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COMPREHENSIVE REVIEW OF SINGLE- AND DOUBLE-SPLIT RING RESONATORS: ANALYTICAL MODELLING, ELECTROMAGNETIC RESPONSE, AND MODERN APPLICATIONS

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ABSTRACT

Split-ring resonators (SRRs) are fundamental meta-atoms in metamaterial research because they enable tailored electromagnetic responses through geometrical design. This review examines the physical principles, analytical modelling, and modern applications of SRRs, with emphasis on the distinction between single split-ring resonators (SSRs) and double split-ring resonators (DSRRs). The discussion synthesizes prior studies on artificial magnetism, subwavelength LC resonance, and the roles of symmetry and bianisotropy, and it further outlines an analytical framework that incorporates magnetic inductance, electron kinetic inductance, gap capacitance, and surface capacitance for improved resonance-frequency prediction, especially at high frequencies. The review also summarizes the electromagnetic behaviour of SRRs at resonance through the distributions of electric field, magnetic field, surface current, and induced dipole moments. In addition, recent applications in microwave filters, antennas, and sensors are discussed to show how these resonant properties are translated into practical device functions. Overall, the review highlights that a rigorous understanding of SRR geometry, equivalent-circuit parameters, and symmetry-dependent coupling is essential for the accurate analysis and effective design of next-generation microwave and optical metamaterial devices.

1. Introduction: Split-Ring Resonators as Canonical Meta-Atom

1.1 Origins of Artificial Magnetism

The split-ring resonator (SRR) is one of the most iconic meta-atoms in metamaterial research. Its importance originates from the idea that the electromagnetic properties of a medium do not need to be determined solely by its intrinsic chemical composition, but can instead be engineered through subwavelength geometry. In this context, Pendry et al. (1999) theoretically showed that nonmagnetic conducting microstructures can produce an effective magnetic permeability, thereby opening the way to artificial magnetism. This discovery laid the foundation for metamaterials, namely artificial media that can exhibit unusual properties such as negative permeability and, when combined with negative permittivity, enable negative-index behaviour (Shelby et al., 2001; Smith et al., 2000).

The basic concept of metamaterials relies on the fact that a periodic array of subwavelength resonators can be approximated as an effective homogeneous medium by an incident electromagnetic wave. When the unit-cell dimensions are much smaller than the operating wavelength, the wave no longer responds to each resonator individually, but rather to the averaged response of the entire array (Pendry et al., 1999; Smith et al., 2000). As a result, bulk properties such as effective permittivity and effective permeability can be tailored through resonator geometry. Within this framework, the SRR acts as an artificial atom that decouples electromagnetic response from intrinsic material composition, which is the central idea of metamaterials (Pendry et al., 1999; Smith et al., 2000).

1.2 SRR as a Subwavelength LC Resonator

At its core, the SRR can be understood as a compact equivalent LC resonator. The conducting loop provides the inductance, L, while the split in the ring acts as a charge accumulation region that gives rise to capacitance, C(Baena et al., 2005; Sydoruk et al., 2009). The interaction between these two elements establishes a distinct resonance frequency at which the structure strongly interacts with the external electromagnetic field.

One of the most important features of the SRR is its ability to resonate at wavelengths much larger than its physical dimensions. Because the capacitance across the split can remain appreciable even in a small structure, the SRR behaves as an electrically compact subwavelength resonator (Hałgas, 2022; Sydoruk et al., 2009). This property is essential in metamaterial theory because it allows periodic SRR arrays to be homogenized into an effective medium with engineered electromagnetic properties (Pendry et al., 1999; Smith et al., 2000).

1.3 Geometrical Overview: Single Split Ring (SSR) vs. Double Split Ring (DSRR)

In general, two major SRR configurations are commonly discussed in the literature, namely the single split-ring resonator and the double split-ring resonator.

Single Split-Ring Resonator (SSR):
The most basic form consists of a single conducting ring with one split (Sydoruk et al., 2009). This geometry is inherently asymmetric because the presence of a single gap breaks the rotational symmetry of the structure. This asymmetry allows the SSR to exhibit not only a magnetic response, but also cross-coupling between electric and magnetic excitations, which leads to bianisotropy.

