I. INTRODUCTION

The aviation industry currently uses multiple installed systems on the runway to guide the aircraft to touchdown points. These include instrument landing system (ILS), microwave landing system (MLS), and precision approach radar (PAR), where the main purpose is to assist the alignment of aircraft with a pre-defined glide path.

A traditional ILS system consists of a ground-based transmitter system and an airborne receiver. The transmitter system consists of two distinct modules, the localizer and the glideslope. The localizer module is located at the far end of the runway from the approaching direction and provides the aircraft with its horizontal deviation from the runway centerline. The glideslope system provides the aircraft with the vertical positioning along a predetermined glideslope, usually 3° with the runway [1]. The ILS system uses a large array of antennas operating at VHF to transmit and generate the localizer beams, but this makes the overall system heavy and non-portable. To address the limitations of the traditional ILS system and the demand for tactical deployments during disasters and emergency landing scenarios, MLS was introduced in 1960 [2].

A basic MLS system consists of azimuth and elevation ground stations and conventional distance measurement equipment (DME). The azimuth and elevation ground stations generate pencil fan beams scanning to and from, to cover a coverage area of ±40° around the runway centerline and 15° above the ground. A traditional phased array is used to produce such scanning of antenna beam patterns [3].

Due to the requirement of a very high scan rate in MLS, portable tactical approach guidance (PTAG) system for aerial landing applications is used [4]. Like ILS, the PTAG system consists of
a split-site localizer and glideslope operation but has four fixed beams that are projected in space to provide landing assistance to an approaching aircraft. However, unlike ILS, the PTAG system enjoys the benefit of portability and fast deployment. In addition, the low complexity of the system architecture as well as operating at high frequency (X-band) makes PTAG suitable to be used for UAV landing. The PTAG system uses multiple pulse transmissions using a switching technique and therefore requires four switched beams with different gain and beamwidth requirements. The antenna system is designed to provide coverage from ±5°. The centerline of four beam patterns forms the proper approach for landing safely. During landing, if the aerial vehicle is not on the center of the four beam patterns, then the intensity of the beam is not balanced. A graphical representation of the four beams is shown in Fig. 1, where two central beams are required to have high gain (maximum 30 dBi) and need to be pointing at +5° and −5°, while the other two antenna are required to have a maximum gain of 20 dBi with main beams pointing towards ±53°.

Compared to the previously reported designs (operating at X-band), the proposed antenna achieves the highest gain, largest scanning range, and smallest size.

Leaky-wave antennas take their inspiration from popular metallic waveguide structures but generally are pieces of microstrip transmission line fabricated on a dielectric substrate with their fields restricted at sides by rows and columns [5, 6]. These antennas are gaining importance due to their high efficiency, high gain, narrow beamwidth, and beam scanning capabilities [7]. Several leaky-wave antennas have been reported in the literature targeting different applications [8–16]. Moreover, different techniques have been applied to the base-slotted waveguide design for performance improvement of different parameters [8, 9, 11, 12, 15–21]. Long slots are placed on the centerline of the substrate-integrated waveguide (SIW) leaky-wave antenna to suppress cross-polarization, while a sinusoidal ridge is placed to create a controllable asymmetric electric field [17]. The periodic phase reversal radiating leaky-wave antenna offers to scan from the broadside to end-fire direction obtaining grating lobe. The antenna element is an antipodal tapered slot and is fabricated with Rogers3210 substrates [18]. A surface wave holographic traveling wave patch array antenna proposed in [22] can scan from end-fire to broadside direction in the H-plane. However, the antenna only radiates at approximately 7.7 GHz [22]. A leaky-wave antenna using piercing periodic dielectric is reported as the best candidate for millimeter-wave applications. The antenna is fabricated on an alumina substrate and can scan from −35° to 70° over a frequency range from 98 to 108 GHz with a moderate gain [10]. The theory of effective radiation section proposed a leaky-wave antenna that generates a radiation null around the desired direction or reduces the sidelobe level of the antenna simply and efficiently. The antenna can be controlled by changing the slot width [23]. The leaky-wave antenna with transverse slots propagates in TE10 mode. Periodic and uniform sets of transverse slots are introduced on the top of the leaky-wave antenna enabling it to scan from broadside to end-fire [24].

