Electronically Tunable High Gain Leaky-wave Antenna using Eighth-mode SIW

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***Abstract*—A novel electronically tunable compact high gain eighth-mode substrate integrated waveguide (EMSIW) based leaky-wave antenna in planar environment is proposed and investigated. The proposed antenna uses $1/8^{th}$ mode SIW resonator incorporated with tunable delay line which help to steer the radiated beam. The beam switching is performed by changing the states of PIN diodes. Basically, by changing the bias voltage systematically, the polarity of diodes are changed accordingly which account a phase delay in the transmission line and steer the main beam at a fixed frequency. Due to the systematic placement of radiating EMSIW resonator unit cell on microstrip environment, the radiation intensity is improved which further enhances the overall gain of the antenna. Simulated results show that the proposed antenna is able to operate within frequency band of 9.5-11.5 GHz with beam scanning range of 48° and maximum gain of 13 dBi. All the experimental results show a fair agreement with the corresponding simulated data that validating the proposed approach.**

I. Introduction

Leaky-wave antenna (LWA) which belongs to the traveling wave antenna family has the frequency beam scanning capability as an inherent property. For advancement of wireless technology, the demand of improved antenna performances such as high gain, high efficiency, larger scanning range etc. are highly desirable in various surveillance systems and many scanning applications. Simultaneously, for real time manipulations, it is necessary for the antenna to scan the visible space at a fixed frequency. The LWA appears to be an appropriate choice for such applications [1]. Recently, several compact LWAs based on SIW technology open a new avenue for frequency scanning antenna design [2]. SIW technology has become popular for integrated microwave and millimeter-wave circuits due to their high-density integration with subsystems, low fabrication cost, low loss and being less bulky compared to a rectangular waveguide with similar performances. By bisecting the SIW along fictitious magnetic wall, EMSIW has been realized [3] to realize the overall geometry in more compact way. For one dimensional LWA, by changing the leaky-mode propagation constant, one can electronically reconfigure the leaky-line boundary condition. In recent years, the active devices such as PIN diodes, varactor diodes etc. are extensively used in beam scanning applications. In [4], a 1D Fabry-Perot (FP) LWA has been reported which is able to scan the space from 9° to 30° at 5.6 GHz using a tunable high frequency surface. In [5], a half-width microstrip LWA has been designed where beam steering is obtained by independently tuning the loaded capacitor of the unit cell. Another FP electronically beam scanning LWA has been reported in [6] where it scans from -25° to 25° at 5.5 GHz. The varactor diodes incorporated with composite right/left-handed (CRLH) media has also been used in designing backward to forward beam scanning LWA where by changing the bias voltage of the diodes make the antenna electronically tunable [7]. Moreover, in [8], a sinusoidally modulated reactive surface has been exploited to design fixed frequency forward quadrant beam scanning electronically tunable LWA. However, most of the earlier proposed LWAs are possesses limited beam scanning with larger radiator length and complex geometry.

In this paper, an eighth-mode substrate integrated waveguide (EMSIW) incorporated with delay line is utilized to design a electronically tunable compact high gain leaky-wave antenna. The delay lines are connected with the main microstrip line based on the various states of the PIN diodes. Basically, these diodes are acting as a switch where depending upon the states of the diodes, the length of the line is changed accordingly. This change in lengths is responsible for the change in phase constant of the periodic transmission line β_n resulting into beam steering. Along with the simplicity, the proposed design is compact (3.5λ_0), providing good scanning range (48°) and fair gain (13 dBi). All the simulations are performed using Ansys High Frequency Structure Simulator (HFSS).

