Design of Substrate Integrated Waveguide-based Periodically-loaded Archimedean Spiral Slot Leaky Wave Antenna

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***Abstract*–A novel structure of a periodic leaky-wave antenna with continuous beam scanning for Ku-band (12-18 GHz) applications is presented here. The design of a frequency-scanning antenna, which comprises of tapered microstrip line for feed and dual spiral slots as the radiator on the upper metallic plate of substrate integrated waveguide, is discussed. Leakage of electromagnetic energy from the leaky line (SIW) occurs through periodic loading of dual spiral slots. Antenna characteristics and performances are illustrated using full-wave simulation. The proposed LWA has features of a high gain of 13.4 dB (at broadside) with a maximum variation of 2 dB in the desired range of frequency. The designed antenna has 7 unit cells that provide directive comprehensive scanning of -60 deg. to +25 deg. over the operating frequency of 12.73-17.35 GHz with a consistent gain of 12 dB (avg.).**

***Index Terms* –Periodic leaky-wave antenna (PLWA), substrate-integrated-waveguide (SIW), beam scanning, high gain.**

I. INTRODUCTION

The popularity of frequency-scanning antennas among the antenna designer is due to its inherent vast scanning ability with a more directive beam which is used for airborne to satellite communication and frequency scanning radar. After the proposal of the leakage aspect of SIW for a fast-wave generation [1], SIW-based periodic leaky-wave antenna (LWA) for one-dimensional scanning has attracted many researchers because of its low profile and easy-to-integrate features with other RF circuits and systems. In this class of antenna, a single beam radiate in the fast wave region by exciting first (n = -1) space harmonics [2].

Several reported design techniques for leaky-wave radiation using this integrated waveguide technology suffer from two potential difficulties during frequency scanning. The first is to achieve continuous scanning in visible space, and the other is broadside radiation. Using the variable distance between the metallic vias [3], transverse slot [4], butterfly wings [5], long slot [6], half-mode SIW [7], and eighth mode SIW [8], beam scanning is achieved only in the second quadrant of visible space. Other reported designs allow the scanning in both the quadrant [9]-[10] but cannot scan through the broadside direction. The problem's root cause, as mentioned earlier, is the open-stop band effect (OSB). This problem arises due to the poor reflection coefficient at the transition [11]. For the elimination/suppression of OSB, excellent idea from various researchers is reported in the open literature, such as: designing resonant stub for minimum leakage [12], using RH-LH transmission line [13]-[14], and creating double periodic SIW for alternate capacitances/inductances loading [15]. There is also some critical idea like the combination of dual-element (both patch and slot) [16] and designing composite right/left-handed media using HMSIW [17] to get consistent beam scanning are reported. Utilizing the quarter-wave transformer/matching stubs for impedance transformation at $\beta = 0$ condition provides continuous scanning [18]. Designing an asymmetric unit cell provides reflection coefficient improvement at the broadside for hassle-free scanning [19]. Incorporating multiple radiating elements placed at quarter wavelength spacing in the unit cell design for cancelation of internal reflection [20]. Other reported work, like using a dielectric image line [21] and slots with both transverse and longitudinal orientation [22] are proposed for seamless scanning through the broadside. Recently, D. K. Karmokar utilized the slots and partial reflecting vias wall (PRW) for achieving continuous beam scanning [23]. With all these different approaches to attain continuous beam scanning through the broadside very limited number of literature has been seen where continuous scanning from forward to backward through the broadside is achieved.

We are presenting a more compact leaky-wave antenna (LWA) structure where the open stop-band problem is completely suppressed using two curvilinear slots. Simulation and analysis of the proposed work demonstrate high gain, wide scanning range, and reduced cross-polarization level. Here the choice of dual spiral slots for unit cell design produces a hassle-free transition from left to right through the balanced condition. The proposed structure exhibits consistent gain in the designed frequency band by solving the problem of variable gain performance. The main advantage of this novel structure is maintaining high and consistent gain with low cross-polarization throughout the operating frequency band. The inherent property associated with curvilinear slots is a high cross-polarization level. This difficulty is solved by proper positioning and angular rotation of slots using parametric sweeps.

