

Chapter 2: Literature Review

This chapter embarks on a thorough investigation of the field of wireless capsule endoscopy (WCE) through a meticulous review of existing research. It critically examines three crucial areas: the design of antennas implantable within the body, the techniques for harvesting energy from radio waves, and the development of dual-band circularly polarized (CP) antennas. By meticulously analysing relevant studies, the chapter not only highlights significant advancements but also identifies critical gaps in our current understanding, paving the way for further research. This critical examination serves as a vital bridge between established knowledge and upcoming innovative contributions, ultimately setting the stage for a deeper exploration into the design and optimization of dual-band antenna and RF rectifier systems for wireless ingestible capsule endoscopy.

2.1 Review of Implantable antenna design for wireless capsule endoscopy

This literature review explores the progression of antenna design for wireless capsule endoscopy, mapping advancements from initial solutions to the real-time transmission of intrabody data. Each study, spanning from early orientation-insensitive designs to recent achievements in miniaturization and biocompatibility, signifies a pivotal stride toward efficient wireless communication within the human body. This chronological investigation unveils intricate developments in form factors, operating frequencies, and biomedical applications, providing a comprehensive insight into the transformative journey of the field.

Antenna design for wireless capsule endoscopy has witnessed significant advancements, as evidenced by a series of seminal contributions in the literature. In [38], an innovative solution addressed the challenge of orientation-insensitive antennas in the 2.4-GHz range. Employing polarization diversity with a bent dipole, Inversed T matching, and meander lines, the study demonstrated superiority through simulations against a standard dipole and human body models. This work bridged a critical gap, laying the foundation for overcoming orientation challenges in wireless capsule endoscopy systems.

Building upon this foundation, [39] presented a compact antenna sensor tailored for 2.4–2.4835 GHz ISM band operation. Achieving high peak gain within a diminutive form factor, the antenna showcased its potential for wireless data transmission and gastric juice detection. The study's validation of simulated results through measured performance strengthened the position of the antenna sensor as a promising tool in capsule endoscopy systems.

In [40], a miniaturized antenna for endoscopy capsules operating in the 2.450 GHz ISM band was introduced. Leveraging Minkowski fractal geometry, the antenna's mere 0.1 mm thickness facilitated conformal wrapping around the capsule. Validation in a human phantom confirmed its viability for biomedical applications, with over 30.6% fractional bandwidth in homogeneous tissue. Beyond design innovation, the study explored the effects of internal electronic components during GI tract movement, assessing biocompatibility through SAR in various organs.

Shifting the focus to real-time intrabody biological data transmission, [41] examined a conformal antenna tailored for ingestible bio-telemetric capsules. The conformal chandelier meandered dipole antenna (CCMDA), introduced in this study, demonstrated characteristics at 1.4 GHz, including return loss, input impedance, and radiation pattern. The evaluation within simplified and precision human-body models explored detuning effects, culminating in a proposal for a miniaturized, circularly polarized receiver antenna for a portable data telemetric link.

In [42], a conformal wideband circularly polarized (CP) antenna for endoscopic capsules in the 915-MHz ISM band achieved a mere 0.2 mm thickness. Leveraging innovative design elements like meandered slots and long arms, the antenna seamlessly integrated within a capsule's inner wall. Experimental validation using minced pork and ASTM phantoms showcased impressive impedance and axial ratio bandwidths, supported by a potential wireless communication link of 78 Mb/s.

Introducing a novel antenna for a 915 MHz ISM band capsule endoscope, [43] featured a folded inverted-F antenna (FIFA) structure. The evaluation, using both spherical and anatomically realistic phantoms, revealed gain variations and realistic tissue impact. The study concluded with comprehensive assessments, including specific absorption ratio

(SAR) calculations and wireless biological telemetry performance evaluations through communication link budget analyses.

In [44], a 915 MHz conformal differentially fed antenna was proposed for in-body core temperature monitoring. Exploiting an ultrathin, flexible substrate, the antenna showcased efficient space utilization. Parametric studies using a cubic homogeneous muscle phantom and measurements in minced pork demonstrated wireless temperature monitoring capabilities.

