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-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 the longitudinal slot in each unit cell, the OSB is suppressed resulting in continuous beam scanning. An equivalent circuit of the proposed unit cell is developed to explain the impedance matching technique used here to suppress OSB. Dispersion diagram is also used to analyze this seamless scanning. This antenna can scan from –49° to +69° 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 14.2 dBi and low level of cross polarization.**

***Index Terms*—Impedance matching, leaky-wave antenna, open stopband, substrate integrated waveguide (SIW), 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, indoor communications, etc. LWAs can be realized in substrate integrated waveguide (SIW) structure. SIW-based LWA provides several advantages such as low loss, easy fabrication, high power-handling capabilities, and narrow beamwidth. Because of these advantages, SIW-based LWAs have received considerable attention from 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 with 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 that corresponds to $\beta_n < k_0$ is a fast wave and leaks the electromagnetic wave through the periodic discontinuity. These periodically modulated LWAs can scan in both forward and backward direction but no broadside radiation, which is known as open stopband (OSB) problem [2]. This OSB problem occurs due to two oppositely directed spatial harmonics with same amplitude, which cause the degradation of the radiation pattern in broad side [3]. The techniques used for OSB suppression in periodic LWAs are impedance matching [4]–[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]. However, 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. However, 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 in 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 the whole operating range. The unit cell of this antenna consists of a longitudinal slot and an inductive post. Combination of post and slot is also exploited in [7] and [8] to suppress OSB but with limited beam scanning. In [7], impedance matching is achieved by placing the slot a 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 in 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 OSB.

II. Proposed Structure and Dimension

In an 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

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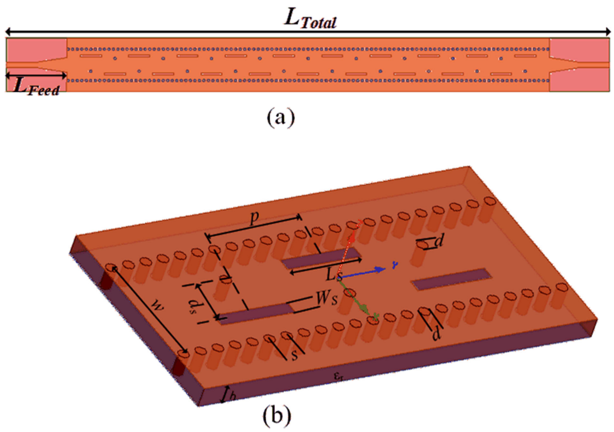

Fig. 1. Configuration of the proposed SIW periodic leaky-wave structure. (a) Top view. (b) 3-D view.

TABLE I
PARAMETERS OF THE 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

d are placed periodically separated by a distance s. A three-dimensional 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. Electromagnetic 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 ($\varepsilon_r = 3.66$ and $\tan\delta = 0.004$).

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

The longitudinal slots on the 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 the antenna radiates at broadside direction can be predicted from unit cell dispersion diagram. In general, main beam direction of the nth space harmonic is given by the following [1]:

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

where β_n and k_0 are the phase constant for the nth space harmonic and free-space wavenumber, respectively. For fast waves $|\beta_n| < k_0$, and in this region the 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 Section III-A with the help of the equivalent circuit and dispersion diagram.

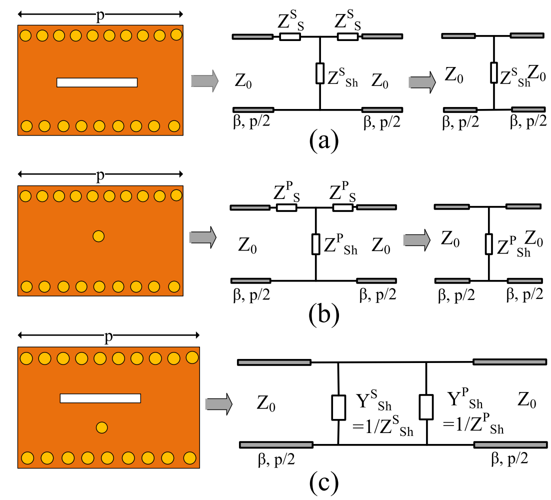

Fig. 2. Equivalent circuit of (a) unit cell with longitudinal slot, (b) post in unit cell, and (c) proposed matched unit cell.

