



OPEN Low-cost Kirigami-inspired deployable dual-polarized MIMO antenna with angular pattern diversity

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This work presents a low-cost, easy-to-fabricate, kirigami-inspired deployable MIMO antenna operating at 2 GHz, featuring dual polarization and angular pattern diversity. Inspired by the Yagi antenna design, the proposed MIMO antenna comprises two orthogonally oriented antennas, each consisting of a rectangular radiating element (monopole) and one parasitic rectangular strip (director). These are integrated onto a foldable, staircase-shaped Kirigami structure made of polyethylene terephthalate (PET) sheet. Each antenna includes a reflector attached to the Kirigami structure's back. Operating at 2 GHz, the antenna achieves a measured peak gain of 9 dBi with a -10 dB impedance bandwidth of 630 MHz (1.82 GHz to 2.45 GHz). Mutual coupling between the radiating elements is maintained below -15 dB, and the total efficiency exceeds 80% across the operating band. The antenna system meets MIMO specifications, demonstrating an Envelope Correlation Coefficient (ECC) below 0.0025 and a Channel Capacity Loss (CCL) below 0.35 bps/Hz. This combination of high performance, low cost, and ease of fabrication makes the proposed design a promising candidate for diverse microwave applications.

Keywords Kirigami antennas, Deployable antenna, Yagi antenna, Foldable antenna

Deployability in satellite communication systems refers to the capability of an antenna structure to expand from a compact, stowed configuration to its full operational form. This attribute is particularly critical for applications requiring rapid mobility, space efficiency, and ease of deployment. In satellite missions, antennas must be sufficiently compact to fit within the constrained volume of launch vehicles, yet capable of expanding to their full dimensions once in orbit¹. Moreover, many modern missions demand antennas that can operate over multiple frequency bands to support diverse communication functions². These dual requirements such as compact stowage and broadband operation have motivated extensive research into innovative deployable antenna systems. Among the commonly explored configurations, planar, reflector, and wire antennas remain popular choices^{3–5}. Planar antennas, including patch and slot types, have attracted attention in Pico and nanosatellite systems due to their low profile and ease of fabrication; however, their inherently narrow bandwidth remains a limitation^{6,7}. Reflector antennas offer higher gain but often involve complex mechanical deployment mechanisms and limited bandwidth⁸. These challenges become even more pronounced at lower frequencies such as HF and UHF, where antennas grow physically larger, complicating integration and transportation³. Consequently, deployable antenna concepts have emerged as viable solutions, offering compact stowage during launch and expansion to full size post-deployment, thereby minimizing cost and volume constraints⁹.

Origami-inspired mechanisms have introduced a promising paradigm for realizing deployable antennas, owing to their lightweight, foldable, and easily reconfigurable structures¹⁰. In particular, for military and remote-area communication systems, origami-based antennas are highly advantageous due to their portability, rapid deployability, and minimal logistical requirements¹¹. Conventional field antennas often require specialized assembly tools or rigid support structures, limiting their usability in harsh or time-sensitive environments¹⁰. In contrast, origami antennas can be fabricated from flexible materials using simple folding patterns, enabling rapid

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setup in remote or emergency scenarios without the need for complex infrastructure^{10,12}. Extending the origami concept, kirigami introduces deliberate cuts into the structure, enhancing flexibility and reconfigurability^{12–14}. Kirigami, by integrating paper-cutting techniques into origami methodologies, retains the benefits of origami while introducing greater adaptability and the capacity to realize more diverse designs^{13–15}. To create intricate three-dimensional (3D) structures that use both compression and tension, kirigami deliberately makes cuts in planar sheets prior to folding, in contrast to traditional origami, which mostly depends on folding. Through the careful design of positional-dependent incisions in certain patterns on flexible substrates, engineers can create precisely customized structures and greatly improve reconfigurability through bending, twisting, and stretching. Recent studies have demonstrated the versatility of kirigami for foldable, stretchable, and reconfigurable electronic systems, expanding their potential for field-deployable communication platforms^{10,12,13,16}.

Multiple-Input Multiple-Output (MIMO) technology introduces an essential advancement in antenna design by utilizing multiple transmitting and receiving elements to achieve higher data rates, improved channel capacity, and enhanced spectral efficiency compared to conventional Single-Input Single-Output (SISO) configurations^{15–17}. Over the past decade, MIMO techniques have been extensively implemented across various wireless communication standards, including 5G, LTE, UWB, and WLAN, owing to their ability to support massive connectivity and mitigate multipath fading effects^{18–25}. Despite these significant developments, the integration of MIMO principles within structurally reconfigurable and deployable antenna platforms, particularly those based on origami and kirigami mechanisms has received limited attention in the literature. To date, only a few studies have reported kirigami-inspired MIMO antenna prototypes^{26,27}. While most origami/kirigami-based antennas remain limited to SISO designs¹⁰. Such configurations inherently restrict data throughput and adaptability in complex field environments, underscoring the need for MIMO-enabled deployable architectures.

To address the mentioned limitations, the present work proposes a foldable and deployable MIMO antenna that combines the structural adaptability of kirigami with the high spectral efficiency of MIMO. The design aims to support robust and high-capacity communication links in remote, mobile, and military field environments, where compactness, rapid deployment, and reliable performance are of paramount importance. The proposed configuration employs two rectangular monopole radiators with directors, integrated on a PET substrate with PCB reflectors. It resonates at 2.0 GHz, offering a measured gain of 9 dBi and a ~ 10 dB impedance bandwidth of 630 MHz. Parametric analysis confirms optimal monopole spacing with mutual coupling maintained below -15 dB, ensuring stable and efficient operation under field-deployable conditions. Furthermore, comparative studies demonstrate superiority of the proposed design to a range of state-of-the-art antennas reported in the recent literature. The novelty of this work lies in the integration of a kirigami-inspired deployable architecture with a dual-polarized, two-element MIMO configuration exhibiting angular pattern diversity, implemented on a low-cost flexible PET substrate.

