Bandwidth and Gain Enhancement Techniques for Single-Band 2.4 GHz Microstrip Antennas: A Systematic Review

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Abstract: Microstrip patch antennas are widely used in 2.4 GHz ISM-band radios, yet narrow bandwidth and modest gain limit them, and no existing review isolates this single-band case. Following PRISMA 2020, we searched Scopus, IEEE Xplore and Web of Science, identified 3,046 records and sought 280 reports; the 191 read in full yielded 137 studies from 2015 to 2025, every value traced to its full text. Five technique families emerged: EBG, metamaterial, FSS and superstrate structures (43 studies); arrays (33); slots, parasitic elements and fractals (26); defected ground structures (22); and air gap or substrate engineering (13). Among single structures, 50 studies pair a baseline bandwidth with an enhanced value and 49 pair a gain. The median changes are +69% and +1.3 dB, and they stay between +32% and +98% and between +0.8 and +2.5 dB under five sensitivity checks. Only one bandwidth pair and four gain pairs are measured; 41 and 39 are simulated, with medians of +54% and +0.8 dB, and the rest leave the validation type of one value unstated. Twenty-eight studies make a claim in the abstract or title that their own results contradict, and in 16 the claim favours the design. The literature reports large simulated improvements and almost no measured before-and-after evidence, so these figures describe what is reported rather than estimate effects.

Keywords: Microstrip antenna, 2.4 GHz, bandwidth enhancement, gain enhancement, a systematic review.

Introduction

Microstrip antennas dominate consumer wireless hardware in the 2.4 GHz industrial, scientific, and medical band. Their planar profile, low mass, low cost, and compatibility with printed-circuit fabrication explain that position (Balanis., 2016; Garg et al., 2001). Wireless local area networks under IEEE 802.11 (IEEE., 2021), Bluetooth links, and Internet-of-Things

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nodes all depend on radiators for this crowded band. Two intrinsic limits constrain the conventional patch. Impedance bandwidth is narrow, typically a few percent, and realised gain is modest (Pozar., 1992). Both limits follow from the geometry rather than from poor design: a thin, high-permittivity substrate stores energy in a high-Q resonator, and a single half-wavelength aperture radiates weakly. Researchers have answered with techniques that modify the ground plane, the radiating patch, the substrate, or the space above the antenna. Reported outcomes resist comparison, because studies differ in substrate, dimensions, feed and reference design, so a designer cannot tell whether a 3 dB gain rise in one paper beats a 200 MHz bandwidth rise in another. Secondary literature has not closed this gap. The most comprehensive recent review, (Ahmed and Kabir ., 2026), covers nineteen techniques and eight feeding methods but spans every band from sub-6 GHz to millimetre wave and reports no protocol or search string. Other reviews aggregate across bands (Castro Alvarez & George., 2026; Elalaouy et al., 2024; Ghewari & Patil., 2025), fix on another band (Albaihani et al., 2026), or report design features rather than paired before-and-after values (Arnaoutoglou et al., 2024; Hassan et al., 2025; Pawar & Deosarkar., 2025; Saeed & Nwajana., 2024). Only (Banale et al., 2025) name their databases and report a screening funnel, and none prints a verbatim search string or a per-record decision log. Two gaps follow: no review isolates the single-band 2.4 GHz case, and none reports a protocol another researcher could rerun. Because we did not search systematically for secondary studies, this is a pattern across the reviews we found rather than a proof.

This review contributes a scope fixed to single-band 2.4 GHz, extraction verified against every full text, and an auditable selection of verbatim strings, written criteria and per-record logs. Fixing the frequency holds the electrical size of a structure, the cavity spacing of a superstrate and the required fractional bandwidth constant, so a reported rise reads as an effect of the technique rather than of the band. Four questions follow. RQ1 asks which technique families the 2015–2025 literature applies to single-band 2.4 GHz microstrip antennas; RQ2, how large the reported improvements are; RQ3, what each family costs; and RQ4, what trends and gaps the literature shows. The sections from Technique families to Trends and gaps answer them in turn, the Interpretation and implications for practice section draws them together and the Limitations section states their bounds.

Research Method

Design and protocol

This review followed the PRISMA 2020 statement (Page et al., 2021), treated as a reporting guideline rather than a methodological prescription (Sarkis-Onofre et al., 2021), with guidance on reviews in engineering and technology (Kitchenham & Charters., 2007; Snyder., 2019). A

written protocol fixed the strings, criteria, extraction fields and synthesis method before screening. No amendments were made to the protocol. The protocol was not registered: PROSPERO accepts health-related reviews only, and no general-purpose registry was used. The written protocol and the decision logs (the Data extraction and transparency section) let a reader check every selection decision instead.

Data sources and search strategy

We searched Scopus, IEEE Xplore and the Web of Science Core Collection (SCI-EXPANDED, CPCI-S and ESCI). Scopus indexes IEEE proceedings alongside other publishers, and IEEE Xplore served as a cross-check on the topic's most prolific publisher. Scopus was searched on 22 September 2026, and IEEE Xplore and Web of Science on 20 September 2026; Table 1 gives each string verbatim with its yield. All strings combine antenna type, four exact enhancement phrases and a frequency or application block; the Scopus string adds a broader block, bandwidth or gain with an explicit 2.4 or 2.45 GHz term, because an earlier round showed that eligible studies often avoid the exact phrases. Language and document-type filters were applied at pre-screening and logged.

IEEE Xplore rejects in-string year limits, so its filters were applied in the results panel, and the field scopes differ (TITLE-ABS-KEY, Topic and All Metadata). Each string was recorded verbatim and its count checked before export. The wording of the strings was then checked against the reference lists of the 122 included studies with a machine-readable full text. Screening those lists on title and venue for reports meeting K1 to K7 found four clearly eligible reports and four borderline ones; the searches had retrieved three of the four and three of the eight. The check covered reference lists only, from 122 of the 137 reports, and did not snowball further, so it tests the wording of the strings and does not estimate recall. The Limitations section gives the reasons for the misses, and S5 lists the eight reports and their matching against the logs.

Table 1 Search strings and identification yields.

Source and date	Field	Query	Filters	Records
Scopus, 22 Sept. 2026	TITLE-ABS-KEY	TITLE-ABS-KEY (("microstrip antenna" OR "patch antenna") AND ((("bandwidth enhancement" OR "gain enhancement" OR "bandwidth improvement" OR "gain improvement") AND ("2.4 GHz" OR "2.45 GHz" OR "WLAN" OR "WiFi" OR "ISM band")) OR ((bandwidth OR gain) AND ("2.4 GHz" OR "2.45 GHz")))) AND PUBYEAR > 2014 AND PUBYEAR < 2026	Years 2015–2025 in string; no language or document-type filter (applied at pre-screening and logged)	2,605
IEEE Xplore, 20 Sept. 2026	All Metadata	("microstrip antenna" OR "patch antenna") AND ("bandwidth enhancement" OR "gain enhancement" OR "bandwidth improvement" OR "gain	Years 2015–2025 and document types of Conferences and	221

Source and date	Field	Query	Filters	Records
		improvement") AND ("2.4 GHz" OR "2.45 GHz" OR "WLAN" OR "WiFi" OR "ISM band"), each term as All Metadata	Journals via the results panel	
Web of Science Core Collection, 20 Sept. 2026	TS (Topic)	TS= (("microstrip antenna" OR "patch antenna") AND ("bandwidth enhancement" OR "gain enhancement" OR "bandwidth improvement" OR "gain improvement") AND ("2.4 GHz" OR "2.45 GHz" OR "WLAN" OR "WiFi" OR "ISM band")) AND PY= (2015-2025) AND LD=(2000-01-01/2026-06-30)	Years and index date in string; editions SCI-EXPANDED, CPCI-S and ESCI	220
			Total identified	3,046

Eligibility criteria

Eight inclusion criteria governed selection, K1 through K8. Criteria K1 to K7 applied at every stage; K8 applied at the eligibility stage. A study qualified only when it met all eight:

K1. It designed a microstrip or patch antenna.

K2. It operated in a single band containing 2.4 or 2.45 GHz.

K3. It applied at least one bandwidth or gain enhancement technique.

K4. It reported a quantitative enhancement outcome.

K5. It presented primary design work rather than a review.

K6. It appeared in an indexed journal or conference between 2015 and 2025.