II. Design of EMSIW unit cell

Firstly, eighth mode SIW is developed where a square SIW resonator is divided across the perfect open symmetry plane (fictitious magnetic wall). EMSIW has two radiating edges and one bounded via edge. The electric and magnetic field components for dominant TE_{110} mode are described in [9]. Several designs of EMSIW resonator with various feeding mechanisms such as gap coupled microstrip line to either of the radiating edges [9-11], diagonal microstrip feeding [12] etc., are reported in recent years. In this paper, for design purpose, EMSIW unit cell is slightly tilted at an angle ζ with proper feeding line position. The layout of the resonator unit cell along with the electric field and surface current distributions are shown in Fig. 1(a). The tip of the open edge of tilted EMSIW resonator has the maximum magnitude of electric field which implies larger accumulation of electric

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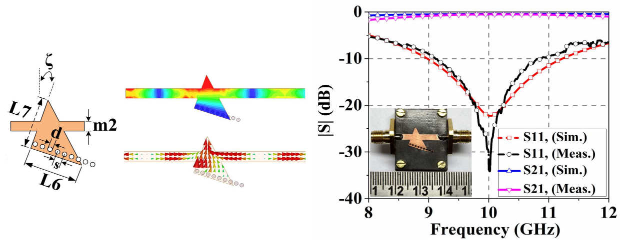
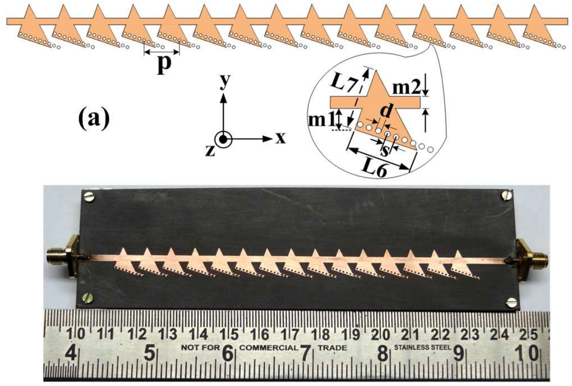


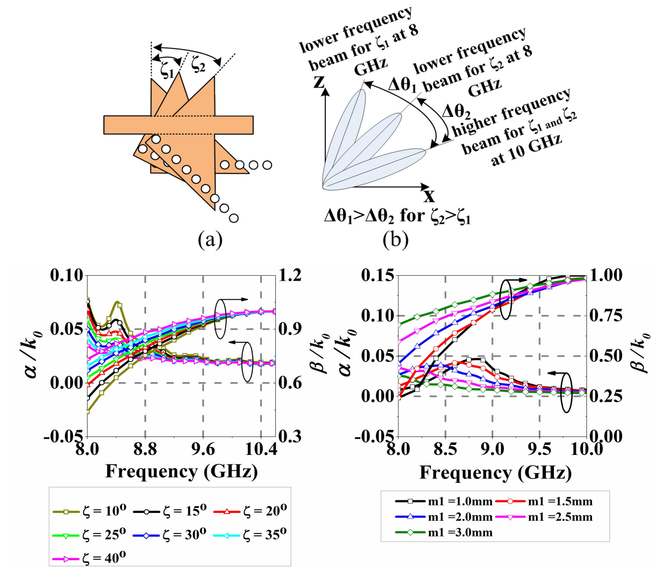
(a) (b)

Fig. 1. (a) Tilted EMSIW resonator unit cell with E-field distribution (top) and surface current distribution (bottom) (b) Comparison of simulated and measured reflection coefficients against frequency of tilted EMSIW resonator (fabricated unit-cell is in inset) with tilt angle ζ = 19°.



(b)

Fig. 2. (a) Layout of the proposed antenna (b) fabricated prototype.



(a) (b) (c) (d)

Fig. 3. (a) Tilt angle (ζ) variation (b) The effect of ζ variation on beam scanning range of the proposed array antenna where ζ_1 =19°, ζ_2=40°, $\Delta\theta_1$=51° and $\Delta\theta_2$=27° (c) dispersion diagram for different tilt angle variation (d) dispersion diagram for different microstrip line positions (m1) variation.

charges and causes disturbances of surface current and as a result a small radiation occurs. The responses of tilted EMSIW are validated by experimental results which are shown in Fig. 1(b).

