$

and

$$Z^i{}_{sh} = \frac{2S_{21}}{(1 - S_{11} + S_{21})(1 - S_{11} - S_{21})} \tag{3}$$

where i=s for Fig. 2(a) and i=p for Fig. 2(b). The simulation of each unit cell is done on HFSS and S-parameters are extracted to calculate series and shunt elements of these network. The calculated normalized impedance plot for unit cell with slot only is shown in Fig. 3(a). This figure indicates that slot loaded unit cell is highly mismatched at 13 GHz, which in turn creates OSB problem. The Fig 3(a) also depicts that all real and imaginary part of the elements used in equivalent T-network is near to zero except the imaginary part of shunt impedance. This concludes that longitudinal slot loaded SIW has capacitive loading effect. Accordingly, the equivalent T-network can further be approximated to a shunt element $Z^S{}_{Sh}$ only. The plot of series element $Z^P{}_S$ and shunt element $Z^P{}_{sh}$ for unit cell with post only are shown in Fig. 3(b). The Fig. 3(b) shows that real and imaginary parts of network elements are zero, except imaginary part of shunt element. This concludes that post loaded SIW structure has inductive loading effect. Equivalent T-network for unit cell with post only can also be approximated to a shunt element $Z^P{}_{Sh}$ only. Considering approximated equivalent circuit as mention in Fig. 2(a) & (b) an equivalent circuit for unit cell consists of slot and post is shown in Fig. 2(c). This equivalent circuit contains only two parallel shunt admittances. The Fig. 4 showing the plot of these two normalized admittances indicates that $Y^P{}_{Sh}$ $(1/Z^P{}_{Sh})$ is negative and $Y^S{}_{Sh}$ is $(1/Z^S{}_{Sh})$ is positive. For impedance matching, equivalent admittance should be approximately zero. So for proper impedance matching the post and slot positions, and

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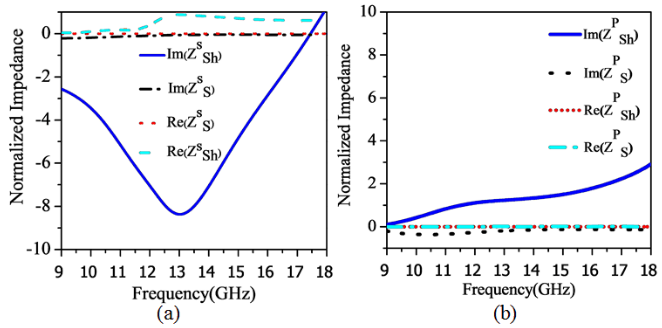

Fig. 3. Normalized impedance plot of series impedance and shunt impedance

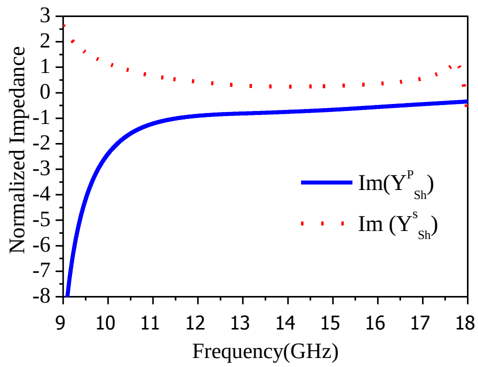

Fig. 4. Normalized shunt admittance plot of unit cell with slot and post

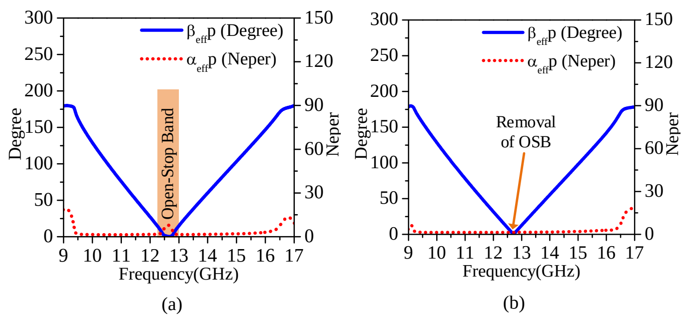

Fig. 5. Dispersion diagram of unit cell with (a) slot (b) slot and post.

dimensions are optimized to have net shunt admittance zero. Due to this, it behaves as an open circuit and correspondingly matching is realized in the unit cell.

