Progress In Electromagnetics Research Letters, Vol. 99, 11–18, 2021

A Low Cost Coplanar Capacitively Coupled Probe Fed Stacked Patch Antenna for GNSS Applications

Muhammad Awais[1, *], Ahmad Bilal[2], and Shuaib Salamat[2]

Abstract—This letter presents a low-cost dual-band circularly polarized microstrip antenna for GNSS applications. The dual-band operation is achieved by stacking two metallic patches on a conventional FR4 substrate. The designed antenna can cover GPS L1 band, BeiDou B1 band, Galileo E1, E5b bands, and GLONASS G1, G3 bands, through a bandwidth of 1.118 GHz–1.215 GHz in lower L-band and a bandwidth of 1.55 GHz–1.61 GHz in the upper L-band. In order to achieve a wide axial ratio bandwidth, a dual-feed mechanism utilizing a capacitively coupled probe feeding scheme is incorporated. The overall size of the proposed antenna is 100 mm by 100 mm. The measured results indicate an excellent correlation with simulations.

1. INTRODUCTION

In recent years, Global Navigation Satellite Systems (GNSS) have gained much interest by the research community as well as the industry due to their ability to provide high precision and accurate navigation [1]. Owing to their low profiles, light weights, ease of fabrication, and compact sizes, circularly polarized stacked patch antennas have been one of the key enabling features of modern GNSS receivers.

Several stacked patch antennas have been proposed in literature [2–10], which try to cover multiple GNSS bands of interest by achieving dual-band or multi-band operation in both lower and upper L-bands. But most of these designs either have poor performance in terms of wide impedance bandwidth, high gain, and/or wide axial ratio bandwidth, etc. In some cases, they incorporate a complex feeding mechanism such as L-probe feeding [2], Capacitive Cap feeding [3–5], or folded-shaped probes [7], or more than one substrate materials are used which results in high cost of manufacturing for these antenna prototypes. For example, Zhou et al. [2] have proposed an L-probe fed dual-band stacked patch antenna, but the return loss performance of this design was poor especially for lower L-band. Wang et al. [3] proposed a proximity-coupled probe fed stacked patch antenna whose radiating patch elements were narrowband, and the design incorporated a complex balun structure. Later, the problem of bandwidth was addressed by Li et al. [4] who presented a capacitively coupled wide band four-probe-fed circular stacked patch antenna for all frequency bands of interest, but the design consisted of a complex feeding network incorporating four feeding probes and multiple substrate layers with various relative permittivities.

A miniaturized antenna array was designed by Caizzone [5] on a high dielectric substrate to achieve a compact overall size. The antenna elements are dual-layer stacked patch antennas, but these antennas are fed using proximity coupled feeding, which adds an additional layer to the antenna stack-up leading to a complex multilayer structure resulting in a costly solution. Recently, Zhong et al. [6] have designed a stacked patch antenna for vehicle satellite navigation applications. This design covers impedance bandwidths of 1.221 GHz–1.229 GHz and 1.568 GHz–1.581 GHz by achieving a dual-band operation, but

Received 3 May 2021, Accepted 30 June 2021, Scheduled 9 July 2021

* Corresponding author: Myhammad Awais (awais@aerospace.pk).
[1] Department of Electrical Engineering, Lahore University of Management Sciences, Pakistan. [2] Department of Avionics Engineering, Air University PAC Campus, Kamra, Pakistan

the impedance bandwidth of this architecture is limited and only covers GPS L1 and L2 bands. Sun et al. [7] have proposed a wideband patch antenna for GNSS applications, but the design incorporates folded shorting pins, which increases the complexity of their design, and it may not be fabricated using simple PCB fabrication techniques. Furthermore, its −10 dB impedance bandwidth is not sufficient to cover all of the intended frequency bands of interest. Some works have also proposed single feed stacked patch antenna architectures for GNSS applications with dual-band/tri-band operation [8–11]. However, due to single feed mechanism all of such designs show narrowband axial ratio performance, which is not sufficient to cover all of the GNSS bands of interest.

