Bi-directional SIW leaky-wave antenna using TE_{20} mode for frequency beam scanning

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A compact bi-directional leaky-wave antenna (LWA) based on TE_{20} mode substrate integrated waveguide (SIW) is proposed at X-band. The microstrip power divider–slotline transitions are utilised to excite TE_{20} mode SIW array in order to enhance the overall radiation capability of the designed structure. The rectangular slots are etched out on the top and bottom plane of SIW such a way that the orientation of the slots can perturb the distribution of electric field at TE_{20} mode and provide bi-directional radiation. The proposed antenna is working within the frequency range of 9.6–11.2 GHz ($S_{11} < -10$ dB) having the beam scanning range of 66° from both top and bottom side of the structure with maximum gain of 14 dBi. All experimental results show a fair agreement with the simulated data.

Introduction: Over the few decades, the use of substrate integrated waveguide (SIW) has extensively increased in designing leaky-wave antennas (LWAs) due to its well-known features of being light weight, low loss, low cost and ease of fabrication process. Besides this, the higher order mode of SIW such as the TE_{20} mode is becoming attractive because of compact size and simplified geometry in order to attain specified characteristics [1]. The TE_{20} mode also appears to be quite advantageous approach of designing antenna array. So far, many researches have been reported on dual-beam LWA based on microstrip configuration [2, 3]. The dual-beam microstrip LWA has also been reported based on aperture coupling [4, 5]. Also, active dual-beam LWA with asymmetrically scanning capability is proposed in [6]. However, it is difficult to achieve higher scanning range, high gain and so on using the microstrip technology without increasing the complexity of design. Moreover, the SIW structure is more suitable for higher microwave range.

In this Letter, a LWA is designed based on the TE_{20} mode SIW. First, a TE_{20} mode SIW array is designed based on microstrip power divider and then it is exploited to design compact bi-directional LWA. Using microstrip–slotline–SIW transition, the TE_{20} mode is excited. Radiating slots are etched out periodically (maintaining the homogeneity condition) on the top and bottom wall of SIW according to the orientation of the electric field distribution.

Antenna design and analysis by TE_{20} mode SIW array: Fig. 1 shows the layout of the TE_{20} mode SIW array having microstrip power divider–slot line transition based feeding network. Microstrip power divider to slot line transition and slotline to SIW transitions are used at the input of the transmission line. By using slotlines, 180° out of phase but equal in magnitude electric fields are formed automatically on both sides of the symmetric plane of slot line (electric wall). The width of the TE_{20} SIW can be determined from [1]. The magnitudes of electric field distribution and electric field vector distribution are shown in Figs. 2*a* and *b*, respectively. The SIW array is fabricated on Rogers RT/duroid 5880 substrate with $\epsilon_r = 2.2$, $\tan\delta = 0.0009$ and height of 0.787 mm. The responses are shown in Fig. 3 which exhibit better matching characteristics along with quite low insertion loss in the designed SIW array structure over the specified frequency range. The fabricated prototype is shown in inset of Fig. 3. The design methodology of the TE_{20} mode SIW is adopted from [1]. For designing LWA rectangular radiating slots are etched on the top as well as bottom plane of the SIW depending on the *E*-field distribution. The upper half of Fig. 2*b* corresponding to side A where slots are on either side of the symmetric plane of slot line (electric wall) are orthogonally oriented (+45° and −45°). Also, for both upper and lower half of the waveguide section, the orientations of slots on top and bottom plane are inverted. Similarly, slots on side B are systematically oriented depending on the *E*-field vector distribution (Fig. 2*b*). Thus, the unit cell is realised utilising eight radiating slots shown by dashed lines in Fig. 4. Now, in order to realise the bi-directional LWA, unit cell is placed with the periodicity *p* along *y*-axis which is much compact in size having good scanning performances. To demonstrate the effectiveness of the concept, a finite lossless structure having 24 cells are designed and optimised by full-wave simulation. The layout of the antenna with unit cell is shown in Fig. 4. The periodicity of the slots is maintained by taking care about the homogeneity condition, i.e. $p \ll \lambda_0/4$. The scanning angle of the proposed antenna depends on n^{th} spatial harmonic β_n and free space wave number k_0. The antenna is working in fast wave region where $\beta_n \ll k_0$ having forward quadrant scanning capability. The direction of maximum radiation from *z*-axis can be determined from the following equation [7]:

