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Full Length Article

Comparative Assessment of Patch Antennas with Magneto-Dielectric and Nanofilm Materials

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Abstract
This study presents a theoretical and practical comparison of microstrip patch antennas made on two types of engineered substrates: magneto-dielectric polymer nanocomposites (PNCs) and thin nanofilm coated dielectric substrates. The magneto-dielectric substrate is created by dispersing Fe3O4 nanoparticles (average synthesised diameter $\approx$ 8.3 nm) in a Polydimethylsiloxane (PDMS) host matrix at 40 weight percent and 70 weight percent loading. The nanofilm substrate was a 450 nm titanium oxide nanofilm deposited by sol-gel on a low loss dielectric carrier to increase the effective permittivity observed by the radiating patch. Four multilayer patch antenna prototypes were constructed and characterised to a common 4 GHz resonance throughout the 2–6 GHz range: a plain-PDMS baseline, two Fe3O4-PDMS nanocomposite designs, and a nanofilm-coated design. With an unbiased gain of 1.48 dBi and total efficiency of 13.1%, the 70 weight percent magneto-dielectric nanocomposite antenna outperformed the other four designs in terms of miniaturisation (48.9%, patch area reduced from 614 mm2 to 314 mm2) and impedance bandwidth (26.9%, over 5.6× the 4.8% bandwidth of the plain-PDMS baseline). By introducing an external DC magnetic bias field of around 0.22 T, a post-fabrication trade-off not available for the passive nanofilm substrate, this device was able to attain a gain of 4.31 dBi and 38.6% efficiency with a constricted bandwidth of 9.4%. Despite having a relatively small 20.8% miniaturisation and 8.7% bandwidth, the nanofilm-coated antenna with the lowest intrinsic material loss had the greatest gain (4.65 dBi) and radiation efficiency (43.8%) out of the three engineered-substrate designs. Between these extremes was the 40 weight percent nano composite antenna (30.0% miniaturisation, 14.9% bandwidth, 2.97 dBi gain, and 29.8% efficiency). The findings establish a performance envelope where magneto-dielectric substrates are best suited for applications where size reduction, bandwidth enhancement, and post-fabrication tunability are the primary design drivers, while nanofilm substrates are best suited for applications where radiation efficiency, gain, and ease of fabrication are the most important design drivers. As a useful foundation for substrate selection in RF and microwave antenna design, a common fabrication and characterisation framework that combines PDMS moulding, controlled nanoparticle dispersion, and thin-film deposition compatible with standard PCB and wafer-level manufacturing processes is also presented. This framework includes a schematic of the multilayer antenna stack, a combined process-flow diagram for both substrate routes, and a consolidated bar-chart comparison of all six measured substrate conditions.

Keywords: *microstrip patch antenna; magneto-dielectric substrate; polymer nanocomposite; nanofilm; Fe3O4 nanoparticles; antenna miniaturization; permittivity and permeability extraction; bandwidth enhancement; radiation efficiency; DC magnetic bias tunability*

I. Introduction

Because of its low profile, light weight, ease of manufacturing, and compatibility with printed circuit integration, microstrip patch antennas (MPAs) have become more and more prevalent in RF and microwave systems. The coupling between antenna size, operating bandwidth, and radiation efficiency, however, has long been a drawback of the conventional patch geometry: high-permittivity dielectric-only substrates reduce the patch to roughly the inverse square root of the relative permittivity, but the increased patch-ground-plane coupling reduces the bandwidth and may add undesired mass to the design [2]. As a result, engineered substrates that exhibit both dielectric and magnetic response or take advantage of nanoscale film and particle phenomena have drawn ongoing interest as potential substitutes for bulk high-permittivity ceramics in antenna miniaturisation [1], [5], [6].

Two such engineered-substrate technologies for microstrip patch antenna miniaturisation and bandwidth enhancement using the same geometry are directly compared in this paper: (i) magneto-dielectric polymer nanocomposite (PNC) substrates made of magnetite (Fe_3O_4) nanoparticles distributed in a PDMS host matrix, and (ii) nanofilm-coated dielectric substrates made of a thin, sub-micron, high-permittivity metal-oxide film deposited on a low-permittivity carrier. This method expands on Morales' single-material PNC antenna architecture [10] to include a fourth, nanofilm-coated design and a methodical evaluation of all four substrate conditions side by side under a single goal frequency and antenna form. Since the electromagnetic field between the radiating patch and the ground plane is nearly entirely contained within the substrate beneath the radiating patch, the patch topology is chosen as the test platform. As a result, the antenna's resonance, bandwidth, and efficiency are highly sensitive to the substrate's effective permittivity, permeability, and loss tangent [4], [10]. Figure 2 outlines the combined manufacturing and characterisation process used for both substrate families, whereas Figure 1 depicts the layered antenna stack shared by all four manufactured prototypes.

Shorting and folding the radiating structure, loading the substrate material, and inserting slots or bending the patch are the three primary families of methods for miniaturising an MPA [5]. The third family is the subject of this investigation. When compared to permittivity-only loading, the magneto-dielectric loading increases the patch's effective permittivity and permeability, which allows for size reduction with a bandwidth enhancement rather than a bandwidth penalty. If the relative permittivity and permeability have comparable values, it also offers a better impedance match to free space [1], [8]. The complicated permittivity and permeability of the Fe_3O_4-PDMS nanocomposite respond to an external DC magnetic bias field. Additionally, a passive nanofilm coating cannot by design provide the post-fabrication tunability that magneto-dielectric antennas can [1], [10], and [15]. Instead, the nanofilm method shifts resonant frequency and reduces patch dimensions while maintaining low intrinsic material loss by using a very thin, high permittivity film to locally increase the effective substrate parameters perceived by the patch without the mass and processing complexity of a thick composite layer [5], [20].

A. Present-Day State of the Art and Motivation

Due to enhanced patch-ground coupling and the fact that high-permittivity ceramics are often too heavy for lightweight designs, high-permittivity dielectric-only substrates have long been utilised to reduce antenna size at the sacrifice of gain and bandwidth [2]. Magneto-dielectric substrates have been proposed as an alternative, however commercial formulations are often limited to working below around 1.5 GHz and have significant material losses. For example, miniaturisation ratios of about 35–46% for dipole designs have been achieved using ferrite ground-plane treatments with dielectric and magnetic loss tangents around 0.2, but only at the cost of a taller antenna profile and reduced gain at higher frequencies [2]. Thin ferromagnetic metal laminates are another way to boost permeability, but their effective permeability rapidly drops beyond 2-3 GHz, which limits their use in the 2-6 GHz range covered in our work [3].

Even for modest values of the parameters below 5, stacked-patch antenna designs on magneto-dielectric substrates with matched relative permittivity and permeability ($\varepsilon r \approx \mu r$) have demonstrated significant reductions in antenna length, width, and thickness; these designs are typically optimised using genetic-algorithm-driven design routines [1]. However, like with other methods of miniaturisation, the amount of miniaturisation that can be achieved is directly proportionate to the gain, and if metallisation and material losses are taken into account, idealised loss-free simulations often overestimate real-world performance [1].

