# Multi-Ring 4×4 UWB–X–Ku MIMO Antennas for High-Resolution Microwave Imaging: A Review

Awais Ahmed[1], Nyi Nyi Naing[2,*]
[1]Research scholar, Tianjin Key Laboratory of Process Measurement and Control, School of Electrical and Information Engineering, Tianjin University, China
[2]Department of Electronic Information Engineering, Tianjin University, China
Email: nyinyi200786@gmail.com

**Abstract**—Wideband antennas for high-resolution microwave imaging must provide broad impedance matching, low mutual coupling, high efficiency, stable radiation, and sufficient spatial diversity. Multi-ring radiators integrated with 4×4 multiple-input multiple-output (MIMO) architectures are attractive because multiple resonant current paths can extend operation across conventional ultra-wideband (UWB) frequencies into the X- and Ku-bands. Lower frequencies provide greater penetration, whereas higher frequencies improve spatial discrimination. This review examines UWB imaging requirements, multi-ring resonance mechanisms, MIMO diversity, broadband isolation techniques, imaging-oriented performance metrics, and reconstruction considerations. Representative designs are compared in terms of bandwidth, isolation, diversity, and imaging relevance. Key research challenges include broadband decoupling, frequency-stable radiation, near-field calibration, realistic imaging validation, and joint optimization of antenna geometry and reconstruction. Multi-ring 4×4 MIMO arrays therefore offer a promising platform for biomedical imaging, nondestructive testing, and short-range high-resolution radar.

**Keywords**— Ultra-wideband, multiple-input multiple-output, multi-ring antenna, microwave imaging, mutual coupling, X-band, Ku-band.

## I. Introduction

Microwave imaging is an inverse problem in which the electromagnetic properties or spatial distribution of an object are reconstructed from transmitted and scattered microwave signals. Unlike communication systems, where antennas are primarily optimized for link performance, imaging antennas also affect spatial resolution, penetration, image contrast, reconstruction artifacts, and localization accuracy. Antenna design is therefore an integral part of the microwave-imaging inverse problem. Ultra-wideband (UWB) antennas are widely investigated because their broad bandwidth supports short time-domain pulses and frequency-dependent discrimination between targets with different electrical properties.

The conventional UWB spectrum in the United States spans 3.1–10.6 GHz. Microwave-imaging studies frequently use this range because it provides a practical compromise among antenna size, temporal resolution, and penetration [1]–[3]. Penetration and resolution, however, are competing requirements. Increasing frequency reduces wavelength and can improve spatial discrimination, but electromagnetic attenuation generally increases. Lower frequencies therefore provide greater penetration, whereas higher frequencies improve localization. The useful imaging bandwidth should consequently be selected according to the required penetration–resolution trade-off [2], [3]. This trade-off motivates antenna systems that operate across multiple microwave regimes. Extending conventional UWB operation through the X-band and toward the Ku-band can combine low-frequency penetration with higher-frequency spatial detail. Because the upper UWB range overlaps part of the X-band,

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Corresponding author. E-mail address: nyinyi200786@gmail.com
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UWB–X–Ku operation is better viewed as a controlled wideband or multi-resonant spectral extension rather than three completely separate bands. Multiple-input multiple-output (MIMO) architectures further increase spatial observations by providing multiple transmitter–receiver paths and a larger effective aperture. A true four-transmitter, four-receiver imaging system provides up to 16 propagation paths. In compact-antenna literature, however, the term 4×4 MIMO antenna often denotes a four-port, four-element antenna and should not automatically be interpreted as a four-transmit, four-receive radar architecture.

Ring and multi-ring MIMO antennas are attractive because circular, annular, fractal-ring, split-ring, and concentric-ring geometries can support multiple resonant current paths within a compact structure. A 2022 four-element fractal circular-ring UWB MIMO antenna achieved measured inter-element isolation greater than 15 dB over approximately 2.77 GHz to above 12 GHz [4]. More recent split-ring and multi-ring designs have investigated resonance control and parasitic-coupling suppression.