III. Design of Frequency Scanning LWA: $Antenna1$

The unit cell shown in Fig. 1(a) is placed periodically with the periodicity p in such a manner that the scanning range of the antenna will be within 8-10 GHz. Fig. 2(a) shows the layout of the frequency beam scanning antenna (referred as $Antenna1$) with tilted EMSIW resonator (unit cell is in inset). The EMSIW unit cells act as a reactive loading in the $Antenna1$. The dispersive nature of $Antenna1$ is studied using 3-D full-wave iterative optimization using Ansys HFSS and is also extracted from measured scattering parameters of the antenna. The tilt angle of the cells, feeding position of the microstrip line and dielectric constant of the substrate controls the radiation characteristics as well as the scanning range of the antenna. Effect of these parameters on dispersion properties of $Antenna1$ is studied below. Fig. 3(a) and (b) show the effect on beam scanning range of $Antenna1$ due to tilt angle variation and its effect on dispersion characteristics of the respective antenna is shown in Fig. 3(c). It is clear that when tilt angle increases, normalized phase constant β increases while attenuation constant α decreases. It is also observed that deviations of β and α (for each ζ variation) with tilt angle variation are more prominent in lower frequencies than the higher end. This causes larger shift of main beam towards the end fire direction at lower frequencies with smaller value of tilt angle while at higher frequency main beam remains almost stationary (Fig. 3(b)). From Fig. 3(b), it is clear that when till angle changes from ζ_1 =19° to ζ_2=40°, the radiated main beam at lowest frequency shifts towards endfire. As a result beam scanning range is decreased from $\Delta\theta_1$ = 51° to $\Delta\theta_1$ = 27°. Similar effect is observed with feeding positions and is shown in Fig. 3(d). The phase constant of the n^{th} spatial harmonic β_n determines the direction of the main beam measured from broadside (θ_m) which is calculated from (1) given below [1]

$$\theta_m = \sin^{-1}\left(\frac{\beta_n}{k_0}\right) = \sin^{-1}\left(\frac{\beta_0}{k_0} + \frac{n\lambda_0}{p}\right) \qquad (1)$$

where k_0 and λ_0 are the wave number and wavelength in free space, respectively. β_0 is the fundamental space harmonic of unloaded microstrip line. The optimized dimensions are given by: s = 1.2 mm, d = 0.8 mm, m2 = 2.32 mm, L6 = 8.51 mm, L7 = 8.41 mm, ζ = 19, p = 8 mm, m1 = 2.4 mm. The measured forward quadrant scanning range ($\Delta\theta$) of the $Antenna1$ is 51° (37° - 88°) as shown in Fig. 4. At higher frequency range the radiation pattern distorts with higher side lobe level and gain is reduced due to the propagation of unwanted higher order modes. To make the antenna electronically tunable, the $Antenna1$ is modified by incorporating the delay line with the previously designed antenna. The design methodology and working principle are elaborately described in the next section.

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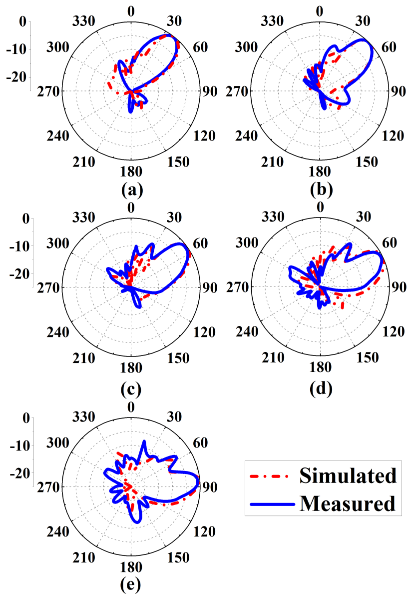

Fig. 4. Normalized simulated and measured radiation pattern in xz-plane (a) at 8 GHz (θ_m=37°), (b) at 8.5 GHz (θ_m=46°), (c) at 9 GHz (θ_m=54°), (d) at 9.5 GHz (θ_m=65°), (e) at 10 GHz (θ_m=88°).