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

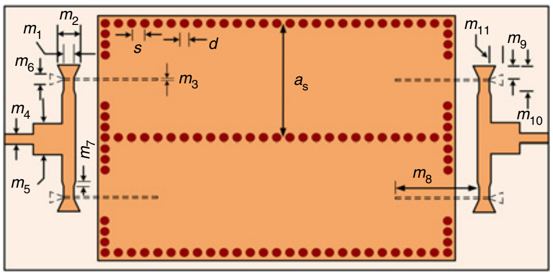

Fig. 1 *Layout of TE_{20} mode SIW transmission line with microstrip power divider–slotline transition. Dimensions are: $a_s = 22.3$ mm, $s = 1.6$ mm, $d = 0.8$ mm, $m_1 = 1.6$ mm, $m_2 = 3.5$ mm, $m_3 = 0.2$ mm, $m_4 = 2.32$ mm, $m_5 = 5.2$ mm, $m_6 = 2$ mm, $m_7 = 1.165$ mm, $m_8 = 22.84$ mm, $m_9 = 3.4$ mm, $m_{10} = 7.865$ mm, $m_{11} = 3$ mm. (not to scale)*

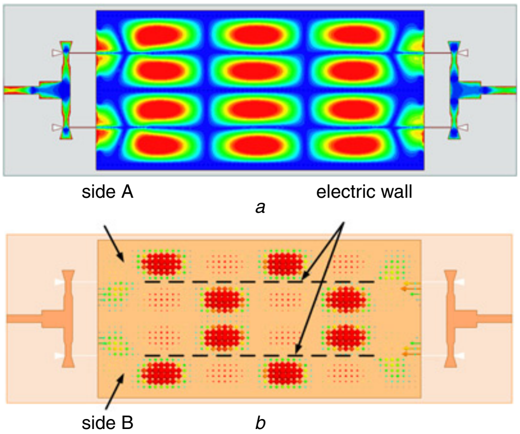

Fig. 2 *Electric field distribution in TE_{20} mode SIW*

a Magnitude of electric field distribution of design shown in Fig. 1
b Distribution of electric field vector from top view

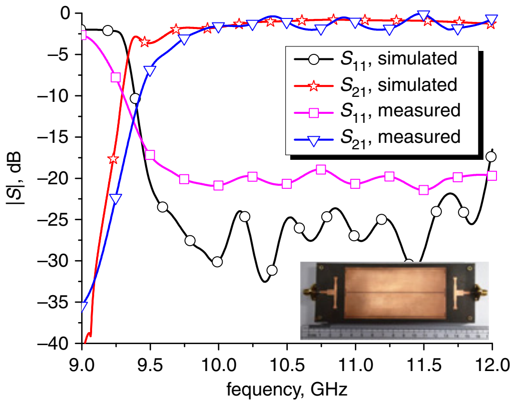

Fig. 3 *Variation of reflection coefficients with frequencies with fabricated prototype is in inset*

Results and discussions: To validate experimentally, the proposed antenna is fabricated on the Rogers RT/duroid 5880 substrate with previously mentioned specifications as shown in Fig. 5. The overall dimensions of the fabricated prototype (including feeding network) are $217 \times 51 \times 0.787\ \text{mm}^3$. The operating frequency band of the antenna is 9.6–11.2 GHz as shown in Fig. 6. The radiation characteristics were simulated and measured to confirm the bi-directional radiation behaviour of the proposed antenna. Fig. 7 shows the simulated and measured normalised radiation pattern in *yz*-plane where the measured radiated bi-directional beam scans in first and fourth quadrant simultaneously with θ increased from 14°, 36°, 46°, 56°, 70° and 80° corresponding to 9.6, 10, 10.3, 10.6, 10.9 and 11.2 GHz, respectively. The scanning range of the antenna is ~66° (9.6–11.2 GHz) in each of the two quadrants. Variation of measured peak gain and main beam direction with frequency are depicted in Fig. 8 where gain varies from 12.25 to 14 dBi within the working frequency range. The measured radiation patterns agreed well with the full-wave simulation.