This OSB suppression can also be explained further with the help of unit cell's dispersion graph. Attenuation constant, α_{eff} and phase constant, β_{eff} are calculated using the formula mentioned in [5]. Fig. 5(a) shows the dispersion graph for a unit cell consists of slot only. This indicates presence of OSB at the vicinity of 12.6 GHz. To suppress this OSB a unit cell consists of inductive post and longitudinal slot is proposed. The dispersion graph of proposed unit cell [Fig. 5(b)] shows that α_{eff} is almost zero in operating band and β_{eff} is zero at single frequency unlike at a band of frequency as shown in Fig. 5(a). This causes removal of OSB which is indicated in Fig. 5(b). Therefore, unit cell with longitudinal slot and post can scan seamlessly from backward to forward through broadside.

IV. Full-Length Structure

Initially, the unit cells are placed side by side to form a periodic leaky-wave structure. This array has problem of less radiation because of lesser number of longitudinal slot in a fixed length array. It also suffers from high cross-polarization due to the coupling effect. To resolve this problem the array structure has been modified.

In the modified design slots are placed asymmetrically such that slots and posts in adjacent cells are in opposite side as shown in Fig. 1. Due to this arrangement, the phase delay of unit cell element reduced to π. In addition, to obtain in-phase radiation the period of unit cell is reduced by half. This structure is densely distributed along the propagation direction, therefore it improves the radiation rate per unit length. In this structure, coupling effect is less compare to initial design. This modification results low level of cross-polarization and in phase excitation with high radiation rate of LWA. All the dimensions of array are adjusted to get optimum results using HFSS.

V. Simulated And Measured Results

Finally, a prototype of the proposed structure is fabricated [Fig. 6] and measurements are done. Simulated S-parameters are compared with that of measured in Fig. 7.

The measured results are close to simulated results. The magnitude of the reflection coefficient S11 is below – 10 dB in the band from 10-18 GHz. Because of reflection caused by the SMA connectors and potential variation, the measured |S11| has shallower resonance dips compared to that of simulated. Due to this measured |S21| spectrum response is also deviated from the corresponding simulated |S21| spectrum.

The proposed antenna can continuously scan in yz-plane. It has fan beam in xz-plane. Measured and simulated radiation pattern in yz-plane at frequencies 10 GHz, 11GHz, 12.5 GHz, 14.5GHz, and 17.5 GHz are shown in Fig. 8. The proposed antenna radiates in broadside direction at frequency 12.5 GHz. Since only longitudinal slot takes part in radiation, maximum cross-polarization level is below 35dB from the main lobe radiation at all frequencies.

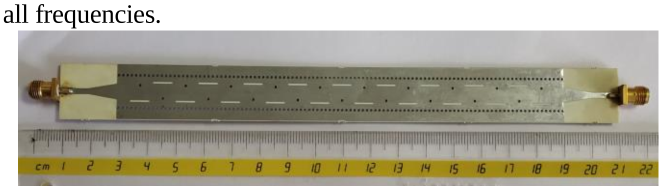

Fig. 6. Prototype of full-length structure of SIW based LWA.

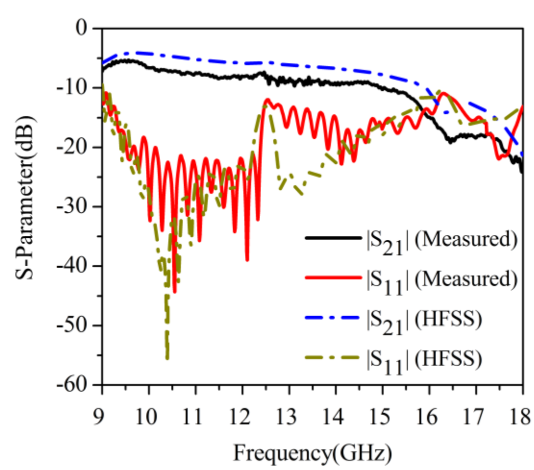

Fig. 7. S-Parameter of proposed LWA.