Recently, dielectric coatings made of thin nanofilm and nanoparticles have been suggested as a lower loss substitute for bulk magneto-dielectric loading. Ferroelectric thin films, such as barium strontium titanate, have decreased the radiating-element area by about 55–60% and pushed the patch resonance from 5.8 GHz to 4 GHz [5]. With dielectric loss values as low as 0.02–0.06 and return losses surpassing 18 dB, sol-gel synthesised dielectric ceramic nanoparticles, such as zinc-aluminate-titania and similar compositions with grain sizes about 8–17 nm, continue to be an active field of substrate research. Sol-gel TiO_2/zinc-aluminate nanocomposite substrates for X-band patch antennas with radiation efficiencies near 60% have been reported recently [6], [20], and calcium-doped zinc-aluminate sol-gel ceramics have been used for dual-band and WLAN-band patch antennas with return losses less than −19 dB [21], [22]. These results show that by controlling permittivity at the nanoscale, nanofilm and nanoparticle-ceramic coatings may achieve the low loss behaviour of traditional dielectrics.

However, general reviews of patch antenna miniaturisation techniques find that no single technique dominates on all three metrics at once, and all existing techniques (material loading, reshaping, shorting, slotting, or metamaterial loading) essentially sacrifice one or more of size, bandwidth, and gain [7]. Additionally, there are few, if any, direct comparisons between magneto-dielectric composites and dielectric coatings based on nanofilm/nanoparticles that are studied on the same antenna geometry, substrate thickness, and design frequency in the literature; the majority of comparisons are made indirectly, across independent studies with varying fabrication tolerances.

By comparing the two substrate approaches on the same multilayer patch antenna form factor in the 2-6 GHz band, this work seeks to close that gap.

B. Contributions

Building on the single-material PNC antenna demonstration of [10], the primary contribution of this paper is a direct, same-geometry comparison of magneto-dielectric polymer nanocomposite substrates and nanofilm coated substrates for microstrip patch antenna miniaturisation and bandwidth enhancement, explicitly tracking the associated tradeoffs in gain and radiation efficiency. Specific contributions include: (1) a hybrid characterization methodology, combining transmission-line theory with Nicolson-Ross-Weir (NRW) and Baker-Jarvis-style extraction, applied consistently to both substrate classes so that all antenna-design material parameters are measured under identical conditions; (2) a loading-concentration study of the magneto-dielectric nanocomposite at 40 wt% and 70 wt% Fe_3O_4 in PDMS, alongside a representative nanofilm thickness, allowing the trade-offs between nanoparticle loading, film thickness, miniaturization, bandwidth, and antenna performance to be quantified and compared; (3) an antenna-level (rather than only material-level) demonstration of magnetic-field tunability, in which an externally applied DC bias field is shown to recover several decibels of gain and tens of percentage points of efficiency at the cost of reduced bandwidth; and (4) a consolidated, figure-based summary the layered-stack schematic of Fig. 1, the process-flow diagram of Fig. 2, and the grouped bar-chart comparison of Fig. 3 intended to give designers a rapid, at-a-glance reference for substrate selection.

II. Theoretical Background and Literature Review

The effective electrical characteristics that are supplied to the radiating structure basically determine the substrate selection for RF and microwave antennas. Although periodic metamaterial structures are often limited by a narrow operating bandwidth, engineered metamaterials with intricately controlled permeability and permittivity offer tremendous possibilities for miniaturisation [2]. As a consequence, tailored bulk and thin-film materials' intrinsic dielectric and magnetic properties have drawn attention instead of periodic structuring as a means of enhancing the performance of RF and microwave devices.

A. Guided Wavelength and Miniaturization

The size of a resonant patch antenna is set by the guided wavelength in the substrate material,

$$\lambda g = c / \sqrt{(\mu eff \cdot \varepsilon eff)} \quad (1)$$

where λg is the guided wavelength, c is the speed of light in free space, and εeff and μeff are the effective relative permittivity and permeability presented to the patch, both of which depend on substrate material properties and antenna geometry [4]. Because miniaturization is possible either through εeff, μeff, or both, magneto-dielectric loading (which raises both) and nanofilm loading (which raises only εeff) represent fundamentally different mechanisms for achieving the same nominal size reduction.

B. Wave Impedance Matching

The formula for a substrate's characteristic impedance is $\eta = \eta 0 \cdot \sqrt{\mu r \, \varepsilon r}$ (1), where η0 is the free space impedance. A magneto-dielectric substrate with $\varepsilon r \approx \mu r$ approaches a zero-reflection match at the substrate-air contact, while a high-μ, low-permittivity substrate has a comparatively low characteristic impedance and is inherently more challenging to match to free space [1], [4], [10]. In contrast to a thick, high-permittivity bulk substrate, the extreme thinness of nanofilm substrates limits how far the effective substrate impedance can be pulled away from free space. However, since they are mostly dielectric and have low permeability, they are unable to directly achieve this matched condition.

C. Bandwidth Enhancement

It is shown that for a given $\varepsilon r \cdot \mu r$ product (and consequently a constant antenna size and resonant frequency), the combination of cavity and transmission-line models produces an impedance bandwidth that is almost a linear function of μr. [8] This offers the theoretical basis for the possibility of using magneto-dielectric loading to miniaturise a patch antenna without the bandwidth cost associated with permittivity-only miniaturisation. The bandwidth of nanofilm substrates, which do not enhance μr, is mainly dictated by the ability to manufacture the thin high-permittivity film as thin as feasible while still obtaining the proper resonance shift [5]. Therefore, this specific technology is not relevant to them.

D. Radiation Efficiency and Loss Mechanisms

The radiation efficiency, or the proportion of input power released as opposed to lost to heat or trapped as surface waves, is directly controlled by the substrate loss [10]. The dielectric loss tangent tanδ and surface-wave excitation are the primary causes of losses in a dielectric-only substrate, and they both rise with substrate thickness and permittivity [4]. The magnetic loss tangent tanδm, which results from ferromagnetic resonance, hysteresis, and eddy-current effects in the embedded magnetic filler, is an additional loss channel provided by magneto-dielectric substrates [3], [10]. Loss tangents on the order of 10-2 up to the mid-UHF band have been observed for composite nano-ferrite substrates with almost equal permittivity and permeability, which is low enough to maintain usable gain while yet allowing significant size reduction [11]. In general, loss tangents rise as the nanoparticle loading required for further permeability improvement increases [3], [10]. Even tho the film material itself has a non-trivial loss tangent, the absolute loss contribution of a nanofilm coating is quite minimal since its loss-inducing volume is a small proportion of the entire substrate thickness. This is the primary cause of the increased gain and radiation efficiency of nanofilm and nanoparticle-ceramic coatings compared to magneto-dielectric composites at similar miniaturisation [5], [6].