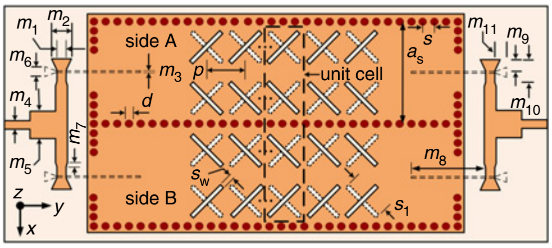

Fig. 4 *Layout of proposed bi-directional LWA where* S_l *= 5.9 mm,* S_w *= 0.8 mm, p = 5 mm (not to scale)*

Fig. 5 *Fabricated prototype of proposed bi-directional LWA*

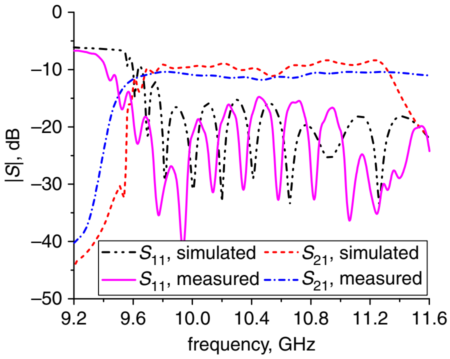

Fig. 6 *Variation of simulated and measured S-parameters (magnitude) with frequency*

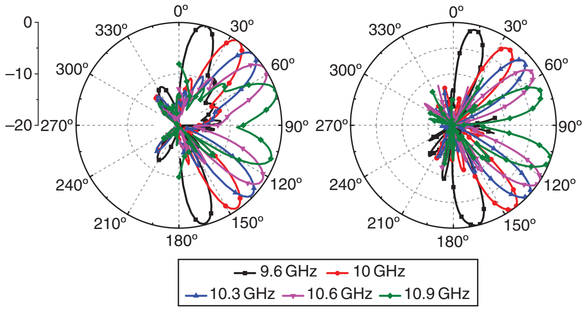

Fig. 7 *Simulated (left) and measured (right) normalised radiation pattern of proposed antenna*

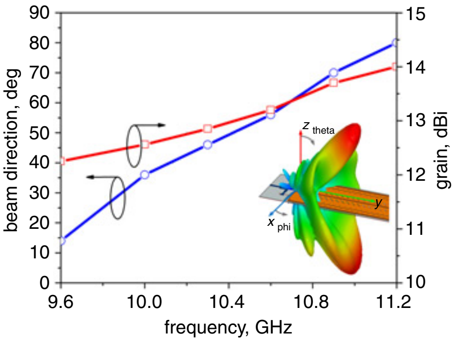

Fig. 8 *Variation of peak gain and main radiated beam direction with frequencies (3D bi-directional radiation pattern is shown in inset)*

Conclusion: A novel bi-directional LWA has been proposed at X-band based on TE_{20} mode SIW based array. By exploiting suitably oriented rectangular slots on both side of the waveguide, dual beam radiation is achieved where a continuous scanning of 66° in the elevation plane for each beam within the frequency range of 9.6–11.2 GHz is achieved. The measured peak gain of the fabricated prototype has been found to be 14 dBi. The proposed antenna is advantageous in terms of compactness, gain and scanning range compared with the conventional waveguide. The measured performances have been found to match well with the corresponding simulated values. The design can be a potential candidate for several frequency beam scanning applications like collision avoidance radars, traffic safety and so on and other microwave applications.

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One or more of the Figures in this Letter are available in colour online.

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