Double Split-Ring Resonator (DSRR):
The classical configuration introduced in the metamaterial context usually consists of two concentric rings with splits located at opposite ends (Baena et al., 2005; Pendry et al., 1999). In a broader sense, this category also includes other symmetric implementations such as a single ring with two or four symmetrically placed splits (Penciu et al., 2008). Preserving

symmetry is important because it suppresses unwanted magnetoelectric coupling and yields a purer magnetic response (Marqués et al., 2003; Smith et al., 2006). Therefore, the distinction between SSR and DSRR is not only a matter of the number of splits, but also of its implications for symmetry, bianisotropy, and resonance purity.

The close relationship between resonator geometry, symmetry, and resonance behaviour highlights the need for a more integrated synthesis of the SRR literature. Although previous review papers have addressed important aspects of metamaterials and resonator-based devices, their scope is often limited to particular application domains. For example, some reviews focus primarily on metamaterial-inspired antenna designs (Milias et al., 2021), whereas others concentrate specifically on microwave and optical biosensors for glucose monitoring (Alsultani et al., 2025; Martins et al., 2025). In parallel, recent studies have introduced increasingly specialized SRR-based structures for sensing and material characterization, including compact single-layer and application-oriented resonator platforms (Rahman et al., 2026). Nevertheless, the literature still lacks a unified review that systematically connects geometrical configuration, symmetry-dependent electromagnetic response, and advanced analytical modelling across both microwave and higher-frequency regimes. In particular, concepts such as electron kinetic inductance and surface capacitance are frequently treated separately from discussions of practical device implementation and emerging applications. The present review therefore addresses this gap by providing an integrated and up-to-date synthesis of single- and double-split ring resonators, linking SSR/DSRR geometry, analytical modelling, electromagnetic response, and modern applications within a single comparative framework.

After distinguishing the basic SSR and DSRR configurations from the viewpoints of geometry and symmetry, the next step is to understand how these physical features quantitatively determine the SRR resonance frequency. Accordingly, the following section discusses the analytical modelling of resonance frequency in a progressive manner, beginning with the basic LC approximation and then extending to more complete formulations.

2. Materials and Methods

To design SRRs effectively, a quantitative understanding of their resonance frequency is essential. At the most basic level, the SRR can be approximated by a simple equivalent LC circuit. However, for more accurate prediction, especially at high frequencies or in structures with finite geometry, additional physical contributions such as surface capacitance and electron kinetic inductance must be taken into account (Hałgas, 2022; Sydoruk et al., 2009; Vallecchi et al., 2019; Zhou et al., 2005).

2.1 Basic Equivalent LC Circuit Model

In the simplest approximation, the resonance frequency of an SRR is given by the standard LC relation

$$f_m = \frac{1}{2\pi\sqrt{L_{\text{total}} C_{\text{total}}}}$$

where L_{total} and C_{total} represent the total inductance and total capacitance of the resonator, respectively (Hałgas, 2022; Sydoruk et al., 2009). This model provides clear physical intuition, but it remains a first-order approximation because it does not yet distinguish the different physical contributions that make up the total inductance and capacitance.

2.2 Inductance (L): Two Main Contributions

The total inductance of an SRR is not a single physical entity, but is composed of two major contributions: magnetic inductance and electron kinetic inductance.

2.2.1 Magnetic Inductance (L_m)

Magnetic inductance is the classical contribution associated with the magnetic energy stored by the circulating current along the conducting loop of the resonator. For a singly split ring, one commonly used analytical expression is

$$L_m \approx \mu_0 \bar{R}_m \left[\ln\left(\frac{8\bar{R}_m}{h+w}\right) - \frac{1}{2}\right]$$

with

$$\bar{R}_m = \frac{l'}{2\pi}$$

where $\mu_0$is the permeability of free space, $\bar{R}_m$is the mean ring radius, $l'$is the current-path length, and $h$and $w$denote the conductor height and width, respectively (Hałgas, 2022; Sydoruk et al., 2009). This expression is useful as a compact analytical model for planar and raised SRRs.