K7. It was written in English.

K8. Its full text was retrievable, so that every extracted magnitude could be verified at source rather than read from the abstract alone.

K2 bounds fractional bandwidth (FBW, the −10 dB impedance bandwidth over its centre frequency). A single band containing 2.4 GHz excludes dual-band and multiband designs, and the protocol fixed a 25% FBW ceiling, applied to the final design's bandwidth, measured where a measurement exists. The ceiling is a protocol choice, not the regulatory ultra-wideband boundary of FBW 0.20 or 500 MHz (Federal Communications Commission, 2024). At 25% it excluded 14 reports under F5, including (Tripathi et al., 2021) at 62.9%, (Khaleghi et al., 2018) at 40% and (Dang et al., 2025) at 28.5%. A 20% ceiling would remove two included studies, (Z. Gao et al., 2025) at 22.0% measured and (Shashi Kumar and Suganthi., 2021b) at 20.8% simulated, and change no paired statistic, since neither reports a baseline; a 30% ceiling would admit (Dang et al., 2025). K3 admits the five families of the Technique families section and separates single structures, one driven element with any passive loading, from arrays of two or more driven elements. The two classes are never mixed in the Magnitude of improvement section; 97 of the 137 studies are single structures. Criterion K6 dates each study by the publication year its database record carries. (Sudesh Darak et al., 2015), presented at a conference held in 2014, carries a 2015 publication year in Scopus and is dated accordingly.

K8 exists because a synthesis of magnitudes is only as sound as its inputs. Retrieval followed one procedure: the publisher's page, the open-access location recorded in OpenAlex and the journal archive. Of the 280 reports sought, 191 were read in full against the criteria, and F6 covers the 89 that remain: 73 were not retrieved and 16 were retrieved but not assessed. The logs name all 89 with their venues (the Study selection section compares them with the included studies). The criterion samples the accessible rather than the eligible literature, a bias that bounds every magnitude reported here, and the accessible set depends on the access the reviewer holds.

Selection process

Pre-screening removed 391 records: 310 duplicates, 26 non-English records, 53 of ineligible document type and 2 outside the 2015–2025 window. Deduplication matched on DOI, then on normalised title checked against authors and year, with the Scopus record carrying the decision. The duplicates comprise 145 IEEE Xplore and 154 Web of Science records matching Scopus, 7 Web of Science records matching IEEE Xplore, and 4 within Scopus.

Title and abstract screening assessed 2,655 records and excluded 2,375: E1, band not containing 2.4 or 2.45 GHz (133); E2, multiband, dual-band or ultra-wideband, including abstracts stating an FBW above 25% (955); E3, not a microstrip patch or no technique in scope (550); E4, secondary literature (6); and E5, specialised applications such as wearable, implantable, rectenna, sensing or radar work (731). Records without an abstract were read on the publisher's page. Rule-based classification proposed codes for 1,135 Scopus records, and the author checked each proposal against the title and abstract before it was logged; the author screened every other record by reading, including all 129 unique IEEE Xplore and Web of Science records. Eligibility assessment sought 280 full texts. Of these, 191 were retrieved and read in full, and 89 remain under F6, not retrieved or, for 16, not assessed (the Eligibility criteria section). Six further reasons excluded 54 of the 191: F1, no quantitative bandwidth or gain data (6); F2, band not containing 2.4 GHz (16); F3, no patch or no technique in scope (9); F4, specialised application (3); F5, FBW above 25% or multiband (14); and F7, duplicate publication (6). The F7 reports are the conference report of (Arnmanee., 2018) whose journal extension (Arnmanee & Phongcharoenpanich,, 2018) is included, three conference reports whose journal versions are included (Alnaiemy et al., 2018; Kawdungta et al., 2017; Yuwono et al., 2020), a second report of the antenna and data of (Bhadade and Mahajan., 2019), and an earlier report of the antenna and data of (Pinsakul and Promwong., 2019). The remaining 137 reports each describe one study. Records whose title and abstract left a criterion undetermined, usually a band given only as ISM or WLAN or a wideband claim without an FBW value, went to full text; where the full text also left it undetermined, the record was

excluded and the reason logged. Records borderline on judgement, chiefly those combining two mechanisms, went to supervisory consultation. One researcher made every screening, eligibility and extraction decision, and we do not claim equivalence with two independent screeners. Each of the 191 retrieved reports was assessed against the written criteria, and the passage that decided each verdict was recorded in the log. Criteria fixed before screening, rules calibrated on known reference studies, supervisory consultation and a per-record log of stage, code and any proposing rule limit the risk and make every decision auditable. No inter-rater agreement statistic exists, so reliability is open to audit but not quantified (the Limitations section).

Data extraction and transparency

A structured form captured geometry, substrate, technique and family, frequency, bandwidth and gain before and after enhancement, efficiency, validation method and single-structure or array status. The author extracted every value from the full text, recorded its source quotation, and verified it against the source figures or tables. No value in Table S4 or the Magnitude of improvement section rests on an abstract. Four rules govern the magnitudes in the Magnitude of improvement section. First, a before-and-after pair is recorded only when both values share a validation type, and a measured pair is preferred; S2 records for every pair whether both values are simulated, both measured, or the source leaves the type of one value unstated (not confirmed), and the Magnitude of improvement section stratifies by that field. Second, gain keeps its source unit, dB, dBi or dBic, without conversion, since within-study differences cancel the reference; directivity never enters a gain pair. Third, where baseline and enhanced designs resonate more than 5% apart in frequency, as in (Ajay et al., 2020 ; Rao and Basarkod., 2020), the change is computed on FBW. Fourth, a pair is taken for the study's primary technique and, among several configurations, for the one whose gain is reported; a secondary step, such as the ground slot of (Vandelle et al., 2019), contributes none. The extraction matrix (S2) names the pair taken from each study. Three per-record decision logs covering all 3,046 records (S1), in which included studies carry the numbers of Table S4, and the extraction matrix (S2) accompany the article, so that with Table 1 another researcher can rerun the process and check every decision.

Synthesis method

Synthesis was narrative, by primary enhancement mechanism. We did not pool, because designs differ in substrate, geometry, feed, solver and validation. For single-structure studies reporting paired values, the Magnitude of improvement section gives the count, median and interquartile range (quartiles by the (n + 1)p rule); arrays are compared only within a study, against their own element or a smaller array. Because validation type and family are

confounded, Table 5 stratifies the pairs by family and by the validation type of the pair itself, simulated, measured or not confirmed, and the pooled medians only summarise it. Five sensitivity checks (Table 6) test the pooled medians: the studies of the previous revision against those added at this one; one report per platform, keeping for each group that reports the same antenna more than once the report with the highest reporting score, then the earliest; removal of the studies that fail an implausibility rule; both removals together; and the reporting-quality split. The implausibility rule has four tests, applied to every pair: R1, the paired value appears only in the abstract; R2, the baseline gain is below 1 dB; R3, baseline and final resonances differ by more than 20%; R4, the final bandwidth exceeds ten times the baseline. These statistics describe the reporting studies and are not effect estimates.

No clinical risk-of-bias instrument fits antenna design studies, so the author appraised each study with a six-item reporting-quality checklist built for this review from the extraction fields: Q1, a baseline is stated for a claimed parameter; Q2, a fabricated prototype is measured; Q3, radiation efficiency is reported; Q4, gain is given against a stated reference (dBi or dBic); Q5, both bandwidth and gain are reported numerically; and Q6, no numeric or factual statement in the abstract or title contradicts the study's own results. Q6 is applied strictly but not pedantically: a difference within rounding (under 2%) passes, and an inconsistency found only between body text and tables does not fail Q6 but is marked in Table S4. Each Q6 failure is classified by the direction of the claimed enhancement, as favouring the design, understating it or neither; the classification was drafted with AI assistance and checked by the author (Declarations), and S2 gives it with the evidence for each. Each item scores 0 or 1, the score is reported per study in S2 and by family in the Characteristics of included studies section, and it describes how completely a study reports its result, not whether the design is good. A sensitivity check in the Magnitude of improvement section compares studies scoring 4 or more with the rest. The family classification involves judgement for the 62 studies that combine mechanisms, which are recorded so that readers can reclassify, and a term co-occurrence map built in VOSviewer (van Eck & Waltman., 2010) from the titles and abstracts of the included studies served as a check on it (Figure 3, the Trends and gaps section), not as evidence.