The exploration of conformal antennas continued with [45], presenting a 915 MHz dual-element capsule endoscopic MIMO antenna system. Operating with LHCP and RHCP circular polarization and opposite radiation directions, Antenna-1 and Antenna-2 introduced both polarization and pattern diversity, contributing to enhanced diversity characteristics in wireless capsule endoscopy systems.

Addressing the role of antennas in Wireless Capsule Endoscopy (WCE) at the 433 MHz ISM band, [46] introduced novel small antenna solutions. The in-body transmitter utilized an ultra-wideband conformal loop antenna, and the on-body receiver featured a printed monopole with a partial ground plane. Numerical studies, validated through in vitro measurements, showcased wideband characteristics, ensuring impedance matching and reliability amidst detuning effects.

In [47], a dual-polarized conformal loop antenna for capsule endoscopy boasted broad impedance bandwidths, stable communication spanning both Medical Device Radio communication Service and ISM bands. High isolation (>33 dB) between bands, coupled with omnidirectional radiation and low cross-polarization (-40 dB), guaranteed robust communication even when integrated with electronics or coatings.

Addressing safety and usability considerations of wireless capsule endoscopy antennas, [48] established seven human abdomen models considering age, tissue thickness, and organ shape. Utilizing plane wave propagating theory in multi-layered media, each model comprised simulated skin, subcutaneous fat, muscle, visceral fat, and gastrointestinal organs. Experimental validation using fresh pork abdominal tissue aligned with real human abdominal characteristics emphasized the antenna's stable ISM band performance. In [49], the study introduced a miniaturized dual-band circularly polarized antenna for wireless capsule endoscopy, operating at 915 and 2450 MHz. Achieving miniaturization through slots and meandered line segments, the antenna exhibited reasonable axial ratio and bandwidths. Measurements in saline and pork validated its performance, making it a suitable candidate for endoscopic applications. The work addressed safety and link budget considerations, contributing to advancements in wireless-capsule endoscopic systems.

The proposed capsule antenna in [50] achieved dual-band performance, efficiently utilizing inner capsule space. Integrating rigid Rogers substrate and flexible polyimide optimally exploited the inner surface for implanted electronics. The antenna structure, based on orthogonal strips and conformal L-strips, incorporated a shorting pin for resonance in the 1.4 GHz ISM band and circular polarization at 2.45 GHz ISM band. Simulation results demonstrated wide impedance and axial ratio bandwidths, validating its dual-band operation.

In [51], the study presented a pattern- and frequency-reconfigurable capsule-conformal antenna array to address the challenges of wireless in-body bioelectronics. Operating at 434 MHz and 2.45 GHz ISM bands, the array featured mirrored dual-band elements with tissue-matched dielectric loading for enhanced radiation efficiency and quasi tissue-independent operation. Shielded from the capsule payload by a full ground plane, the

antenna achieved efficiencies close to fundamental limits. A single switch enabled null-free omnidirectional pattern synthesis, demonstrated through prototypes characterized in tissue-equivalent liquid phantoms, showcasing potential advancements for next-generation in-body bioelectronics.

A conformal monopole antenna designed for wireless capsule endoscopy was introduced in [52]. Tailored for radiating in the human body environment, the antenna adhered to specific WCE requirements: proper size, location, gain, omnidirectional radiation pattern, and bandwidth in the Industrial, Scientific, and Medical (ISM) band. Utilizing Babinet's principle for bandwidth enhancement and placed in the capsule's dome, the antenna simulations demonstrated a gain of -30 dB and an 89% bandwidth, positioning it as a suitable choice for WCE applications.

The focus shifted to microwave backscattering in implantable medical devices with [53], proposing a uniquely designed, miniaturized dual-band antenna. Operating at 2.4 GHz for signal reception and 4.8 GHz for signal reflection, the antenna achieved compact dimensions ($8.5 \times 8.5 \times 1.27$ mm³) without shorting pins or ground plane slots. CST simulations validated its performance in heterogeneous and homogeneous human tissue phantoms, and parametric analysis assessed fabrication tolerance effects. Experimental evaluation in a muscle-mimicking liquid confirmed dual-band characteristics, low specific absorption rate (SAR), and sufficient gain, positioning it as a viable choice for fully-passive implantable medical devices.