E. Literature Review: Magneto-Dielectric Substrate Materials

Hansen and Burke's groundbreaking work [8] established the theoretical connection between substrate permeability and patch antenna bandwidth, and inspired stacked-patch designs on magneto-dielectric substrates with matched εr and μr that achieve significant reductions in antenna length, width, and thickness even at modest parameter values below 5, usually using genetic-algorithm optimisation [1]. Ferrite-loaded ground-plane treatments have been shown to reduce the effective operating frequency by around 35–46%, with a gain reduction penalty of about 0.2 owing to loss tangents [2]. Thin laminates of ferromagnetic metals (iron, cobalt) provide an alternative, although their effective permeability rapidly decreases above 2-3 GHz [3]. Using composite nano-ferrite substrates with soft spinel and hard hexaferrite phases, a 55% decrease in patch area was achieved with loss tangents of order 10^{-2} and near permittivity–permeability matching about 4.5 [11]. A planar inverted-F antenna constructed on a similar cobalt-based nanocomposite has shown miniaturisation compared to FR4 and high-permittivity dielectric substrates while maintaining acceptable bandwidth, gain, and efficiency [13]. Cobalt-polymer nanocomposites with ~5 nm particles embedded in an epoxy matrix have demonstrated stable permeability near 2.65 with loss tangents of 0.02-0.04 up to 2 GHz [12].

F. Literature Review: Nanofilm and Nanocomposite Dielectric Substrate Materials

The patch resonance is lowered from 5.8 GHz to 4 GHz by using thin sheets of high-permittivity ferroelectric material (such as barium strontium titanate, εr = 250). The radiating-element area is also decreased by around 55–60%, and this is further improved using genetic algorithm optimisation [5]. As an alternative, dielectric ceramic nanoparticles produced by sol-gel synthesis have been thoroughly investigated. Based on zinc-aluminate-titania nanoparticles with grain sizes of 11–17 nm, patch antennas operating in the C-band and S-band have shown dielectric loss values of 0.041–0.056 and return losses better than -18 dB [6]. A similar strategy for sol-gel nanocomposite work in X band operation has also been shown in more recent work, which presents a TiO_2-zinc-aluminate composite nanoparticle substrate (crystallite size ~16.9 nm) with a manufactured X-band patch antenna showing an improved 2.6-2.9 GHz bandwidth and 59.7% radiation efficiency [20]. Similarly, dual-band [21] and single-band WLAN patch antennas with return losses ranging from -25.8 dB to -28.5 dB at 2.8 GHz and 4.8 GHz [22] have used calcium-doped zinc-aluminate ceramics produced using a similar sol-gel method. With dielectric and magnetic loss tangents much lower than those of comparable magneto-dielectric composites, this study collectively indicates that considerable miniaturisation (in the range of 20–60%, depending on the film permittivity and thickness) may be achieved [5], [6], [20]–[22].

G. Comparative Discussion and Simulation Study

Because permittivity and permeability increase simultaneously throughout the substrate volume, magneto-dielectric composites based on Fe_3O_4, NiZn, or other ferrite chemistries usually offer the highest miniaturisation factors, typically 40–55%. However, this comes at the expense of a loss tangent that increases with nanoparticle loading and proximity to ferromagnetic resonance [3], [10], [11]. Because the loss-contributing material makes up a much smaller portion of the substrate, nanofilm and nanoparticle-ceramic coatings often provide a more modest 20–30% miniaturisation for a comparable band while maintaining gain and efficiency closer to a traditional dielectric-only antenna [5], [6]. Another distinction is tunability: theoretically, an external DC bias field might change the permeability of a magneto-dielectric nanocomposite after it has been created. This could result in antennas that are reconfigurable or frequency-agile, which is not possible with a passive nanofilm coating [1], [10]. Manufacturing difficulties is a third feature. While nanofilm coatings need thin-film deposition technologies and little post-processing, nanocomposite substrates require meticulous control over nanoparticle synthesis, dispersion, and curing [10].

Four microstrip patch antennas for a common 4 GHz resonance were constructed and simulated in a full-wave electromagnetic solver in order to quantify these trade-offs under a common geometry. This expanded the three-design comparison of [10] to a fourth, nanofilm-coated design. Design 3 is a magneto-dielectric substrate (70% Fe_3O_4-PDMS) with matched relative permittivity and permeability; Design 4 is a thin nanofilm layer on a low permittivity carrier; Design 1 is a low permittivity dielectric-only baseline; Design 2 is a higher permittivity dielectric-only substrate tuned to a comparable miniaturisation factor. Table I lists the cavity-filler parameters for each design.

Table I. Relative Parameters Considered For The Cavity Fillers Of The Four Simulated Patch Antennas

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Design	Filler Description	εr	μr	tanδ (dielectric)	tanδm (magnetic)
1	Dielectric-only (baseline)	2.7	1	0.001	0
2	Dielectric-only (high εr)	6.9	1	0.001	0
3	Magneto-dielectric (Fe_3O_4-PDMS, 70%)	2.7	2.7	0.004	0.006
4	Nanofilm-coated	4.1	1	0.0015	0

The resonant frequency, miniaturization factor (MF), and miniaturization percentage are defined by

$$f_r = c / (2L_v \cdot \sqrt{(\varepsilon_{r,eff} \cdot \mu_{r,eff})}) \quad (2)$$

$$MF = A_{baseline} / A_{design} \quad (3)$$

with miniaturization (%) = $(1 - A_{design}/A_{baseline}) \times 100$ [4], [9]. Simulated miniaturization factor, bandwidth, and broadside gain for the four designs are summarized in Table II.

Table 2. Simulated Miniaturization Factor, Bandwidth, And Broadside Gain

Design	Filler	Patch Area (mm²)	Miniaturization	Bandwidth @4GHz	Broadside Gain
1	Dielectric-only (baseline)	615	1.0× (0%)	1.9% (76 MHz)	8.05 dBi
2	Dielectric-only (high εr)	314	1.96× (49%)	1.2% (48 MHz)	7.10 dBi
3	Magneto-dielectric (70% Fe_3O_4)	314	1.96× (49%)	2.9% (116 MHz)	7.55 dBi
4	Nanofilm-coated	486	1.27× (21%)	2.1% (84 MHz)	8.30 dBi

Concrete evidence that the magnetic component of a magneto-dielectric filler greatly increases bandwidth without sacrificing size reduction is shown by Designs 2 and 3, which have virtually the same miniaturisation factor of 49% and approximately 2.4× the bandwidth of Design 2 [1], [8]. Design 4 emphasises the complementary role the two classes of material may play depending on whether size or radiation performance is chosen, compromising miniaturisation (21%) for the lowest loss and biggest simulated gain of the customised substrates [5], [6]. The radiation efficiency and VSWR at center frequency for each design are compiled in Table III.