To reduce the opening or cavity size of resonators, different techniques have been proposed such as half-mode, quarter-mode, and eighth-mode. This technique allows for decreasing the size of the resonators [25–30]. The eighth-mode substrate leaky-wave antenna operates in TE110 mode. The antenna operates in eighth-mode providing miniaturization and high gain as well as improving scanning performance. The leaky-wave antenna operates from 8 GHz to 10 GHz frequency with a beam scanning angle of 51° and maximum gain of 13.3 dBi [8].

In this paper, we have presented an X-band leaky-wave antenna array for an autonomous UAV landing system following the PTAG approach. Leaky-wave technology is used for its natural beam squint, making the overall design process easier. Moreover, a single input feed allows seamless connectivity to an SP4T RF switch for switching from one beam to another.

Four such arrays are designed to direct the precision beams at ±5° and sector beams at ±53°. The arrays are placed sequentially to achieve continuous coverage of 75° where two central arrays achieve the maximum gain of 30 dBi with 60 elements each while the side arrays achieve 20 dBi gain with 30 elements each. The ADR5040 SP4T RF switch is selected to change between different beams. Section II elaborates on the design procedure of the proposed leaky-wave antenna. Section III presents the theoretical analysis of the designed prototype. Section IV presents a discussion on results, while Section V presents the conclusion.

II. ANTENNA DESIGN

The overall antenna design process was accomplished in two
steps. Firstly, an appropriate shape was selected based on the highest achievable gain. Once an appropriate shape was selected, several parameters such as feeding length, resonating tip, tilt angle, inter-element distance, and so on were analyzed and adjusted to optimize the performance.

1. Design Selection

Five previously reported resonator shapes [8, 27, 28]—bowtie, polygon, circle, rectangle, and triangle—were designed and compared against achievable gain and efficiency. Performance based on a single element is presented in Table 1, where it can be seen that the polygon shape performs best with regards to gain and radiation efficiency.

In contrast to previously reported designs, an elliptical-shaped element is proposed as the primary radiating element for the leaky-wave antenna. An ellipse with specific major and minor axes has a great impact on the antenna performance. The ellipse antenna can offer larger gain, bandwidth, and beam scanning compared with previously reported shapes due to its tip. Table 1 shows the performance advantage of the ellipse shape over the other previously proposed shapes, where the elliptical element achieves the highest gain and radiation efficiency.

2. Parametric Analysis

Once the base design was selected to be an ellipse, its other design parameters were calculated and implemented in the simulation software. Several design parameters were analyzed to find out the optimum dimensions for achieving the desired performance. Parametric analysis of important parameters along with simulation results is presented in the following.

2.1 Feeding length

Feeding length was the first parameter that was varied to see the effect on antenna performance. The results of changing feeding length are shown in Fig. 2, and the $S_{11}$ (reflection coefficient) result shows the best performance for a feeding length of $\lambda = 16$ mm.

2.2 Ellipse shape

Another important parameter that affects the impedance bandwidth of the antenna is the overall shape of the ellipse. Different values of major and minor axes were studied to assess $S_{11}$ performance, and it was observed that the best performance is achieved for major axis and minor axis values of 4 mm and 12 mm, respectively. This changes the ellipse direction from horizontal to vertical. Simulation results of the same are presented in Fig. 3.

2.3 Tilt angle

The tilt angle of the antenna also has a huge impact on the $S_{11}$ parameter. The reflection coefficient performance of the antenna was observed for several tilt angle values and is presented in Fig. 4. A straight vertical ellipse with $0^\circ$ tilt angle demonstrated

| Table 1. Comparison of the proposed shape of the antenna to other shape designs |
|-------------------------------|----------------|---------|
| Shape            | Gain (dBi) | Efficiency |
| Ellipse (proposed design) | 5.71       | 0.99    |
| Rectangle        | 4.83       | 0.93    |
| Bowtie           | 3.94       | 0.88    |
| Circle           | 4.33       | 0.93    |
| Polygon          | 5.46       | 0.94    |
| Triangle         | 3.91       | 0.94    |

Fig. 2. Feeding length reflection coefficient response.