In this work, we design an efficient and low-cost dual-band stacked patch antenna which covers all of the intended frequency bands of interest (GPS L1, Galileo E1 and E5b, BeiDou B1, and GLONASS G1 and G3 bands) simultaneously. The −10 dB impedance bandwidth and 3 dB axial ratio bandwidth are wide enough to ensure high performance antenna requirements. In addition, the total numbers of substrate layers and feeding ports are kept minimum to realize a simple and low-cost antenna prototype.

This paper is organized as follows. Section 2 outlines the design procedure and presents a parametric analysis of various critical geometric variables. Section 3 gives a comparison of the simulated and measured responses while Section 4 concludes this article.

2. ANTENNA DESIGN

2.1. Antenna Configuration

The proposed antenna has a dual-layer stacked patch architecture utilizing a conventional FR4 substrate ($\epsilon_r = 4.4$, $\tan\delta = 0.02$). These two patches, i.e., upper and lower patches operate at upper and lower L-bands of the intended GNSS spectrum, respectively. The substrate thicknesses are H_1 (3.2 mm) and H_2 (6.4 mm) for lower and upper layers, respectively. The thickness of both layers is carefully chosen to not only fulfill the bandwidth requirements of the GNSS antenna but also be selected as multiples of standard layer thickness (1.6 mm) of FR4 sheets to minimize the cost. The lengths of lower and upper patches are L_{P1} (52 mm) and L_{P2} (37 mm), respectively, which are chosen to be half of the guided wavelengths (λ_g) to achieve a dual-band impedance matching at center frequencies of Galileo E5b and GPS L1 bands, respectively.

To counter the inductive effects of long feeding pin, many stacked patch designs [2–7] proposed for GNSS applications use complex proximity coupled L-probes, folded pins, non-coplanar capacitive feeds or aperture coupled feeding techniques which require additional substrate layers. However, our

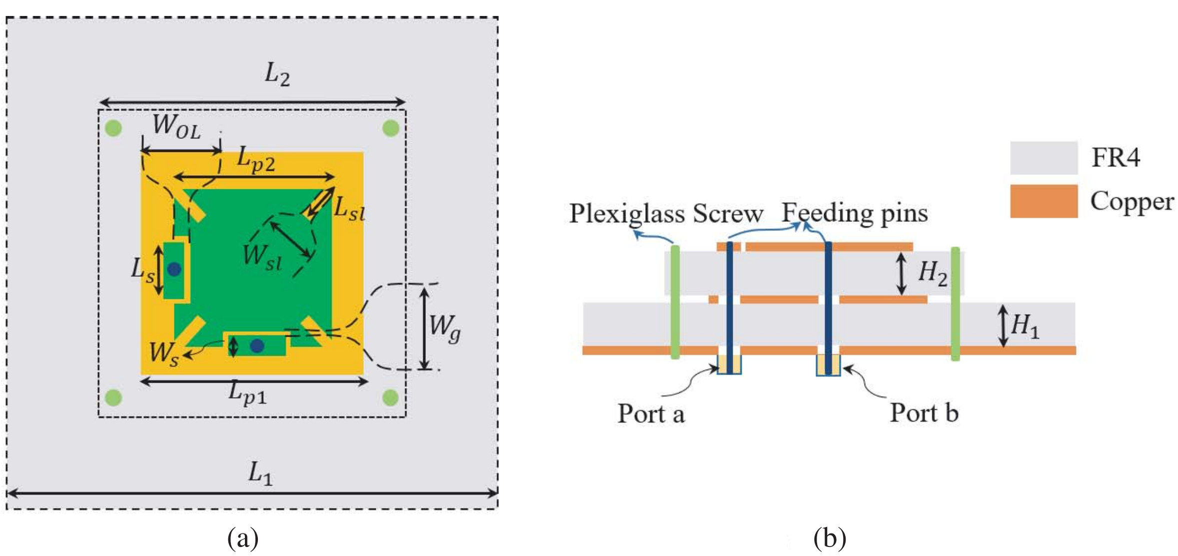


Figure 1. Proposed low-cost capacitively coupled probe fed stacked patch antenna for GNSS applications. (a) Top view. (b) Stackup (final design).

proposed design consists of a simple coplanar capacitively coupled probe feeding mechanism as shown in Fig. 1.