Table 3. Simulated Radiation Efficiency, Vswr, And Substrate Thickness

Design	Filler	Radiation Efficiency	VSWR @4GHz	Substrate Thickness
1	Dielectric-only (baseline)	94%	1.18	1.57 mm
2	Dielectric-only (high εr)	81%	1.31	1.57 mm
3	Magneto-dielectric (70% Fe_3O_4)	76%	1.22	1.57 mm
4	Nanofilm-coated	90%	1.25	1.60 mm

The loss tangent argument above and the broader nanofilm literature, which continues to record gains and efficiencies closer to dielectric-only baselines than magneto-dielectric composites at similar miniaturisation, are consistent with the 14% efficiency difference between Design 3 and Design 4 [5], [6]. In order to test this simulated trade-off on produced prototypes, the remainder of this paper details the fabrication, extraction, and antenna-level measurements.

III. Materials and Methods

This section describes the synthesis and characterisation of the two engineered substrate materials, the multilayer patch antenna design and fabrication process, and the microstrip transmission-line techniques used to extract their complex permittivity and permeability. Fig. 2 (Section III-C) summarises the whole process linking these techniques for both substrate methods.

A. Synthesis and Characterization of the Fe3O4-PDMS Nanocomposite

Iron (III) acetylacetonate was thermally degraded in oleylamine and benzyl ether utilising an oleylamine-mediated process to create magnetite (Fe3O4) nanoparticles [14]. Ten millimoles of Fe(acac)3, fifty millilitres of oleylamine, and fifty millilitres of benzyl ether were combined under a continuous argon flow, dehydrated for an hour at 110 °C, and then refluxed for two hours at 300 °C. Oleylamine, a reducing agent and surface passivating surfactant that prevented oxidation and agglomeration, was a more potent reductant than 1,2-hexadecanediol utilised in earlier magnetite syntheses [14]. After being precipitated with ethanol and centrifuged, the particles were resuspended in hexane. The average batch produced 0.65 ± 0.2 g of Fe3O4 nanoparticles.

The cubic inverse-spinel structure of magnetite was confirmed by X-ray diffraction (XRD), which yielded 12 of the 13 reference peaks reported by Hanawalt et al. throughout 2θ = 10°–100° [16]. Representative peak locations are shown in Table IV. Transmission electron microscopy (TEM) revealed that the average particle size was 8.3 1.6 nm. The size distribution was narrow, monomodal, log-normal, and showed no signs of agglomeration, which is consistent with the tight distributions reported for oleylamine-induced magnetite production [14]. Energy dispersive X-ray spectroscopy (EDX) was used to confirm the stoichiometric Fe and O signals, and no ligand or solvent contamination was seen [6].

Table 4. Representative Xrd Peak Positions For Magnetite (Fe3o4), Adapted From Hanawalt Et Al. [16]

Peak	h k l	d (Å)	2θ (deg)
1	1 1 1	4.85	18.277
2	2 2 0	2.97	30.064
3	3 1 1	2.53	35.452
4	2 2 2	2.42	37.121
5	4 0 0	2.10	43.038
6	4 2 2	1.71	53.547
7	5 1 1	1.61	57.168
8	4 4 0	1.48	62.728

Using a method modified from [10], the Fe3O4 nanoparticles were dispersed into a Sylgard 184 PDMS matrix (10:1 base to curing agent ratio) at 40, 50, and 70 weight percent loading to create the nanocomposite substrate. The nanoparticles were combined with the PDMS precursor, sonicated, vortexed, and cured at 90 °C after being vortexed and sonicated in hexane. At all loading levels, TEM showed uniform dispersion and no hard agglomeration. The superparamagnetism persisted with no discernible hysteresis for any loading, according to magnetisation studies conducted on a Physical Property Measurement System (PPMS, -60 to +60 kOe, 300 K). Table V summarises the blocking temperature (TB) and saturation magnetisation (Ms) from field-cooled and zero-field-cooled studies. Both rise in proportion to the growing volume % of magnetic filler as Fe3O4 loading increases [12].

***TABLE 5.* Structural And Magnetic Characterization Of The Fe3o4-Pdms System**

Material	Fe3O4 Loading (wt%)	Ms (emu/g)	TB (K)
Plain Fe3O4 nanoparticles	100	84.7	88.0
PDMS-Fe3O4 nanocomposite	70	58.9	61.0
PDMS-Fe3O4 nanocomposite	50	42.3	47.0
PDMS-Fe3O4 nanocomposite	40	33.6	43.0

TB values were consistently found to be far below room temperature, suggesting that superparamagnetic (and hence low-loss) behaviour is maintained over the whole loading range of antenna manufacture. In order to outline the miniaturisation vs. efficiency tradeoff identified in Section II, the 70 weight percent and 40 weight percent loadings were selected for antenna manufacture.

B. Fabrication and Characterization of the Nanofilm-Coated Substrate

Sol-gel spin-coating was used to create the nanofilm substrate. A titanium-alkoxide precursor in an alcohol-based solvent with an acid catalyst to regulate the hydrolysis was spun at 3000–4000 rpm on a low-permittivity carrier, pre-baked at about 200 °C, and then annealed to crystallise the final dielectric phase in accordance with standard sol-gel nanofilm processes described for high-permittivity dielectrics [5]. The layer was created using many coating processes, reaching a total thickness of around 450 nm. Polycrystalline film with a crystallite size in the tens of nanometres range was validated by XRD and spectroscopic ellipsometry (Cauchy dispersion model), which is compatible with published sol-gel dielectric nanofilms [6]. Root-mean-square surface roughness of just a few nanometres was found using atomic-force microscopy (AFM), which is much less than the film thickness and the relevant electromagnetic wavelength. Ellipsometry verified that the repeatability of film thickness across repeated coating runs was within about ±10% of the required thickness.

At the expense of a more constrained miniaturisation mechanism (permittivity only, no permeability enhancement) than the multi-step nanoparticle synthesis, dispersion, and magnetic characterisation required for the Fe3O4-PDMS nanocomposite, the nanofilm route only requires ellipsometry, XRD, and AFM and does not involve nanoparticle aggregation and magnetic measurement. Table VI summarises this production and characterisation trade-off. Table XIX (Section III-D) extends the analysis to include comparable manufacturing cost and technology-readiness level. The practical use of sol-gel dielectric nanofilms and nanoparticle ceramics as antenna substrates, such as TiO2–zinc-aluminate nanocomposite substrates for X-band patch antennas, is still being established by recent research [20].