Results and Discussion

Study selection

The searches identified 3,046 database records: 2,605 from Scopus, 221 from IEEE Xplore and 220 from the Web of Science Core Collection. Pre-screening removed 391 records, and title and abstract review excluded 2,375 of the remaining 2,655. Of the 280 reports sought, 191 were assessed in full, 54 were excluded and 137 reports, one per study, were included; 89 remain under F6 (Figure 1).

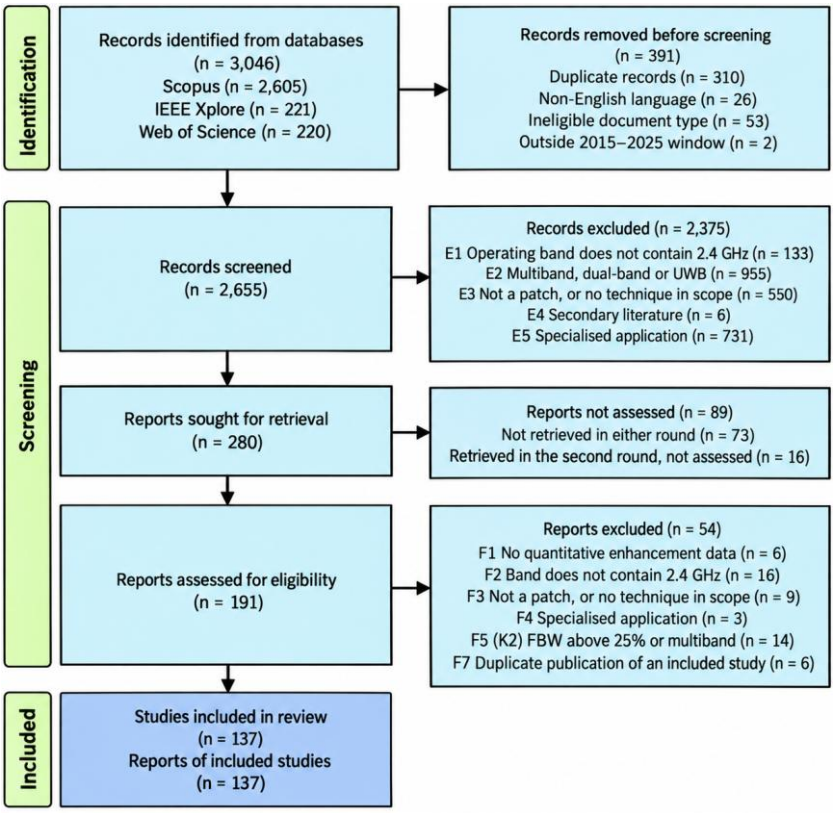


Figure 1 PRISMA 2020 flow of study selection.

Overlap is high: 145 of 221 IEEE Xplore and 154 of 220 Web of Science records duplicated Scopus, and the 76 and 66 records absent from Scopus produced one included study (Anita & Chaitanya Kumar., 2015), with 3 under F6. This reflects the broader Scopus string and its indexing of IEEE proceedings, and measures the relation between the strings, not the completeness of the search. E2 accounted for 955 of the 2,375 screening exclusions and was the largest reason in every database (892 of 2,526 Scopus records screened, 29 of 76 from IEEE Xplore, 34 of 53 from Web of Science): most 2.4 GHz antenna research indexed under these terms targets multiband operation, so a single-band synthesis covers ground few have worked. E5 accounted for 731 exclusions, E3 for 550, E1 for 133, mostly 5.8 GHz and sub-6 GHz designs, and E4 for 6.

The 89 reports under F6 differ from the included studies in venue and period. At least 67 (75%) are conference papers, against 81 of the 137 included studies (59%); 42 (47%) carry an IEEE DOI, against 69 (50%); and by period they split 29 to 60, against 74 to 63 for the included studies. A record counts as a conference paper when its source title names a conference, proceedings, symposium, workshop, seminar or proceedings book series. The corpus therefore under-represents recent conference proceedings, and every family proportion and trend carries that skew.

Characteristics of included studies

Table 2 lists the 137 studies by family, separating single structures from arrays, and Table S4 gives each study's technique, outcome, combined mechanisms and validation, numbered by family and year.

Table 2 Included studies by technique family (study-level characteristics in Supplementary Table S4)

Family (studies)	Mechanism and typical implementations	Studies (single structures; arrays)
EBG, metamaterial, FSS and superstrate (43)	Mushroom and uniplanar EBG, AMC and metamaterial ground planes; CSRR and SRR loading; FSS; superstrates, lenses and partially reflecting surfaces above the patch; metasurface reflectors behind it	Single structures (39): Pandeeswari & Raghavan, 2015; Sudesh Darak et al., 2015; Abu et al., 2016; Farooq et al., 2016; Mi & Lee, 2016; Bakar et al., 2017; Bian et al., 2017; Ekke & Zade, 2017; Kawdungta et al., 2017; Al-Bawri & Jamlos, 2018; Alnaiemy et al., 2018; Amsaveni et al., 2018; Arnmanee & Phongcharoenpanich, 2018; Bakar et al., 2018b; Bakar et al., 2018c; Belen, 2018; Güneş et al., 2018; Rambe et al., 2018; Branco et al., 2019; El Yassini et al., 2019; Pinsakul & Promwong, 2019; Shah et al., 2019; Alnaiemy & Nagy, 2020; Geetharamani & Aathmanesan, 2020; Serres et al., 2020; Shashi Kumar & Suganthi, 2021b; Arun Shaji & Pradeep, 2022; Deb et al., 2022; Ramesh & Vakula, 2022; Khouyaoui et al., 2023; Kumar et al., 2023; Sneha et al., 2023; Arun Shaji et al., 2024; Khouser et al., 2024; Kumar & Kumar, 2024; Tiwari et al., 2024; Ainthachot et al., 2025; Oner et al., 2025; Shaji et al., 2025. Arrays (4): Baviskar & Jeyakumar, 2015; Baviskar et al., 2015; Hariyadi et al., 2020; Shashi Kumar & Suganthi, 2021a.
Arrays (33)	Two to 25 elements; corporate, series and parallel feeds with quarter-wave transformers; some with slotted, truncated or stagger-tuned elements	Arrays (33): Salleh et al., 2015; Latha & Anand, 2016; Meneses González et al., 2016; Raju et al., 2016; Kumar & Suganthi, 2017; Ayn et al., 2018; de Oliveira et al., 2018; El Abbasi et al., 2018; Sotyohadi et al., 2018; Ying et al., 2018; Yunus et al., 2018; Ismail, Permana, et al., 2019; Shekhar, 2019; Shravan et al., 2019; Bhattarai et al., 2020; Kumar & Suganthi, 2020; Oliveira et al., 2020; Prakasam et al., 2020; Yuwono et al., 2020; Mahajan et al., 2021; Nandedkar et al., 2021; Patel & Singh, 2021; Ram et al., 2021; Venkataramanan et al., 2021; Alsawaf & Kanaan, 2023; Rahardi et al., 2023; Reddy et al., 2023; Alaba et al., 2024; Kumar et al., 2024; Patil & Patil, 2024; Boukredine et al., 2025; Hossain et al., 2025; Kopbay et al., 2025.
Slots, parasitic elements and fractals (26)	U, V, P and cross slots in the patch; coplanar, stacked and director parasitic patches; microstrip Yagi arrangements; fractal perimeters	Single structures (25): Majed, 2015; Xu et al., 2016; Nornikman et al., 2017; Malek et al., 2018; Wang et al., 2018; Zain et al., 2018; Ali et al., 2019; Clark et al., 2019; Islam et al., 2019; Ismail, Oktafiani, & Permana, 2019; Panda et al., 2019; Ramos et al., 2019; Roy et al., 2019; Kalaiyarasan et al., 2020; Sener, 2020; Zhao et al., 2021; Nawaz & Niazi, 2022; Choudhary et al., 2023; Jayanth et al., 2023; Kalaiyarasan et al., 2023; Zhang et al., 2023; S. Gao et al., 2025; Z. Gao et al., 2025; Prottoy et al., 2025; Sathish et al., 2025. Arrays (1): Viswanadh Raviteja, 2018.
Defected ground structures (22)	Rectangular, dumbbell, CSRR, hexagonal and fractal defects etched in the ground; partial grounds	Single structures (21): Anita & Chaitanya Kumar, 2015; Deb et al., 2015; Anita & Chaitanya Kumar, 2016; Fistum et al., 2016; Marotkar & Zade, 2016; Marotkar et al., 2016; Aravindraj & Ayyappan, 2017; Tawfeeq, 2017; Islam et al., 2018; Prasad et al., 2018; Singh et al., 2018; Abdulkareem & Srivatsun, 2019; Anapana et al., 2019; Ajay et al., 2020; Rao & Basarkod, 2020; Laabadli et al., 2023; Zambak et al., 2023; Ahasan & Billah, 2025; Bansal et al., 2025; Chakradhar et al., 2025; Deshpande et al., 2025. Arrays (1): Patil & Yadav, 2024.