The length (L_S) and width (W_S) of the metallic strip, the gap between the radiating patch and strip (W_G), and the overlap between the strip and radiating patch (W_{OL}) are the most critical design parameters. The impact of these geometric parameters on the performance of the antenna is discussed briefly in the following subsection.

2.2. Detailed Design Guidelines and Parametric Analysis

We started with the initial design of our antenna as shown in Fig. 2, which is a dual-layer stacked patch antenna with square metallic patches. The upper patch was capacitively coupled by coplanar metallic strips using coax probes, while the lower patch was parasitically fed. A two-port quadrature phase feeding [2, 5] was employed to excite right-hand circularly polarized (RHCP) modes. In the initial design, substrate thicknesses H_1 and H_2 were set at 3.2 mm and 6.4 mm, respectively, and lengths of lower and upper patches L_{P1} and L_{P2} were set at 52 mm and 37 mm, respectively, as described in the Section 2.1. However, the remaining design parameters (W_G, L_S) of this initial prototype are optimized, and effects of these critical design parameters are presented in Fig. 3.

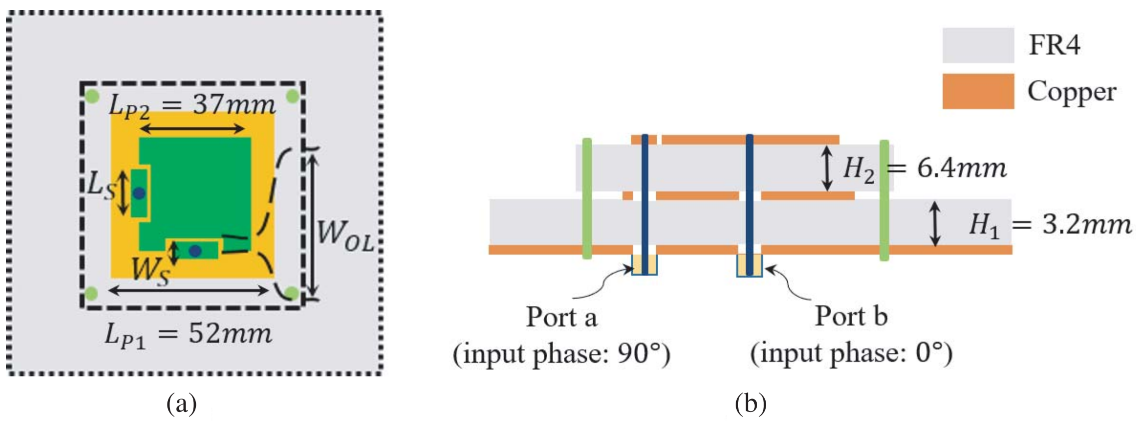


Figure 2. Initial design of the antenna (Design I). (a) Top view. (b) Stackup.