2.2.2 Electron Kinetic Inductance (L_e)

As the operating frequency increases toward the terahertz and optical regimes, metals can no longer be treated as perfect conductors. At this scale, the inertia of the charge carriers becomes significant and contributes to the resonator response. This effect is modelled as an additional series inductance known as electron kinetic inductance, L_e (Zhou et al., 2005), given by

$$L_e = \frac{l'}{S'\omega_p^2\varepsilon_0}$$

where $l'$is the current path length, $S'$is the effective conductor cross-sectional area, $\omega_p$is the plasma frequency of the metal, and ε_0 is the vacuum permittivity (Zhou et al., 2005). This term becomes increasingly important as the resonator is miniaturized and pushed to higher resonance frequencies.

2.3 Capacitance (C): Beyond the Split

Like the inductance, the total capacitance of an SRR does not arise from a single mechanism alone. Although the split region is the dominant source of capacitance, additional contributions must be considered for a more accurate model.

2.3.1 Gap Capacitance (C_{gap})

Gap capacitance is the primary capacitive contribution produced by charge separation across the split. In a commonly used approximation for a singly split ring, it may be written as

$$C_{gap} = \varepsilon_0 \frac{hw}{g} + C_0$$

with the fringing-field correction

$$C_0 = \varepsilon_0 (h + w + g)$$

so that

$$C_{gap} = \varepsilon_0 \left(\frac{hw}{g} + h + w + g \right)$$

where ε_0 is the free-space permittivity, $h$is the conductor height, $w$is the conductor width, and g is the gap width (Sydoruk et al., 2009). This form retains both the parallel-plate contribution and the fringing-field correction.
For a three-dimensional square SRR, another commonly used expression is

$$C_{gap} = \varepsilon_0 \frac{(h + g)(w + g)}{g}$$

which explicitly accounts for fringing by enlarging the effective dimensions of the gap region (Vallecchi et al., 2019).

2.3.2 Surface Capacitance (C_{surf})

More advanced models show that charge accumulation is not confined only to the split region. Instead, charge is distributed over the resonator surface, leading to an additional contribution known as surface capacitance. For a singly split ring, a widely cited analytical form is

$$C_{surf} = \frac{2\varepsilon_0 (h + w)}{\pi} \ln \left(\frac{4R}{g} \right)$$

where $R$is the ring radius, $h$is the conductor height, $w$is the conductor width, and $g$is the gap width (Sydoruk et al., 2009). This expression shows that the surface capacitance may become appreciable, particularly for narrow gaps or larger resonator dimensions.

For a three-dimensional square SRR, the surface capacitance may be written in general form as

$$C_{surf} = (h + w)\, C_{surf}^{\text{p.u.h.}}$$

and the total capacitance of the resonator is then

$$C_{tot} = C_{gap} + C_{surf}$$

which emphasizes that both components must be included in resonance estimation (Vallecchi et al., 2019).

In the simplest approximation, the resonance frequency of an SRR is given by the standard LC relation

$$f_m = \frac{1}{2\pi\sqrt{L_{\text{total}} C_{\text{total}}}}$$

where $L_{\text{total}}$and C_{total}represent the total inductance and total capacitance of the resonator, respectively (Hałgas, 2022; Sydoruk et al., 2009). This model provides clear physical intuition, but it remains a first-order approximation because it does not yet distinguish the different physical contributions that make up the total inductance and capacitance.

2.4 Integrated Resonance Frequency Formula

By including both inductive and capacitive contributions discussed above, the SRR resonance frequency can be written in a more complete form as

$$f_m = \frac{1}{2\pi\sqrt{(L_m + L_e)(C_{gap} + C_{surf})}}$$

(Sydoruk et al., 2009; Zhou et al., 2005).

This expression clearly shows that SRR resonance is determined by the combined effects of magnetic inductance, kinetic inductance, gap capacitance, and surface capacitance. At conventional microwave frequencies, L_m and $C_{gap}$are often the dominant terms. However, as the resonator is miniaturized for operation at increasingly high frequencies, the contribution of L_e becomes significant and can no longer be ignored (Zhou et al., 2005). Under these conditions, the increase in resonance frequency through geometrical scaling becomes limited, giving rise to resonance-frequency saturation. In other words, the resonance frequency approaches an upper bound and no longer increases proportionally with further size reduction (Zhou et al., 2005). At the same time, the role of C_{surf} becomes critical in maintaining accurate resonance prediction (Sydoruk et al., 2009; Vallecchi et al., 2019).