Development and characterization of 4×4 MIMO antennas for UWB, X-, and Ku-band imaging also form part of an Indian research programme for 2024–2026. The programme identifies compactness, mutual coupling, multiport characterization, beamforming, switching, reconfigurability, and imaging-radar integration as key challenges [5]. These requirements confirm that the field remains active. The present review connects UWB imaging antennas, multi-ring resonance engineering, compact 4×4 MIMO arrays, and high-frequency microwave imaging to define antenna- and system-level requirements for high-resolution UWB–X–Ku MIMO imaging.

## II. Microwave-Imaging Requirements and Frequency Selection

### A. UWB Operation

A UWB imaging antenna requires broad impedance matching together with stable radiation characteristics. Impedance bandwidth alone is insufficient; phase response, group delay, radiation pattern, polarization, and pulse distortion should also remain stable because frequency-dependent distortion introduces errors when measurements are transformed from the frequency domain to the time domain. The approximate range resolution $\Delta R$ is given by (1):

$$\Delta R \approx v / (2B) \tag{1}$$

where $\Delta R$ is the approximate range resolution, $B$ is the effective signal bandwidth, and $v$ is the propagation velocity in the medium. Increasing the effective bandwidth reduces the minimum separation between resolvable neighboring scatterers. In biological and other dielectric media, however, wave velocity and attenuation depend on complex permittivity, so free-space resolution estimates are only approximate. Higher frequencies can improve resolution but also increase attenuation, producing an inherent penetration–resolution trade-off [2], [3].

### B. Role of X- and Ku-Band Extension

The conventional X-band is approximately 8–12 GHz, while Ku-band frequencies extend above 12 GHz. The lower X-band therefore overlaps the upper portion of standard UWB operation. A UWB radiator operating above 10.6 GHz can provide additional X-band and lower Ku-band spectral information, but the useful extension depends on the application. In biomedical imaging, tissue attenuation increases at higher frequencies, limiting the extent to which Ku-band components can replace lower UWB frequencies.

Higher-frequency components remain valuable for shallow structures, surface abnormalities, small targets, nondestructive inspection, concealed-object detection, material characterization, and short-range radar. A UWB–X–Ku system can therefore support frequency-diverse imaging: lower frequencies provide information from greater depths, while X- and Ku-band observations refine boundaries and localize fine features. Reconstruction algorithms can combine these frequency-dependent measurements using application-specific weighting rather than treating all frequencies equally.

## III. Evolution of Antennas for UWB Microwave Imaging

Microwave-imaging antennas include monopoles, microstrip patches, bow-ties, tapered-slot and Vivaldi antennas, planar slots, metamaterial-loaded antennas, flexible antennas, and modified monopoles. Biomedical imaging requires wide impedance bandwidth, compact size, low reflection near the target, suitable directivity, stable time-domain behavior, and low fabrication cost [1]–[3]. Planar monopoles are attractive because partial ground planes and slots can provide broad bandwidth with relatively simple geometries.

Vivaldi and tapered-slot antennas generally offer higher directivity and favorable high-frequency scaling, but their physical dimensions can complicate dense array integration. Directivity must therefore be balanced against spatial coverage. Omnidirectional antennas provide broad coverage but radiate substantial energy outside the region of interest, whereas directional antennas concentrate energy toward the target and can reduce environmental clutter. Excessively narrow beams, however, reduce coverage and may require additional array elements or scanning positions.

A recent low-cost breast-imaging system, for example, used 12 UWB antennas arranged around a breast phantom over approximately 3.1–11.6 GHz [6]. The results demonstrate the benefit of multiple measurement positions and the need to control coupling between closely spaced elements. This transition from mechanically scanned single antennas to multistatic arrays provides a direct system-level motivation for MIMO imaging.

## IV. Importance of MIMO

Conventional monostatic imaging may reposition the transmitting and receiving antennas to obtain measurements from multiple locations, but mechanical scanning increases acquisition time. MIMO imaging instead uses multiple spatially distributed transmitters and receivers. For NT transmitting antennas and NR receiving antennas, the number of possible multistatic channels is given by (2):

$$N_{ch} = N_T N_R \tag{2}$$

where $N_{ch}$ is the number of possible multistatic channels, $N_T$ is the number of transmitting antennas, and $N_R$ is the number of receiving antennas.