Family (studies)	Mechanism and typical implementations	Studies (single structures; arrays)
Air gap and substrate engineering (13)	Air gaps and suspended patches; porous, magneto-dielectric, artificial-dielectric, 3D-printed and curved substrates; spaced reflectors	Single structures (12): Mekki et al., 2015; Phoo et al., 2015; Yon et al., 2016; Bakar et al., 2018a; Bhadade & Mahajan, 2019; Hasanah et al., 2019; Paul et al., 2019; Vandelle et al., 2019; Al Kharusi et al., 2020; Bhongale et al., 2020; Fernandez et al., 2022; Muntoni et al., 2023. Arrays (1): Jais et al., 2015.

Single structure: one driven element with any passive loading; array: two or more driven elements (the Eligibility criteria section). Studies are listed by year within each cell and appear once, under their primary family; the other mechanisms of the 62 studies that combine families are given in Table S4.

Table 3 crosses family against validation type. Simulation alone validated 72 of 137 studies; 63 combined simulation with measurement and 2 reported measurement only, so 65 studies carry a measurement. The share differs by family: 7 of 13 air gap and substrate studies, 15 of 26 slot, parasitic and fractal studies and 22 of 43 periodic-structure studies report a measurement, against 15 of 33 arrays and 6 of 22 defected-ground studies. These proportions describe this corpus, which criterion K8 shaped, not the families' literatures at large.

Reporting quality varies more than validation alone shows. On the six-item checklist of the Synthesis method section the median score is 3 of 6: 64 studies score 4 or more, 44 score 2 or less, and 6 score 6 (Arnmanee & Phongcharoenpanich., 2018; El Yassini et al., 2019; Kawdungta et al., 2017; Khouser et al., 2024; Muntoni et al., 2023; Pinsakul & Promwong, 2019). Across the corpus 89 studies state a baseline, 66 measure a prototype, 48 state the gain reference, 37 report efficiency, 96 report both bandwidth and gain, and 109 have an abstract and title consistent with the full text. Air gap and substrate studies (median 4) and periodic-structure studies (median 4) report most completely, slot-family (3.5) and defected-ground studies (3) less so, and arrays least (median 2), because most array studies give a final gain in dB without a baseline, efficiency or measurement.

Table 3 Included studies by technique family and validation type

Family	Simulation only	Simulation and measurement	Measurement reported	Total
DGS	16	6	0	22
Slot/Parasitic/Fractal	11	15	0	26
EBG/MTM/FSS/Superstrate	21	22	0	43
Array	18	13	2	33
Air gap/Substrate	6	7	0	13
Total	72	63	2	137

Table 4 crosses family against publication period. The two periods cover five and six years and contributed 74 and 63 studies, 14.8 and 10.5 a year. Per year, arrays rose from 2.8 to 3.2, while periodic-structure work fell from 4.8 to 3.2, slot, parasitic and fractal work from 2.8 to 2.0, defected ground structures from 2.6 to 1.5 and air gap and substrate engineering from 1.8 to 0.7. The two period totals are the sums of the annual counts plotted in Figure 2, and both tables and the figure sum to 137.

Table 4 Included studies by technique family and publication period

Family	2015–2019 (5 years)	2020–2025 (6 years)	Total
DGS	13	9	22
Slot/Parasitic/Fractal	14	12	26
EBG/MTM/FSS/Superstrate	24	19	43
Array	14	19	33
Air gap/Substrate	9	4	13
Total	74	63	137

FR-4 is the most common substrate, chosen for its price, and Rogers RT/duroid 5880 the most common low-loss alternative; the Trade-offs section returns to that choice as a cost-efficiency trade-off. Edge and inset feeding dominate. Conference papers account for 81 of the 137 studies and journal articles for the rest.

Technique families (RQ1)

Five families answer RQ1, distinguished by physical mechanism rather than by geometry

EBG, metamaterial, FSS and superstrate structures (43 studies) shape the field around the patch. Periodic structures in or around the ground suppress surface waves and return that power to the main beam; superstrates form a partially reflecting cavity above the patch (Trentini., 1956). Because the cavity condition depends mainly on spacing in wavelengths, similar gains might be expected across implementations, but paired changes in this family run from −1.57 to +7.86 dB across 27 single-structure studies and three arrays compared with their bare counterparts (the Magnitude of improvement section). Slots, parasitic elements and fractals (26 studies) modify the radiating patch. Slots lengthen the current path and can add a nearby resonance that widens the band (Wang et al., 2018); stacked parasitics can raise gain and bandwidth together (Zhang et al., 2023); and fractal perimeters widen the band in steps with iteration order (Bansal et al., 2025). The family costs no footprint; cross-polarisation is the price the mechanism predicts, but no included study reports it in paired numeric form.

Arrays (33 studies), from two to twenty-five elements with corporate or edge feeds, raise directivity by aperture synthesis, about 3 dB per doubling less the power the feed dissipates. Every gain of 15 dB or more in the corpus comes from an array, while the highest single-structure value is 13.4 dBi under a large EBG layer (Alnaiemy & Nagy., 2020); the family's cost is board area and feed loss rather than height.

Defected ground structures (22 studies) etch a defect that adds an LC resonance beside the patch resonance. Where the two merge, the band widens, which lies behind several of the largest bandwidth figures (Marotkar & Zade., 2016; Marotkar et al., 2016; Ajay et al., 2020;

Rao & Basarkod., 2020; Laabadli et al., 2023); where they do not, resonance shifts downward and the band can narrow (Anapana et al., 2019; Ahasan & Billah., 2025). Radiation through the defect is expected to raise back radiation, but none of the 22 studies reports a front-to-back ratio, so the corpus neither confirms nor sizes that cost.

Air gap and substrate engineering (13 studies) alters the dielectric. Lower effective permittivity should lower the quality factor and widen the band, and lower loss should raise efficiency. (Muntoni et al., 2023) report both after curving the 3D-printed substrate of a gap-coupled patch (FBW 6.1% to 16.3%, efficiency 77.7% to 95.6%), (Paul et al., 2019) after replacing FR-4 with porous glass (174.3 against 101.3 MHz, efficiency 51.2% to 68.8%, simulated), and an air gap lifts a paper-substrate patch from 1.6% to 80% efficiency (Vandelle et al., 2019). The bandwidth expectation does not hold across the family: a 3 mm air gap under an RT/duroid 5880 substrate narrows the measured band from 111.1 to 72.9 MHz while raising gain (Al Kharusi et al., 2020), and a reflector spaced 0.04λ_0 behind the radiator narrows it from 55 to 44.7 MHz while raising gain from 2.22 to 5.4 dB (Mekki et al., 2015). The corpus therefore supports the efficiency effect but no general bandwidth rule. Sixty-two studies combine mechanisms from two or more families, usually a mode-adding mechanism with an aperture-enlarging one. Each went to the family its authors name as the primary source of the improvement or, in staged comparisons, to the family behind the largest step, and none was counted twice. The families are disjoint as counts but not as physics, and the Combines column of Table S4 lets a reader reclassify any of the 62.