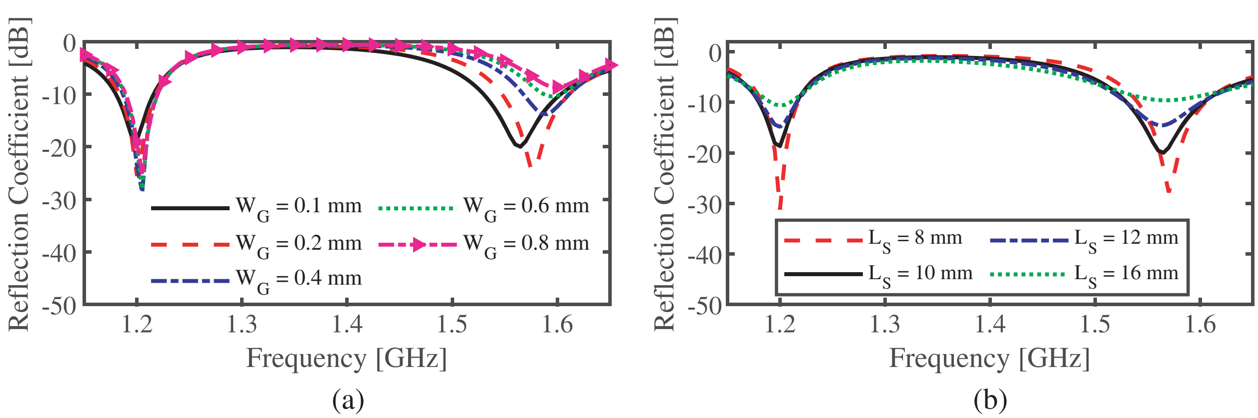
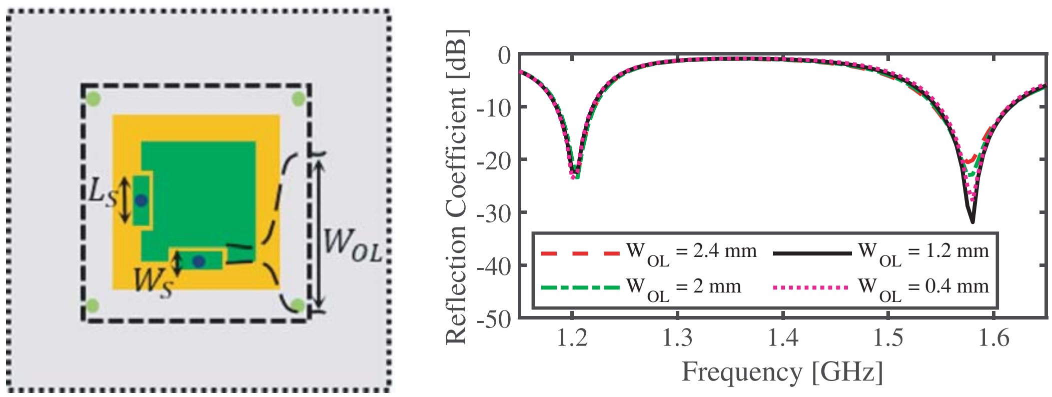


Figure 3. Effect of design parameters (a) W_G and (b) L_S on the reflection coefficient performance of Design I.

As shown in Fig. 3(a), by decreasing the gap between the metallic patch and the feeding strip (W_G) from 0.8 mm to 0.1 mm, the reflection coefficient (S_{11}) response improves and becomes wider. Fig. 3(b) illustrates the effect of the length of the metallic strip (L_S) on the reflection coefficient performance of the antenna (S_{11a}, S_{11b}). For the upper L-band, S_{11} response improves and becomes wider as L_S varies from 8 mm to 12 mm, but -10 dB impedance bandwidth tends to become narrow if L_S is further increased. It can be inferred from Fig. 3 that the optimum values of W_G and L_S are 0.1 mm and 10 mm, respectively. However, realizing a W_G of 0.1 mm using traditional PCB fabrication methods is extremely challenging, if not impossible.

To address this issue, we modified our Design I to Design II, as shown in Fig. 4(a), by cutting slots in the upper patch and partially pushing the capacitive strips into the patch thus causing an overlap feature. This design modification introduces an additional design parameter (W_{OL}) that denotes the overlap of feeding strip and the patch. The effect of W_{OL} on the reflection coefficient performance is presented in Fig. 4(b). Increasing W_{OL} results in improving the S_{11} for the upper L-band, and for the lower L-band it remains stable. Thus, W_{OL} serves as an additional degree of freedom to help achieve suitable W_G values which can be realized using traditional PCB fabrication processes.



(a) (b)

Figure 4. (a) Improved design of the antenna (Design II) and (b) effect of W_{OL} on the reflection coefficient performance of Design II.

Lastly, in the final design architecture, we enhanced Design II by adding 4 slots at each corner of upper radiating patch element, which leads to slightly compact upper patch and shifting the feed points towards the center of the antenna. This in turn improves the coupling with the lower patch. The final GNSS antenna prototype is shown in Fig. 1. All the optimized geometric parameters of the final fabricated prototype are listed in Table 1 while the fabricated antenna prototype is shown in Fig. 5.

Table 1. Optimized design parameters for proposed co-planar capacitively coupled stacked patch microstrip antenna.