Four transmitters and four receivers therefore provide 16 measurement channels before frequency samples are considered. Each transmitter–receiver pair observes the target along a different spatial path, increasing angular diversity and the effective reconstruction aperture. Experimental UWB imaging has shown that MIMO beamforming can provide higher resolution than simple monostatic and bistatic delay-and-sum methods [7]. Sparse-array studies further indicate that high-performance three-dimensional (3-D) microwave imaging can be achieved with fewer physical elements than a fully populated array [8].

A major limitation of compact MIMO systems is mutual coupling. Closely spaced elements exchange electromagnetic energy through near fields, surface waves, shared ground currents, and radiation. Coupling can alter effective element patterns and measured scattering parameters, producing false responses in reconstructed images. Imaging-oriented MIMO design therefore requires both electromagnetic isolation, characterized by $S_{ij}$ parameters, and imaging-channel separability so that different transmit–receive paths remain sufficiently distinct. The latter criterion can be overlooked when antenna performance is evaluated only with communication-oriented diversity metrics.

## V. Multi-Ring Radiators and Multi-Resonance Engineering

Multi-ring structures are well suited to UWB–X–Ku antennas because each ring introduces an additional current path and potential resonance. A simplified ring-resonance relation is given by (3):

$$2\pi r_{eff} \approx n\lambda_g \quad (3)$$

where $r_{\text{eff}}$ is the effective ring radius, $\lambda_g$ is the guided wavelength, and $n$ is the supported modal order. Concentric or coupled rings with different radii can place several resonances close enough to merge into a broad impedance bandwidth. The interaction among these resonances depends on ring width and spacing, feed position, ground-plane dimensions, slots, and substrate permittivity.

This mechanism differs from combining separate narrowband radiators for UWB, X-, and Ku-band operation. Closely spaced ring resonances can merge into a continuous or quasi-continuous impedance response within a compact planar structure. Ring loading can support bandwidth enhancement, miniaturization, high-frequency resonance generation, current redirection, polarization control, frequency notching, and mutual-coupling suppression. Frequency-notch generation and broadband decoupling serve different purposes: notches can suppress interfering services but are undesirable when the rejected frequencies carry useful imaging information. High-resolution imaging antennas should therefore prioritize useful modal diversity and broadband matching while avoiding unnecessary stop bands. A circular-ring UWB MIMO system extended operation beyond the conventional Federal Communications Commission (FCC) UWB limit [4]. A 2024 4×4 MIMO design using split-ring resonators and a defected ground structure reported ECC below 0.25, diversity gain above 9.8 dB, and peak realized gain of 11.3 dB at 9.38 GHz [9]. Another 2024 multi-ring octagonal design reported mutual coupling near or below −20 dB and a maximum gain of 6.76 dB [10]. These results illustrate the progression from single-ring bandwidth control toward multi-ring MIMO structures with enhanced isolation and higher-frequency operation.

## VI. Isolation Techniques for 4×4 Wideband MIMO Antennas

Integrating four elements into a compact structure creates multiple adjacent and diagonal coupling paths, making broadband isolation difficult. A practical UWB–X–Ku design therefore requires coupling suppression across a very large fractional bandwidth.

### A. Orthogonal Element Placement

Rotating neighboring elements by approximately 90° can introduce polarization and pattern diversity while reducing coupling without additional decoupling structures. This approach is attractive for low-loss UWB designs. Reported orthogonally arranged four-port UWB antennas achieve isolation better than 15 dB, particularly when combined with ground modification and cross-polarization control.

### B. Defected Ground Structures

Slots, cuts, and modified ground planes interrupt coupling currents between antenna elements. Defected ground structures (DGSs) are simple to fabricate and can also improve impedance matching. Excessive ground modification, however, may distort radiation patterns, increase back radiation, or introduce unwanted resonances. These effects are especially important in imaging because reconstruction algorithms depend on predictable element responses.