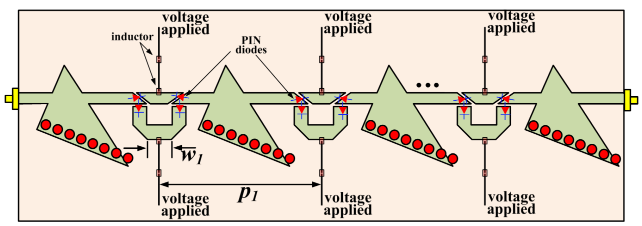

Fig. 5. Proposed electronically tunable LWA: $Antenna2$, Dimensions are: 5.36 mm, p_1=20 mm.

IV. Design of Proposed Electronically Tunable LWA: $Antenna2$

To realize the compact tunable LWA, periodic section of delay lines are incorporated in the previously designed $Antenna1$. The connectivity of the periodic sections of the delay line with the main microstrip line is realized using PIN diodes. The states of the PIN diodes control the connectivity of the transmission line as well as n^{th} harmonic phase constant which facilitate beam steering. The layout of the proposed antenna, referred as $Antenna2$ is shown in Fig. 5. In Fig. 5, it is clearly visible that for each delay line section connectivity with the main line, four PIN diodes are used. The biasing of the PIN diodes are made using biasing lines. By controlling the applied voltages of the biasing lines, the polarity of the PIN diodes are changed and thus the transmission line length is changed. The first unit cell connectivity with proper bias voltage is shown in Fig. 6. From Fig. 6, it is clear that the bottom two diodes, named as D_{1a} are used to keep the delay line section in active condition and the upper two diodes, named as D_{1b} are used to maintain the main line connectivity. If we apply the positive and negative voltages in the top and bottom pad respectively, the bottom two diodes will be ON and upper two diodes will be OFF. Hence, the signal will flow through the delay line ($green$ colored) keeping the main line isolated (red colored) as shown in Fig. 6(a). Similarly, if we now apply reverse voltages to the circuit, then the states of the diodes will be reversed and the main line will be active as shown in Fig. 6(b). The simulated response of E-field magnitude distribution of the proposed antenna is shown in Fig. 7 where in Fig. 7(a) only one delay line is active and in Fig. 7(b), two delay lines are active.

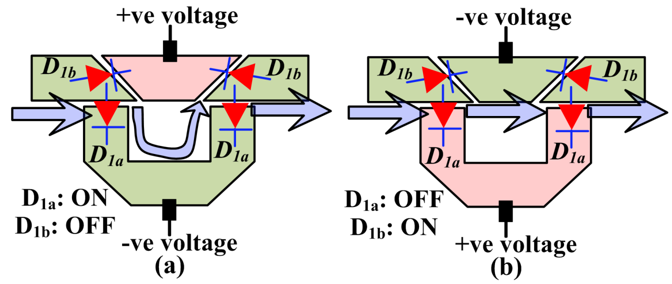

Fig. 6. Connectivity of the delay line for first unit cell with (a) D_{1a}:ON; D_{1b}:OFF, (b) D_{1a}:OFF; D_{1b}:ON

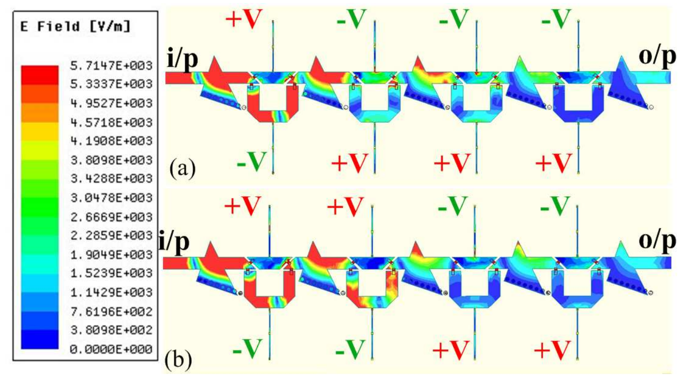

Fig. 7. E-field magnitude distribution of the proposed antenna with (a) activated one delay line, (b) activated two delay lines.