This phenomenon shows that geometrical scaling alone is insufficient to describe SRR behaviour at optical frequencies. Instead, an accurate analytical model must incorporate both advanced inductive and capacitive effects so that resonator design can remain predictive and physically reliable.

Table 1. Analytical Expressions for the Equivalent-Circuit Parameters of an SRR

Parameter	Symbol	Analytical Expression	Description of Variables	Ref.
Magnetic Inductance	L_m	$L_m \approx \mu_0 \bar{R}_m \left[\ln\left(\frac{8\bar{R}_m}{h+w}\right) - \frac{1}{2}\right]$, $\bar{R}_m = l'/(2\pi)$	μ_0: free-space permeability; $\bar{R}_m$: mean current-path radius; l': current-path length; h: conductor height; w: conductor width	Hałgas (2022); Sydoruk et al. (2009)
Kinetic Inductance	L_e	$L_e = \frac{l'}{S'\omega_p^2 \varepsilon_0}$	l': current-path length; S': effective cross-sectional area; ω_p: plasma frequency; ε_0: free-space permittivity	Zhou et al. (2005)

Gap Capacitance	C_{gap}	$C_{gap} = \varepsilon_0 \left(\frac{hw}{g} + h + w + g \right)$	ε_0: free-space permittivity; h: conductor height; w: conductor width; g: gap width	Sydoruk et al. (2009)
Gap Capacitance (3D square SRR variant)	C_{gap}	$C_{gap} = \varepsilon_0 \frac{(h+g)(w+g)}{g}$	same as above	Vallecchi et al. (2019)
Surface Capacitance	C_{surf}	$C_{surf} = \frac{2\varepsilon_0 (h+w)}{\pi} \ln\left(\frac{4R}{g}\right)$	ε_0: free-space permittivity; h: conductor height; w: conductor width; R: ring radius; g: gap width	Sydoruk et al. (2009)

3. Electromagnetic Field Distribution and Surface Current

To visualize the physics of resonance, it is necessary to examine the field and current distributions in detail. Such analysis is commonly carried out using full-wave electromagnetic solvers, such as CST Microwave Studio or HFSS (Hossain et al., 2022).

3.1 Excitation and Surface Current Path

The primary magnetic resonance of an SRR is excited when a time-varying magnetic field, H, is applied normal to the plane of the resonator (Baena et al., 2005). According to Faraday's law, the varying magnetic flux induces an electromotive force, which in turn drives a surface current, J_{surf}, along the conducting path of the ring (Marqués et al., 2003). At resonance, the effective impedance of the equivalent LC circuit reaches its minimum value, allowing the induced current to attain its maximum magnitude. Full-wave simulations show that this current is concentrated along the main conductive path of the ring (Hossain et al., 2022).

3.2 Figures and Tables

The strong circulating surface current, through Ampere's law, generates a strong and localized induced magnetic field oriented along the SRR axis [(Hossain et al., 2022). This magnetic field is predominantly confined within the resonator aperture. Near resonance, the induced field becomes sufficiently strong relative to the external excitation to produce a pronounced magnetic dipole moment, thereby giving rise to a negative effective permeability region, $\mu_{\mathrm{eff}} < 0$, which is one of the defining characteristics of metamaterials (Linden et al., 2004; Smith et al., 2000).

3.3 Concentration of the Electric Field (E-Field)

As the current circulates around the loop, positive and negative charges accumulate on opposite sides of the split (Marqués et al., 2003). This charge separation creates a highly concentrated electric field, E, within the split region (Hossain et al., 2022). The strong localization of the electric field is the physical manifestation of the split capacitance.

From an energy perspective, the resonant state may be understood as a continuous exchange between two forms of stored energy: magnetic energy stored in the inductive loop, L_m, and electric energy stored in the capacitive gap, C_{gap} (Linden et al., 2004; Marqués et al., 2003; Zhou et al., 2005; Vallecchi et al., 2019)..

4. Dipole Moments and Bianisotropic Response

The response of an SRR to an incident electromagnetic wave generally combines both magnetic and electric polarization because of the split geometry. The structural symmetry of the resonator governs the strength of magnetoelectric cross-coupling, that is, bianisotropy, and therefore determines how closely the resonance approaches a purely magnetic one (Sim et al., 2003; Smith et al., 2006).