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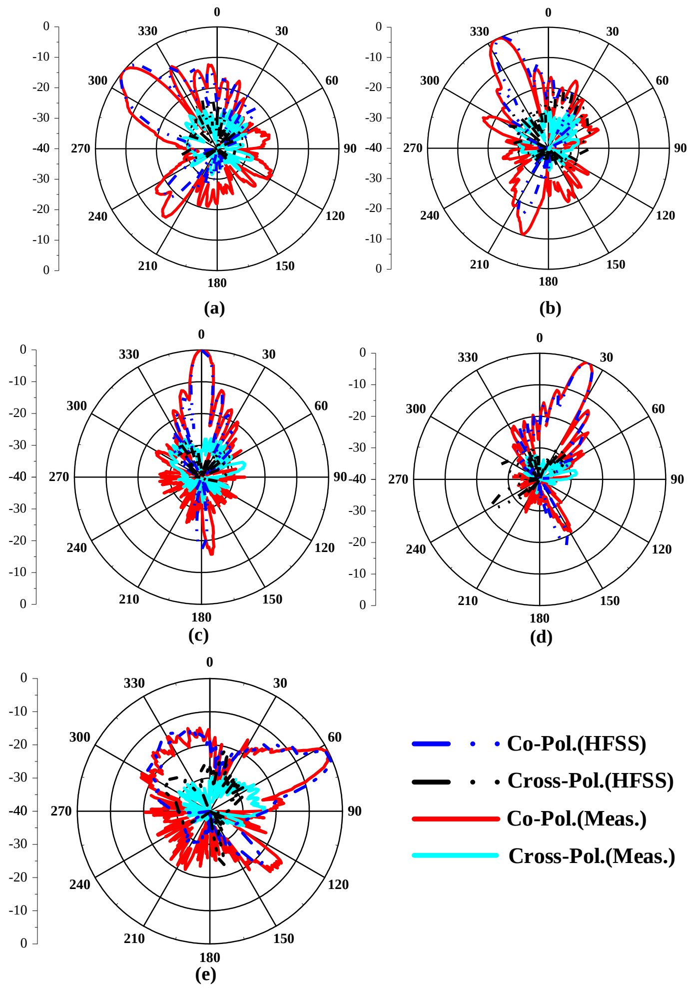

Fig. 8. Simulated and measured radiation pattern at (a) 10 GHz, (b) 11 GHz, (c) 12.5 GHz, (d) 14.5 GHz, and (e) 17.5 GHz.

The measured and simulated main-beam direction and gain of the antenna is shown in Fig. 9. The measured results are well agreed with the simulated result for main beam direction from -49^0 to +69^0 and maximum gain of 14.2 dBi. Radiation efficiency is also above 68% throughout the operating band.

The proposed antenna is compared with different types of reported LWAs in Table II. Proposed antenna provides the highest beam scanning angle.

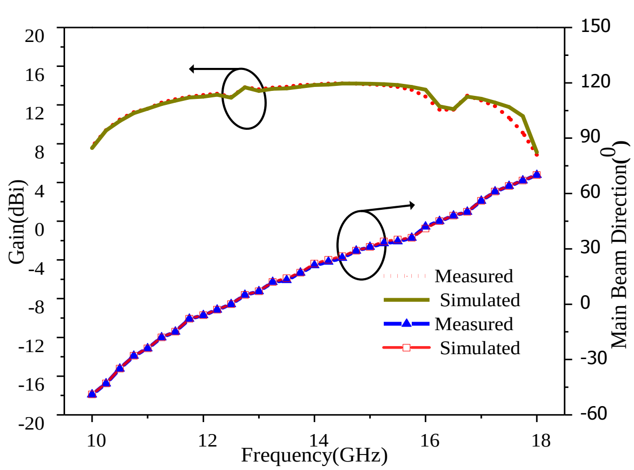

Fig. 9. Gain and main-beam direction of antenna

TABLE II
COMPARISON OF PERFORMANCE OF SIW BASED LWAS

Ref	Type of Antenna	ε_r	Total Length (λ_0)	Bandwidth	Scanning Range (^{0})	Maximum Gain (dBi)
4	Periodic Microstrip	2.2	11.64	8-11.4	-25 to 10	16
5	Periodic SIW	3.66	6	9-14	-40 to 35	12
7	Periodic SIW	10.2	11.2	13.2-15.6	-61 to 42	14.1
8	Periodic SIW	3.66	6	6-12.9	-55 to 34	12.9
9	Periodic Microstrip	6.15	7.6	20-29	-50 to 45	12.2
10	Periodic Ridge SIW	3.55	NA	8-12	-35 to 35	12.5
11	DIL	10.2	7	11.8-17	-65 to 25	16
12	CLRH	2.32	NA	7.5-11.9	-52 to 28	8
Proposed	Periodic SIW	3.66	6	10-17.5	-49 to 69	14.2

VI. CONCLUSION

In this paper, a new periodic LWA with unit cell consists of longitudinal slot and post supporting wide scanning range is proposed. This antenna is consists of an array of impedance matched unit cells along the direction of propagation in order to provide continuous scanning from −49° to +69°. Shunt inductance of post is matched with shunt capacitance of slot resulting suppression of OSB. Wide impedance bandwidth of 56% over the desired frequency band is achieved. This design has a low level of cross-polarization and sufficient gain over whole beam scanning range.

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