Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Received: 11 April 2025; Accepted: 24 June 2025
Published online: 09 August 2025

References

1. Elayan, H., Amin, O., Shihada, B., Shubair, R. M. & Alouini, M.-S. Terahertz band: The last piece of RF spectrum puzzle for communication systems. *IEEE Open J. Commun. Soc.* **1**, 1–32. https://doi.org/10.1109/OJCOMS.2019.2953633 (2020).
2. Tonouchi, M. Cutting-edge terahertz technology. *Nat. Photon.* **1**(2), 97–105. https://doi.org/10.1038/nphoton.2007.3 (2007).
3. Uhd Jepsen, P. et al. Terahertz spectroscopy and imaging—modern techniques and applications. *Laser Photon. Rev.* **5**(1), 124–166. https://doi.org/10.1002/lpor.201000011 (2011).
4. Malhotra, I., Jha, K. R. & Singh, G. Terahertz antenna technology for imaging applications: A technical review. *Int. J. Microwave Wirel. Technol.* **10**(3), 271–290. https://doi.org/10.1017/S175907871800003X (2018).
5. Gupta, A., Kumar, V., Garg, D., Alsharif, M. H. & Jahid, A. Performance analysis of an aperture-coupled THz antenna for diagnosing breast cancer. *Micromachines* **14**(7), 1281. https://doi.org/10.3390/mi14071281 (2023).
6. Kürner, T. & Priebe, S. Towards THz communications-status in research, standardization and regulation. *J. Infrared Millim. Terahertz Waves* **35**, 53–62 (2014).
7. Nella, A. et al. A novel conformal quasi-Yagi antenna with offset feed for high directional 300 GHz applications. *IEEE Access* **11**, 37335–37346 (2023).
8. Divya, G., Jagadeesh Babu, K. & Madhu, R. Isolation improvement in dual-band astroid shaped MIMO DRA for LTE & ISM applications. *Int. J. RF Microwave Comput. Aid. Eng.* **32**, 22929 (2021).
9. Ahmad, K. S. & Al-Gburi, A. J. A. Graphene-based frequency reconfigurable slot antenna for terahertz applications. *Optik* **330**, 172343 (2025).
10. Wang, L. et al. Grid dielectric resonator antenna planar arrays with simple feeding network. *IEEE Trans. Antennas Propag.* **71**(11), 9084–9088. https://doi.org/10.1109/TAP.2023.3312952 (2023).
11. Addepalli, T. et al. Four-element equilateral triangular-shaped MIMO antenna with connected ground for 5G sub: 6 GHz N79 and WiFi-6E band applications. *Int. J. Commun. Syst.* **37**(16), e5895 (2024).
12. Ma, C., Zheng, S. Y., Pan, Y. M. & Chen, Z. Millimeter-wave fully integrated dielectric resonator antenna and its multi-beam application. *IEEE Trans. Antennas Propag.* **70**(8), 6571–6580. https://doi.org/10.1109/TAP.2022.3161361 (2022).
13. Vishwanath, Sahana, B. C. & Varshney, G. Tunable terahertz dual-band circularly polarized dielectric resonator antenna. *Optik* **253**, 168578 (2022).
14. Divya, G., Jagadeesh Babu, K. & Madhu, R. A novel inverted elliptical frustum shaped multi-band MIMO DRA with bandwidth and isolation enhancement. *AEU Int. J. Electron. Commun.* **135**, 1–10 (2021).
15. Hussein, Y. M., Rahim, M. K. A., Murad, N. A., Hanoosh, H. O. & Nadzir, N. B. M. Substrate integrated waveguide antenna at millimeter wave for 5G APPLICATION. *ACES J.* **37**(04), 478–484 (2022).
16. Cheh Lin, I. K., Jamaluddin, M. H. & Gaya, A. A triple band substrate integrated waveguide with dielectric resonator antenna for 4G and 5G applications. *Micromachines* **14**(7), 1294 (2023).
17. Chemweno, E. K., Kumar, P. & Afullo, T. J. O. Design of high-gain wideband substrate integrated waveguide dielectric resonator antenna for D-band applications. *Opt.-Int. J. Light Electron Opt.* https://doi.org/10.1016/j.ijleo.2022.170261 (2023).
18. Abdel-Wahab, W. M., Wang, Y., Al-Saedi, H. & Safavi-Naeini,. Miniaturized SIW-integrated 2D DRA array for 5G mm wave applications. *Microwave Opt. Technol. Lett.* **58**, 2804–2807. https://doi.org/10.1002/mop.30154 (2016).