In [54], a comprehensive wireless power transfer (WPT) system was proposed for deep-body implants, addressing challenges in efficiency due to miniaturization and implantation depth. The 6 cm \times 6 cm patterned WPT transmitter, a 5 mm \times 10 mm optimized voltage doubler, and an implantable antenna supporting quad-band operations were integrated. Experimental measurements in diverse phantoms demonstrated the

system's ability to transfer 6.7 mW power to millimeter-sized implants located 5 cm deep, affirming its potential for passive operation and battery-charging of deep-body implants.

A dual-/tri-band conformal capsule antenna was introduced in [55], addressing the challenge of additional resonances in inverted-F antennas (IFAs). By modifying the ground structure and shifting the feed point, the proposed antenna achieved simultaneous simplicity and miniaturization while covering MedRadio and ISM bands. Its configuration remained stable even with the inclusion of a battery and changes in size or position.

In [56], a dual-circular-polarized conformal endoscopic antenna was introduced, spanning the medical implant communication service band and ISM bands. Printed on flexible polyamide, the compact antenna design (8 mm³) optimized capsule space. Evaluation in muscle and Duke human phantoms demonstrated superior performance. Measurements revealed substantial impedance bandwidths and gains, ensuring compliance with safety standards. Numerical analysis and real-time telemetry validated its potential for robust communication in endoscopic applications, meeting range and high data-rate requirements.

Finally, [57] presented an innovative conformal ultrawideband (UWB) dual-polarized capsule antenna tailored for wireless capsule endoscope (WCE) systems. Pioneering UWB dual polarization using a step-shaped monopole and an irregular rectangular loop antenna, the antenna provided an expansive -10 dB impedance bandwidth spanning 2.15-14.75 GHz. Experimental results closely matched simulations, affirming the antenna's promise for wireless body area network applications, supported by thorough SAR and link budget analyses.

Table 2.1: Comparative Analysis of Multi-Band and Wideband Implantable Antenna Designs for Wireless Capsule Endoscopy

Ref.	Size (λ_g^3)	Frequency (GHz)	$ S_{11} \leq -10$ dB BW (MHz)	BW (%)	Peak Gain (dBi)	1g-SAR (W/kg)	Polarization	Implant depth (mm)
[53]	0.02×0.014×0.0008	0.403 /0.915 /1.40 /2.45	630	9.4 /33.3 /7.07 /26.25	-34 /-29.6 /-28.2 /-22.4	NA /113.8 /NA /NA	linear	70
[54]	0.022×0.009×0.0005	0.403 /0.915 /2.45	47 /85 /49	11.6 /9.3 /2.0	-29.7 /-24.9 /-23.2	216.6 /92.4 /98.5	linear	70
[55]	0.2×0.06×0.0016	0.948 /0.951 /1.357	948 /951 /1357	236 /104 /55	-29.71 /-24.9 /-23.2	247 /291 /235	linear	100
[56]	0.15×0.10×0.0018	1.57 -14.75	1318	192	-23.2 /-18.5	272.3 /331.3	Dual- linear	70

In summary, Table 2.1: Comparative Analysis of Multi-Band and Wideband Implantable Antenna Designs for Wireless Capsule Endoscopy encapsulates the notable advancements in wireless capsule endoscopy antenna design. The collective efforts outlined herein not only tackle technical challenges but also present solutions that redefine possibilities for biomedical applications. Navigating this spectrum of ingenuity, it becomes evident that these contributions pave the way for future breakthroughs, shaping the trajectory of wireless capsule endoscopy technology towards improved diagnostic and therapeutic capabilities in the medical domain.