The remainder of the paper is structured as follows. The development process of the proposed antenna along with fabrication steps is explained in Section II. Section III presents the parametric analysis of the designed antenna. Section IV summarized the findings from both simulation and experimental data. The paper's final section, Section V, concludes with a summary of the main contributions and potential future work.

Kirigami geometry design and antenna fabrication

A. Kirigami Geometry:

The kirigami geometry depicted in Fig. 1 was designed to enable a compact stowed configuration and a stable three-dimensional deployed state, while maintaining good electromagnetic performance. The staircase-shaped kirigami pattern was selected because it provides discrete elevation levels, allowing precise control of the spacing between the radiating elements and the reflector.

Strategic vertical cuts enable out-of-plane deformation, while the horizontal fold lines define the stair heights, providing precise control over the elevation of each step. This staircase configuration also allows controlled

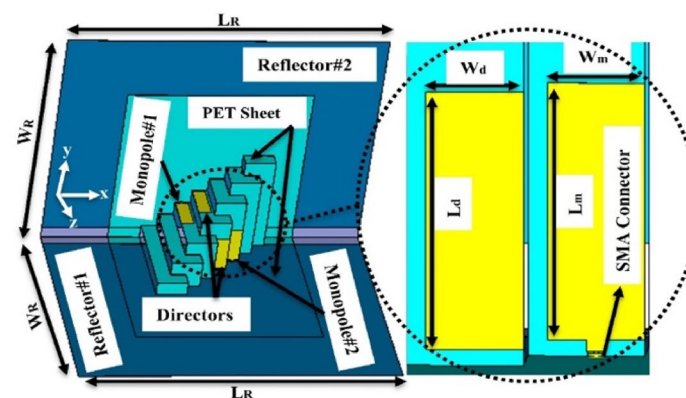


Fig. 1. Proposed Kirigami antenna with key dimensions such as $L_r = 145$ mm, $W_r = 145$ mm, $L_d = 30$ mm, $W_d = 10$ mm, $L_m = 30$ mm, $W_m = 10$ mm.

placement of the two monopole radiators at specific levels of the kirigami structure. In the optimized design, the two monopoles are positioned symmetrically on the third staircase level, providing appropriate electrical spacing from the reflector and ensuring stable mechanical deployment. Consequently, the kirigami geometry not only enables deployability but also supports the spatial arrangement of the monopoles and directors, contributing to improved radiation characteristics, polarization diversity, and reduced mutual coupling between the antenna elements.

The monopole radiators were positioned to achieve an optimal trade-off among isolation, polarization diversity, and deployability. As the proposed structure is symmetric, the director associated with antenna-2 (monopole-2) is fixed on the fourth staircase level on the right side, while antenna-2 is located on the third staircase. In contrast, the position of antenna-1 (monopole-1), starting from the first step on the left side together with its director, was varied along the horizontal direction to determine the optimal configuration. The resulting three configurations, denoted as cases a, b, and c, along with their corresponding S-parameters and radiation patterns, are illustrated in Fig. 2.

For case a, the resonant frequency of antenna-1 shifts upward to 2.2 GHz and is accompanied by degradation in S_{21} and the radiation pattern, as shown in Fig. 2(a). In case b, the resonant frequencies and radiation pattern of antenna-1 become distorted, although S_{21} improves within the desired band, as illustrated in Fig. 2(b).

In contrast, case c exhibits improved S-parameter performance along with stable gain and radiation characteristics, as shown in Fig. 2(c). However, in this configuration, the isolation between the two antennas S_{21} is degraded. So, for optimal trade-off between S-parameters, gain along with stable radiation we choose the optimized design shown in Fig. 1. In the optimized designed the two monopole radiators were placed in a way that provided the best trade-off regarding isolation, polarization diversity and deployability. The two monopoles are positioned symmetrically on the third level of the staircase of the kirigami structure to maintain the mechanical stability and uniform deformation throughout the deployment. Their orthogonal format allows dual polarization and low correlation of patterns, and their opposite layout reduces the interaction of surface currents, which enhances isolation without further decoupling networks. The 36 mm spacing between each monopole and the corresponding reflector was optimized to maximize forward radiation and gain and ensure that mutual coupling is less than -15 dB which was verified by parametric analysis.

B. Antenna Fabrication:

The Kirigami geometry is implemented on a PET sheet with a dielectric constant of 3 and a loss tangent ($\tan \delta$) of 0.02. The Kirigami-based pop-up geometry shown in Fig. 1 ensures that the antenna is radially deployable. The complete and step-by-step procedure of the proposed design is shown in Fig. 3. The proposed Kirigami-based MIMO antenna consists of two radiating elements (monopoles), with a parasitic element (director), in front of each monopole. Two reflectors made of copper sheets are attached at backside of Kirigami geometry. The metallic reflectors positioned behind each monopole serve to suppress backward radiation, enhance forward gain, and improve front-to-back ratio. In addition, the reflectors contribute to reduced mutual coupling by limiting surface wave propagation between the radiating elements. The orientation of the two antennas is orthogonal; one is horizontal while the other one is vertical.

