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An Assessment of Progress in 5.8 GHz Quasi-lumped Element Resonator Antennas

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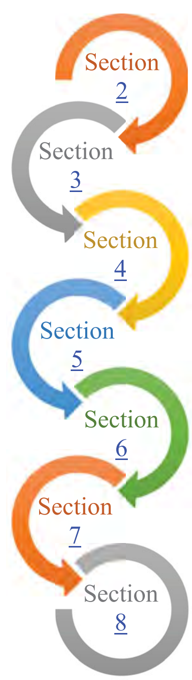
ABSTRACT
The revolutionary microstrip technology for wireless communication suffers from relatively large size and low radiation efficiency when modeled for the current challenging hardware. An efficient solution to this subject is the quasi-lumped element (LE) approach. Therefore, this manuscript is a tutorial on the progress in quasi-LE resonator antennas, and it has been transcribed as an introduction or assessment for the readers. The paper traces the LEs' history and fundamental principles. The modeling procedures of the quasi-LE resonator and its essential outline are summarized. A review of the quasi-LE resonator antennas for 5.8 GHz applications has been presented. Measurement reports of a unique quasi-LE antenna are also illustrated. Finally, the intended methods are compared with other configurations while considering the several important performance parameters of antennas.

KEYWORDS
5.8 GHz; antennas; electromagnetics; feeding array; microstrip; quasi-lumped element resonator; wave propagation

1. INTRODUCTION

An exceptional advancement in computer architecture and technology has influenced to the need for antenna designs with multiple features and operational advantages [1–4]. The antennas are designed to transmit or receive electromagnetic waves. Their history dates back to 1873 when electricity and magnetism theories were unified, and exemplified through a set of equations [5–7]. The printed antenna systems possess several fascinating attributes necessary for the modern electronic gadgets, for instance, mechanical simplicity, ease of integration with active circuits, etc. However, they suffer from numerous functional difficulties, namely a narrow frequency pattern, deprived scan performance, spurious feed radiation, insufficient polarization purity, modest power, and relatively large extent [8–11]. An alternative and effective technique to circumvent these shortcomings is the method of employing a combination of quasi-LEs in the systems. This approach was introduced by Ain *et al.* in 2013 [12]. Consequently, various designs of the quasi-LE resonator antennas were reported in many publications, but mostly for the ISM (industrial, scientific and medical) or 5.8 GHz band applications [8,12–20]. Therefore, this communication presents a detailed literature analysis of the quasi-LE resonator antennas for 5.8 GHz band. In order to substantiate the previous works, a quasi- LE resonator antenna with distinct dimensions was designed and fabricated. The performance of the articulated technique is also compared with other configurations.

The remaining of this paper is organized as follows.



Portrays the fundamental perception of lumped elements (LEs) or quasi-LE.

Describes the theoretical analysis for the outline of a quasi-LE resonator antenna.

Presents a discussion on the design procedures to improve the quasi-LE resonator antennas.

Communicates the typical radiation patterns of the quasi-LE resonator antennas.

Reports a study on the effect of edge-feeding a quasi-LE resonator antenna.

Highlights a comparative analysis of the various design methods for 5.8 GHz bands.

Represents a conclusion.

2. THEORY OF LUMPED ELEMENTS

A resonator represents any structure consisting of at least one oscillating electromagnetic field. It can be categorized as the LE (or quasi-LE) and the distributed element [21–23]. The LEs were initially utilized by Vincent for the microwave integrated circuits [24]. In due course, several layouts, measurements, and applications have been described by multiple authors [25–47]. The LEs typically comprise of three fundamental passive components, namely inductor (L), capacitor (C) and resistor (R). However, in several circumstances, balun or lumped inductor transformer is utilized in the circuits. At radio or microwave frequencies, the LEs are designed with limited sections of transverse electromagnetic lines where the size of each component across any measurement is kept considerably miniature than the free space wavelength (λ_0) of the highest operating frequency *i.e.* less than $0.1\lambda_0$ to avoid substantial phase shift between the input and the output terminals. The quasi-LEs are short line or stub sections with dimensions more compact than a quarter of a guided wavelength (λ_g). They are considered as LEs when their physical lengths are relatively smaller than $\lambda_g/8$. The following theory summarizes various necessary terms involved in LEs or quasi-LEs.

Taking into consideration an ideal L, C and R; the mathematical dealings between the terminal voltage and current across each element can be illustrated as depicted in Figure 1 [22].