Fig. 3. $S$-parameter results for variable major and minor axis.

Fig. 4. Variation of tilt angle against frequency.
the best results for the input reflection coefficient.

2.4 Periodic distance

The periodic distance (P) between the resonating ellipses has a very high impact on the antenna radiation characteristics; it not only controls the beam direction but also changes the antenna mode of operation. The beam scans from the backward quadrant (270°) to the forward quadrant (5°) by increasing the periodic distance (P), as shown in Fig. 5. Periodic distances are fixed at 19 mm and 15 mm for pointing the beam at 5° and 53°, respectively.

Table 2 shows the optimized values of the key design parameters. These values have been selected based on the parametric simulations and have been shown to demonstrate the best results.

### III. SIMULATION RESULTS

The final values of the key design parameters are presented in Table 2. A leaky-wave antenna based on these design values was simulated in High-Frequency Structural Simulator (HFSS). The antenna was designed using Rogers Duroid5880 ($\varepsilon_r = 2.2$, $\tan\delta = 0.0009$) with a thickness of 1.575 mm. Simulation results such as reflection coefficient, radiation patterns, and antenna efficiency are presented in Figs. 6–8. It can be seen from Fig. 6 that the antenna operates from 9.3 GHz to 12.5 GHz, which is more than is required for the PTAG system. Moreover, simulated radiation patterns showing antenna beams at the

![Simulated radiation patterns for different values of periodic distance (P): (a) P = 14 mm, (b) P = 15 mm, (c) P = 16 mm, and (d) P = 17 mm.](image)

**Table 2. Optimized parameter values of the antenna**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feeding length (mm)</td>
<td>8</td>
</tr>
<tr>
<td>Periodic distance (mm)</td>
<td>19</td>
</tr>
<tr>
<td>Tilt angle (°)</td>
<td>0</td>
</tr>
<tr>
<td>Feeding width (mm)</td>
<td>2.32</td>
</tr>
<tr>
<td>Major axis (mm)</td>
<td>4</td>
</tr>
<tr>
<td>Minor axis (mm)</td>
<td>12</td>
</tr>
<tr>
<td>Layout size (mm)</td>
<td>$20 \times 30$</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>1.575</td>
</tr>
</tbody>
</table>
required ±5° and ±53° are shown in Figs. 7 and 8, where the designed array achieves the required gain.

Antenna efficiency is plotted against frequency in Fig. 9, and the value is more than 90% for most of the bandwidth. The antenna leakage rate is also plotted in Fig. 10, where leakage loss (α) is gradually increased with the frequency while the propagation phase constant (β) shows the forward wave region within the operating frequency band. Outside the operating frequency band, the phase propagation constant is in the backward-wave region, where antenna performance is poor.

**IV. THEORETICAL ANALYSIS**

This section verifies the performance of the proposed structure against theoretical formulas. This is done to further the confidence in the selected design parameters, presented in Table 2, as only a sub-array is fabricated and measured.

The dominant mode of the periodic leaky-wave antenna is slow-wave mode and calculated from Eq. (1):

\[
v_p = \frac{k_0}{\beta}c.
\]  

(1)

Calculating the values at 10 GHz and parameters reported in Table 2, we find that:

\[
k_0 = \frac{2\pi(10\times10^9)}{3\times10^8} = 209.
\]

Thus, \(\beta = 220\). Calculated from the simulation at the given frequency the phase velocity is:

\[
v_p = \frac{k_0}{\beta}c = \frac{209}{220} c = 0.95c.
\]

\(v_p = 0.95c\), which is less than the speed of light, indicating that the traveling wave antenna is propagating in slow-wave mode.