4.1 Primary Magnetic Dipole Moment (m)

The primary objective of the SRR design is to generate a strong magnetic response. The circulating loop current gives rise to a pronounced magnetic dipole moment, m, oriented normal to the plane of the SRR (Baena et al., 2005; Smith et al., 2000). This magnetic dipole moment enables the bulk medium to exhibit an engineered effective permeability.

4.2 Electric Dipole Excitation and Bianisotropy

One of the key features of the single split-ring resonator is its structural asymmetry. The presence of a single split breaks the rotational symmetry of the ring (Linden et al., 2004). As a result, an electric field, E, aligned with the split axis can also excite the fundamental resonance (Baena et al., 2005). In this case, the electric field drives current around the loop, and the resulting current circulation generates a magnetic response.

This type of cross-coupling, in which an electric field induces a magnetic dipole moment and vice versa, is referred to as bianisotropy (Szymanski et al., 2021; Zhou et al., 2005). Because of its lack of symmetry, the single split-ring resonator is intrinsically bianisotropic (Marqués et al., 2003).

4.3 Induced Electric Dipole Moment (p_E)

When the SRR is excited, charge accumulation across the split gives rise to a strong electric dipole moment, p_E, oriented across the gap (Marqués et al., 2003). Interestingly, under the standard excitation by an axial magnetic field, the induced magnetic dipole moment, m, is normal to the SRR plane, whereas the induced electric dipole moment, p_E, lies within the plane of the resonator. Thus, the two moments are orthogonal to one another (Baena et al., 2005; Smith et al., 2006).

4.4 Symmetric Design and Suppression of Bianisotropy

Bianisotropic response is often undesirable because it complicates the design of media intended to exhibit a purely magnetic response. To overcome this issue, various symmetric resonator configurations have been developed (Marqués et al., 2003; Penciu et al., 2008; Smith et al., 2006). Structures such as the classical DSRR, or single-ring resonators with two or four symmetrically placed splits, can suppress or even eliminate magnetoelectric cross-coupling (Baena et al., 2005; Penciu et al., 2008). By preserving symmetry, the resonance can be excited more selectively by the magnetic field component normal to the resonator plane, thereby yielding a cleaner and more nearly purely magnetic response (Baena et al., 2005).

In general, resonators with an odd number of splits tend to exhibit bianisotropic behaviour, whereas resonators with an even number of symmetrically arranged splits can be designed to avoid this effect (Kodama et al., 2024).

5. Discussion and Analysis

This section synthesizes the preceding review and presents the discussion in a more structured manner under three main themes, namely analytical modelling, electromagnetic response, and modern applications. Such an organization allows the distinct characteristics of single split-ring resonators (SSRs) and double split-ring resonators (DSRRs) to be evaluated more clearly and systematically.

5.1 Analytical Modelling

From an analytical modelling perspective, the resonance behaviour of SRRs is governed primarily by the interaction between inductive and capacitive elements. In SSRs, the basic LC representation provides a compact and intuitive description of resonance, where the loop contributes to inductance and the split region forms the dominant capacitance (Baena et al., 2005; Hałgas, 2022; Sydoruk et al., 2009). However, as the operating frequency increases and the geometry becomes more compact, the classical LC approximation becomes insufficient on its own. Under such conditions, additional terms such as electron kinetic inductance and surface capacitance must be incorporated to obtain a more accurate prediction of resonance frequency (Sydoruk et al., 2009; Vallecchi et al., 2019; Zhou et al., 2005).

For DSRRs and other symmetric multi-gap configurations, the analytical description becomes more involved because mutual coupling, distributed capacitance, and symmetry-dependent current paths play a stronger role (Penciu et al., 2008; Smith et al., 2006). These structures often support a more balanced field distribution and may offer improved resonance sharpness, although at the cost of greater modelling complexity (Durán-Sindreu et al., 2012; Marqués et al., 2003). Therefore, analytical modelling not only explains the resonance mechanism of SRRs, but also highlights how structural symmetry and gap arrangement influence equivalent-circuit behaviour and frequency prediction.