Magnitude of improvement (RQ2)

Complete before-and-after pairs are scarce even in full texts: 89 of the 137 studies pair a baseline with an enhanced value for at least one claimed parameter (70 for gain and 65 for bandwidth, across single structures and arrays), 9 state a change without its baseline and 39 report a final value only. The statistics below describe that reporting subset, across designs that share no platform. Full-text verification matters because 28 studies make a statement in the abstract or title that their own tables or figures contradict (Q6, the Synthesis method section). The comparison was not systematic, so these are the discrepancies found, not their frequency. Classified by the direction of the claimed enhancement (S2), 16 favour the design, 6 understate it and 6 favour neither. (Tawfeeq., 2017) reports an “improvement in both the gain of 3.45 dB”, which is the final gain after a rise of +0.49 dB; (Deshpande et al., 2025) state 16.969 dB where their own gain plot reads 6.57 dBi; (Roy et al., 2019) state 174 MHz for a band reported as 50 MHz simulated and 75 MHz measured; and (Anapana et al., 2019) present as a bandwidth enhancement a defected ground that narrows the band from 26.5 to 21.2 MHz. Elsewhere, abstracts present simulated results as measured (Venkataramanan et al., 2021;

Yunus et al., 2018), claim a gain improvement where gain falls from 7.19 to 7.15 dBi (Ramos et al., 2019), describe a +5.2 dB rise as a gain enhancement of about 13 dBi (Ying et al., 2018) or give a return loss of −46.13 dB where the table reads −26.13 dB (Hasanah et al., 2019); others understate the result, as when a bandwidth rise from 84.85 to 148.60 MHz is reported as 2.61% (Baviskar et al., 2015). Table S4 carries the full-text figures. Of the 137 studies, 72 report simulated values only and 65 report a measurement. A study that measures a prototype does not always pair measured values: Rule 1 of the Data extraction and transparency section prefers a measured pair, but the pair can only be what the source reports, so Table 5 splits the pairs by their own validation type, not by the study's.

Bandwidth. Table 5 gives the paired changes by family and by the validation type of the pair. Across 50 single-structure studies the median relative change is +69% (interquartile range +4% to +261%; range −42% to +1,567%). Of the 50 pairs, 41 are simulated (median +54%), one is measured (Al Kharusi et al., 2020, −34%) and eight leave the validation type of one value unstated (median +153%). A measured before-and-after bandwidth pair exists in one study, and the eight unconfirmed pairs carry the largest changes. Within families the simulated medians run from +16% (slot family, 5 studies) to +98% (defected ground, 15); every measured cell is empty or holds one study. The largest rise is +1,567%, a 33 MHz patch widened to 550 MHz in simulation under a partial reflective surface (Oner et al., 2025), followed by an asymmetric defected ground at +654% (Marotkar et al., 2016), a near-zero-index metasurface at +611% (Kumar et al., 2023) and a stacked parasitic patch at +557% (Zhang et al., 2023); all four are simulated pairs from studies that also measured a prototype. Nine studies report a narrower band, eight of them gain- or efficiency-oriented treatments, and one reports no change (Branco et al., 2019). On the K2 rule, the widest final bands are 22.0% (Z. Gao et al., 2025, measured) and 20.8% (Shashi Kumar & Suganthi, 2021b, simulated).

Gain. Across 49 single-structure studies the median change is +1.30 dB (interquartile range +0.18 to +4.06 dB; range −1.58 to +7.86 dB). Of the 49 pairs, 39 are simulated (median +0.81 dB), four are measured (median +3.05 dB: Al Kharusi et al., 2020; Arnmanee & Phongcharoenpanich., 2018; Bian et al., 2017; Khouser et al., 2024) and six leave the validation type of one value unstated (median +3.9 dB); the pair of El Yassini et al. (2019), whose baseline is simulated and whose enhanced value carries no stated type, is one of the six. Four measured pairs cannot be set against 39 simulated ones, so the corpus does not show whether measured gains exceed simulated gains; it shows that measured pairs are rarely reported. Within the periodic-structure family the 18 simulated pairs have a median of +1.79 dB and the three measured pairs +5.0 dB. The distribution has a gap: 29 studies report +1.8 dB or less, 20 report +2.6 dB or more, and none falls between. (Ali et al., 2019) pair directivity

(7.1 to 7.78 dBi) and are excluded. The largest rises are +7.86 dB (Arnmanee & Phongcharoenpanich., 2018) and +7.1 dB (Alnaiemy & Nagy., 2020). Among the 21 studies that place a layer above the patch, the median is +3.2 dB, but the 13 simulated pairs have a median of +0.32 dB and three of them lose gain (Bakar et al., 2017,2018b, 2018c); the larger values come from the three measured pairs (median +5.0 dB) and five unconfirmed ones. A superstrate adds several decibels in about half the cases.

Sensitivity. Table 6 gives the five checks. The 30 bandwidth and 26 gain pairs of the previous revision have medians of +77% and +2.45 dB, and the 20 and 23 pairs added at this revision +69% and +1.10 dB, so the added studies halve the gain median. Four groups report the same antenna more than once (Anita & Chaitanya Kumar., 2015, 2016; Bakar et al., 2017, 2018a, 2018b, 2018c; Ismail, Oktafiani & Permana, 2019; Ismail, Permana, et al., 2019; Marotkar & Zade, 2016; Marotkar et al., 2016); keeping one report per platform gives +85% (46 studies) and +1.69 dB (46). Six studies fail the implausibility rule of the Synthesis method section: (Jayanth et al., 2023) under R1, whose +6.8 dB appears only in the abstract; (Chakradhar et al., 2025; Ekke and Zade., 2017) under R2, with baseline gains of 0.37 and −1.66 dB; (Hasanah et al., 2019; Rao and Basarkod ., 2020) under R3, with baselines resonating at 3.0 and 3.09 GHz; and (Oner et al., 2025) under R4. Without them the medians are +65% (45) and +1.09 dB (44), and with both removals +72% (41) and +1.10 dB (41). Studies scoring 4 or more on the reporting checklist give +32% (29) and +1.76 dB (30), against +98% (21) and +0.81 dB (19) for the rest. Across the five checks the bandwidth median lies between +32% and +98% and the gain median between +0.81 and +2.45 dB. Every median is positive, and the gain median responds most to which studies were retrievable. The superstrate median of +3.2 dB (21 studies) becomes +3.4 dB (19) with one report per platform.

Table 5 Paired changes of single-structure studies by family and by the validation type of the pair: median (number of studies)

Bandwidth change (%)	**Simulated pair**	**Measured pair**	**Not confirmed**	**All pairs**
Defected ground	+98 (15)	–	+277 (1)	+122 (16)
Slot, parasitic, fractal	+16 (5)	–	+106 (2)	+100 (7)
EBG, MTM, FSS, superstrate	+22 (15)	–	+160 (4)	+25 (19)
Air gap, substrate	+64 (6)	−34 (1)	+168 (1)	+64 (8)
All single structures	+54 (41)	−34 (1)	+153 (8)	+69 (50)
Gain change (dB)	**Simulated pair**	**Measured pair**	**Not confirmed**	**All pairs**
Defected ground	+0.71 (9)	–	–	+0.71 (9)
Slot, parasitic, fractal	+0.61 (7)	–	–	+0.61 (7)
EBG, MTM, FSS, superstrate	+1.79 (18)	+5.00 (3)	+3.90 (6)	+2.64 (27)
Air gap, substrate	+3.18 (5)	+0.81 (1)	–	+2.13 (6)
All single structures	+0.81 (39)	+3.05 (4)	+3.90 (6)	+1.30 (49)

Layer above the patch (21 studies)	+0.32 (13)	+5.00 (3)	+4.60 (5)	+3.19 (21)

Single-structure studies only; arrays are compared within their own study (the Magnitude of improvement section). Pair validation: simulated, both values simulated; measured, both values measured; not confirmed, the source leaves the validation type of one value unstated or pairs a simulated baseline with a value of unstated type. Bandwidth change is relative, computed on FBW where baseline and final resonances differ by more than 5%; gain change is in the unit of the source. Cells of fewer than five studies are listed for completeness and are not compared in the text.

Table 6 Sensitivity of the pooled medians of Table 5: median (number of studies).

Check	Bandwidth (%)	Gain (dB)
All pairs	+69 (50)	+1.30 (49)
Studies of the previous revision	+77 (30)	+2.45 (26)
Studies added at this revision	+69 (20)	+1.10 (23)
One report per platform	+85 (46)	+1.69 (46)
Without the six studies failing the implausibility rule	+65 (45)	+1.09 (44)
Both removals	+72 (41)	+1.10 (41)
Reporting score 4 or more	+32 (29)	+1.76 (30)
Reporting score 3 or less	+98 (21)	+0.81 (19)
Layer above the patch, all / one report per platform		+3.19 (21) / +3.41 (19)

Median of the paired change (number of studies). The implausibility rule (R1 to R4) is stated in the Synthesis method section; the six studies that fail it are named in the Magnitude of improvement section. One report per platform keeps, for each group that reports the same antenna more than once, the report with the highest reporting score, then the earliest.