B. Equivalent Circuit and Dispersion Analysis

A unit cell with periodicity $p = 16$ mm and all other relevant dimensions as mentioned 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. 2(a). Furthermore, a unit cell that 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]:

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

and

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

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 networks. 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 the OSB problem. Fig. 3(a) also depicts that all real and imaginary parts of the elements used in equivalent T-network are near to zero except for 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

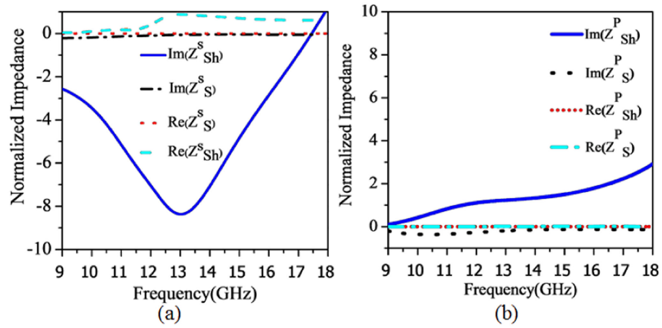

Fig. 3. Normalized impedance plot of (a) series impedance and (b) shunt impedance.

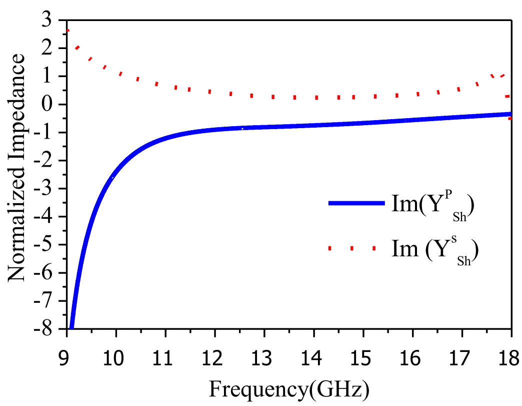

Fig. 4. Normalized shunt admittance plot of unit cell with slot and post.

only is shown in Fig. 3(b). Fig. 3(b) shows that real and imaginary parts of network elements are zero, except for the imaginary part of the shunt element. This concludes that a 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_{Sh}^{P} only. Considering an approximated equivalent circuit, as mentioned in Fig. 2(a) and (b), an equivalent circuit for unit cell consists of slot and post, as shown in Fig. 2(c). This equivalent circuit contains only two parallel shunt admittances. Fig. 4 showing the plot of these two normalized admittances indicates that Y_{Sh}^{P} $(1/Z_{\mathrm{Sh}}^{P})$ is negative and Y_{Sh}^{S} $(1/Z_{\mathrm{Sh}}^{S})$ is positive. For impedance matching, equivalent admittance should be approximately zero. Thus, for proper impedance matching, the post and slot positions and 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 the 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 consisting of slot only. This indicates the presence of OSB at the vicinity of 12.6 GHz. To suppress this OSB, a unit cell consisting of inductive post and longitudinal slot is proposed. The dispersion graph of the proposed unit cell [see Fig. 5(b)] shows that α_{eff} is almost zero in operating band and

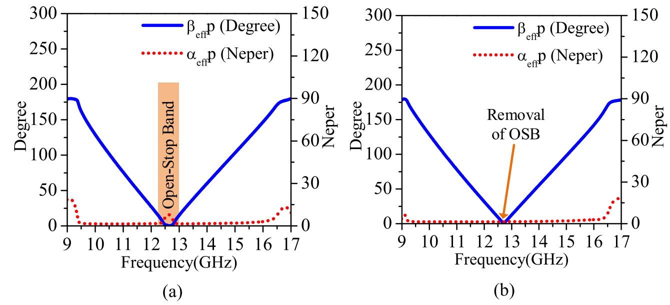

Fig. 5. Dispersion diagram of unit cell with (a) slot and (b) slot and post.