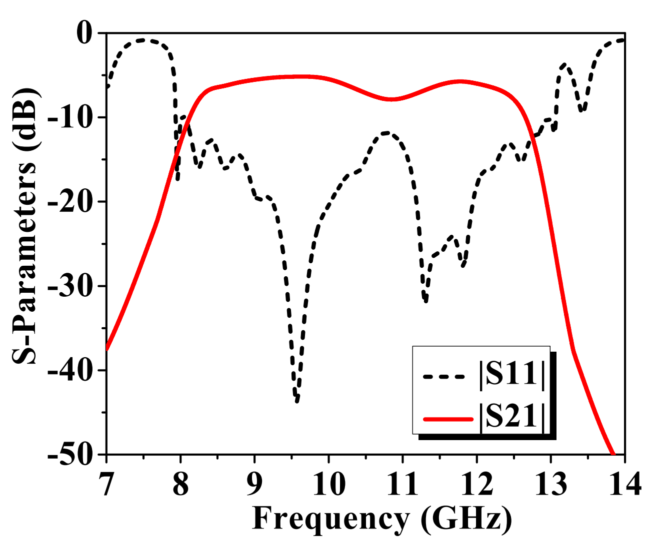

Fig. 8. Simulated response of the S-parameter for $Antenna2$.

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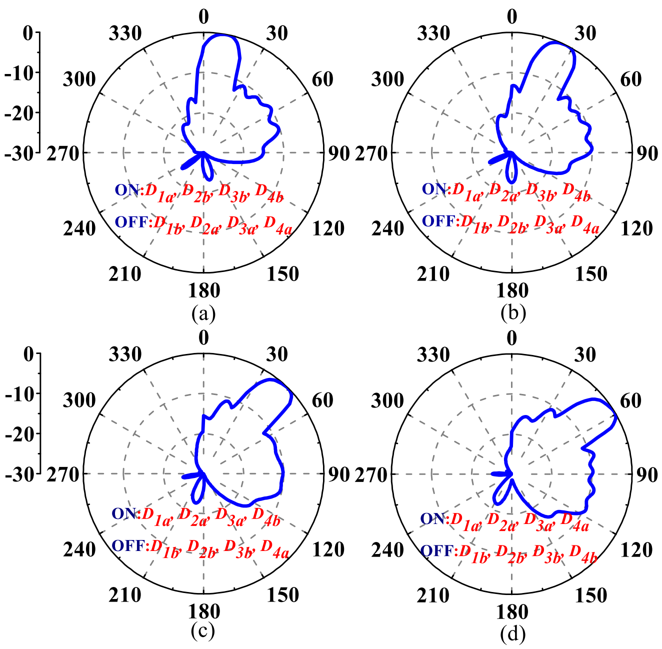

Fig. 9. Radiation patterns of the proposed antenna at 10.5 GHz for different conditions (a) 12° with activated one delay line, (b) 28° with activated two delay lines, (c) 45° with activated three delay lines and (d) 60° with activated four delay lines.

V. Results and Discussions

Since, the SIW section in this paper is radiating, the radiating space harmonic is fundamental space harmonic i.e $n = 0$. In the proposed geometry, the periodicity of the antenna is changed from the value of $Antenna1$. Thus, the operating region is also slightly changed. The S-parameter responses of the proposed antenna is shown when only two delay line sections are active as shown in fig. 8. The radiation patterns of the proposed antenna is shown in Fig. 9. at 10.5 GHz. From Fig. 9, it is observed that the periodic activation of the delay lines make the radiated beam switchable at a fixed frequency. The proposed antenna is providing a overall gain of 13 dBi with the beam steering range of 48°.