2.2 Review of RF energy harvesting

The investigation into RF energy harvesting technologies has experienced notable progress, as evident from a comprehensive literature review. Researchers have tackled challenges like inadequate power for high modules, presenting inventive solutions that incorporate ambient energy harvesting and dedicated Wireless Power Transfer (WPT). Various rectifier designs have surfaced, encompassing voltage doublers, impedance matching networks, and novel methods for efficient RF-to-DC conversion. This thorough analysis reveals a landscape of promising advancements, showcasing the evolution of compact, efficient, and dual-band rectifiers for RF energy harvesting across a range of applications.

The literature has extensively explored the limitations of ambient RF energy harvesting for Wireless Sensor Networks (WSNs) in [58]. The authors identified insufficient power for high-power modules and proposed a solution involving cooperative integration of ambient harvesting and dedicated Wireless Power Transfer (WPT). This approach enabled low-power modules to run on ambient energy while high-power modules utilized dedicated WPT. To facilitate efficient energy capture and channelling, a low-threshold

rectifier and circulator were employed, demonstrating the suitability of this method for WSN applications.

In [59], researchers delved into energy harvesting (EH) for microscale applications such as the Internet of Things (IoT), wearable's, and implantable. They introduced an adaptive high-performance rectifier design based on a voltage doubler, expandable for the desired output voltage without modifying the impedance matching network. The core structure featured a duplicated voltage doubler stage and an L-network with series-inductive and shunt LC branches. Prototypes validated the approach, achieving a peak measured efficiency of 65% at 10 dBm input power and 3.3 k Ω load, with simulations suggesting 70% efficiency. The aim was to enhance output voltage while maintaining matching network stability.

In [60], a comprehensive examination of a Wireless Energy Harvesting (WEH) device was conducted, consisting of a voltage-doubler rectifier and a folded dipole antenna. The literature review detailed the rectifier and antenna design steps, presenting simulation and measurement results to support the design choices.

A high-performance, wideband rectenna for 2.4 GHz RF energy harvesting was proposed in [61]. This design incorporated a stacked patch antenna with a driven patch and four parasitic patches, achieving excellent return loss and gain within the 2.41-2.47 GHz band. The rectifying circuit demonstrated high efficiency (up to 63%) at input powers as low as -20 dBm, showcasing its effectiveness for low-power energy harvesting applications.

In [62], a wideband rectifier for RF energy harvesting was presented, capable of efficiently capturing signals across a broad 0.87-2.7 GHz range. The matching circuit employed a high-pass L-section for lower frequencies and an inductive L-section for higher frequencies. The rectifier, utilizing a voltage doubler configuration with optimized

Schottky diodes, achieved a measured conversion efficiency exceeding 30% from 870 MHz to 2.5 GHz at 0 dBm input power. The work demonstrated a promising approach for efficient broadband RF energy harvesting in diverse environments.

A multi-octave voltage doubler rectifier was introduced in [63], achieving broadband impedance matching via a T-type network and voltage doubler topology. The design process and a fabricated prototype were discussed, with measured power conversion efficiency (PCE) exceeding 50% across 0.2-3.2 GHz at 15 dBm input. The peak PCE of 78.2% was observed at 1.9 GHz with 18 dBm input, highlighting the effectiveness of the proposed approach for high-performance broadband energy harvesting.

In [64], a compact, broadband RF rectifier for ambient energy harvesting was proposed and tested. Its novel multistage transmission line impedance matching network provided three key functions broadband matching, reduced line count, and high conversion efficiency. Theoretical analysis and simulations were validated by a fabricated rectifier demonstrating excellent performance, with efficiency exceeding 50% over a wide bandwidth at 5 dBm input power.

The authors in [65] investigated a broadband high-efficiency RF rectifier for ambient energy harvesting from various wireless communication systems. Source pull simulation was employed to identify the optimal source impedance, and a 3rd transmission line low-pass matching network was designed. The measured results closely matched the simulations, with a peak efficiency of 81% and a frequency band of 0.78-1.43 GHz exceeding 50% efficiency at an input power level of 25 mW.