The design process begins with the preparation of a sketch containing the required dimensions, was drawn on paper as shown in Fig. 3(a). A PET sheet of $145 \text{ mm} \times 145 \text{ mm} \times 0.25 \text{ mm}$ was then placed over the paper sketch. The PET sheet was carefully aligned with the central reference lines as illustrated in Fig. 3(b). The red vertical solid lines which are shown in Fig. 3(c) with yellow dotted circles BB' were cut using a standard cutter. While the green horizontal solid line highlighted by black dotted circles CC' and red horizontal solid line which is encircled by black dotted circles DD' which are indented with a screwdriver and marker shown in Fig. 3(d) are bends inward (red lines) and outward (green lines), after which the paper was removed, yielding the staircase-shaped PET sheet which is shown in Fig. 3(e). After this a copper strip with required dimensions which as shown in Fig. 3(f) are pasted on PET sheet. The copper strips which comprise of two monopoles and two directors with required dimensions, shown in Fig. 1, are pasted at two different locations on PET sheet. The two monopoles along with directors on PET sheet can be seen in Fig. 3(g) and Fig. 3(h) respectively. Each monopole was fed using a 50- Ω SMA connector, with the inner conductor soldered to the monopole and the outer conductor connected to the ground/reflector. The inner conductor (pin) of SMA connector soldered with monopole can be seen in Fig. 3(i) while the outward structure of SMA connected with ground/reflector can be seen in Fig. 3(j). The final assembled design, comprising two reflectors, two monopoles, and directors, is shown in Fig. 3(k). The antenna system was modeled and simulated using CST Microwave Studio, a commercial full-wave electromagnetic solver.

Parametric analysis

A parametric study was performed at a resonance frequency of 2.0 GHz to optimize the radiation performance of the antenna, specifically gain, beamwidth, and mutual coupling. The number of parasitic directors, the monopole length L_m , and the distance S_L between the monopole and reflector were the main parameters investigated. The proposed antenna incorporates two rectangular monopole resonators placed symmetrically on the third staircase level, positioned opposite each other and located 36 mm away from the reflector, as illustrated in Fig. 1. This configuration yields an optimal bandwidth of 630 MHz with mutual coupling below -15 dB within the resonance band. A systematic investigation of the design parameters revealed that increasing the distance between the resonating monopoles further reduces mutual coupling. However, this adjustment also shifts the resonance frequency and reduces gain. Conversely, decreasing the spacing by moving the monopoles closer to the reflectors further reduced coupling but also diminished gain and altered the resonance frequency. The optimal monopole length of 30 mm was determined to provide a balance of high gain, wide bandwidth,

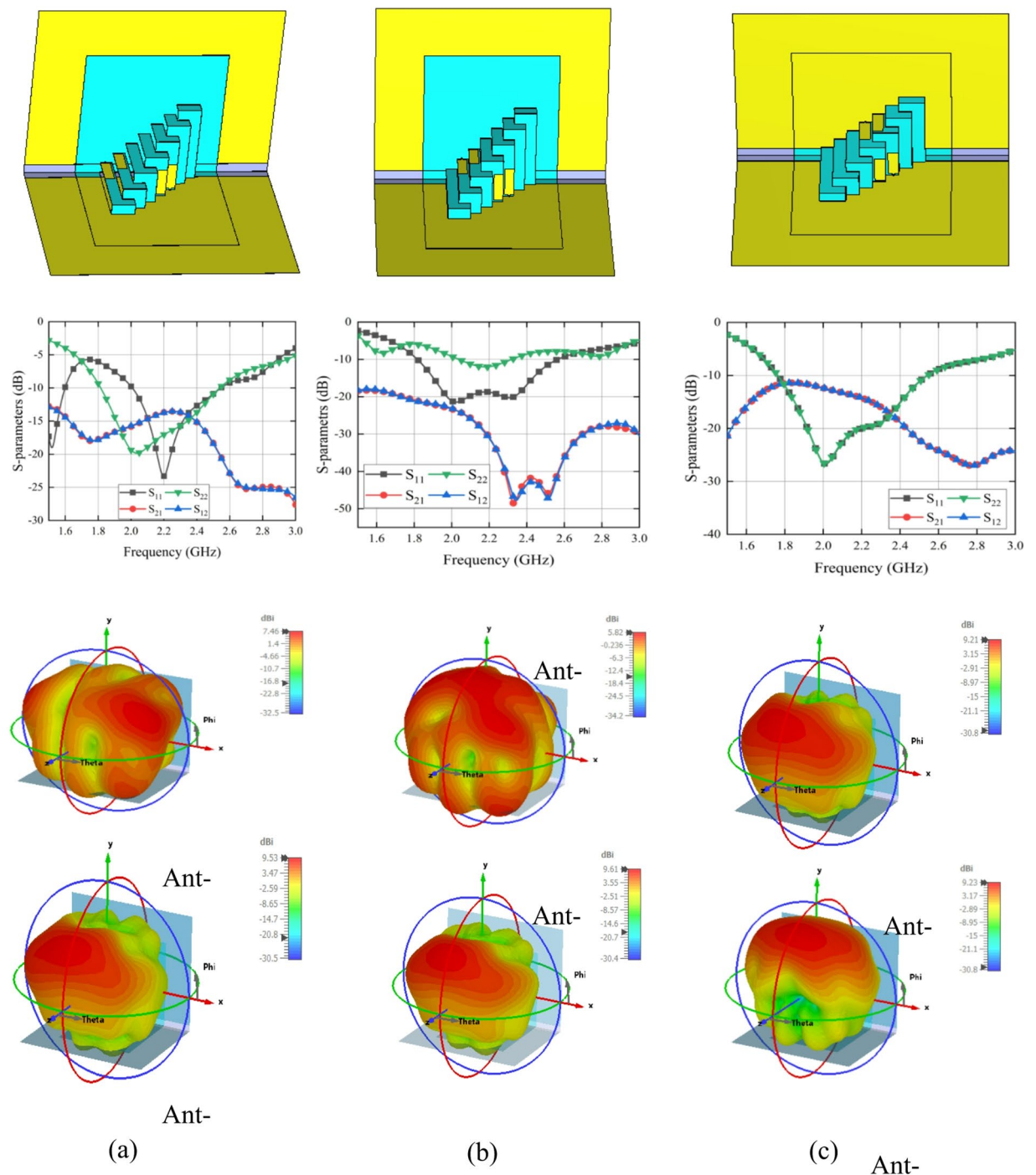


Fig. 2. S-parameters and 3D radiation pattern for Ant-1 and Ant-2 for the three cases: (a), (b) and (c).

and minimized mutual coupling. Deviations from this length shift the resonance frequency, with longer monopoles exhibiting lower coupling than shorter ones. Even though the suggested design already exhibits a large beamwidth compared to conventional Yagi antennas, the gain was not appreciably increased by adding a second director. Therefore, a single director was adopted to achieve a peak azimuthal measured gain exceeding 9 dBi. The width of the monopole (set at 10 mm) was found to have negligible impact on antenna performance.