Arrays are reported apart because they enlarge the aperture. In five same-platform comparisons, the first doubling returns +1.98 to +3.83 dB against an ideal 3 dB, and four elements return +3.15 to about +5 dB against an ideal 6 dB (Alaba et al., 2024; Alsawaf & Kanaan, 2023; Kopbay et al., 2025; Kumar & Suganthi., 2017; Ram et al., 2021), a shortfall of up to about a decibel; (Kumar and Suganthi., 2017) exceed the ideal because their two-element design also truncates the patch corners. Seven further comparisons, all simulated, agree in the main: four elements return +4.3 to +5.83 dB (Kumar & Suganthi., 2020; Latha & Anand., 2016; Patil & Patil., 2024; Shekhar., 2019; Ying et al., 2018) and sixteen return +11.66 dB against an ideal 12 dB (Bhattarai et al., 2020; Rahardi et al., 2023) report +6.39 dB for four elements from a 2.5 dBi slotted element, above the ideal, and are treated as unconfirmed. Eight further studies pair values against a bare or smaller array (Table S4), so their changes measure loading, element geometry or array size rather than aperture synthesis.

Gains of 15 dB or more appear only in arrays, all with simulated gain: 16.07 dB (Ayn et al., 2018), 16.76 dB for sixteen elements (Kumar et al., 2024), 17.91 dBi for sixteen elements (Bhattarai et al., 2020), 18 dB (Boukredine et al., 2025) and 19.29 dBi (Jais et al., 2015); the last two exceed what four elements can deliver by aperture arithmetic and are treated as

unconfirmed. The highest single-structure values are 13.4 and 11.1 dBi under EBG layers, from 6.3 and 5.6 dBi patches (Alnaiemy & Nagy., 2020; Alnaiemy et al., 2018). Relative and absolute gains answer different questions: the largest relative rises start from bands of 33 to 67 MHz or from 2 to 3 dBi patches, so a designer should read the absolute values in Table S4 and a researcher assessing a mechanism the relative ones.

Efficiency is reported by 37 studies and paired by 16. Changing the dielectric the patch sees moves it by 6 to 78 percentage points (Muntoni et al., 2023; Paul et al., 2019; Pinsakul & Promwong., 2019; Vandelle et al., 2019), ground-plane loading by 6 to 50 points (Abu et al., 2016; Ahasan & Billah., 2025; Mi & Lee., 2016; Singh et al., 2018), a spaced reflector by 20 and 40 points (Kumar & Kumar., 2024; Mekki et al., 2015) and a superstrate or cover layer by 1 to 2.5 points (Branco et al., 2019; Kawdungta et al., 2017; Yon et al., 2016), while total efficiency falls under the metasurface of (Bakar et al., 2018) and rises under the defected ground of (Islam et al., 2018); a four-element array adds 7 points over its element (Latha & Anand., 2016). With four, four, two and three studies in the main groups, this ordering is an observation to be tested. Without efficiency, a technique that cuts loss cannot be separated from one that concentrates the beam.

In answer to RQ2, bandwidth and gain respond to different families on different scales. Bandwidth responds to added or merged resonances and to a lower quality factor, reaching several multiples of baseline in simulation; single-structure gain rises stay below 2 dB for most ground-plane and patch modifications, while layers above or behind the patch split between rises of 3 to 8 dB and rises below 1.5 dB; and only arrays reach 15 dB or more. Nearly every magnitude behind those statements is simulated: one bandwidth pair and four gain pairs in the corpus are measured, so the size of an improvement on a prototype is not established for any family. All comparisons across families are indirect.

Trade-offs (RQ3)

Five trade-off categories run across the corpus

Height and area. Superstrates need a gap above the patch, from 1 mm (Bakar et al., 2018c) to 130 mm, about one wavelength, under the 240 × 240 mm lens of (Alnaiemy et al., 2018), with near-zero-index and cavity designs at 0.08λ to 0.128λ, about 10 to 16 mm (Arun Shaji & Pradeep., 2022; Shaji et al., 2025). The highest single-radiator gains come with the largest apertures and gaps, which compact devices cannot accommodate. Fabrication complexity. Multilayer stacks and suspended superstrates add assembly steps (Arnmanee & Phongcharoenpanich., 2018; Oner et al., 2025; Shaji et al., 2025), and air-gap results move with gap height (Al Kharusi et al., 2020; Ayn et al., 2018). No study reports yield or cost, so complexity is inferred from layer count, not measured. Resonance shift. Path-lengthening

techniques move resonance downward, from 2.86 to 2.47 GHz (Ajay et al., 2020) and from 3.09 GHz into the 2.4 GHz band (Rao & Basarkod., 2020), adding a retuning step that studies rarely report. Substrate cost versus efficiency. FR-4 is cheap and lossy and RT/duroid 5880 costly and low-loss, while removing or curving the dielectric reaches 95.6% efficiency on an FR-4-class board at a mechanical cost (Muntoni et al., 2023). No study reports board price, so only the direction of this trade-off is supported.

Feed network loss. Each array doubling adds branching that absorbs part of the ideal gain, up to about a decibel per doubling (the Magnitude of improvement section); twelve designs on different substrates are not a loss model. Used as a checklist, the five categories become budgets, height, board area, assembly steps, frequency shift and substrate cost, and each family passes or fails on its own line, so no family is superior in general. Where compactness governs, defected ground structures and coplanar slots add no footprint or height and buy bandwidth or a decibel or two of gain; the back radiation and cross-polarisation their mechanisms predict are not reported. Where gain governs and space allows, only arrays reach 15 dB or more and, apart from one simulated result that fails the implausibility rule (Jayanth et al., 2023; the Magnitude of improvement section), only superstrates add 5 to 8 dB to a single radiator, charging height, and then in about half the cases; the five studies that report a paired front-to-back ratio all report it rising, four of them with a layer above or around the patch (Arnmanee & Phongcharoenpanich., 2018; Branco et al., 2019; Deb et al., 2022; Sneha et al., 2023) and one with a substituted substrate (Paul et al., 2019). Where bandwidth governs, three of the four largest widenings place a layer above the patch and charge height (Kumar et al., 2023; Oner et al., 2025; Zhang et al., 2023), and defected ground structures carry the fourth and five of the next eight. Where fabrication simplicity governs, defected ground structures and slots need only the etching the board already requires.

Trends and gaps (RQ4)