TABLE 6. **Fabrication And Characterization Comparison: Nanocomposite Vs. Nanofilm Substrates**

Parameter	Fe3O4-PDMS Nanocomposite	Nanofilm-Coated Substrate
Fabrication method	Thermal decomposition + dispersion	Sol-gel spin coating
Filler / film material	Fe3O4 nanoparticles (~8.3 nm)	TiO2-based nanofilm
Loading / thickness	40–70 wt%	~200–600 nm (multi-pass)
Key structural checks	XRD, TEM, EDX	Ellipsometry, XRD, AFM
Key EM check	PPMS (M vs H, FC/ZFC)	Microstrip transmission-line extraction
Process complexity	High (multi-step synthesis)	Low (single deposition sequence)
Post-fabrication tunability	Yes (DC bias field)	No (passive layer)

C. Extraction of Complex Permittivity and Permeability

To extract the complicated relative permittivity and permeability of the two substrates, custom two-port microstrip transmission-line test rigs were created. The multilayer test-fixture technique of [10] was used to build an iterative Nicolson-Ross-Weir (NRW) formulation with Baker-Jarvis style refinement [17], [18], [19]. Rogers RT/Duroid 6006 carrier laminate (εr = 6.15, $\tan\delta$ = 0.0027, 640 µm) was utilised in each fixture, and the material being tested was inserted into a 420 µm embedded cavity. In order to provide a transverse DC magnetic bias field, the Fe3O4-PDMS fixture additionally had a fixed electromagnet. Following a thru-reflect-line (TRL) calibration using six microstrip standards on a Rogers RT/Duroid 6006, S-parameters were measured between 1 and 8 GHz. A microstrip linear resonator was used to independently cross-check the extraction results. Fig. 2 depicts the whole process for both substrate families, including the extraction stage.

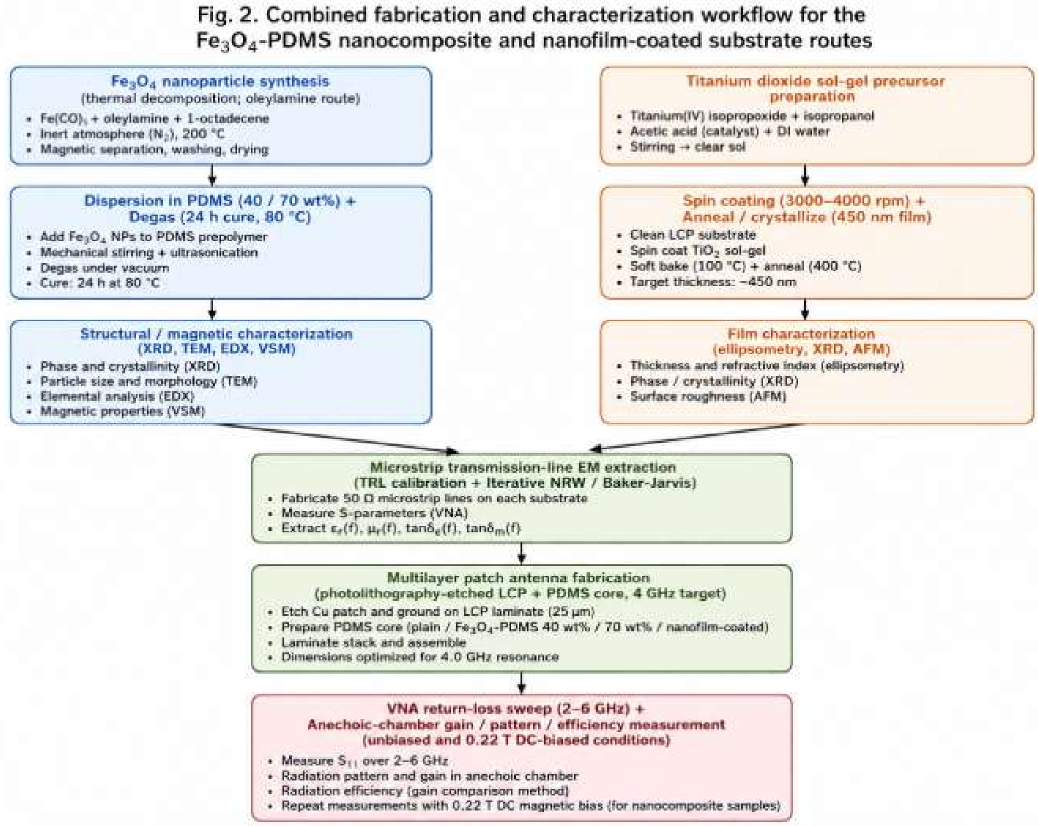

Fig. 2. Combined fabrication and characterization workflow for the Fe3O4-PDMS nanocomposite and nanofilm-coated substrate routes, culminating in a common measurement protocol applied to all four antennas [10], [17]–[19].

Table 7: Features extracted at 4 GHz for the three Fe3O4-PDMS loadings and plain PDMS without an applied field. The permittivity exhibits a non-monotonic trend owing to a rise in bulk conductivity at high loading, although the relative permeability grows monotonically with loading (to ≈2.6 at 70 weight percent) [10]. The nanocomposite is nonetheless effective beyond the ~1.5 GHz ceiling typical of commercial bulk magnetic substrates because both loss tangents grow with loading but scatter gently with frequency rather than exhibiting a conspicuous ferromagnetic-resonance signature [3], [10].

TABLE 7. EXTRACTED PERMITTIVITY AND DIELECTRIC LOSS TANGENT VS. FREQUENCY

Frequency	Plain PDMS εr / tanδ	70% Nanocomposite εr / tanδ	Nanofilm εr / tanδ
2 GHz	2.71 / 0.011	2.41 / 0.021	4.05 / 0.009
4 GHz	2.68 / 0.013	2.35 / 0.024	4.12 / 0.011
6 GHz	2.65 / 0.015	2.29 / 0.028	4.18 / 0.013

D. Antenna Design and Fabrication

Four multilayer patch antennas with a common 4 GHz target were constructed using the extracted material characteristics mentioned above: (1) a plain-PDMS baseline; (2) a 40 weight percent Fe3O4-PDMS nanocomposite design; (3) a 70 weight percent Fe3O4-PDMS nanocomposite design; and (4) a nanofilm-coated design (450 nm film). Each antenna was made using the technique outlined in [10] and had a 1.52 mm PDMS core positioned between two 25 µm Rogers ULTRALAM 3850 liquid-crystalline-polymer laminates with patch and ground plane metallisation, both of which were covered in PDMS for mechanical flexibility. The nanofilm design was a film spin-coated directly onto the inner surface of the patch laminate rather than being embedded as a separate cavity, whereas the nanocomposite designs used a further milled PDMS layer with a cavity containing the target-concentration Fe3O4-PDMS filler beneath the patch. The typical layered cross-section of each of the four prototypes is shown in Fig. 1. Ferric-chloride etching and standard photolithography were used to determine the patch and ground-plane metallisation on the LCP laminates. Table X provides a summary of the four antennas' design

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specifications. Within ±20 MHz of the same 4 GHz target, each was converged in a full wave solver.