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II. ANTENNA CONFIGURATION AND SIMULATION

A. *Design of a Unit Cell*

For leaky-mode excitation, the design procedure starts with the unit cell design. Simulated model of the proposed unit cell with detailed geometrical dimensions is shown in Fig. 1(a). First, substrate (Rogers RT/Duriod 5880) having a thickness(h), dielectric permittivity (ε_r), and dielectric loss tangent $(tan\delta)$ of 0.787 mm, 2.2, and 0.0009, respectively, is chosen for maximum coupling of input power to the first higher-order space harmonic. The width (effective) of SIW is found using the equation in [24] and designed for generating fundamental TE_{10} mode at 14.98 GHz. After that, we optimized the period $(p)$of the unit cell (λ_g) for uninterrupted transition through the balanced condition. It is known that a periodically loaded transmission line contains an infinite set of spatial harmonic solutions and for this Brillouin diagram repeats in βp with the period of 2π [27]. The periodicity of the unit cell has been optimized for exciting first-order space harmonic only so that no mode coupling occurs. After this, dual spiral slots are loaded on the upper layer of the grounded substrate and positioned asymmetrically with the center line to eliminate the OSB effect [25]. Using the curvilinear slots as radiator cross-polarization is significant in the far-field pattern. To reduce this, proper positing and angular rotation of the slots has been carried out through parametric sweep. To completely eliminate the open stop-band (OSB) problem in periodic LWA, two spiral openings having the same length and width with proper orientation and positioning have been created at the upper layer of the synthetic waveguide. In Table I, the detailing of the final geometrical parameters of an optimized unit cell and complete LWA are listed.

B. *Study of Dispersion Diagram*

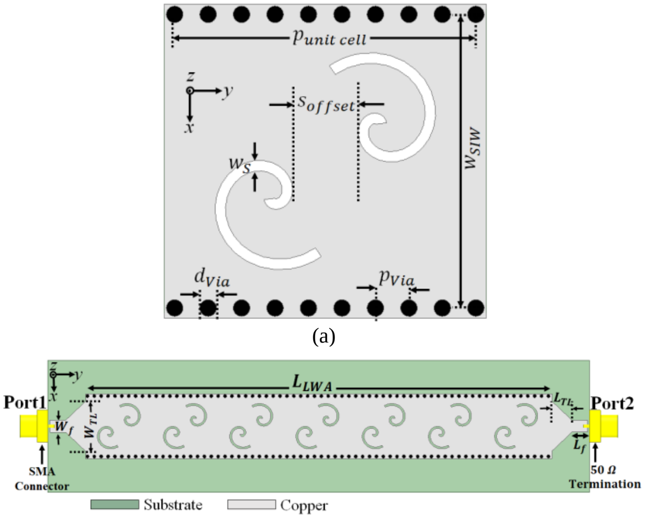
The study of the dispersion diagram for the designed unit cell is carried out using a 3D Electromagnetic simulator (ANSYS HFSS V. 19.0). The phase response and leakage response are calculated from equations (1) and (2), respectively, using the Bloch-Floquet technique [26], which is shown in Fig. 2. The balanced condition is achieved at 15.2 GHz. From the phase constant plot, frequency range for backward (12.73-15.2 GHz) and forward radiation (15.2-17.6 GHz) can be easily depicted. The broadside-directed beam is seen at a transition frequency of 15.2 GHz. The balanced condition $(\beta = 0)$is seen at 15.2 GHz. The dotted green line is the airline $\left(\omega\sqrt{\mu_0\varepsilon_0}\right)$. The fast wave region in the case of periodic LWA is defined as the region where $(\beta < k_0)$. The main beam is pointing at an angle θ at a specific frequency, which can be determined by using the equation (3), mentioned below [2]:

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

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

$$\theta(f) = sin^{-1}\left[\frac{\beta_n(f)}{k_0(f)}\right] \qquad (3)$$

where, $n = -1$ as we have excited the first space harmonic.



(a)

(b)

Fig. 1 Schematic of (a) unit cell (b) complete LWA

TABLE I

OPTIMIZED GEOMETRICAL PARAMETERS OF UNIT CELL AND LWA (IN MM)

$p_{unit\ cell}$	W_{SIW}	D_{via}	P_{via}	W_f	L_f
14.4	14	0.8	1.6	2.8	4.5
L_{LWA}	W_s	W_{TL}	L_{TL}	S_{offset}	L_s
107.2	0.5	7.6	9.2	3.27	2.2*pi