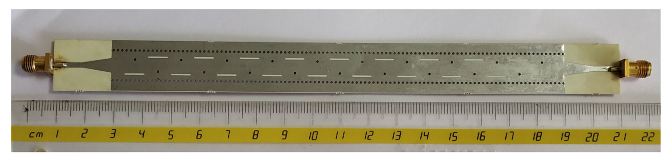

Fig. 6. Prototype of full-length structure of SIW-based LWA.

β_{eff} is zero at single frequency unlike at a band of frequency as shown in Fig. 5(a). This causes the 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 the problem of less radiation because of fewer number of longitudinal slots 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 the opposite side, as shown in Fig. 1. Due to this arrangement, the phase delay of unit cell element is 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, the coupling effect is less as compared to the initial design. This modification results in low level of cross polarization and in-phase excitation with high radiation rate of LWA. All the dimensions of the array are adjusted to get optimum results using HFSS.

V. Simulated and Measured Results

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

The measured results are close to the simulated results. The magnitude of the reflection coefficient S_{11} is below -10 dB in the band from 10 to 18 GHz. Because of the reflection caused by the SMA connectors and potential variation, the measured $|S_{11}|$

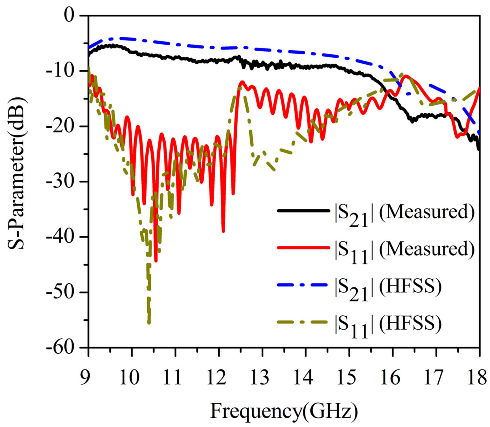

Fig. 7. *S*-parameter of the proposed LWA.

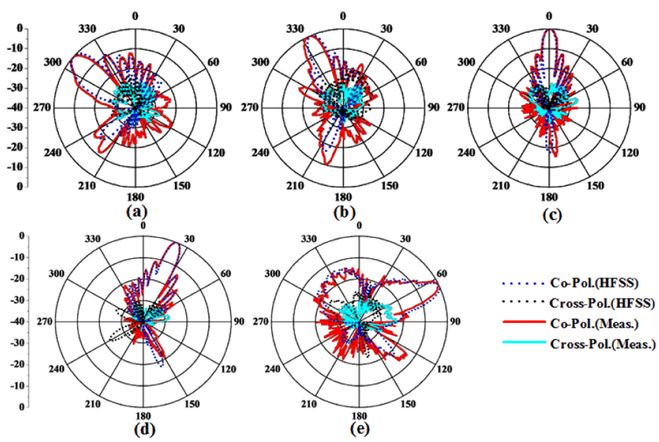

Fig. 8. Simulated and measured radiation pattern at (a) 10, (b) 11, (c) 12.5, (d) 14.5, and (e) 17.5 GHz.

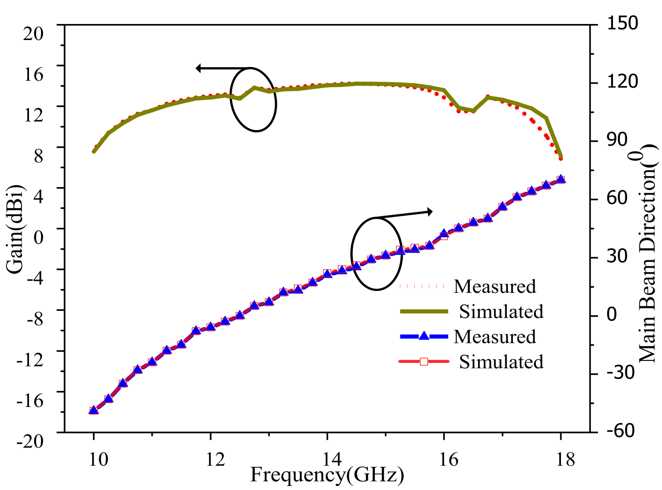

Fig. 9. Gain and main-beam direction of antenna.

has shallower resonance dips compared to that of the simulated. Due to this, measured $|S_{21}|$ spectrum response is also deviated from the corresponding simulated $|S_{21}|$ spectrum.