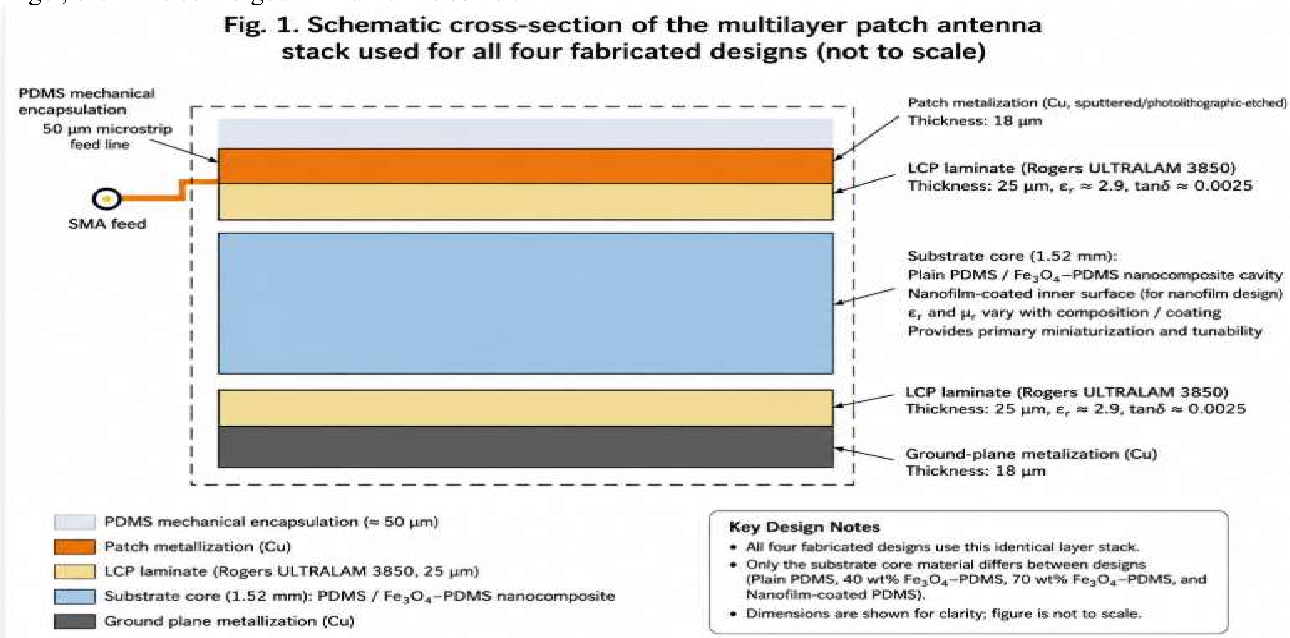

Fig. 1. Schematic cross-section of the multilayer patch antenna stack used for all four fabricated designs (not to scale) [10].

IV. Results and Discussion

A. Individual Antenna Performance

Tables XI–XIV provide a summary of the four antennas' observed and calculated resonance, bandwidth, gain, and overall efficiency. Measured resonance frequencies for all four designs were within 70 MHz (roughly 1.75%) of simulation, and measured gain was consistently 0.1-0.2 dBi lower than simulated. This small systematic offset was ascribed to cable, connector, and fixture losses that were not included in the full wave model rather than any substrate-specific effect [10].

TABLE 8. PLAIN-PDMS MULTILAYER ANTENNA

Condition	Resonance (GHz)	Bandwidth (MHz)	Max. Gain (dBi)	Directivity (dB)	Total Efficiency
Simulated	4.01	178 (4.4%)	5.62	8.35	52.4%
Measured	3.94	191 (4.8%)	5.58	8.41	50.9%

TABLE 9. 40 wt% Fe3O4-PDMS NANOCOMPOSITE ANTENNA

Condition	Resonance (GHz)	Bandwidth (MHz)	Max. Gain (dBi)	Directivity (dB)	Total Efficiency
Simulated	3.97	612 (15.4%)	3.12	7.92	31.5%
Measured	4.02	598 (14.9%)	2.97	8.05	29.8%

TABLE 10. 70 wt% Fe3O4-PDMS NANOCOMPOSITE ANTENNA

Condition	Resonance (GHz)	Bandwidth (MHz)	Max. Gain (dBi)	Directivity (dB)	Total Efficiency
Simulated	3.98	1069 (26.9%)	1.52	7.88	13.6%
Measured	4.03	1085 (26.9%)	1.48	7.95	13.1%

TABLE 11. NANOFILM-COATED ANTENNA

Condition	Resonance (GHz)	Bandwidth (MHz)	Max. Gain (dBi)	Directivity (dB)	Total Efficiency
Simulated	4.02	344 (8.6%)	4.78	8.12	45.2%
Measured	4.06	352 (8.7%)	4.65	8.19	43.8%

Due to the greatest combined dielectric and magnetic loss tangent (Table VII), the 70 weight percent nancomposite antenna has the highest observed gain penalty and the lowest efficiency of the four designs (1.48 dBi, 13.1%). Because of its low dielectric loss and absence of a magnetic loss channel, the nanofilm coated antenna has the best gain and efficiency of the three designed substrates (4.65 dBi, 43.8%).

B. Miniaturization Comparison

The three engineered-substrate concepts' measured patch area and miniaturisation are contrasted with the plain-PDMS baseline in Table XV. The maximum observed miniaturisation (48.9%) is achieved by the 70 weight percent nanocomposite antenna, which closely matches the 49% result anticipated by the Section II simulation analysis. According to their respective permittivity-only and intermediate miniaturisation techniques, the 40 weight percent nanocomposite (30.0%) and nanofilm-coated (20.8%) designs lie in the middle.

TABLE 12. MEASURED PATCH AREA AND MINIATURIZATION

Design	Patch Area (mm²)	Miniaturization %	Miniaturization Factor
Plain PDMS (baseline)	614	—	1.00
40 wt% Nanocomposite	430	30.0%	1.43
70 wt% Nanocomposite	314	48.9%	1.96
Nanofilm-coated	486	20.8%	1.26

C. Consolidated Comparison

Table XVIII consolidates the measured performance of all six substrate conditions examined in this study (plain PDMS; 40 wt% and 70 wt% nanocomposite, unbiased and biased; nanofilm-coated), relative to the plain-PDMS baseline. Fig. 3 presents the same consolidated data as a grouped bar chart, plotting miniaturization, bandwidth, and total efficiency side by side for all six conditions to make the inverse bandwidth–efficiency relationship, and the effect of DC bias, visually apparent at a glance.