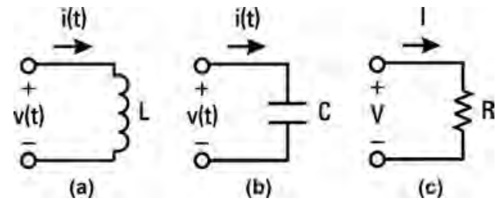


Figure 1: Two-terminal voltage and current representations of the quasi-LEs: (a) Inductor, (b) capacitor and (c) resistor [22]

In quasi-LEs, the relative values of the three essential passive components are decided based on their intended use. An ideal quasi- LE is unattainable even at low microwave frequencies as the fringing fields contribute to parasitic reactance. Moreover, every element possesses magnetic and electric fields along with finite disperse loss. Consequently, the magnetic and electric energies are released or stored across the components and their resistance accounts for the dissipated power. However, at resonance, the magnetic and electric energies are similar. Therefore, the resonating frequency "ω_0" can be expressed as,

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{1}$$

The electrical behavior is typically expressed from the equivalent circuit (EC) representations which can be achieved by analytical, electromagnetic simulation or measurement procedures [20,50,51,53,55–68]. A few notable analytical modeling methods are listed in Table 1. However, these techniques are adequate typically up to the first parallel resonant frequency. Extraction of the EC limits by corresponding the measured DC and S-parameter information is the most generally employed approach of achieving precise models.

Table 1: Analytical modeling methods of the quasi-lumped elements

References	Approach
[48]	Thin metallic straight-line inductor equation
[49]	Rectangular metal strip inductor expression
[50]	Circular spiral inductor formula
[51]	Inductance calculations for numerous geometries
[52]	Formula for interdigital capacitors
[53]	Distributed representation of the MIM capacitor
[54]	Lumped element models on GaAs
[55]	Microstrip/network analysis/lumped element models

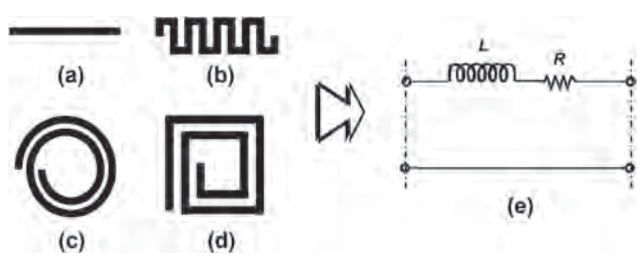


Figure 2: The quasi-LE inductors: (a) High-impedance line, (b) meander line, (c) circular spiral, (d) square spiral and (e) ideal circuit representation [23]

The quasi-LEs offer the benefit of accumulating the electric and magnetic energies in distinct parts of the resonator. This ultimately initiates the direct transformation of an EC consisting of inductors and capacitors into a microstrip structure. A lumped capacitor and inductor can be realized using an open-circuit and close-circuit microstrip section, respectively. A few standard arrangements of the planar microwave lumped inductors, and capacitors are shown in Figure 2 and 3, respectively [23].

The quality factor "Q" of a resonant circuit can be ascertained by utilizing the following equation,

$$Q = \omega \frac{W_m + W_e}{P_l} \tag{2}$$

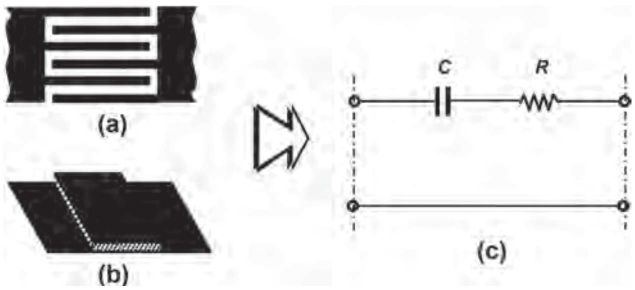


Figure 3: The quasi-LE capacitors: (a) Interdigital, (b) metal-insulator-metal and (c) ideal circuit representation [23]

where $W_m + W_e$ is the average energy stored and P_l is the power dissipated.

The essential insight of lumped elements or quasi-LEs was conferred in this section. The discussion on quasi-LEs is continued in Section 3, where the method of utilizing passive components to function as radiating elements is treated in detail.

3. THE QUASI-LUMPED ELEMENT RESONATOR ARRANGEMENTS

The principal outline of a quasi-LE resonator involved a multi-fingered periodic interdigital capacitor in parallel with a single-striped straight inductor, Figure 4 [12]. This design was completed by encompassing the parasitic capacitors or pads. The finalized model proved progressive as it exhibited an enhanced impedance bandwidth by engaging 32.48 sq. mm area with reasonable radiation characteristics and efficiency. Consequently, the approach has been widely adopted and discussed thoroughly as follows.