### C. Neutralization and Parasitic Structures

Neutralization strips, stubs, floating parasitic elements, and multimode resonators can create secondary current paths that oppose the original coupling currents. A compact 4×4 UWB MIMO design using multimode-resonator stubs achieved isolation of approximately 15 dB or higher [11].

### D. EBG and Metamaterial Decoupling

Electromagnetic-band-gap (EBG) structures suppress surface-wave propagation over selected frequency ranges. Split-ring resonators and complementary split-ring structures can similarly modify surface currents and create stop-band behavior. Although these techniques can improve isolation, they also increase design complexity. Narrowband EBG behavior may be inadequate for UWB–X–Ku operation; broadband decoupling across the useful imaging band is preferable to isolation improvement at only a few resonant frequencies.

### E. Characteristic-Mode-Based Isolation

Characteristic Mode Analysis (CMA) provides physical insight into the current modes supported by an antenna before the feed arrangement is finalized. CMA can guide port and stub placement to suppress strongly coupled modes while preserving useful orthogonal modes. A reported four-element UWB MIMO antenna with elliptical isolation stubs operated from 3.1 to 13.75 GHz with isolation above 25 dB and radiation efficiency above 92.5% [12]. The upper frequency extends into the lower Ku-band, demonstrating the relevance of characteristic-mode-based design to UWB–X–Ku development.

## VII. Performance Metrics for Imaging-Oriented MIMO Antennas

Imaging-oriented MIMO antennas should not be characterized only by return loss and isolation. At minimum, the following impedance, diversity, time-domain, and imaging-specific metrics should be considered.

### A. Impedance Bandwidth

The −10 dB return-loss criterion, $|S_{ii}| < -10$ dB, is a convenient measure of impedance matching. The useful imaging bandwidth must also satisfy radiation-pattern, phase, and time-domain requirements.

### B. Mutual Coupling

Lower $|S_{ij}|$ values for $i \neq j$ indicate stronger port isolation. Isolation above approximately 15 dB is common in compact UWB systems, while values above approximately 20–25 dB are desirable for imaging systems that require high dynamic range.

### C. Envelope Correlation Coefficient

The envelope correlation coefficient (ECC) estimates correlation between MIMO radiation channels; lower values indicate better diversity. Values below 0.5 are generally acceptable for conventional MIMO systems, while compact UWB designs often report ECC well below 0.1.

### D. Diversity Gain

When ECC is small, diversity gain approaches 10 dB. Values above approximately 9.5 dB are generally considered indicative of strong diversity performance.

### E. TARC and Channel Capacity Loss

The total active reflection coefficient (TARC) evaluates multiport matching under simultaneous excitation and is relevant when imaging transmitters excite different ports with different phase relationships. Channel capacity loss (CCL) provides complementary information about correlation and efficiency. A common design target is CCL below approximately 0.4 bit/s/Hz together with low TARC across the operating band.

### F. Time-Domain Fidelity and Group Delay

Time-domain fidelity and group-delay stability are more critical for UWB imaging than for many communication applications. The transmitted pulse should retain its shape after propagation through the medium. Large group-delay variation can broaden a short pulse and create false target responses.

### G. Imaging-Specific Metrics

Multi-ring MIMO studies intended for imaging should report point-spread-function width, localization error, target-to-clutter ratio, signal-to-clutter ratio, image entropy, reconstruction error, sidelobe level, and minimum resolvable target spacing. These metrics determine whether improvements in antenna characteristics produce measurable improvements in reconstructed images.

## VIII. Representative Literature Comparison

Representative studies are compared in Table 1.