The radiation condition for the periodic leaky-wave antenna is \(\beta_n d < 1\), where \(\beta_n\) is the phase propagation constant and \(k_0\) is the wave number. The antenna can scan from end-fire (backward quadrant) to broadside (forward quadrant) within the range of 9.3–12.3 GHz. Beyond the proposed frequency range, the antenna goes to \(\beta_n d = 1\), which is a necessary condition for stopband, where the antenna radiation performance starts declining. The dispersion characteristic of the periodic antenna is presented by the Brillouin or \(k - \beta\) diagram, shown in Fig. 11, and is determined by:

\[
\beta = \sqrt{k^2 - k_c^2} \quad \text{or} \quad k = \sqrt{\beta^2 + k_c^2},
\]  

(2)

where \(k_c\) is the cut-off wavenumber mode.

When \(k < k_c\), no real solution is possible for \(\beta\), so the periodic antenna will be in non-propagating mode. However, when \(k > k_c\), the antenna will be in propagating mode.
Further to the Brillion diagram, the equation for pass band and stop band is given by:

\[ \cos \beta d = \cos kd - 1.4kd \sin kd. \] (3)

The most straightforward way is to calculate the numerical value of the right hand of Eq. (3) with the value of \( kd \), starting from 0. For the magnitude of the right-hand side less than or equal to the unity, we have pass band, and Eq. (3) can be solved for \( \beta d \). However, when the magnitude of the right-hand side is greater than unity we have a stop band. Fig. 12 shows the pass band and stop band values at different positions.

In the pass band region, the wave propagates along with the structure and the characteristic parameters of the antenna show optimal results. In stop band, the characteristic parameters of \( S_{11} \), efficiency, gain, and so on are declined. Moreover, the wave does not propagate along with the structure but is attenuated along the line. It can be seen from Fig. 12 that the proposed elliptical structure operates in a pass band for the desired frequency.

Boresight direction (\( \theta_m \)) of the antenna and beamwidth (\( \Delta \theta \)) are calculated using:

\[ \theta_m = \sin^{-1} \left( \frac{\beta_0}{k_0} \right) = \sin^{-1} \left( \frac{\beta_0}{k_0} + n \frac{\lambda_0}{d} \right), \] (4)

where \( \theta_m \) is measured from the broadside direction while \( \beta_0 \) is the fundamental space harmonic propagation phase constant.

\[ \Delta \theta \approx \frac{1}{\lambda \cos \theta_m}, \] (5)

\( L \) is the length of the leaky-wave antenna, \( \Delta \theta \) is the beamwidth of the antenna, and \( k_0 \) is the wavenumber \( \frac{2\pi}{\lambda} \).

V. FABRICATION AND MEASURED RESULTS

To validate the performance, a smaller sub-array of 15 elements was designed and manufactured. The fabricated 15 element array is shown in Fig. 13.

A comparison of the simulated and measured patterns is presented in Fig. 14. It can be seen from the figure that the antenna can scan from 10° to 85°. The measured and simulated gain is plotted in Fig. 15. The gain varies from 10 dBi to 17 dBi, and the frequency where the maximum gain is achieved is 10.5 GHz. The fabricated 3 dBi gain bandwidth is on 10.2 and 10.3 GHz.

Table 3 compares the performance of the proposed design with that of previously reported works. Parameters chosen for comparison are percentage bandwidth, achievable gain, and scanning range. In comparison to [22], the proposed antenna achieves a higher gain with fewer resonating elements. In terms of bandwidth, gain, and beam steering, the proposed design performs better against [14] while having the same size and resonating elements.
VI. CONCLUSION

A new ellipse-shaped traveling leaky-wave antenna is presented. The antenna operates from 9.3 GHz to 12.3 GHz, achieving a maximum gain of 30 dBi. A smaller sub-array is fabricated for performance verification, achieving a gain from 10 dBi to 17 dBi over the operating frequency range. A 75° beam scanning is achieved. The proposed antenna can be easily designed and has a simple feeding mechanism, with low cost and high gain. This proposed antenna is a proficient antenna for different microwave applications at X-band, such as for use in autonomous landing systems.

REFERENCES


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