VI. Conclusion

The eighth-mode substrate integrated waveguide incorporated with delay lines has been used to implement a fixed frequency beam scanning leaky-wave antenna. By changing the states of the PIN diodes connected for the activation of delay lines, the phase constant of the geometry has been changed accordingly which is responsible for beam steering. The proposed antenna is providing overall gain of 13 dBi and at 10.5 GHz, the antenna is showing a beam scanning range of 48°. Having the advantages of being much more compact, lightweight and fair gain with simpler feeding mechanism, the proposed antenna could be the potential candidate for several fixed frequency beam scanning applications and other microwave applications.

References

[1] D. R. Jackson, A. A. Oliner '*Leaky-wave antennas*', *in Modern Antenna Handbook*. C. A. Balanis, Ed. Hoboken, NJ, USA: Wiley, blue.

[2] D. Deslandes and Ke Wu, "Accurate modeling, wave mechanisms, and design considerations of a substrate integrated waveguide," in IEEE Transactions on Microwave Theory and Techniques, vol. 54, no. 6, pp. 2516-2526, June 2006.

[3] S. Sam and S. Lim, "Electrically small eighth-mode substrate-integrated waveguide (EMSIW) antenna with different resonant frequencies depending on rotation of complementary split ring resonator," *IEEE Trans. Antennas and Propag.,* vol. 61, no. 10, pp. 4933-4939, 2013.

[4] R. Guzman-Quiros, J. L. Gomez-Tornero, A. R. Weily, and Y. J. Guo, "Electronically steerable 1-D Fabry-Perot leaky-wave antenna employing a tunable high impedance surface," *IEEE Trans. Antennas Propag.*, vol. 60, no. 11, pp. 5046-5055, Aug. 2012.

[5] D. K. Karmokar, K. P. Esselle, and S. G. Hay, "Fixed-frequency beam steering of microstrip leaky-wave antennas using binary switches," *IEEE Trans. Antennas Propag.*, vol. 64, no. 6, pp. 2146-2154, Jun. 2016.

[6] R. Guzman-Quiros, J. L. Gomez-Tornero, A. R. Weily, and Y. J. Guo, "Electronic full-space scanning with 1-D FabryProt LWA using electromagnetic band-gap," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 1426-1429, Nov. 2012.

[7] S. Lim, C. Caloz, and T. Itoh, "Electronically scanned composite right/left handed microstrip leaky-wave antenna," *IEEE Microw. Wireless Compon. Lett.*, vol. 14, no. 6, pp. 277-279, Jun. 2004.

[8] A. H. Panaretos, and D. H. Werner, "Leaky-wave antennas based on capacitively tuned modulated reactance surfaces," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 678-681, Aug. 2016.

[9] S. Sam and S. Lim, "Electrically small eighth-mode substrate-integrated waveguide (EMSIW) antenna with different resonant frequencies depending on rotation of complementary split ring resonator," *IEEE Trans. Antennas and Propag.*, vol. 61, pp. 4933-4939, 2013.

[10] H. Kang and S. Lim, "Electrically small dual-band reconfigurable complementary split-ring resonator (CSRR)-loaded eighth-mode substrate integrated waveguide (EMSIW) antenna", *IEEE Trans. Antennas and Propag.*, vol. 62, 2368-2373, 2014.

[11] H. Kang and S. Lim, "Compact right-angled triangle-shaped eighth-mode substrate-integrated waveguide antenna", *Microwave Opt. Technol. Lett.*, vol. 57, pp. 690-694, 2015.

[12] M. Mujumdar and A. Alphones, "Eighth mode substrate integrated resonator antenna at 2.4 GHz", *IEEE Antennas Wireless Propagat. Lett.*, vol. 15, pp. 853-856, 2016.

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