32. Barry W. Knight, SWIVEL MOUNTED ANTENNA. United States patent US 9,742,061. 2017 Aug 22.
33. Joannopoulos, J. D., Mead, R. D. & Winn, J. N. *Photonic crystals: Molding the flow of light* (Princeton University Press, 1995).
34. Dong, Y. & Zhang, X. Unusual transmission properties of wave in one-dimensional random system containing left-handed-material. *Phys. Lett. A* **359**(5), 542–546 (2006).
35. Fathollahi Khalkhali, T., Rezaei, B. & Kalafi, M. Enlargement of absolute photonic band gap in modified 2D anisotropic annular photonic crystals. *Opt. Commun.* **284**(13), 3315–3322 (2011).
36. Mizuguchi, J., Tanaka, Y., Tamura, S. & Notomi, M. Focusing of light in a three-dimensional cubic photonic crystal. *Phys. Rev. B* **67**(7), 075109 (2003).
37. Dey, U., Das, S., De, S. & Deyasi, A. Computation of photonic bandgap in 1D photonic crystal using dispersion relation. In *2019 3rd International Conference on Electronics, Materials Engineering & Nano-Technology (IEMENTech)*, Kolkata, India, 2019, pp. 1–5. https://doi.org/10.1109/IEMENTech48150.2019.8981016.
38. Paschotta, R., article on "Mode Competition" in the RP Photonics Encyclopedia, retrieved 2025-05-23, https://doi.org/10.61835/twz
39. Tolmachev, V., Perova, T. & Berwick, K. Design criteria and optical characteristics of one-dimensional photonic crystals based on periodically grooved silicon. *Appl. Opt.* **42**, 5679–5683 (2003).
40. Tolmachev, V., Astrova, E., Perova, T., Zharova, Y. & Moore, A. Design and fabrication of the periodical structures based on grooved Si for middle infrared microphotonics. *Phys. Status Solidi (C)* **2**, 3288–3292. https://doi.org/10.1002/pssc.200461145 (2005).
41. Yeh, D.-W. & Chien-Jang, Wu. Analysis of photonic band structure in a one-dimensional photonic crystal containing single-negative materials. *Opt. Express* **17**, 16666–16680 (2009).
42. Sharma, M. et al. Flexible four-port MIMO antenna for 5G NR-FR2 tri-band mmWave application with SAR analysis. *Sci. Rep.* **14**(1), 29100 (2024).
43. Cheh Lin, I. K., Jamaluddin, M. H. & Gaya, A. A triple band substrate integrated waveguide with dielectric resonator antenna for 4G and 5G applications. *Micromachines.* **14**(7), 1284 (2023).
44. Chemweno, E., Kumar, P. & Afullo, T. Substrate integrated waveguide-dielectric resonator antenna for future wireless communication. *SAIEE Afr. Res. J.* **113**, 119–128 (2022).
45. Rahmati, E., Burasa, P., Baladi, E. & Sharawi, M. S. Fully embedded dual-element dielectric-based antenna for sub- and terahertz applications. *IEEE Open J. Antennas Propag.* **5**(3), 778–787 (2024).
46. Youssef, A., Halkhams, I., El Alami, R., Jamil, M. O. & Qjidaa, H. A new approach to designing a multiband antenna using photonic crystals and load graphene for terahertz application. *Results Eng.* **22**, 102327 (2024).

Acknowledgements

The authors gratefully acknowledge Universiti Teknikal Malaysia Melaka (UTeM) and the Malaysian Ministry of Higher Education (MOHE) for supporting this project, and they also extend their thanks to the Research and Innovation Management Center (CRIM).

Author contributions

G. Divya led the initial design and simulation of the dielectric resonator antenna (DRA) structure and contributed to drafting the manuscript. K. J. Babu focused on the modeling and optimization of the substrate integrated waveguide (SIW) and assisted in result validation. I. Balakrishna contributed to the development and implementation of the nested Photonic Band Gap (PBG) crystal and supported the analysis of its impact on gain enhancement. T. Addepalli and D.Z. Mohammed were responsible for the parametric analysis and performance evaluation across the terahertz frequency spectrum. Z. Zakaria provided technical supervision, critical review, and guidance on the integration strategy and performance optimization of the proposed antenna system. A. J. A. Al-Gburi conceptualized the overall antenna design framework, coordinated the research activities, and finalized the manuscript for submission.

Funding

The authors express their gratitude to Universiti Teknikal Malaysia Melaka (UTeM) and the Ministry of Higher