5.2 Electromagnetic Response

From the electromagnetic-response perspective, the distinction between SSRs and DSRRs is strongly linked to symmetry and field coupling. In SSRs, the single split breaks rotational symmetry, making the structure more susceptible to magnetoelectric cross-coupling and therefore to bianisotropic behaviour (Linden et al., 2004; Marqués et al., 2003; Sim et al., 2003; Smith et al., 2006). As a result, the excitation mechanism is not purely magnetic, since the electric field aligned with the split axis may also contribute to resonance excitation (Baena et al., 2005; Linden et al., 2004). This feature gives SSRs a strong but less selective electromagnetic response.

By contrast, DSRRs and other symmetrically arranged multi-gap resonators suppress such unwanted cross-coupling more effectively (Penciu et al., 2008; Smith et al., 2006). Their improved symmetry enables a cleaner magnetic response, stronger control over field confinement, and reduced bianisotropy (Baena et al., 2005; Durán-Sindreu et al., 2012; Marqués et al., 2003). This also affects the induced dipole moments, current distribution, and the degree of electric- and magnetic-field localization within the resonator (Hossain et al., 2022; Linden et al., 2004; Marqués et al., 2003; Smith et al., 2000). Consequently, the electromagnetic behaviour of these two resonator classes differs not only in excitation mode, but also in resonance purity, field confinement, and suitability for different engineering purposes.

5.3 Modern Applications

The practical implications of these structural and electromagnetic differences are reflected in modern applications. In general, SRR-based configurations have been widely exploited in filters, antennas, and sensors because their compact resonant behaviour, strong field localization, and geometry-dependent coupling provide considerable flexibility for electromagnetic design.

5.3.1 Microwave Filters

In microwave filters, SRRs are valued for compact band-stop and band-pass implementations (Marqués et al., 2002). Because SRRs operate as subwavelength resonators, filter designs based on them can achieve reduced size while maintaining useful frequency selectivity. Recent developments have gone beyond fixed passive filters and increasingly focus on reconfigurable and tunable architectures. Such tunability is commonly achieved by incorporating active or responsive elements into the split region, thereby allowing the effective capacitance to be controlled (Bouyge et al., 2009; Liu et al., 2019). In addition, the filtering concept has expanded into broader wave-control platforms, including filtering reconfigurable intelligent surfaces for interference suppression and enhanced communication performance (Liang et al., 2024). At the same time, artificial-intelligence-assisted design methods are being introduced to optimize SRR and CSRR filter geometries more efficiently (Hou et al., 2020; Zhang et al., 2024).

5.3.2 Antenna Design

In antenna engineering, SRRs act as effective meta-atoms for controlling current distribution, localized fields, and radiation properties. One of their most important advantages is antenna miniaturization, since SRR resonance occurs at dimensions much smaller than the operating wavelength (Ali et al., 2025; Milias et al., 2021). This feature is especially valuable in compact wireless and IoT platforms. In addition to size reduction, SRRs are widely used to realize multiband operation and to improve the effective bandwidth of antennas (Khan et al., 2025; Selvi et al., 2020). In more advanced designs, SRRs are also employed as superstrates or metamaterial layers to enhance gain and directivity by focusing electromagnetic energy (Moniruzzaman et al., 2022). These strategies have been successfully applied in a variety of communication systems, including 5G base-station antennas, multiband antennas, and broadband low-profile designs (Kaur et al., 2022; Reis et al., 2021).

5.3.3 Sensors

Sensing is one of the most active application areas of SRRs and CSRRs. The basic sensing mechanism relies on the high sensitivity of resonance frequency to changes in the permittivity of materials placed within the region of concentrated electric field (Liu et al., 2019; Roslan et al., 2022; Ye et al., 2022). Consequently, even small perturbations introduced by the material under test can generate measurable resonance shifts. This feature has supported the development of microwave sensors that are low cost, rapid, sensitive, and, in many cases, non-invasive (Buragohain et al., 2021; Siddiky et al., 2022).

In the biosensing domain, SRRs have been applied to both invasive and non-invasive glucose monitoring by exploiting dielectric-property variations in biological samples at microwave frequencies (Alsultani et al., 2025; Martins et al., 2025). More recent studies have extended microwave resonators to virus detection, including SARS-CoV-2, through compact cavity-resonator immunosensor platforms (Elsheakh et al., 2021). At the same time, optical approaches such as multilayer surface-plasmon-resonance biosensors have been developed to achieve very high refractive-index sensitivity (Moznuzzaman et al., 2021). To further improve performance, nanomaterials such as antibody-AuNP conjugates have been introduced into microwave sensing platforms (Wang et al., 2024), while two-dimensional materials such as MoS_2 have been incorporated into plasmonic biosensor configurations (Tene et al., 2025). Hybrid microwave-plasmonic microfluidic platforms have also been demonstrated, indicating a broader trend toward integrated multiparameter sensing (Firmansyah et al., 2025).