The inductor was designed to behave like a conductor whose magnitude could be increased by utilizing a meander line. Its inductance was controlled by the magnetic field near the median strip and the current distribution witnessed across the same was comparable to an isolated strip. The inductance was evaluated by using the successive equation.

$$L = 200 \times 10^{-9} I_L \left[ln \left(\frac{2I_L}{W_1 + t} \right) + \left(0.50049 + \frac{W_1}{3I_L} \right) \right] \quad (3)$$

On the other hand, the interdigital capacitance was controlled by increasing the number of fingers or employing a thin layered high dielectric constant material between the conductors and substrate. Since, the capacitance for every finger was lumped at each finger's end, equal currents were spotted in all the capacitor fingers. The interdigitated structures' series capacitance, physical length and width were estimated from Equations (4–8) [52,69,70].

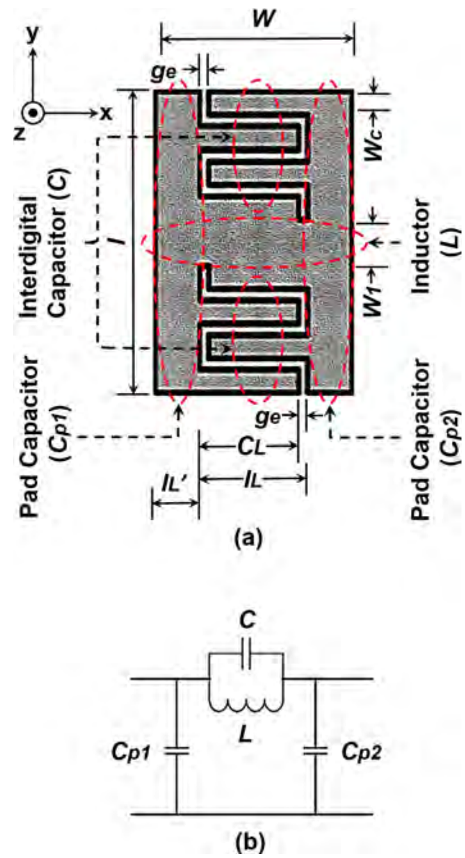


Figure 4: (a) The principal outline of a quasi-LE resonator and (b) its equivalent circuit model [12]

$$C = \varepsilon_0 \left(\frac{\varepsilon_r + 1}{2} \right) [(N - \Delta) C_L] \quad (4)$$

$$I_L = C_L + g_e \quad (5)$$

$$w = 2 \times I_{L'} + I_L \quad (6)$$

$$l = [(g_e + w_c) \times N] + (w_1 + 2g_e) \quad (7)$$

$$\Delta = 0.5(w_{eff} - w) \quad (8)$$

The pads acted as capacitors to ground and were developed for tuning the resonant frequency. Their capacitances were independent of the finger's dimension or quantity. Therefore, realizing large values of the interdigital capacitor without increasing the parasitic capacitances became possible. However, this was possible by increasing the separation space between the interdigitated construction and the ground plane in addition to the number of fingers. In order to determine the pad capacitances, the subsequent formula was considered [71].

$$C_P = \frac{2.85\varepsilon_{eff}}{\ln\left[1+\left(\frac{1}{2}\right)\left(\frac{8h}{w_{eff}}\right)\left[\left(\frac{8h}{w_{eff}}\right)+\sqrt{\left(\frac{8h}{w_{eff}}\right)^2+\pi^2}\right]\right]} \times \frac{l}{25.4\times10^{-3}} \quad (9)$$

The resonant frequency of the quasi-LE resonator was decided by solving Equations (3–4 and 9–13) [39,52,70–72].

$$f = \frac{1}{2\pi\sqrt{L\left(\left(\frac{C_{P1}\times C_{P2}}{C_{P1}+C_{P2}}\right)+C\right)}} \quad (10)$$

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left(1+\frac{10h}{w}\right)^{-0.5} \quad (11)$$

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_{eff}\left[\left(\frac{w}{h}\right)+1.393+0.667ln\left(\left(\frac{w}{h}\right)+1.4444\right)\right]}} \quad (12)$$

$$\varepsilon_0 = 8.85\times10^{-12} \quad (13)$$

In conclusion, the magnetic field lines loop around the interdigital width. Therefore, the complete cross section of $l \times w$ performs precisely similar to a printed transmission line and follow the microstrip theory.