Parameter	Value (mm)	Parameter	Value (mm)	Parameter	Value (mm)
L	100	L_{P2}	36.57	L_{SL}	9
L_1	60	L_S	10	W_{SL}	2
L_{P1}	51.8	W_S	3.5	W_{OL}	1.2
W_G	0.2	H_1	3.2	H_2	6.4

3. SIMULATIONS AND MEASUREMENTS

A comparison of simulated and measured reflection coefficient performances is shown in Fig. 6, which indicates an excellent match of measured response with the simulations. It can be seen that -10 dB impedance bandwidth is achieved in the desired frequency ranges (1.118 GHz–1.215 GHz and 1.53 GHz–1.61 GHz) covering all of the major GNSS bands of interest, i.e., GPS (L1), BDS (B1), GLONASS (G1, G3), and Galileo (E5b, E1).

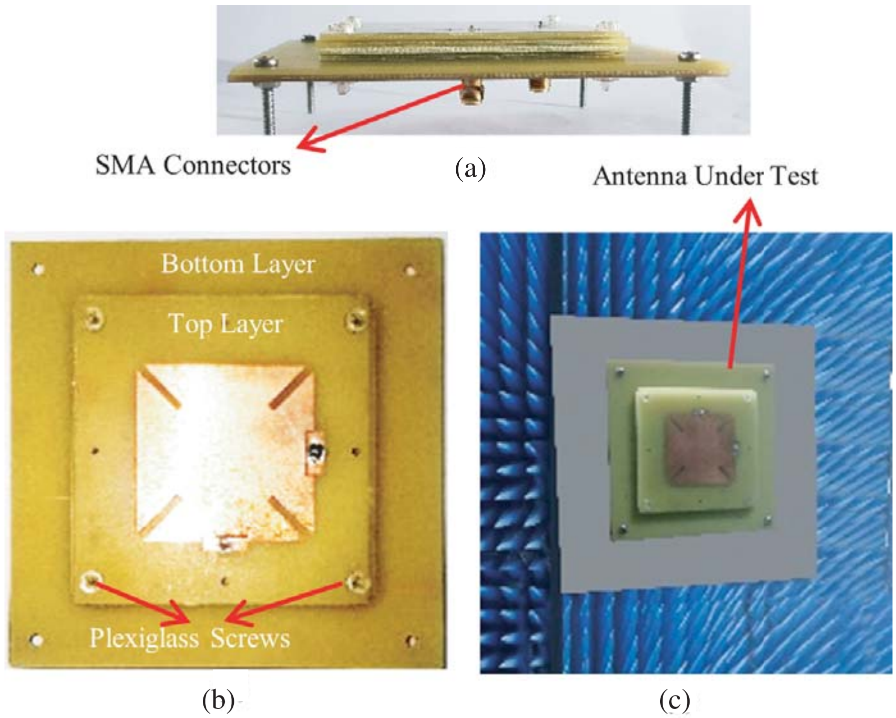


Figure 5. Fabricated prototype of proposed low-cost capacitively coupled probe fed stacked patch antenna (final design). (a) Side view. (b) Top view. (c) Antenna mounted inside the anechoic chamber.

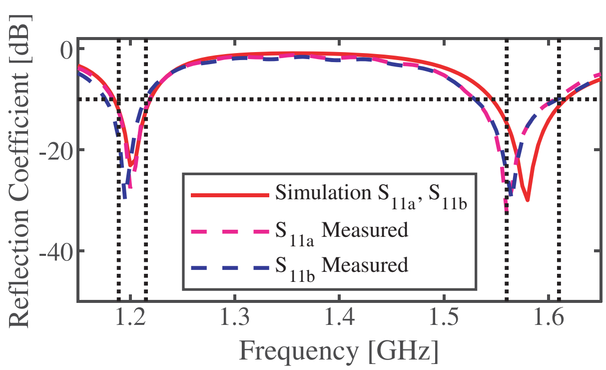


Figure 6. Reflection coefficient performance of proposed stacked patch antenna for GNSS applications.

The normalized radiation patterns of our proposed antenna at various GNSS bands are shown in Fig. 7. It is evident that our designed antenna is able to achieve highly stable broadside radiation characteristics, and it maintains an excellent cross polarization levels of better than 18 dB.

The simulated broadside axial ratio and gain performance vs frequency is shown in Fig. 8. The gain of proposed antenna is approximately 2.5 dBi in the lower L-band and approximately 4.4 dBi in the upper L-band (Fig. 8). The achieved axial ratio is less than 3 dB over the entire band of interest.