Beyond biosensing, SRRs and CSRRs are also widely employed for dielectric-property characterization, which remains one of the dominant application areas in the metamaterial-sensor literature (Prakash & Gupta, 2022). Representative examples include soil water-content determination using CSRR-based sensors (Oliveira et al., 2020), monitoring of water pollutants such as ammonia and iron ions (Yee et al., 2021), and detection of contaminants in aquatic environments (Viskadourakis et al., 2023). High-performance sensor configurations such as tri-composite SRRs further demonstrate that electric-field enhancement and quality-factor improvement can be achieved simultaneously, thereby enabling more accurate and more sensitive permittivity measurements (Alibakhshikenari et al., 2023). Overall, these applications show that the core SRR features, namely field localization and sharp resonance, can be translated directly into practical systems relevant to healthcare, environmental monitoring, and industrial diagnostics.

5.4 Parameter-Based Comparison Between SSR and DSRR

To provide a more systematic evaluation, the comparison between SSR and DSRR should be classified according to specific study parameters rather than presented only as a broad descriptive summary. These parameters include geometrical characteristics, excitation behaviour, bianisotropy, resonance quality, miniaturization capability, modelling complexity, fabrication practicality, and application suitability. Such a classification enables a clearer and more meaningful interpretation of how each resonator type performs under different analytical and practical considerations.

Table 2. Parameter-Based Comparison Between SSR and DSRR/Symmetric SRRs

Parameter Category	Specific Study Parameter	Single Split-Ring Resonator (SSR)	Double Split-Ring / Symmetric SRRs (DSRR)	Analytical / Practical Implication
Geometrical characteristics	Number and arrangement of splits	One split; rotational symmetry is broken (Pendry et al., 1999; Sydoruk et al., 2009)	Two or more symmetrically arranged splits (Baena et al., 2005; Penciu et al., 2008)	Symmetry strongly affects resonance purity and coupling behaviour
Geometrical characteristics	Structural symmetry	Inherently asymmetric (Linden et al., 2004; Marqués et al., 2003)	Structurally more symmetric (Penciu et al., 2008; Smith et al., 2006)	DSRR generally suppresses unwanted cross-coupling more effectively
Analytical modelling	Equivalent-circuit simplicity	Simpler LC representation (Baena et al., 2005; Sydoruk et al., 2009)	More complex due to coupling and distributed effects (Penciu et al., 2008; Smith et al., 2006)	SSR is easier to model; DSRR requires more detailed treatment
Analytical modelling	Capacitance distribution	Dominated by a single split region (Sydoruk et al., 2009)	Distributed across multiple gaps or coupled rings (Penciu et al., 2008; Vallecchi et al., 2019)	DSRR may support stronger capacitive control and tuning flexibility
Electromagnetic response	Primary excitation mechanism	Primarily magnetic, but in-plane electric-field excitation may also occur (Baena et al., 2005; Smith et al., 2006)	More selectively excited by the magnetic field component normal to the plane (Baena et al., 2005; Smith et al., 2006)	DSRR provides a cleaner magnetic response
Electromagnetic response	Bianisotropy level	Higher due to asymmetry (Marqués et al., 2003; Smith et al., 2006)	Lower due to symmetry (Penciu et al., 2008; Smith et al., 2006)	DSRR is preferable when reduced magnetoelectric coupling is needed
Electromagnetic response	Resonance purity	Less pure because of cross-coupling (Marqués et al., 2003)	More purely magnetic resonance (Baena et al., 2005; Penciu et al., 2008)	Symmetry improves selectivity and interpretability
Electromagnetic response	Field confinement and current distribution	Strong localized response, but less balanced distribution (Hossain et al., 2022; Marqués et al., 2003)	More balanced field and current distribution (Baena et al., 2005; Durán-Sindreu et al., 2012)	DSRR may improve resonance stability and response consistency
Performance characteristics	Quality factor (Q)	Generally lower in asymmetric single-split configurations (Marqués et al., 2003)	Generally higher in symmetric or multi-ring configurations; for example, a recent H-shaped nested split-ring resonator (H-NSRR) reported a high unloaded quality factor of approximately 346 in air (Marqués et al., 2003; Durán-Sindreu et al., 2012; Rahman et al., 2026)	DSRR and related multi-ring structures often support sharper resonance and better spectral selectivity
Performance characteristics	Miniaturization capability	Good compactness, typically around ~0.1λ in reported comparisons (Marqués et al., 2003)	Stronger capacitive coupling may enable smaller electrical size, e.g., around ~0.015λ in reported comparisons (Marqués et al., 2003)	DSRR may achieve smaller electrical size for the same frequency
Practical implementation	Fabrication complexity	Simpler and easier to fabricate (Marqués et al., 2003; Sydoruk et al., 2009)	More complex due to multi-gap or multi-ring layout (Baena et al., 2005; Penciu et al., 2008)	SSR is advantageous for low-cost and straightforward fabrication