Figures 4(a)–(d) show the relationship between monopole length L_m and the resonant frequency, antenna gain and the number of directors, Kirigami stairs height or the steps height S_L and its effect on S_{11} and S_{21} , gain and its relation with stairs height S_L and S_{21} . Figure 4(a) shows the parametric analysis of monopole length L_m in the range from 25 mm to 45 mm. We choose a value of $L_m = 30$ mm due to good matching and an optimal bandwidth. Figure 4(b) illustrates the relationship between the antenna gain and the number of directors. As the number of directors increases to one, the gain improves due to enhanced directivity and constructive field

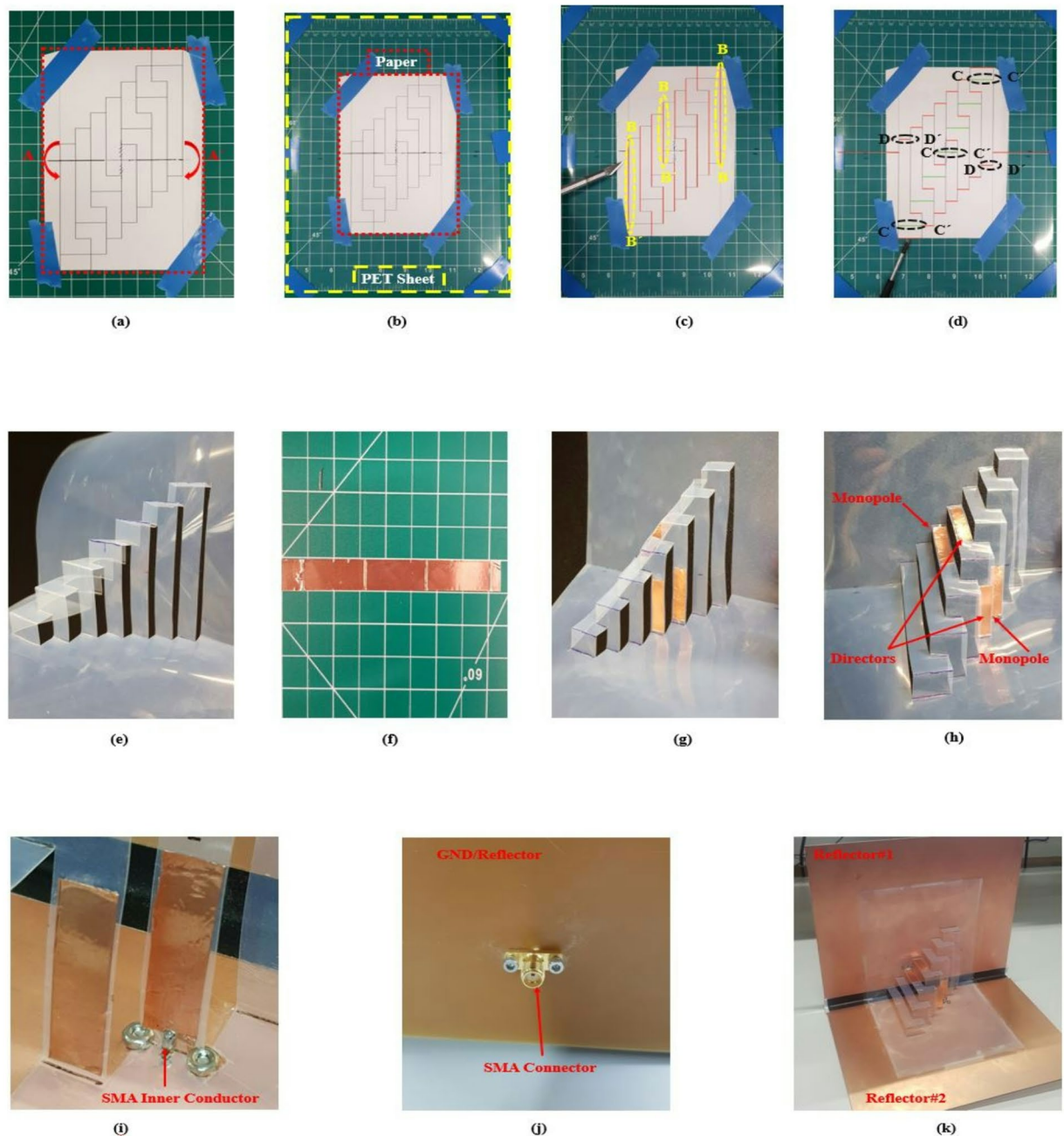


Fig. 3. Kirigami antenna fabrication steps: (a) Paper sketch (b) Paper with PET sheet pasted (c) Cutting vertical solid red lines (d) indenting horizontal green and red solid lines (e) 3D PET only shape (f) Copper strip (g) PET sheet with copper strips (h) PET sheet with copper strips' front view (i) Zoomed view of monopole & director (j) SMA connector (k) Final design with reflector.

combination, and it remains relatively stable up to two directors. However, when the number of directors reaches three, mutual coupling effects become dominant, leading to a degradation in gain performance. Figure 4(c) depicts the variation of S_L and its effect on the S-parameters while the monopole length is kept constant. Figure 4(d) depicts gain and S_{21} variation against the stair's height with discrete values such as 12 mm, 17 mm, 22 mm and 27 mm. When the stairs height increases from 12 mm to 17 mm the gain increases above 9 dB while S_{21} decreases further touching the value of -22.5 dB. When the stairs height changes to 22 mm the gain drops and the S_{21} decreases further till the value reverses and increases while the gain value is lowest. This optimized design offers an optimal beamwidth compared to traditional Yagi antennas.