In [66], a broadband RF-to-DC rectifier featuring a simple matching approach was proposed and tested. Utilizing a voltage doubler configuration, the rectifier achieved wideband matching through the addition of two series inductors per diode. Validation via

simulation and measurement showed an efficiency exceeding 50% over an 83% bandwidth at 5 dBm input power, peaking at 80% efficiency at 10 dBm.

A 64-element dual-circularly-polarized spiral rectenna array was designed and characterized in [67] for low-power RF energy harvesting over a 2-18 GHz band. The integrated antenna-rectifier design eliminated matching filtering circuits for a compact footprint. This approach demonstrated a compact, efficient solution for broadband, low-power RF energy harvesting across diverse applications.

In [68], a broad dual-band rectifier with a wide input power range was proposed, utilizing a dual-band matched voltage doubler (DMVD). This DMVD, comprised of a voltage doubler and L-type matching networks for each diode, independently transformed input reactance across wide power and dual-band ranges. The compact rectifier achieved measured power conversion efficiency (PCE) exceeding 50% in wide input ranges, demonstrating a promising approach for efficient dual-band energy harvesting with exceptional input power tolerance.

A compact dual-band impedance matching network for rectifier design was introduced in [69]. This network simultaneously handled two arbitrary frequencies and complex impedances, achieving peak efficiencies in a validated dual-band rectifier operating at 0.915 and 2.45 GHz.

In [70], a compact, single-stage T-type network with three transmission line segments was proposed as a dual-band impedance matching network (DBIMN) for RF rectifiers. Closed-form design equations and a rectifier design methodology were provided. Two prototype rectifiers (0.915 and 2.45 GHz) were built for different input power levels, demonstrating the proposed DBIMN's effectiveness in achieving high efficiency and compactness compared to previous designs.

In [71], a dual-band rectifier for RF energy harvesting and microwave power transfer was presented, building on a single-band design. A half-wavelength transmission line (HWTL) in the matching network enabled operation at a second frequency. The rectifier achieved simultaneous harvesting with PCEs for the 3.5-GHz 5G band and 5.8-GHz Wi-Fi band.

In [72], a novel single-diode approach for dual-band Wireless Power Transfer (WPT) operation was proposed. The design leveraged three transmission lines for impedance matching between the diode and source, achieving peak efficiencies at distinct frequencies with a wide dynamic range.

A high-performance dual-band rectifier utilizing a stepped impedance stub matching circuit was presented in [73]. Theoretical analysis revealed the circuit's ability to achieve wide frequency ratios, confirmed through simulations. A fabricated prototype demonstrated peak efficiencies at the respective frequencies, showcasing the potential for efficient dual-band energy harvesting.

In [74], a compact dual-band rectenna leveraging composite right left-handed (CRLH) technology was proposed for Wi-Fi (2.5 GHz) and WiMAX (3.6 GHz) energy harvesting. The rectenna combined a balanced CRLH microstrip antenna with a novel CRLH rectifier, achieving measured RF-to-DC conversion efficiencies exceeding 59% at 2.5 GHz and 41% at 3.6 GHz.

A novel dual-band transmission line resonator-coupled network (TLRCN) improved rectifier performance in [75] by boosting low-power efficiency and dynamic range. This network reduced sensitivity to input power variations at two frequencies while maintaining peak efficiencies, showcasing its potential for enhancing dual-band rectifier performance.

In [76], a novel automatic impedance matching technique extended RF rectifier input power range without sacrificing efficiency. The design employed two sub rectifiers, each optimized for specific power ranges, and connected them through a $\lambda/4$ T-junction. This configuration automatically adjusted input impedance, ensuring optimal power delivery and high efficiency across a wide dynamic range.

In [77], a single-branch dual-band rectifier achieved high efficiencies for RF energy harvesting at low power levels. Leveraging a microstrip dual-band impedance transformer and optimized diode selection, the design surpassed previously reported efficiencies at these frequencies, showcasing its promise for efficient dual-band energy harvesting.

A comprehensive wireless power transfer system (WPTS) for biomedical implants was presented in [78]. This system featured a self-diplexing implantable antenna, efficient rectifier, and compact transmitter, addressing data transmission and battery recharge needs. The compact rectifier converted RF power to DC with high efficiency.