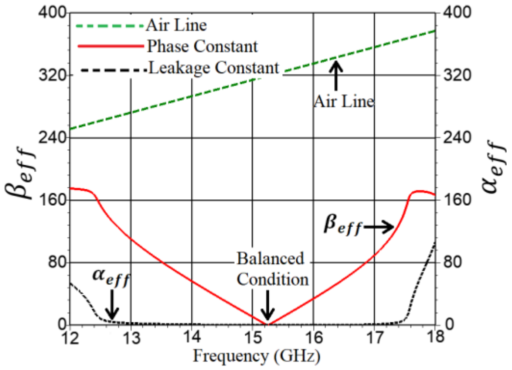


Fig. 2 Frequency response of phase and leakage constant of an optimized unit cell

C. *Surface Current Density*

For a single unit cell, the surface current density is shown in Fig. 3. Vector form of current density at a frequency of 15.2 GHz is plotted for understanding the mechanism of leakage. From the current distribution, we can say that maximum radiation in the broadside is due to the starting edges of the curvilinear slots. The current direction in both the slot's edges is opposite. The lower spiral slot has an *x*-directed current, whereas the upper slot has a *y*-directed current. This opposite current sense is responsible for high cross-polarization in the far-field pattern.

D. *Antenna Geometry*

The top view of the designed antenna is shown in Fig. 1 (b). The structure comprises seven unit cells arranged periodically along the longitudinal direction of the leaky-line. The total antenna size $(14 \times 107 \times 0.787)mm^3$ is more compact with high gain characteristics. Increasing the antenna length can surely increase the directivity and gain. On the left and right of the structure tapered microstrip line connected with an SMA (designed) connectors are used to feed and terminate the antenna port1 and port2 respectively. Tapering in feed is associated with matching impedance during the transition from the microstrip line to SIW. Due to this planar feeding technique, integration between the antenna and other RF components becomes relatively easy. In our simulation model, we have designed an SMA connector which is also incorporated in the simulation for a more accurate analysis of results. In the place of rectangular wave ports, SMA connectors are used as an EM-wave feed and termination at the two ends of the LWA. This is shown in Fig. 1(b).

III. SIMULATED RESULTS AND DISCUSSION

A. *Scattering Characteristics*

After optimizing the openings and unit cell dimensions, the complete LWA is designed using a seven cascaded unit cell. The frequency scanning antenna is simulated with an electromagnetic simulator. The Scattering parameters in dB of the proposed antenna are shown in Fig. 4. The simulated reflection coefficient (S_{11}) shows below -10 dB results from 11.6 GHz to 17.8 GHz. Though, S_{11} is not too much below -10 dB in the complete band of interest, it is showing good results at every operating frequency. The fractional bandwidth below -10 dB in the leaky space is 30.39 %. The transmission coefficient S_{21} shows the lower values in the operational band. This smaller value of S_{21} signifies the usage of maximum EM-wave for leakage.

B. *Radiation Characteristics*

The normalized two-dimensional radiation patterns in the *x-z* plane are plotted and shown in Fig. 5. The direction of main beam is along -60^0 at 12.73 GHz and $+25^0$ at 17.35 GHz. The antenna has the prospective for continuous frequency scanning from -60^0 to $+25^0$ when the source frequency sweeps from 12.73 GHz to 17.35 GHz. Initially, the side lobe level and high ripples in the E-plane pattern is observed, which start reducing with the increased frequency. This is quite obvious due to the finite length of the antenna. In Fig. 6(e) and (f), one can point out that in addition to the actual beam pointing along $+10^0$ and $+25^0$, another beam is pointing around -60^0. This is due to the secondary source exciting on the left side of the LWA. This secondary source is exciting due to the reflection of electromagnetic energy from the termination. This reflected EM-wave in the dielectric medium has low power amplitude. This complete phenomenon of secondary beam suggests that there is a slight mismatch between radiator and feed. The beam width in the leaky region is consistent at all the operating frequencies due to the controlled leakage constant in that region. The combined plot of co- and cross-pol. radiation of the fast-wave antenna is also shown in Fig. 6. The maximum and minimum peak gain is 13.4 and 9.8 dB, respectively. The gain variation in the leaky region is found to be less than 2 dB, except near the broadside. Near broadside, high variation in gain is due to reflection of EM-wave at transition frequency. The broadside patterns for both the principal planes are also shown in Fig. 7.