Table 2 presents a brief comparison of our proposed GNSS antenna with the state-of-the-art work found in literature. It can be seen that the proposed design in this research covers most of the GNSS frequency bands of interest with an excellent impedance matching performance of $S_{11} \leq -10$ dB while utilizing a minimal number of substrate layers and feeding pins. In addition, our proposed antenna is designed on a conventional FR4 substrate, which results into a highly cost-effective solution.

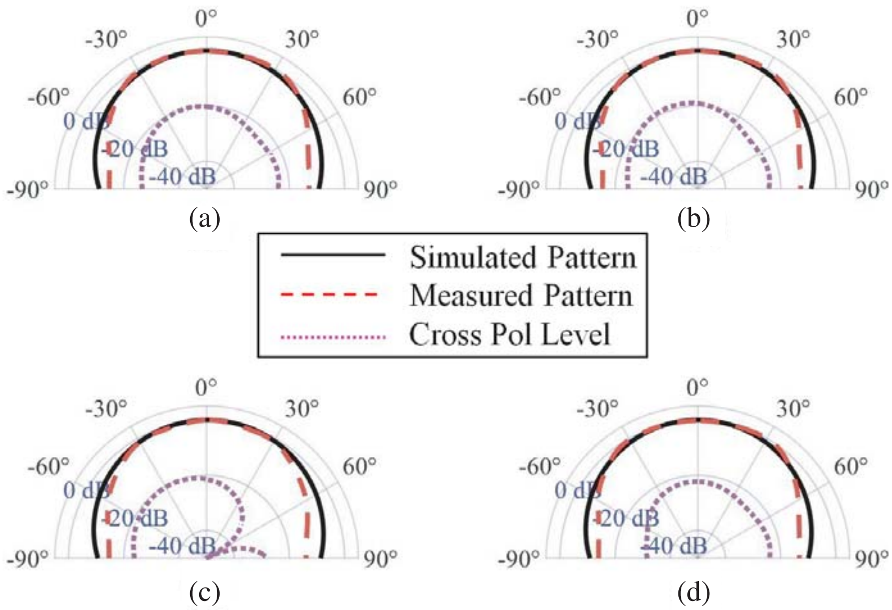


Figure 7. Simulated and measured normalized radiation pattern of proposed stacked patch antenna for GNSS applications at (a) GPS L1, (b) BeiDou B1, (c) Galileo E5a, and (d) GLONASS G1 band.

Table 2. A comparison of the proposed co-planar capacitively coupled stacked patch microstrip antenna with the state-of-the art work reported in literature.

Ref.	Antenna type	Number of Substrate Layers	ϵ_r	$S_{11} \leq -10dB$				Size	Number of Feeding Pins
				GPS	GLONASS	BeiDou	Galileo		
[2]	Stacked Patches	2 (with capacitive L-brobes between substrate layers)	15, 30	L1	No	No	No	$0.125\ \lambda_0 \times 0.125\ \lambda_o$ (30.48mm patch length)	2
[3]	Stacked Patches	4	10.2	L1, L2	No	No	No	100 mm x 100mm	2
[4]	Circular Stacked Patches	3 (Capacitive feeding between patch elements)	N.A.	L1, L2	G1, G3	B1	E1, E5	160mm dia	4
[5]	Stacked Patches	3 (Top CAP feeding above the upper patch)	10	L1, L5	No	No	E5a, E1	50mm x 50mm	2
[6]	Cicular Stacked Patches	2 with air gap capacitive feeding and backed by a metallic cavity	N.A.	L1, L2	No	No	No	$0.368\ \lambda_0$ dia (90mm)	2
[10]	Stacked Patches	3	9.85, 2.55	L1	G1	B1	No	115mm x 115mm	3
This work	**Stacked Patches**	**2 (Coplanar capacitive feeding)**	**4.4**	**L1**	**G1, G3**	**B1**	**E1, E5b**	**100mm x 100 mm**	**2**