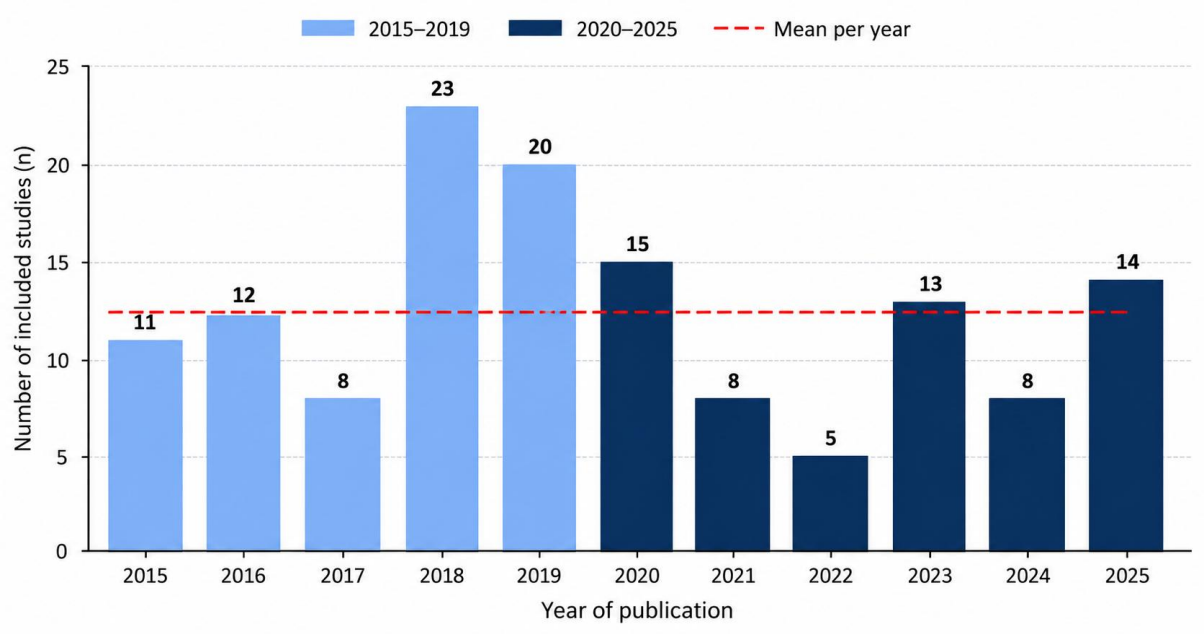


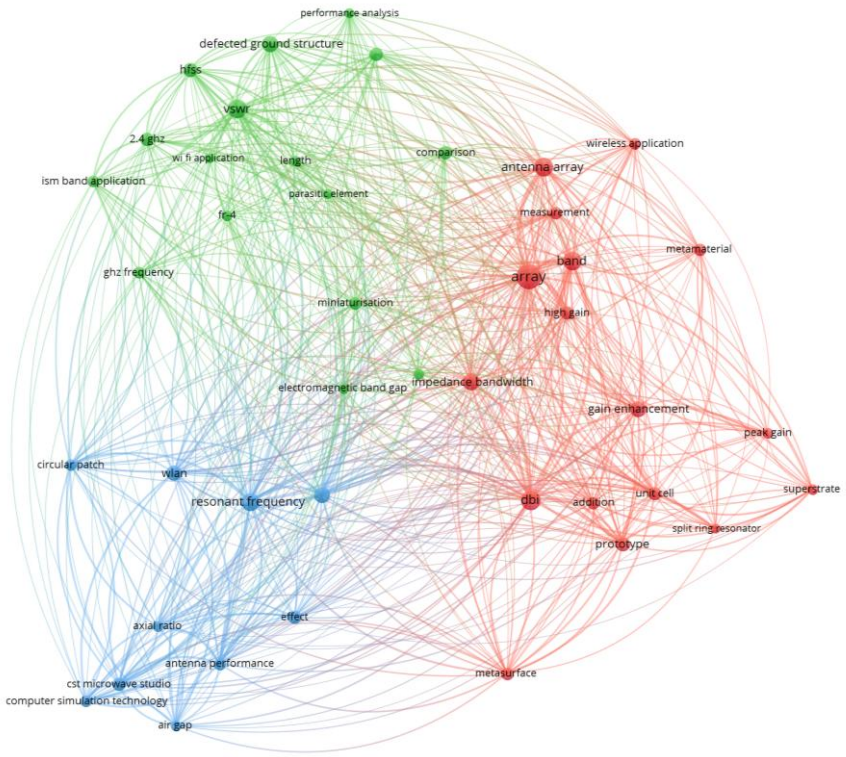
Figure 2 Annual distribution of the 137 included studies, 2015–2025.

The single peak falls in 2018, with 23 studies, nine of them periodic-structure designs, followed by 2019 with 20; other years hold 5 to 15. Three cautions apply: 2025 records may still be entering the indexes; the bars count retrievable studies, so thin years such as 2022 (5 studies) show what could be verified, not what was published; and five of the 2018 studies come from two groups publishing companion papers (Bakar et al., 2018a, 2018b, 2018c; Belen., 2018; Güneş et al., 2018). The 2018 peak is therefore a concentration within this corpus, not a measured peak in activity.

Three trends describe the corpus, stated per year because the periods cover five and six years. Periodic structures are the largest family throughout (11 of 31 studies in 2015–2017, 24 of 74 in 2015–2019), easing from 4.8 to 3.2 a year. Arrays rose from 2.8 to 3.2 a year, the only family to rise, while slot, parasitic and fractal work fell from 2.8 to 2.0 and defected ground structures from 2.6 to 1.5. Combinations are common (62 of 137), and new materials and processes have entered: graphene (Ram et al., 2021), paper (Vandelle et al., 2019), biodegradable films (Serres et al., 2020), magneto-dielectric substrates (Bhongale et al., 2020; Pinsakul & Promwong., 2019), 3D-printed and curved substrates (Muntoni et al., 2023; Oner et al., 2025) and surrogate-assisted optimisation (Alaba et al., 2024). Trends of this size lie within what a different retrievability outcome produces, and retrievability favours earlier work (the Study selection section); these trends are indicative.

Figure 3 maps the terms of the titles and abstracts of the 137 included studies (43 terms in three clusters) as a check on the classification, not as evidence about the antennas. The red

cluster joins the array vocabulary (array, antenna array, high gain, peak gain) to the periodic-structure terms (metamaterial, metasurface, superstrate, unit cell, split ring resonator) with prototype and measurement, so the two routes to large gain in the Magnitude of improvement section share a cluster; the green cluster places defected ground structure, parasitic element and electromagnetic band gap beside design and matching terms, so the ground-plane and patch-level families do not separate in the abstracts; and the blue cluster gathers the vocabulary of suspended circularly polarised patches (Bakar et al., 2017, 2018a; Phoo et al., 2015). No slot term appears at the settings used (S3), so the map cannot test that family. In the overlay (Figure 3b), electromagnetic band gap and air gap date near 2018 and metasurface, superstrate, prototype and measurement near 2021, consistent with the move in Table S4 from ground-plane loading toward layers above the patch and measured prototypes. A term map of 137 abstracts moves with a few documents and depends on how authors word them, so Figure 3 is consistent with Table 4, not independent evidence for it.



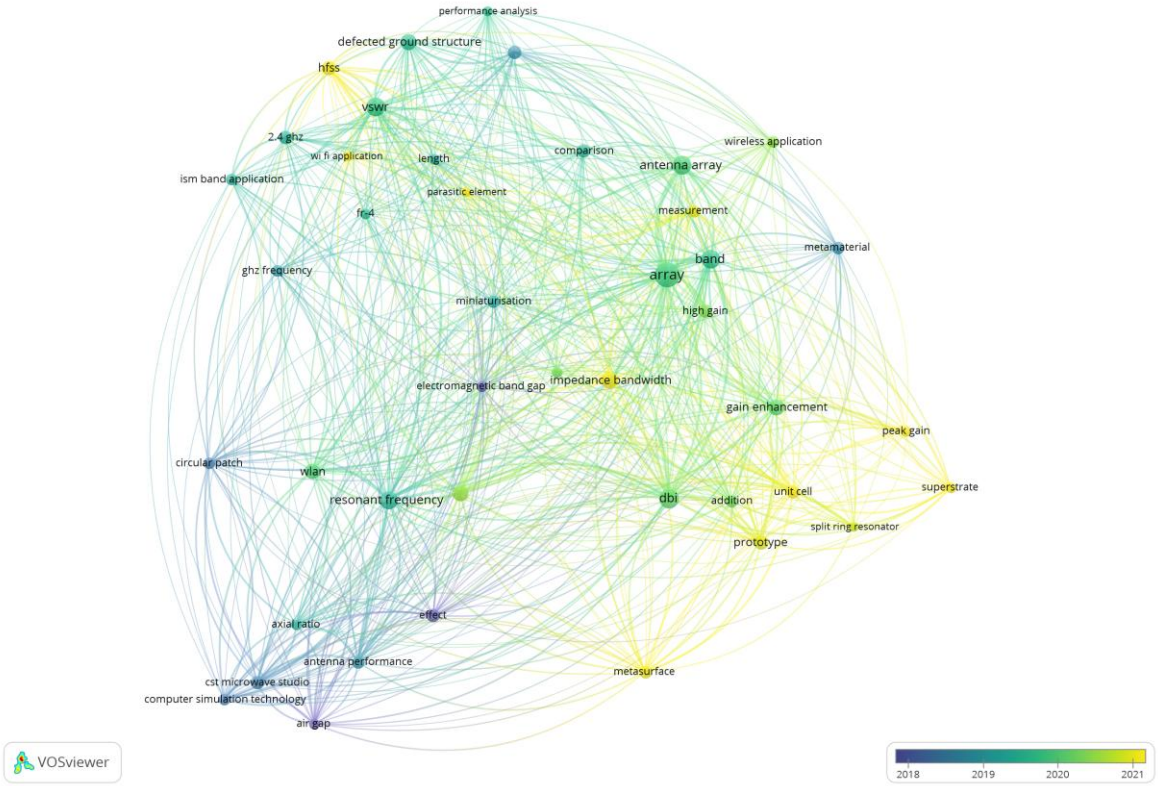


Figure 3. Term co-occurrence map of the titles and abstracts of the 137 included studies, built in VOSviewer (van Eck & Waltman, 2010). (a) Cluster view: three clusters. (b) Overlay view: each term coloured by the mean publication year of the studies that carry it, about 2018 to 2021. Node size reflects the number of studies carrying the term; VOSviewer omits some labels to avoid overlap. The map describes how the studies are written, not how the antennas perform.