In [79], a complete WPT system for deep-body implants addressed miniaturization and tissue penetration limitations. The system featured a patterned transmitter focused on power at 1470 MHz and a high-efficiency rectifier, achieving impressive performance in various phantoms and minced pork. The integration of the rectifier with the antenna in a capsule endoscope demonstrated its feasibility for practical applications, confirming compliance with human safety standards.

In summary, this literature review highlights the remarkable advancements in RF energy harvesting, emphasizing the strides made in rectifier design and integration. From cooperative energy solutions to novel impedance matching networks, the studies showcased inventive methodologies and achieved impressive efficiency gains. This

synthesized knowledge not only underscores the progress made but also paves the way for continued innovation, promising a future where RF energy harvesting plays a crucial role in powering diverse applications, from powering Internet of Things devices to enabling implantable medical technologies.

2.3 Review of dual-band dual-sense circularly polarized (CP) antenna

In the domain of circularly polarized antennas, recent progress has seen a notable rise in dual-band dual-sense designs, augmenting versatility across applications. The exploration encompasses varied technologies, ranging from substrate integrated waveguides to coplanar-waveguide-fed monopoles and magnetoelectric dipoles. Each investigation unveils inventive structures and methodologies, contributing to the evolution of dual-band circular polarization. This thorough literature review delves into these innovations, outlining the journey from V-shaped resonators to chiral structures. It sheds light on collective endeavors propelling the development of dual-band dual-sense circularly polarized antennas for emerging wireless communication and biotelemetry applications.

In a previous study [80], researchers investigated a dual-band dual-sense circularly polarized (CP) antenna using substrate integrated waveguide technology. This design incorporated four V-shaped asymmetrical resonators on a circular substrate, strategically positioned for left-hand circular polarization (LHCP) in the lower band and right-hand circular polarization (RHCP) in the upper band. The measured axial ratios below 3 dB and return loss exceeding 10 dB over 8.78-8.90 and 9.52-9.66 GHz validated its performance, all achieved without requiring a ground plane perturbation.

Expanding on this work, another research endeavour [81] introduced a planar dual-band dual-sense circularly polarized (CP) microstrip array. This antenna, implemented on a

single-layer substrate with easy scalability, utilized nonradiative resonators symmetrically placed on the square patch's four side edges. The design, rooted in an equivalent circuit model, facilitated parameter calculations for the patch and resonators. Theoretical and simulation results were followed by the successful fabrication and measurement of a 2×2 element dual-band dual-sense CP array, demonstrating a small frequency ratio of 1.117 and realized gains of approximately 11.7 dBi and 11.8 dBi in the low and high bands, respectively.

Continuing with dual-band dual-sense circularly polarized (CP) antennas, a unique approach was presented in [82]. This study focused on a switchable dual-band dual-sense (DBDS) CP patch antenna equipped with a dual-band phase shifter providing $\pm 90^\circ$ phase shift. Featuring two annular-ring radiators, four H-shape slots, and two phase-controlled feeding networks, the antenna supported simultaneous dual-band functionality. Switchable CP characteristics were achieved through two pairs of single pole single throws (SPSTs), showcasing a prototype at 2.45 GHz/5.8 GHz with a low profile of $0.036 \lambda_0$.

In [83], researchers explored a high-gain dual-band dual-sense circularly polarized (CP) metasurface (MTS) antenna. The study began with an investigation into a 2×3 square patch array as the basic MTS, revealing undesired side lobes from higher order modes. Modifications involving coupled-fed slots effectively cancelled these side lobes, resulting in a fabricated MTS antenna with 3 dB axial ratio bandwidths of 4.37–4.45 and 6.03–6.24 GHz, along with peak gains of 10.22 and 10.72 dBic in the lower and higher bands, respectively.