**Table 1.** Representative Literature Comparison

| Study | Antenna concept | Frequency behavior | Isolation/diversity feature | Relevance to high-resolution imaging |
|---|---|---|---|---|
| Kiem et al., 2014 [11] | Compact four-element UWB MIMO with multimode-resonator stubs | UWB operation | Isolation approximately ≥15 dB | Demonstrated compact four-port UWB decoupling |
| Alharbi et al., 2022 [4] | 4×4 fractal circular-ring MIMO | Approximately 2.77 GHz to >12 GHz | Isolation >15 dB | Important transition from UWB into X-band using ring geometry |
| CMA-based UWB MIMO, 2022 [12] | Four-element antenna with elliptical isolation stubs | 3.1–13.75 GHz | Isolation >25 dB; efficiency >92.5% | Demonstrates UWB/X/lower-Ku feasibility |
| Savcı, 2023 [13] | Four-element coplanar-waveguide (CPW)-fed UWB MIMO | UWB | Multi-element spatial diversity | Explicitly designed for microwave-imaging applications |
| Kiani et al., 2023 [14] | Two-port shared-radiator UWB MIMO | 2.3–11.5 GHz | Isolation enhancement up to 16 dB | Shows importance of time-domain analysis for imaging |
| Abouelnaga et al., 2023 [15] | Four-element wearable circular UWB MIMO array | UWB | Spatially distributed array | Experimentally motivated tumor detection/localization |
| Manage et al., 2024 [9] | 4×4 UWB MIMO with split-ring resonators and DGS | 3.1–10.6 GHz with notches | ECC <0.25; diversity gain >9.8 dB | Demonstrates ring-assisted four-port MIMO control |
| Singam et al., 2024 [10] | Multi-ring octagonal MIMO antenna | UWB with higher-frequency potential | Coupling below approximately −20 dB | Direct evidence for multi-ring isolation engineering |
| Hammouch et al., 2025 [6] | 12-antenna UWB imaging system | 3.1–11.6 GHz | Circular multistatic measurement | Confirms system-level benefit of wideband multi-antenna imaging |

The literature shows a clear progression from basic UWB impedance-bandwidth design toward polarization diversity, coupling reduction, higher upper-frequency limits, and the use of ring, fractal, metamaterial, and characteristic-mode concepts. Recent antennas increasingly extend beyond 10.6 GHz. The next step is to jointly optimize multi-ring broadband elements and the complete 4×4 array for stable UWB–X–Ku imaging performance rather than optimizing individual antenna metrics in isolation.

## IX. Integration with the Microwave-Imaging Chain

### A. Switching and Measurement Architecture

A practical MIMO imaging system requires a broadband transceiver or vector network analyzer, radio-frequency (RF) switching, power division or dedicated multichannel electronics, and phase control. Sequential switching can reduce hardware cost by reusing the same measurement equipment across antenna pairs. Switching repeatability and cable phase drift must be calibrated, while connector, cable, and switch losses become increasingly important at Ku-band frequencies.

### B. Beamforming

Delay-and-sum (DAS) reconstruction at a candidate imaging location r can be expressed by (4):

$$I(\mathrm{r}) = \Sigma_m \Sigma_n w_{mn} s_{mn}(\mathrm{t} = \tau_{mn}(\mathrm{r})) \quad (4)$$

where $I(r)$ is the reconstructed image intensity at candidate location $r$, $s_{mn}$ is the measured signal for transmitter index $m$ and receiver index $n$, $t$ denotes time, $\tau_{mn}(r)$ is the propagation delay through the imaging medium to location $r$, and $w_{mn}$ is a channel-dependent weighting factor. The increased transmitter–receiver diversity of a 4×4 system strengthens coherent contributions at the true target location while helping suppress incoherent clutter.

### C. Frequency-Domain Reconstruction

UWB measurements are often acquired as swept-frequency data, such as $S_{21}(\mathrm{f})$, and transformed into the time domain using an inverse Fourier transform. Alternatively, frequency-domain migration, back-projection, diffraction tomography, or inverse-scattering algorithms can operate directly on spectral measurements. UWB–X–Ku systems also enable multiresolution reconstruction: lower-frequency data can identify candidate target regions, while higher-frequency X- and Ku-band data can refine localization. This strategy can exploit the additional high-frequency resolution while limiting the impact of increased attenuation.

## X. Major Challenges

### A. Maintaining Contiguous Wideband Matching

Multiple resonances can be generated readily, but merging them into stable contiguous UWB–X–Ku operation is difficult. Poorly controlled resonances can produce large group-delay variation and waveform distortion.

### B. Broadband Mutual Coupling

A decoupling structure effective at one frequency may be ineffective elsewhere. The 4×4 array therefore requires broadband isolation across the intended operating range without introducing unwanted stop bands.