Practical implementation	Tolerance sensitivity	Less demanding	More sensitive to alignment and gap precision (Baena et al., 2005; Penciu et al., 2008)	DSRR may require tighter manufacturing control
Application suitability	Filters	Suitable for compact and simple resonant filters (Bouyge et al., 2009; Marqués et al., 2002)	Suitable for higher-selectivity and more stable filter designs (Liang et al., 2024; Liu et al., 2019)	Choice depends on whether simplicity or resonance purity is prioritized
Application suitability	Antennas	Useful for compact and multiband antenna loading (Ali et al., 2025; Selvi et al., 2020)	Useful when better field control and reduced coupling artefacts are needed (Kaur et al., 2022; Moniruzzaman et al., 2022)	DSRR may be preferred in more performance-sensitive antenna systems
Application suitability	Sensors	Effective for localized-field sensing and compact sensing platforms (Buragohain et al., 2021; Prakash & Gupta, 2022)	Effective for sensing requiring higher Q and reduced bianisotropy (Alsultani et al., 2025; Martins et al., 2025)	Geometry selection should match sensing objective and required stability

As shown in Table 2, the distinction between SSR and DSRR extends beyond geometric appearance alone, since symmetry directly influences analytical modelling complexity, electromagnetic response, resonance quality, fabrication tolerance, and application suitability. Therefore, the selection of an SRR configuration should be guided by the specific performance priorities of the intended device rather than by geometric simplicity alone.

6. Conclusion

The split-ring resonator is one of the most fundamental and influential elements in metamaterial research because it enables the realization of electromagnetic properties that do not occur naturally, through structural engineering. This review has presented a comprehensive discussion of SRRs, beginning from the origins of artificial magnetism, moving to the understanding of SRRs as subwavelength LC resonators, and then extending to the roles of geometry, symmetry, analytical modelling, and electromagnetic-field response in governing their behaviour.

The analysis presented here shows that an accurate understanding of SRR resonance requires a model that goes beyond the simplest LC approximation. In particular, the inclusion of surface capacitance, C_{surf}, and electron kinetic inductance, L_e, is essential for more precise resonance prediction, especially when the structure is scaled toward the terahertz and optical regimes. In addition, the examination of electric-field, magnetic-field, and surface-current distributions reveals that SRR resonance is the result of a highly organized energy exchange between the inductive and capacitive components of the resonator.

The discussion of dipole moments and bianisotropy further highlights that structural symmetry plays a crucial role in determining the electromagnetic response. Although single-split resonators naturally tend toward bianisotropic behaviour because of their asymmetry, symmetric designs such as DSRRs are able to suppress magnetoelectric cross-coupling and thereby produce a purer magnetic response.

Finally, the fundamental principles discussed throughout this review have proven to be highly relevant to a broad range of modern applications, including microwave filters, antennas, and sensors. From increasingly compact and agile communication platforms to dielectric, biological, and environmental sensing systems, SRRs and related structures continue to show considerable value as tools for electromagnetic-wave engineering. Therefore, a deep understanding of the physical mechanisms, analytical models, and design implications of SRRs will remain essential for the development of next-generation metamaterial devices.

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