Moving to coplanar-waveguide-fed antennas, [84] introduced a dual-band dual-sense circularly polarized monopole antenna. Featuring two rectangular parasitic elements and an I-shaped grounded stub, this antenna achieved a wide 10-dB impedance bandwidth of

71.63% at 2.82 GHz. Innovative design elements contributed to 3-dB axial-ratio bandwidths of 27.45% at 2.55 GHz (right-hand circular polarization) and 7.1% at 3.53 GHz (left-hand circular polarization).

Expanding the scope to dielectric resonator antennas (DRA), [85] proposed a dual-band circularly polarized DRA with a modified circular patch. Centrally fed by a probe, the antenna exhibited omnidirectional patterns with distinct circular polarization in two bands. The lower and upper bands were controlled by the patch and dielectric resonator, simplifying dual-band antenna design. The prototype demonstrated 10-dB impedance bandwidths of 2.64% and 18.03%, along with 3-dB axial-ratio bandwidths of 3.16% and 5.06% in the lower and upper frequency bands, respectively.

In [86], a dual-band antenna with dual-sense circularly polarized (CP) operation utilized two orthogonal dipoles to achieve either right-hand CP (RHCP) or left-hand CP (LHCP) radiation. The lower 2.4 GHz band featured RHCP, while LHCP characterized the higher 3.5 GHz band. The fabricated prototype demonstrated good performance with usable bandwidths of 2.9% (2.36-2.43 GHz) and 1.7% (3.48-3.54 GHz), exhibiting unidirectional radiation patterns and broadside gains of approximately 7.7 and 7.4 dBic across the frequency ranges.

For RFID reader applications, [87] presented a dual-band, dual-sense CP stacked patch antenna. This design employed two orthogonally configured elliptical-ring patches, achieving impedance matching ($S_{11} < -10$ dB) and 3-dB axial ratio bandwidths of 2.99% and 1.07% at 842.5 MHz, and 2.72% and 1.19% at 922.5 MHz, respectively. The compact design, with a frequency ratio of 1.10 and gain exceeding 4.5 dBic across both bands, demonstrated potential for practical RFID reader implementation.

A novel approach was taken in [88], introducing a dual-band CPW-fed slot antenna with a C-shaped grounded strip. This design achieved dual-sense circularly polarized radiation using corner slots for the lower-band CP and a C-shaped strip for the upper band. A tuning stub improved impedance matching across a wide bandwidth (106.9%, 1.01-3.33 GHz), resulting in axial ratio bandwidths of 32.35% (1.41-1.96 GHz) and 5.6% (2.45-2.59 GHz) for the lower and upper bands, respectively.

In [89], a dual-band, dual-sense CP magneto electric dipole antenna utilizing a cavity reflector, copper plate pairs, and a crossed Γ -shaped feed was presented. Shorted vertical plates acted as quasi-magnetic dipoles, while connected horizontals functioned as electric dipoles. Separate operating bands were achieved through differing plate dimensions, generating left-hand CP in the 2.15-3.4 GHz band and right-hand CP in the 4-6.3 GHz band. The antenna exhibited a unidirectional pattern with high front-to-back ratio (>22 dB) and achieved high gain (>8 dBi) and radiation efficiency ($>90\%$).

Shifting to a single-layered design, [90] introduced a simple dual-band circularly polarized microstrip patch leaky-wave antenna (LWA). Featuring two linear circular patch arrays coupled to a 50Ω microstrip line, the antenna provided high gain with opposite rotating senses in each band. Tailored for uplink and downlink satellite communication, the antenna operated at 5.0 and 8.0 GHz, demonstrating satisfactory measured axial ratio with peak realized gains of approximately 12 and 13.6 dBi at 5.0 and 8.0 GHz, respectively.

In [91], researchers presented a compact millimeter-wave (MMW) dual-band CP antenna leveraging a chiral structure. An arc parasitic patch loaded on a circular patch imparted chiral characteristics, enabling bi-isotropic interaction with electromagnetic waves. Linear polarization converted into orthogonal LHCP (23.75-24.25 GHz) and RHCP (27.75-28.25 GHz) waves. The fabricated antenna achieved peak gains of 6.9 dBic at 24

GHz and 7.1 dBic at 28 GHz, with a profile of 0.08λ and footprint of $0.54\lambda \times 0.54\lambda$, demonstrating its potential for compact, high-gain array implementations.