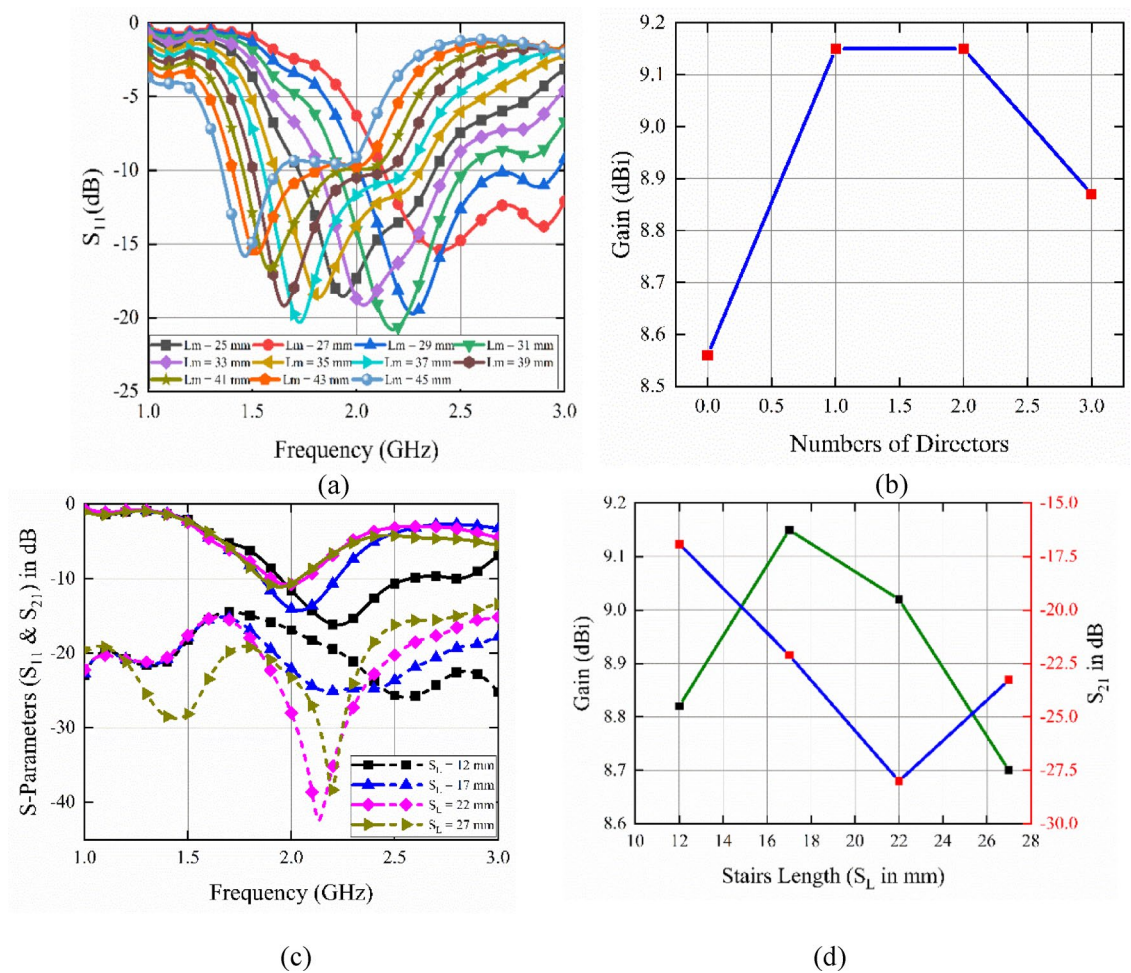


Fig. 4. Parametric analysis of Kirigami antenna: (a) Monopole length L_m , (b) Number of Directors (Parasitic elements) (c) S-parameter variation as a function of S_L (d) Distance between the reflector and the monopole depicted as S_L variation.

Results and discussion

This section discusses the results obtained for the proposed design. Figure 5 shows the reflection coefficient for both resonating elements. The peak dip for both S_{11} and S_{22} is observed at 2.0 GHz. The results show that the proposed MIMO system achieved a bandwidth of 630 MHz (1.82–2.45 GHz). In the intended operating band, the mutual coupling between the resonating parts is less than -15 dB, as observed in Fig. 5. Furthermore, to demonstrate that the presented system works as a viable MIMO system for future modern microwave devices, efficiency and one of the key performance indicators for MIMO system, the Envelope Correlation Coefficient (ECC) is calculated. The antenna gain and directivity are first measured using a reference horn antenna with known gain. The efficiency is then calculated using a well-known relationship between gain and directivity proposed in^{28,29} i.e. $G = \eta D$. The measured antenna total efficiency at resonating frequency is almost 95% and it remains above 80% across the operating band, as shown in Fig. 6(a). The ECC value in the operating band is less than 0.0025 as shown in Fig. 6(b). ECC was estimated with the help of S-parameter-based formulation, which is popular with compact MIMO antennas because it is simple and accurate in the case of stable radiation patterns. The relevant S-parameter equation for ECC computation is³⁰:

$$ECC = \frac{|S_{11} * S_{12} + S_{21} * S_{22}|^2}{(1 - |S_{11}|^2 - |S_{21}|^2)(1 - |S_{22}|^2 - |S_{12}|^2)} \quad (1)$$