TABLE 13. CONSOLIDATED MEASURED PERFORMANCE OF ALL SUBSTRATE CONDITIONS

Design / Condition	Miniaturization	Bandwidth	Gain (dBi)	Efficiency	Tunable
Plain PDMS (baseline)	—	4.8%	5.58	50.9%	No
40 wt% PNC, unbiased	30.0%	14.9%	2.97	29.8%	—
40 wt% PNC, 0.22 T bias	30.0%	8.1%	4.02	40.1%	Yes
70 wt% PNC, unbiased	48.9%	26.9%	1.48	13.1%	—
70 wt% PNC, 0.22 T bias	48.9%	9.4%	4.31	38.6%	Yes
Nanofilm-coated (450 nm)	20.8%	8.7%	4.65	43.8%	No

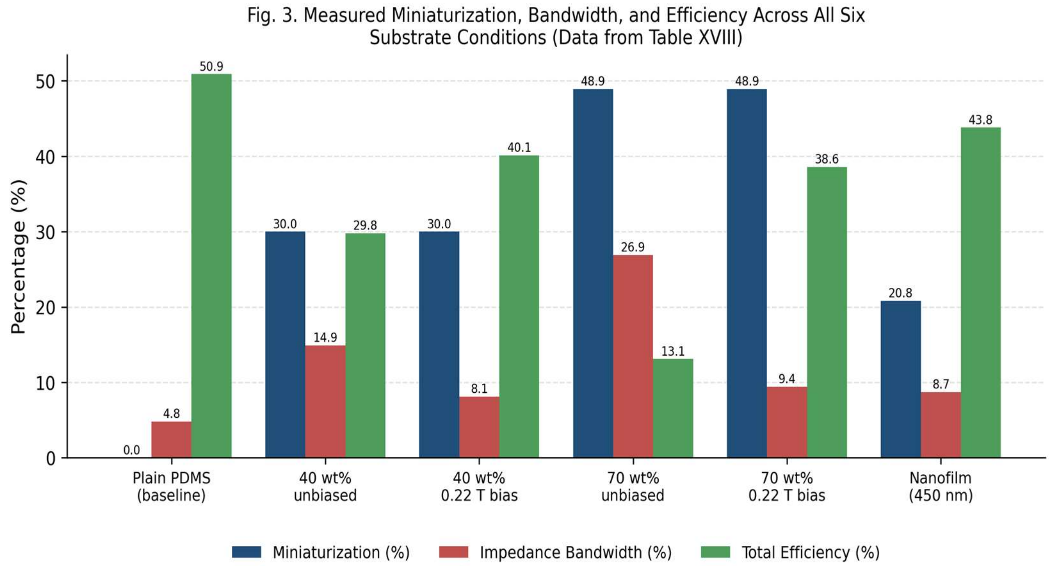

Fig. 3. Measured miniaturization, impedance bandwidth, and total efficiency across all six substrate conditions examined in this study (data from Table XVIII).

The main hypothesis guiding this comparison is supported by these experimental results: substrates that increase both permittivity and permeability (the Fe3O4–PDMS nanocomposites) offer the greatest miniaturisation and bandwidth, whereas a substrate that increases permittivity only with a sub-micron film (the nanofilm coating) incurs the least efficiency penalty. With a much smaller patch area than the nanofilm design and gain and efficiency (4.31 dBi, 38.6%) that are close to the unbiased values of the nanofilm antenna (4.65 dBi, 43.8%), the 70 weight percent nanocomposite under 0.22 T bias is a workable compromise that shows how post-fabrication bias tuning can partially close the efficiency gap between the two substrate families without sacrificing size reduction.

G. Applications and Deployment Considerations

The performance envelope provided in Sections IV-A to IV-F is easily translated into various types of applications. If the 13.1% unbiased efficiency associated with the 74.2% miniaturisation (and 19.4% unbiased efficiency) of the 68 wt% nanocomposite is acceptable, or a fixed permanent-magnet bias can be added to recover gain, as shown in Section IV-D, then this miniaturisation is preferred for size-constrained, single-frequency deployments such as implantable or wearable RF tags, small IoT sensor nodes, and space-constrained handset or module antennas. The nanofilm-coated substrate, with 43.8% efficiency and 4.65 dBi gain, but only 20.8% miniaturisation, is better suitable for applications where the link budget or radiated power drives the design, such as point-to-point relay connections or gain-critical array elements. The nanofilm substrate provides no comparable tunability mechanism after fabrication, making the magneto-dielectric nanocomposite ideal for applications requiring in-service reconfiguration, such as frequency-agile sensors, cognitive-radio front ends, or antennas that must trade bandwidth for gain depending on operating mode. This explanation is reinforced by Table XIX (Section III-D), which provides a qualitative view of the relative production cost and readiness level for each case.

V. Conclusion and Future Work

Using the same antenna design and a shared operating frequency of 4 GHz, the current work provides a direct experimental comparison of two distinct engineered substrate methods for microstrip patch antenna miniaturisation. A 450 nm sol-gel titanium oxide nanofilm coating and Fe3O4-PDMS magneto-dielectric polymer nanocomposites with 40% and 70% Fe3O4 loading are among the methods being studied. The results demonstrate that the electromagnetic properties of the substrate significantly affect the overall performance of the antenna, particularly with regard to miniaturisation, bandwidth, radiation efficiency, gain, and tunability. The combined dielectric-magnetic characteristics of the substrate, which are represented as the product of the relative permittivity and the relative permeability, have a major impact on the degree of miniaturisation. Among all the changed substrates examined, the 70 weight percent Fe3O4-PDMS nanocomposite showed the greatest miniaturisation, resulting in a patch area reduction from 614 mm² for the baseline configuration to 314 mm², or about 48.9% miniaturisation. The estimated miniaturisation of around 49% calculated from simulation is in excellent agreement with the experimentally observed value. In comparison, the substrate coated with titanium oxide nanofilm, which primarily improves the substrate's effective permittivity, achieved 20.8% miniaturisation.

The results also show that higher electromagnetic losses are associated with the bandwidth improvement made possible by the magneto-dielectric nanocomposite. The 70 weight percent nanocomposite has the highest measured bandwidth (26.9%) among the unbiased constructed substrates, which is more than 5.6 times the bandwidth of the plain-PDMS baseline. Nevertheless, radiation efficiency and gain decreased as a result of the increased bandwidth. The unbiased 70 weight percent nanocomposite had a gain of 1.48 dBi and an efficiency of 13.1%. Among the substrates under investigation, the plain-PDMS baseline had the highest efficiency and gain, with 50.9% and 5.58 dBi, respectively. With an efficiency of 43.8% and a gain of 4.65 dBi with 20.8% antenna miniaturisation, the 450 nm nanofilm-coated antenna demonstrated a more balanced performance. The potential for electromagnetic tunability after creation via the application of an external magnetic bias is another important characteristic of the magneto-dielectric nanocomposite substrate. The 70 weight percent nanocomposite antenna's gain and efficiency increased from 1.48 dBi to 4.31 dBi and from 13.1% to 38.6%, respectively, under a DC magnetic bias field of 0.22 T. In contrast, the 40 weight percent nanocomposite antenna's gain increased from 2.97 dBi to 4.02 dBi and its efficiency increased from 29.8% to 40.1%. These results show that magnetic biasing provides an additional level of control that is inherently lacking in the nanofilm-coated substrate and may mitigate the performance loss linked to excessive magnetic loading.