* N.A. represents not available

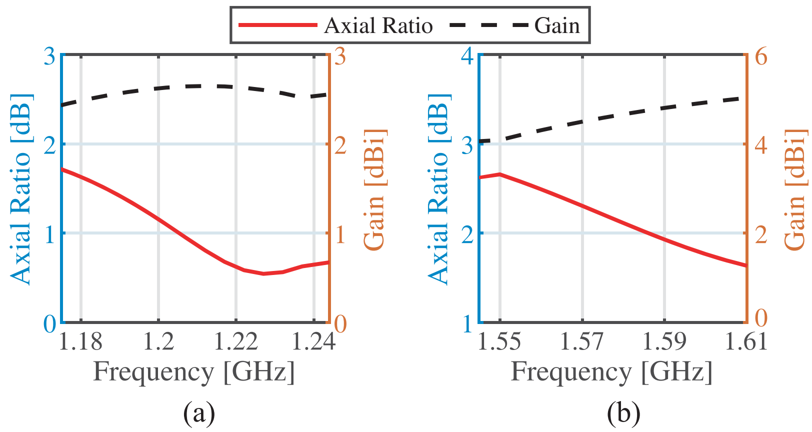


Figure 8. Simulated axial ratio and gain performance of proposed antenna at (a) lower L-band and (b) upper L-band.

4. CONCLUSION

A novel dual-feed microstrip stacked patch antenna utilizing a conventional FR4 substrate is proposed. The key feature of this design is a coplanar capacitively coupled dual-feed mechanism, which enables it to achieve the required wide bandwidth without the requirements of any additional substrate layers or complicated feeding structures. Measured results of our antenna showed excellent correlation with the simulations. The designed antenna is able to achieve a dual-band operation with reflection coefficient less than −10 dB and axial ratio less than 3 dB, and covers GPS L1 band, BeiDou B1 band, Galileo E1, E5b bands, and GLONASS G1, G3 bands. The proposed antenna would find applications in multi-band electromagnetic interference (EMI) resistant and electromagnetic jam-resistant systems.

REFERENCES

1. Hegarty, C. J. and E. Chatre, "Evolution of the Global Navigation Satellite System (GNSS)," *Proceedings of the IEEE*, Vol. 96, No. 12, 1902–1917, Dec. 2008.
2. Zhou, Y., C. Chen, and J. L. Volakis, "Dual band proximity-fed stacked patch antenna for tri-band GPS applications," *IEEE Transactions on Antennas and Propagation*, Vol. 55, No. 1, 220–223, Jan. 2007.
3. Wang, Z., S. Fang, S. Fu, and S. Lu, "Dual-band probe-fed stacked patch antenna for GNSS applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 8, 100–103, 2009.
4. Li, D., P. Guo, Q. Dai, and Y. Fu, "Broadband capacitively coupled stacked patch antenna for GNSS applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 11, 701–704, 2012.
5. Caizzone, S., "Miniaturized E5a/E1 antenna array for robust GNSS navigation," *IEEE Antennas and Wireless Propagation Letters*, Vol. 16, 485–488, 2017.
6. Zhong, Z., et al., "A compact dual-band circularly polarized antenna with wide axial-ratio beamwidth for vehicle GPS satellite navigation application," *IEEE Transactions on Vehicular Technology*, Vol. 68, No. 9, 8683–8692, Sept. 2019.
7. Sun, C., Z. Wu, and B. Bai, "A novel compact wideband patch antenna for GNSS application," *IEEE Transactions on Antennas and Propagation*, Vol. 65, No. 12, 7334–7339, Dec. 2017.
8. Falade, O. P., M. U. Rehman, Y. Gao, X. Chen, and C. G. Parini, "Single feed stacked patch circular polarized antenna for triple band GPS receivers," *IEEE Transactions on Antennas and Propagation*, Vol. 60, No. 10, 4479–4484, Oct. 2012.
9. Agarwal, K. and A. Alphones, "Triple-band compact circularly polarised stacked microstrip antenna over reactive impedance meta-surface for GPS applications," *IET Microwaves, Antennas & Propagation*, Vol. 8, No. 13, 1057–1065, 2014.

10. Liu, Y., et al., "Multiband antenna for satellite navigation system," *IEEE Antennas and Wireless Propagation Letters*, Vol. 15, 1329–1332, 2015.
11. Pham, N., J.-Y. Chung, and B. Lee, "A proximity-fed antenna for dual-band GPS receiver," *Progress In Electromagnetics Research*, Vol. 61, 1–8, 2016.