Where S_{11}/S_{22} and S_{21}/S_{12} are the reflection and transmission coefficient of the proposed design respectively. The antenna gains and channel capacity loss are also calculated. The simulated and measured gain of the antenna are presented in Fig. 7(a). The measured gain value for Ant-1 at resonating frequency is 9.05 dBi while for Ant-2 the gain value is 8.94 dBi. Channel capacity loss (CCL) which is actually the maximum limit of data transmission rate at which a signal can be sent continuously without any interruption for proposed antenna is found to be less

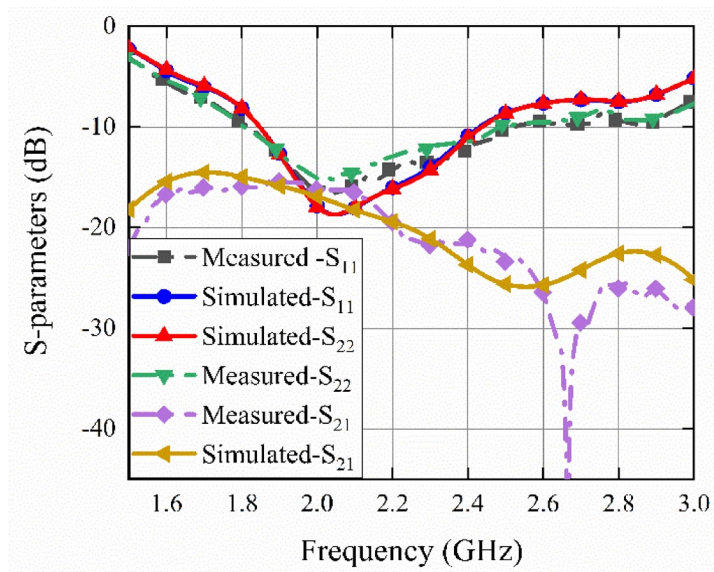


Fig. 5. Scattering parameters of the proposed MIMO system.

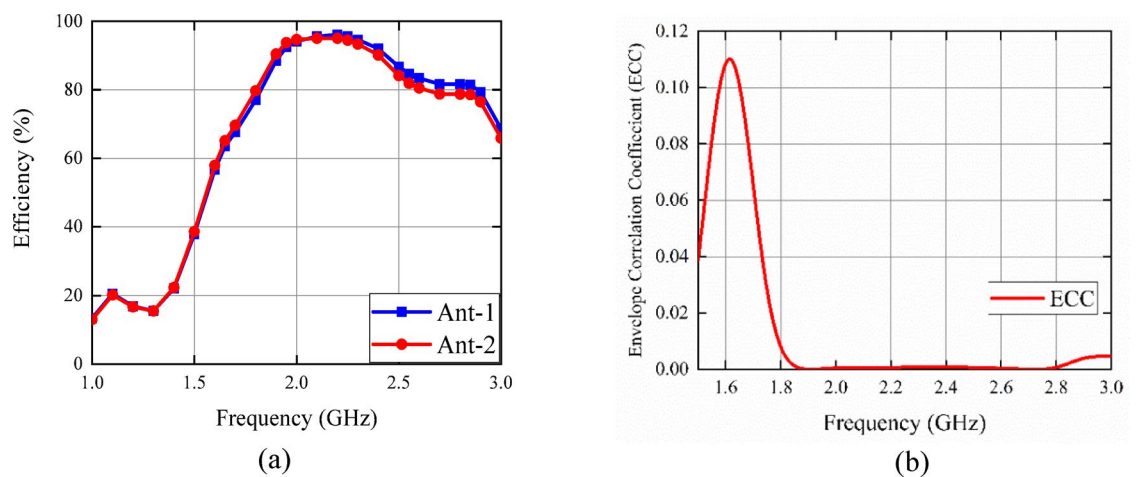


Fig. 6. (a) Antenna efficiencies; (b) ECC derived from S-parameters of the proposed MIMO system.

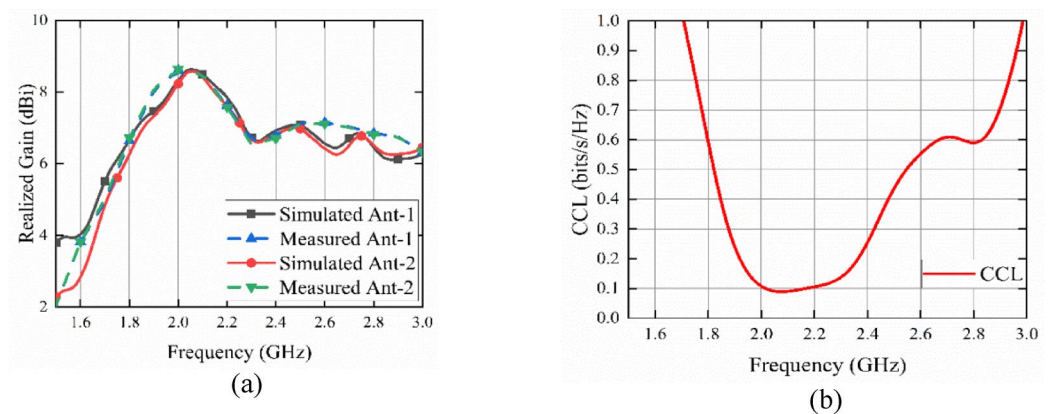


Fig. 7. Proposed Kirigami based system: (a) Gain vs Frequency (b) CCL vs Frequency.