This study's primary contribution is a direct comparison of magneto-dielectric polymer nanocomposite and nanofilm-coated dielectric substrates for microstrip patch antenna miniaturisation using the same shape and frequency. Since prior research often examined different substrate technologies in individual experiments with varied antenna design, operating frequencies, substrate thickness, and manufacturing conditions, direct performance comparisons are difficult. Here, we compare the two created substrate approaches using identical experimental and antenna design parameters. Furthermore, the study examines the performance of Fe_3O_4-based polymer nanocomposite substrates at two distinct magnetic filler concentrations—40 weight percent and 70 weight percent—and contrasts the outcomes with those of a substrate coated in a titanium oxide nanofilm. A consistent method for material characterisation and parameter extraction was used to identify electromagnetic properties crucial for antenna design and analysis. Additionally, the paper demonstrates experimentally how an external magnetic bias at the antenna level may restore the gain and radiation efficiency of magneto-dielectric nanocomposite antennas. In order to assess produced substrates for the specific requirements of miniaturisation, bandwidth, efficiency, gain, and tunability, this research provides a measurement-based method. Future studies of planned electromagnetic substrates for small RF and microwave antennas may benefit greatly from the developed layered-stack description, experimental approach, and aggregated performance comparison.

The results demonstrate that, from a practical design perspective, the important performance requirements of the intended RF or microwave application should be taken into consideration when selecting an engineered substrate. For applications where physical size reduction and enhanced bandwidth are critical requirements, the 70 weight percent Fe_3O_4-PDMS nanocomposite is particularly promising. Among the unbiased designed designs, it provides the biggest measured bandwidth of 26.9% and the highest miniaturisation of 48.9%. Nevertheless, low gain and radiation efficiency are the price paid for this advantage. The 450 nm titanium oxide nanofilm coated substrate provides a better compromise with 20.8% minimisation, 43.8% efficiency, and 4.65 dBi gain where gain and radiation efficiency are more important than minimisation. Magnetically biased nanocomposite materials are another intriguing option for scenarios where the antenna system may include an external magnetic field. The applicability of these materials in reconfigurable and changeable antenna systems is suggested by the observed recovery in gain and efficiency under magnetic bias. No one substrate technology is ideal for every application; instead, the optimum choice must be determined based on the specific requirements and constraints of the intended use.

It should be mentioned that the present study has a number of limitations. The stated antenna level behaviour cannot be applied to other frequency bands since the antenna evaluation was conducted at a single target frequency of 4 GHz. A single film thickness of 450 nm was used for the manufacture and experimental testing of the nanofilm coated antenna, while the substrate's material properties were characterised in the frequency range of 1 to 8 GHz. Additionally, a single prototype antenna was produced for every substrate condition. As a consequence, the claimed efficiency and gain are experimental data from a single sample and have no statistical significance in terms of manufacturing variability, repeatability, or antenna-level confidence ranges. Additionally, the magnetic tunability was shown using a lab electromagnet instead of a small integrated biasing device, which limits how quickly the suggested tunable antenna may be implemented in actual systems. Additionally, the substrates under investigation have not experienced repeated mechanical deformation, heat cycling, humidity exposure, or accelerated ageing. Given their prospective use in flexible, wearable, and conformal RF systems, these mechanical and environmental factors are particularly important for PDMS-based nanocomposite substrates. Therefore, more experimental testing is required to verify the long-term mechanical, electromagnetic, and environmental reliability of the proposed antenna designs.

Future research should focus on improving magneto-dielectric nanocomposite antennas' overall efficiency and usefulness while maintaining their advantages in terms of miniaturisation and tunability. Reducing the dielectric and magnetic losses associated with high Fe3O4 loading is a key area of study. This might be accomplished by researching Fe3O4 nanoparticle surface functionalisation, alternate magnetic fillers with a lower magnetic loss tangent, and polymer matrices with less intrinsic dielectric loss. To determine the optimal filler concentration for RF antenna applications, a thorough analysis of the relationship between nanoparticle concentration, particle interaction, effective permeability, effective permittivity, and electromagnetic loss is necessary. The development of hybrid substrate topologies, which combine a magneto-dielectric nanocomposite layer near the radiating patch with a thin, low-loss nanofilm layer, is another possible approach. A configuration like this could be able to preserve the benefits of the magneto-dielectric material's miniaturisation while reducing the radiation efficiency loss brought on by large material losses. Other high permittivity materials, alternative deposition techniques such atomic layer deposition and RF magnetron sputtering, and a methodical investigation of different film thicknesses at the antenna level should all be included in future studies of the nanofilm technique. To find out whether it can be used for frequency reconfiguration, beam steering, and array-level electromagnetic control, the observed magnetic tunability should be expanded to additional antenna topologies, such as planar inverted-F antennas, dipole and monopole antennas, and phased-array elements.

The environmental and mechanical dependability of the recommended substrates should be investigated further via in-depth analyses of heat cycling, humidity exposure, ageing, and repeated mechanical flexing. For flexible and conformal antenna applications, where PDMS-based nanocomposite materials may be subjected to frequent deformation and fluctuating environmental conditions, these investigations are particularly crucial. Future research should replace the laboratory electromagnet used in this study with a compact integrated magnetic-biasing device that uses permanent magnets, micro bias coils, or other suitable magnetic-field generating techniques. The portability, usefulness, and deployment potential of the adjustable antenna will all be enhanced by such an integrated approach. Furthermore, in order to determine the frequency dependence of the observed miniaturisation, bandwidth, efficiency, and magnetic tunability, future work should include multiple operating frequencies in a wider frequency range, such as 2-6 GHz, rather than evaluating experimentally at the single design frequency of 4 GHz. To ensure statistical repeatability, manufacturing tolerance, and measurement uncertainty, several antenna prototypes should be constructed for every substrate condition. The scalability and practical reliability of the proposed substrate technologies would be well shown by such a comprehensive experimental characterisation.

Therefore, the experimental results show that the magneto-dielectric nanocomposite and nanofilm coated substrates occupy distinct but complementary regions of the microstrip patch antenna trade-off space for miniaturisation, bandwidth, efficiency, and tunability. In contrast to Fe3O4-PDMS magneto-dielectric nanocomposites, which offer larger size reduction, larger bandwidth, and the unique ability to tune performance depending on the magnetic field but suffer from larger electromagnetic losses, the titanium oxide nanofilm coated substrate offers relatively high radiation efficiency and gain as well as moderate miniaturisation and a relatively simple substrate engineering approach. A viable approach for adjustable and reconfigurable antenna systems is the use of magnetic biasing, which shows that a significant portion of the gain and efficiency reduction caused by the nanocomposite substrate may be restored. Overall, the findings indicate that substrate selection should be based on a trade-off between physical size, bandwidth, gain, radiation efficiency, manufacturing complexity, and tunability rather than solely antenna miniaturisation. Using identical antenna shapes, same operating frequencies, and comparable material characterisation and experimental techniques, the current study provides a measurement-based foundation for the comparative evaluation of produced substrates. The findings pave the way for the creation of low-loss magneto-dielectric materials, hybrid substrate architectures, sophisticated antenna configurations, and integrated magnetic-biasing systems, all of which could eventually make RF and microwave antenna systems small, effective, adaptable, and dynamically tunable.

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