The proposed antenna can continuously scan in *yz* plane. It has fan beam in the *xz* plane. Measured and simulated radiation

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

pattern in the *yz* plane at frequencies 10, 11, 12.5, 14.5, 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 35 dB from the main lobe radiation at all frequencies.

The measured and simulated main-beam direction and gain of the antenna are shown in Fig. 9. The measured results agree well with the simulated result for the main beam direction from –49° to +69° 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. The proposed antenna provides the highest beam-scanning angle.

VI. CONCLUSION

In this letter, a new periodic LWA with unit cell that consists of longitudinal slot and post supporting wide scanning range is proposed. This antenna 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 the post is matched with the shunt capacitance of the slot, resulting in the 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 the whole beam scanning range.

REFERENCES

[1] D. R. Jackson, C. Caloz, and T. Itoh, "Leaky-wave antennas," *Proc. IEEE*, vol. 100, no. 7, pp. 2194–2206, Jul. 2012.
[2] J. Liu, D. R. Jackson, and Y. Long, "Substrate integrated waveguide (SIW) leaky-wave antenna with transverse slots," *IEEE Trans. Antennas Propag.*, vol. 60, no. 1, pp. 20–29, Jan. 2012.

[3] Z. L. Ma, K. B. Ng, C. H. Chan, and L. J. Jiang, "A novel supercell-based dielectric grating dual-beam leaky-wave antenna for 60-GHz applications," *IEEE Trans. Antennas Propag.*, vol. 64, no. 12, pp. 5521–5526, Dec. 2016.

[4] J. T. Williams, P. Baccarelli, S. Paulotto, and D. R. Jackson, "1-D combline leaky-wave antenna with the open-stopband suppressed: Design considerations and comparisons with measurements," *IEEE Trans. Antennas Propag.*, vol. 61, no. 9, pp. 4484–4492, Sep. 2013.

[5] Y. L. Lyu *et al.*, "Leaky-wave antennas based on noncutoff substrate integrated waveguide supporting beam scanning from backward to forward," *IEEE Trans. Antennas Propag.*, vol. 64, no. 6, pp. 2155–2164, Jun. 2016.

[6] S. Otto, A. Al-Bassam, A. Rennings, K. Solbach, and C. Caloz, "Transversal asymmetry in periodic leaky-wave antennas for bloch impedance and radiation efficiency equalization through broadside," *IEEE Trans. Antennas Propag.*, vol. 62, no. 10, pp. 5037–5054, Oct. 2014.

[7] W. Zhou, J. Liu, and Y. Long, "Investigation of shorting vias for suppressing the open stopband in an SIW periodic leaky-wave structure," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 6, pp. 2936–2945, Jun. 2018.

[8] R. Ranjan and J. Ghosh, "An enhanced beam scanning leaky-wave antenna with suppressed open-stop band," in *Proc. 3rd Int. Conf. Microw. Photon.*, Dhanbad, India, 2018, pp. 1–2.

[9] M. H. Rahmani and D. Deslandes, "Backward to forward scanning periodic leaky-wave antenna with wide scanning range," *IEEE Trans. Antennas Propag.*, vol. 65, no. 7, pp. 3326–3335, Jul. 2017.

[10] A. Mallahzadeh and S. Mohammad-Ali-Nezhad, "Periodic collinear-slotted leaky wave antenna with open stopband elimination," *IEEE Trans. Antennas Propag.*, vol. 63, no. 12, pp. 5512–5521, Dec. 2015.

[11] C. S. Prasad and A. Biswas, "Dielectric image line-based leaky-wave antenna for wide range of beam scanning through broadside," *IEEE Trans. Antennas Propag.*, vol. 65, no. 8, pp. 4311–4315, Aug. 2017.

[12] P. Pan, F.-Y. Meng, and Q. Wu, "A composed right/left-handed waveguide with open-ended corrugations for backward-to-forward leaky-wave antenna application," *Microw. Opt. Technol. Lett.*, vol. 50, no. 3, pp. 579–582, Mar. 2008.

[13] N. Marcuvitz, *Waveguide Handbook*. New York, NY, USA: McGraw-Hill, 1951.