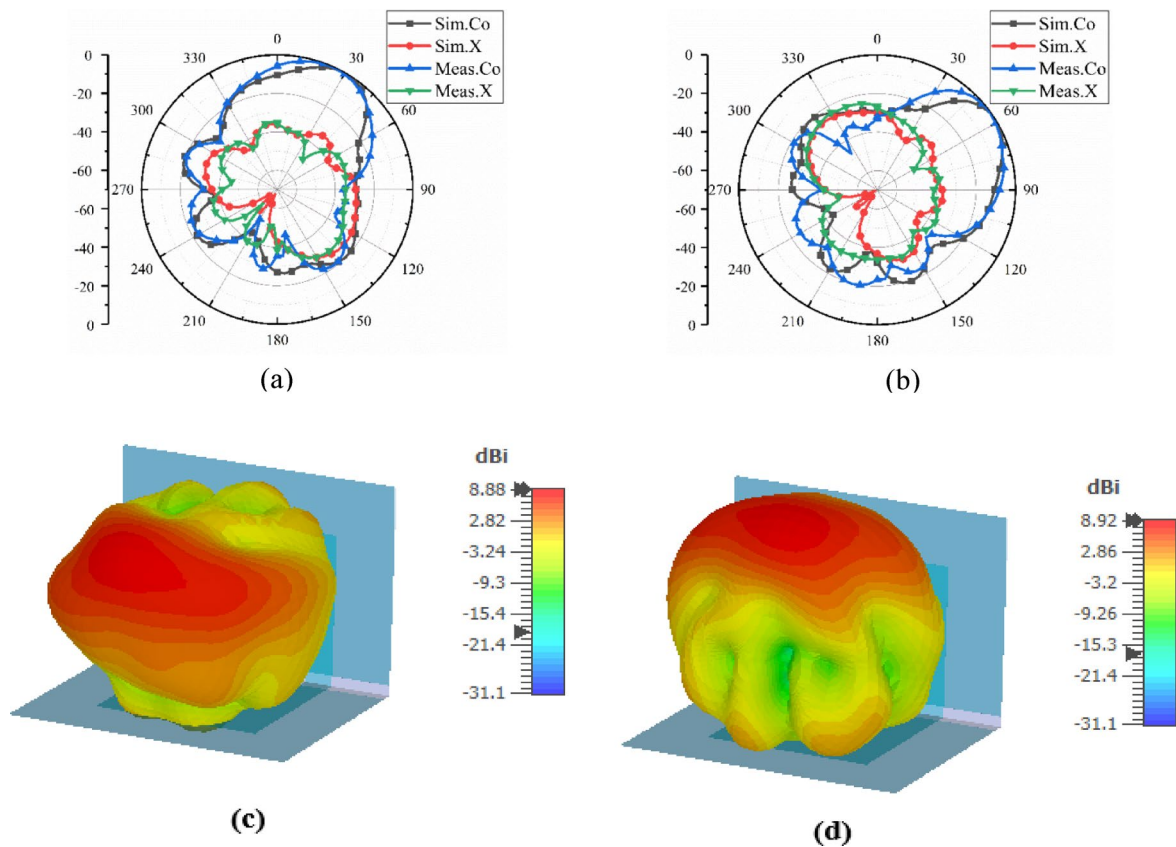


Fig. 8. Far-field radiation patterns at 2.0 GHz (a) Normalized E-plane of Ant-1. (b) Normalized E-plane of Ant-2 (c) 3D pattern of Ant-1. (d) 3D pattern of Ant-2.

Ref.	Number of Antenna Elements	Dim (mm)	Resonance Frequency (GHz)	Isolation (dB)	Resonance Bandwidth (GHz)	Peak Gain (dBi)	Technique	Design Complexity	Foldability	Cost
14	4	250 × 200	2.5	– 15	0.86	11.1	Kirigami	Simple	Available	Moderate
18	2	50 × 70	2.4/2.91/3.27/3.4/5.1	– 30	0.48/1.08/0.7/0.4/0.7	4	3D printing	High	Not Available	Low
31	2	210 × 210	2.4/5.2	– 15	0.45/1.60	2.78	Shape Memory alloy (SMA)	High	Available	Low
32	4	100	9.5	– 20	3.3	4.8	3D printed Origami	High	Available	High
33	2	120 × 155	2.47	Not reported	0.27	7.63	Flexible Patch	Simple	Available	Low
34	1	150 × 200	2	NA	0.2	9	Origami	Moderate	Available	Low
Proposed Work	2	250 × 200	2	– 15	0.630	9.05	Kirigami	Simple	Available	Low

Table 1. Comparison with state of the art flexible and foldable antenna designs.

than 0.35 bps/Hz, shows how reliable proposed MIMO system is for transmission. The CCL results against the frequency are depicted in Fig. 7(b).

The far-field radiation pattern in both 2D polar and 3D form of the proposed MIMO antenna system is shown in Fig. 8. It can be seen that Ant-1 exhibits a maximum beam tilt of 30° with a peak simulated gain of 8.85 dBi. The maximum cross-polarization level is -18.5 dB below the co polarized component, with the main cross-polarization lobe directed at 128° which can be seen in Figs. 8(a) and (c), respectively. Ant-2 exhibits a maximum beam tilt of 60°, a peak simulated gain of 8.89 dBi, a maximum cross-polarization level of -20.20 dB below the co polarized component, and a cross-polarization main lobe direction at 37°, as shown in Figs. 8(b) and 8(d). The simulated and measured gain results show good agreement as evidenced by the normalized plots in Fig. 8(a–b), with both antennas exhibiting an identical angular width of 34°. Table 1 compares the performance of the proposed MIMO antenna with the relevant designs reported in the recent literature. The deployable kirigami array in¹⁴ achieved the highest reported gain (11.1 dBi) with a wide 0.86 GHz bandwidth at 2.5 GHz.