Lastly, [92] presented a novel dual-band, dual-sense CP annular slot antenna utilizing reactive loading. Two concentric slots, fed by a common microstrip line, achieved dual-band operation with the help of reactive components (capacitors or inductors) at specific locations. This design allowed for flexible control of the frequency ratio (FR) between the two oppositely-polarized bands. Prototypes with FRs of 1.63 and 2.41 demonstrated good agreement between simulated and measured results, highlighting the effectiveness of the reactive loading approach for tunable dual-band CP radiation.

In summary, the surveyed research reveals a spectrum of possibilities within dual-band dual-sense circularly polarized antennas, presenting a diverse array of designs and methodologies. From metasurfaces to chiral structures, each approach makes a distinct contribution to the landscape of wireless communication and biotelemetry applications. As this exploration concludes, the synergistic evolution of these antennas holds the promise of ongoing advancements, providing unprecedented potential for future wireless technologies and diverse communication scenarios.

2.4 Research Gap and Research objective

2.4.1 Research Gap

- ❖ Existing WCE antennas often *lack wide impedance* bandwidths and suffer from *non-optimal radiation patterns*.
- ❖ Limited research has investigated dual-band rectifiers for efficient wireless power transfer in WCE systems.
- ❖ Compact and efficient CP antennas for dual-band bio-telemetry applications are scarce.

- ❖ The impact of polarization mismatch between capsule and external antennas on communication reliability needs further investigation.
- ❖ Robustness of antenna performance under various implantation scenarios requires further analysis.
- ❖ Exploring the feasibility of integrating antenna and rectifier into a single unit for miniaturization.

2.4.2 Research objective

- ❖ Design and develop compact and efficient dual-band antennas and RF rectifiers for wireless capsule endoscopy (WCE) applications.
- ❖ Utilize Characteristic Modal Analysis (CMA) approach to gain valuable physical insights into antenna behaviour and operation.
- ❖ Perform Link Budget analysis to evaluate the communication link's performance, considering transmission power and path loss in complex medium.
- ❖ Ensure low specific absorption rate (SAR) for safe human implantation.
- ❖ Achieve high power conversion efficiency (PCE) for efficient wireless power transfer.
- ❖ Investigate the dual-band circularly polarized (CP) antenna performance for bio-telemetry applications.
- ❖ Reduce polarization mismatch between capsule antenna and external antenna for improved communication reliability.

2.5 Summary

In this study, the analysis of prevailing wireless capsule endoscopy (WCE) technology uncovers critical gaps, notably the inadequacy of wide impedance bandwidths and

suboptimal radiation patterns in existing antennas. Furthermore, the scarcity of research on efficient dual-band rectifiers for wireless power transfer and compact, effective circularly polarized antennas for bio-telemetry applications accentuates the need for advancement in WCE systems. Embracing this challenge, this research charts a comprehensive course of objectives. It aims to craft compact, high-performing dual-band antennas and RF rectifiers for WCE deployment, leveraging the insightful Characteristic Modal Analysis (CMA) approach. The overarching goals encompass ensuring safe implantation through low specific absorption rates (SAR) and maximizing wireless power transfer efficiency (PCE). Moreover, the investigation delves into the performance intricacies of dual-band circularly polarized antennas, aiming to mitigate polarization mismatches for bolstered communication reliability. Addressing these research gaps and pursuing these objectives not only advances bio-telemetry but also endeavours to optimize WCE systems by bridging the divide between theoretical research and practical applications. The envisioned outcome seeks to revolutionize WCE technology, enhancing reliability, efficiency, and performance, ultimately fostering more effective and patient-centric healthcare solutions.

In the forthcoming Chapter 3, the pursuit of a Dual Wide-Band Ingestible Antenna for Enhanced Wireless Capsule Endoscopy Applications directly addresses identified research gaps. Leveraging CMA insights, it targets shortcomings in current WCE antennas, offering potential solutions to overcome impedance bandwidth limitations and refine radiation patterns.