Four gaps follow, ordered by how much they constrain the field

Reporting. Sixteen of the 28 discrepancies between an abstract or title and the study's own results favour the design (the Magnitude of improvement section), so a synthesis built from abstracts alone risks inheriting that bias, and 48 of 137 included studies state no baseline for the parameter they claim to improve. Before-and-after reporting on a common platform, carried into the abstract with efficiency and an explicit gain reference, would address both problems.

Experimental validation. Seventy-two of 137 studies stop at simulation, and the share is highest in the two families that cost least to fabricate: 16 of 22 defected-ground studies and 18 of 33 arrays report no measurement. That is a property of this corpus, not of those literatures in general; what it supports is that the cheapest techniques to test are the ones least often tested in the retrievable single-band 2.4 GHz literature.

Efficiency. One hundred of 137 studies report no radiation efficiency, so most gain figures cannot be decomposed into directivity and loss. Air gap and substrate engineering, the

smallest family at 13 studies, holds the largest paired efficiency change in the corpus, so the gap between attention and results is widest there.

Absence of common-platform comparison. No study compares several families side by side on one substrate, one set of dimensions and one evaluation tool, so every cross-family comparison in this literature, this review included, is indirect.

Interpretation and implications for practice

No family wins outright: the choice depends on the prioritised parameter and the binding budget. The magnitudes behave as the mechanisms predict in direction, which supports the classification: the largest widenings come from added resonances or a lower quality factor; superstrate gain has a median of +3.2 dB across 21 studies, consistent with (Trentini., 1956) in sign, although its spread from −0.6 to +7.9 dB, and a median of +0.3 dB across the 13 simulated pairs, show that the principle predicts the direction of the effect but not its size; and array gain falls short of 3 dB per doubling in all but two studies.

This review extends prior secondary literature rather than contradicting it. (Ahmed and Kabir .,2026) cover more techniques in a finer taxonomy; this review fixes the frequency, reports its protocol and logs, and reports what the corpus fails to report, which separates it equally from reviews of metasurface loading (Castro Alvarez & George., 2026; Elalaouy et al., 2024), optimisation (Ghewari & Patil., 2025), applications (Arnaoutoglou et al., 2024; Hassan et al., 2025; Pawar & Deosarkar., 2025; Saeed & Nwajana., 2024), an adjacent band (Albaihani et al., 2026) and wearable antennas (Banale et al., 2025).

Limitations

Four limitations bound the conclusions directly. First, K8 introduces access bias. Of the 89 screened-in reports not assessed, 73 were not retrieved and 16 were retrieved but not assessed; the accessible set depends on the access the reviewer holds, so the corpus samples the accessible literature. Second, only 89 studies pair a baseline with an enhanced value, five of the single-structure pairs are measured, and family and validation are confounded, so every statistic carries its count and stratum and none is pooled into an effect. Third, 72 studies are simulated only and none is replicated. Fourth, 62 studies combine mechanisms and no two groups share a platform, and publication bias may skew the reported ranges upward in ways this heterogeneity prevents us from testing. The reporting-quality checklist was built for this review and applied by the author alone, so its items are transparent but unvalidated.

The search carries three more. Three databases and an English-language restriction leave regional and non-English venues out; the narrower IEEE Xplore and Web of Science strings test the Scopus string only within shared phrases; and a study naming only WLAN or ISM is

reached only through the exact-phrase block. The reference-list check (the Data sources and search strategy section) shows that weakness. The eligible report the searches missed calls a WLAN array one “with improved bandwidth” and gives no spaced “2.4 GHz” in its abstract (Naik & Virani., 2016). Of the four further misses among the borderline reports, two use other wording (“performance enhancement”, “broadband”), one appeared in a venue outside the three databases and one may be missing from Scopus. The missed reports were not added: the check was not a systematic citation search, and adding the one eligible report it found would make the corpus depend on which reference lists happened to be machine-readable. A backward citation search of all 137 reference lists, reported as a second identification route under PRISMA 2020, would be the remedy; it was not carried out here. A single screener, the author, made every decision with rule-based assistance and supervisory consultation, and no agreement statistic quantifies the reliability of the 2,375 screening exclusions. The 25% K2 ceiling is a protocol choice whose effect at 20% and 30% the Eligibility criteria section reports.

Conclusions and Recommendations

From 3,046 records in Scopus, IEEE Xplore and Web of Science, a four-stage selection with written criteria and per-record logs produced 137 single-band 2.4 GHz studies published between 2015 and 2025, drawn from the 191 of 280 eligible reports read in full. Five mechanism-based families carry the literature, periodic and superstrate structures the largest and air gap or substrate engineering the smallest, and 62 studies combine families. Single-structure bandwidth changes have a median of +69% (50 studies; +32% to +98% across the sensitivity checks) and gain changes +1.3 dB (49 studies; +0.8 to +2.5 dB), with 29 at or below +1.8 dB and 20 at or above +2.6 dB. Only one bandwidth pair and four gain pairs are measured; superstrates add 5 to 8 dB in the few measured cases; and only arrays reach 15 dB or more. Each gain is charged against height and area, fabrication complexity, resonance shift, substrate cost or feed loss.

The most consequential finding concerns the evidence. Only 89 of 137 studies pair a baseline with an enhanced value, 72 stop at simulation and five single-structure pairs are measured. About a quarter of the studies report efficiency, and 16 of the 28 discrepancies found between abstract or title and the study’s own results favoured the design. Evidence strength and improvement size are separate quantities, since the largest magnitudes come from unreplicated single-group simulations, and comparison across families is conditional on platforms that differ. Within those bounds, the review shows which mechanism moves which parameter at what cost, and what the field must report before that becomes a ranking.

Three requirements follow for the field: measured S-parameters, gain and radiation efficiency beside simulated values, for the baseline as well as the enhanced design, starting with

defected-ground and array designs; a baseline and an enhanced value for every claimed parameter, with the gain reference and efficiency, carried into the abstract; and cross-family comparisons that hold substrate, geometry, footprint, feed, solver and measurement setup constant. Two tasks fall to reviewers of this literature: comparing abstracts with full texts systematically, and a backward citation search of the included reports, which this review did not perform.

Declarations and Statement

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Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data availability

The three per-record decision logs covering all 3,046 identified records (S1); the extraction matrix of the 137 included studies with the numeric fields behind the Magnitude of improvement section, the validation type and implausibility flag of every pair, the reporting-quality scores with the Q6 discrepancy classification and, for 64 studies, the source quotation behind each value (S2); the supplementary term co-occurrence map and its procedure, with the VOSviewer input file, thesaurus and settings behind Figure 3 (S3); the study-level characteristics table (Table S4); the reference-list check of the Data sources and search strategy section and its matching against the logs (S5).

AI Delecaration

All screening, eligibility and extraction decisions, every reported value, all figures and tables, and the text were produced by the author. An AI assistant (Claude, Anthropic) was used only for language editing of the draft text; the author reviewed every suggestion and takes full responsibility for the content. No generative AI tool produced any figure, table or value. Figures. Figures 1 and 2 are original illustrations prepared by the author from the decision logs and the extraction matrix, and Figure 3 was prepared by the author in VOSviewer from the titles and abstracts of the 137 included studies held in the supplementary reference-manager file; every value they display traces to the supplementary material. No figure reproduces or adapts a figure from another publication, except that Figure 1 follows the PRISMA 2020 flow-diagram template of Page et al. (2021) as that statement intends.

Author Contribution

Alie Fikry: conceptualisation, methodology, protocol design, database searching, screening and eligibility assessment, full-text retrieval and verification, data extraction, formal analysis, visualisation, writing of the original draft, and revision. The author read and approved the final manuscript.

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