It also reported very low ECC (< 0.003), but did not provide channel capacity loss (CCL) or other system-level evaluations. Despite having a 250×200 mm footprint, the operating frequencies of the proposed design and Ref¹⁴ are different. The proposed antenna runs at 2.0 GHz, while Ref¹⁴ operates at 2.5 GHz. The lower operating frequency ($\lambda = 150$ mm at 2.0 GHz) naturally requires greater physical dimensions because antenna size scales with wavelength. The proposed antenna is electrically more compact ($\approx 1.67\lambda$) when normalized to wavelength than Ref¹⁴ ($\approx 2.08\lambda$). Furthermore, within the same geometry, the arrangement of the four MIMO elements can be designed. However, proposed 2 elements MIMO configuration reduces hardware complexity and power consumption by halving the number of required RF chains, which is a critical factor for effective thermal management in deployable devices.

Additionally, to provide angular pattern diversity, low ECC (< 0.0025), and isolation below -15 dB, the proposed strategy uses a two-element architecture with optimum inter-element spacing. In contrast to Ref¹⁴, the proposed antenna is fabricated on a low-cost PET substrate instead of a flexible PCB, reducing material costs and simplifying manufacturing. Furthermore, the kirigami pop-up structure enables a simpler deployment mechanism without additional structural support, further easing fabrication and deployment. The multiband 3D MIMO antenna in¹⁸ demonstrated excellent isolation (-30 dB) and included comprehensive MIMO metrics such as ECC (< 0.18) and CCL (< 0.35 bps/Hz). However, its structural complexity, additional FSS layers, and rigid construction limited its suitability for portable or foldable applications. The reconfigurable helix antenna using shape memory alloys in³¹ offered mechanical reconfigurability with moderate bandwidths (0.45/1.60 GHz), but only reported pattern correlation coefficients rather than ECC/CCL. In addition, its low gain (2.78 dBi), mechanical actuation requirements, and paper substrate reduced robustness. An origami-inspired, foldable MIMO antenna in³² covers a wideband range from 8.7 to 12 GHz. It features a 2-element MIMO setup that is physically reconfigurable. The antenna can transition between three distinct physical states and achieves a stable gain of 4 to 6.2 dBi and high radiation efficiency ($> 90\%$). However, it uses 3D-printed dielectric resonators, which adds significant profile height (thickness) and weight to the antenna. Also, 3D printing dielectric resonators with specific permittivity can be expensive or difficult to mass-produce compared to standard PCB/substrate processes. In³³ a flexible 2-element MIMO patch antenna for 2.45 GHz applications was presented. While their work demonstrates excellent ECC and flexibility on Kapton substrates, however it is a standard flexible antenna. It can bend, but it does not change its fundamental physical shape or “unfold” to improve gain or change beam direction. Similarly, in³⁴ an origami-inspired pattern reconfigurable antennas based on magic spiral cubes is presented but it is single element and lack polarization diversity.

In contrast, the proposed PET-based two-element Kirigami MIMO antenna delivers high measured gain (9.05 dBi) with optimal impedance bandwidth (630 MHz) at 2.0 GHz using a lightweight, low-cost, and foldable PET substrate. Although its bandwidth is narrower than¹⁴, it provides a more effective balance of gain, bandwidth, and simplicity, while avoiding the complexity of¹⁸ and³¹. Importantly, it offers excellent MIMO-specific performance, with ECC consistently below 0.0025, total efficiency above 80% (peaking near 95%), and CCL under 0.35 bps/Hz, values comparable to or better than those in¹⁴ and¹⁸. The orthogonal orientation and spatial separation of the two monopole elements result in angular pattern diversity, providing distinct radiation patterns for Ant-1 and Ant-2. This arrangement facilitates dual linear polarization, with each element emitting an orthogonal polarization state. The measured radiation parameters confirm that such polarization and pattern variety lead to a lower envelope correlation coefficient (ECC) and improved MIMO performance. These results demonstrate not only robust diversity performance but also the advantage of achieving it with just a two-element configuration instead of more costly four-element array. Overall, the proposed design distinguishes itself by combining foldable simplicity, low cost, and reliable MIMO diversity, making it a strong candidate for modern deployable communication systems.

Conclusion

This work presented a novel, low-cost, deployable dual-polarization MIMO antenna based on a Kirigami pop-up geometry. The proposed design, realized on a PET substrate with monopoles, directors, and a reflector, demonstrated an optimal impedance bandwidth of 630 MHz and a peak gain of 9.05 dBi at 2.0 GHz. In addition to its structural simplicity and reconfigurability, the antenna exhibits excellent MIMO performance, with an ECC below 0.0025 and a CCL below 0.35 bps/Hz across the operating band. The achieved combination of high gain, compact deployable form, and robust diversity characteristics, surpasses the capabilities of the state-of-the-art Kirigami-based antenna systems reported in the literature. Although this study primarily focuses on electromagnetic performance, the antenna architecture is also well suited for satellite and field-deployable missions owing to its lightweight PET substrate, compact stowed configuration, and passive deployment mechanism. These attributes ensure compatibility with launch volume constraints and rapid deployment requirements. Consequently, the proposed antenna is a strong candidate for field-deployable military communication systems, rapidly deployable emergency and disaster-relief networks, and portable microwave communication platforms that demand compact stowage, high gain, and reliable MIMO performance.

Data availability

The corresponding author can provide the data supporting the study's conclusions upon reasonable request at the email: *Imran.shah@oulu.fi*.

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Ullah: Data curation, validation, review & editing. Sadiq Ullah: review & editing. Aadel Mohammed. Alatwi: Funding acquisition, supervision. Syed Imran Hussain Shah: Conceptualization, simulations, data curation, validation, supervision, review & editing.

Declarations

Competing interests

The authors declare no competing interests.

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