### C. Frequency-Dependent Radiation Patterns

At higher frequencies, electrically larger antenna dimensions support additional radiation modes. Beam splitting or rotation can reduce coherent reconstruction accuracy if radiation behavior changes substantially across the operating band.

### D. Material and Fabrication Losses

FR4 substrates are inexpensive but become increasingly lossy at higher frequencies. Low-loss substrates, including Rogers materials, can improve efficiency and phase stability at the cost of higher fabrication expense.

### E. Calibration

Practical measurement systems are affected by mutual coupling, connector mismatch, cable response, antenna-position errors, switching errors, and environmental reflections. Calibration must separate these system effects from target scattering.

### F. Imaging Validation

Many MIMO antenna studies claim imaging suitability based only on bandwidth, ECC, and gain. Such evidence is insufficient for imaging validation. Realistic targets, phantoms, or nondestructive-testing samples should be measured, and localization accuracy should be demonstrated in reconstructed images.

## XI. Research Gaps and Future Directions

### A. True UWB–X–Ku Multi-Ring Coverage

Further study is required to determine whether a single planar multi-ring element can maintain stable radiation across the useful Ku-band range without detrimental pattern changes. Ring parameters could be hierarchically optimized so that outer rings primarily support lower frequencies while inner rings contribute more strongly to X- and Ku-band resonances.

### B. Reconfigurable Multi-Ring Structures

p–i–n (PIN) diodes, varactors, RF microelectromechanical systems (MEMS) devices, or tunable materials can selectively connect ring segments and enable reconfigurable operation. Such an antenna could switch between a lower-frequency penetration mode and a higher-resolution X/Ku-band mode. Reconfigurable MIMO operation is also identified as a goal of ongoing multi-ring 4×4 research [5].

### C. Joint Antenna and Reconstruction Optimization

Antenna optimization and reconstruction-algorithm selection should be treated as a coupled computational electromagnetic problem. Antenna geometry could be optimized directly with respect to reconstructed point-spread-function width, localization error, or image contrast rather than antenna-only metrics. Multi-ring arrays involve many design variables, including ring radii and widths, gaps, feed positions, ground slots, element orientations, and decoupling dimensions. Exhaustive parameter sweeps are computationally expensive. Surrogate models, Bayesian optimization, and neural-network-assisted optimization can reduce this burden.

### D. Frequency-Adaptive Imaging

Frequency samples do not contribute equally to an image. Frequency-adaptive reconstruction can emphasize lower-frequency measurements for deeper penetration and assign greater weight to higher-frequency data when the corresponding signal-to-noise ratio is sufficient for shallow, high-resolution features.

### E. Sparse and Virtual MIMO Apertures

Sparse and virtual MIMO apertures can increase spatial coverage without proportionally increasing the number of physical antennas. Transmitter and receiver positions can be optimized to maximize aperture coverage, as demonstrated by recent high-resolution 3-D microwave imaging studies using sparse MIMO planar arrays [8].

### F. Experimental UWB–X–Ku Phantom Validation

A major experimental gap is the absence of systematic comparisons among UWB-only, UWB+X-band, and UWB+X+Ku-band imaging under matched conditions. Such experiments are needed to quantify whether Ku-band information improves target localization sufficiently to justify the additional attenuation, calibration requirements, and hardware complexity.

## XII. Conclusion

Multi-ring 4×4 MIMO antennas provide a promising route to high-resolution microwave imaging by combining multistatic spatial diversity with broad spectral coverage. Existing UWB MIMO studies show that ring loading, defected grounds, orthogonal element placement, and characteristic-mode-based design can provide wideband operation and strong isolation, with some designs extending into the lower Ku-band. The central challenge is to maintain impedance matching, isolation, radiation stability, time-domain fidelity, and predictable near-field behavior across the complete imaging band. Future development should therefore emphasize system-level imaging validation rather than S-parameter performance alone. Broadband decoupling, accurate calibration, frequency-adaptive reconstruction, and jointly optimized multi-ring geometry are key requirements for practical UWB–X–Ku imaging systems.

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