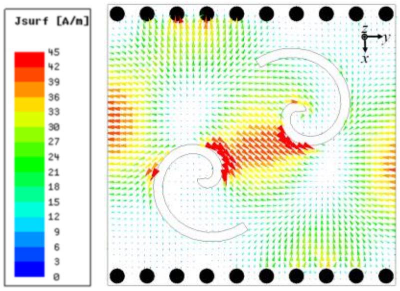


Fig. 3 surface current density of single unit cell

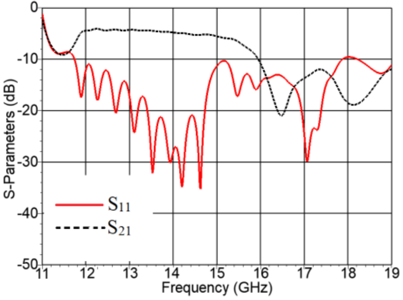


Fig. 4. S-parameters characteristics of designed leaky-wave radiator

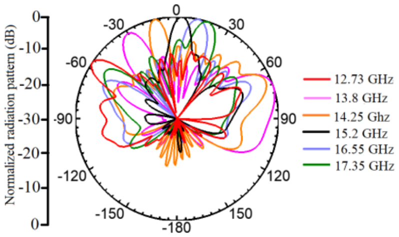
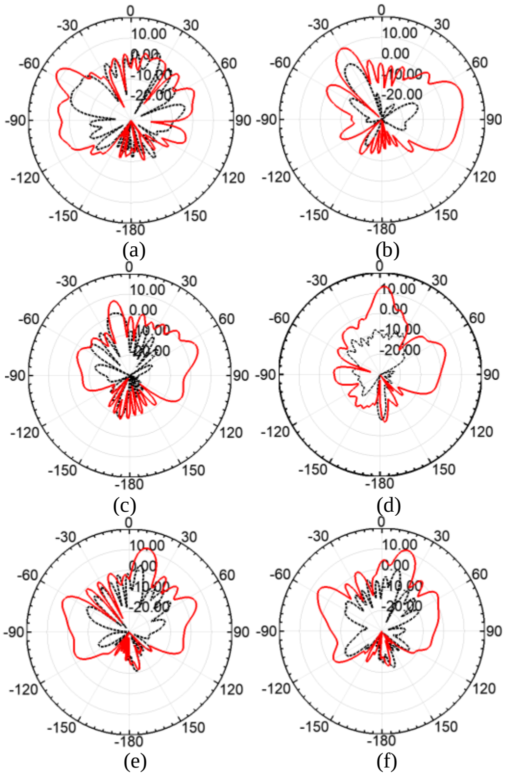
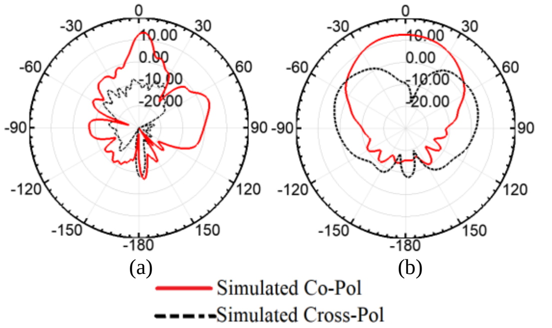


Fig. 5. Simulated radiation characteristics of proposed leaky-wave radiator



(a) (b) (c) (d) (e) (f)

Fig. 6 Radiation pattern of designed LWA for *x-z* plane $(\varphi = 90^o)$ (a) at 12.73 GHz (b) at 13.8 GHz (c) 14.25 GHz (d) 15.2 GHz (e) at 16.55 GHz (f) at 17.35 GHz



(a) (b)

Fig. 7 Radiation pattern of designed LWA at broadside (a) *x-z* plane ($\varphi = 90^o$) (b) *y-z* plane ($\varphi = 0^o$)

IV. CONCLUSION

An idea of a compact high gain frequency scanning antenna is numerically simulated and studied. The open stop band problem is completely eliminated by using a pair of Archimedean spiral slots placed asymmetrically concerning the center line. Unlike the traditional rectangular slots-based leaky-wave antennas (LWAs), the radiator is curvilinear shaped. This curvilinear-shaped perturbation produces high cross-pol. level. The problem of increased cross-pol. level is solved with proper orientation of slots through the parametric sweep. The optimized designs of a unit cell and complete LWA are determined using a full-wave FEM-based simulator. The proposed antenna has the potential to produce consistent gain, suppressed cross-pol., and a wide scanning range for Ku-band applications.

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