The authors of [14] reported that the resonant frequency in the dominant mode for the quasi-LE resonator depicted in Figure 4 cannot be identified clearly [12]. Furthermore, they justified that the structure exhibits multiple resonances along with essentially distinguishable wavelengths (radiation and spatial) [22,73–78]. Consequently, they introduced a dielectric resonator made of CCTO ($CaCu_3Ti_4O_{12}$) material into the antenna design to reduce the excessive harmonic resonances and accomplish an adequate impedance bandwidth or gain. Its schematic and equivalent circuit representation is portrayed in Figure 5.

The equations mentioned in this section are proficient in determining the antenna's dimensions and resonant frequencies. Hence, the radiating elements can be designed according to the required specifications. Furthermore, antennas occupying different cross sections can be modeled for the same resonant frequency. Therefore, it can be stated that the quasi-LE resonator antenna arrangement offers a high degree of flexibility and freedom.

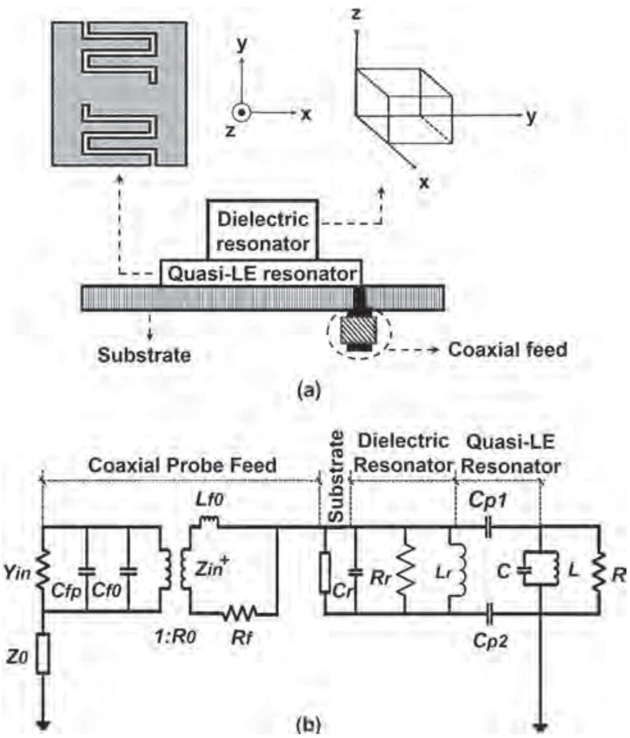


Figure 5: The dielectric loaded quasi-LE resonator antenna and (b) its equivalent circuit model [14]

4. THE QUASI-LUMPED ELEMENT ARRAY RESONATOR ANTENNAS

Fundamentally, the single element antennas designed for the modern compact devices experience severe restrictions in term of gain, directivity, radiation resistance or efficiency exclusively due to their miniature outline [79–85]. Consequently, antennas realized by employing multiple radiating elements interconnected through a feed network to form an antenna array have been reported by several authors to overcome the restrictions of single element antennas [86–93]. Yet again these efforts, although are array structures either suffer from low gain, or relatively large antenna area or both. Therefore, numerous quasi-LE resonator-based array antennas were introduced to achieve compactness with reasonable performance characteristics [8,12,16–20]. Moreover, the layout of quasi-LE resonator described in all these publications implicated the exact resonator design mentioned in Figure 4 [12]. However, the antenna array configurations were experimented to discover novel footprints. In an array configuration, the feed mechanism plays a vital role of exciting the antenna elements via transmission lines, Figure 6 [5,82,94–99]. Hence, the following sections summarize the various designs of quasi-LE resonator-based feeding array antennas.

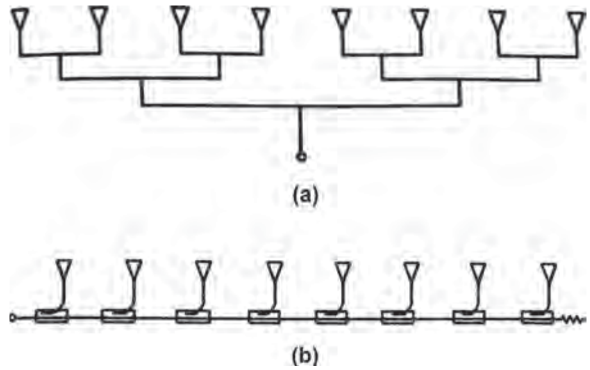


Figure 6: The antenna array feed examples: (a) Corporate/ parallel and (b) series [5]

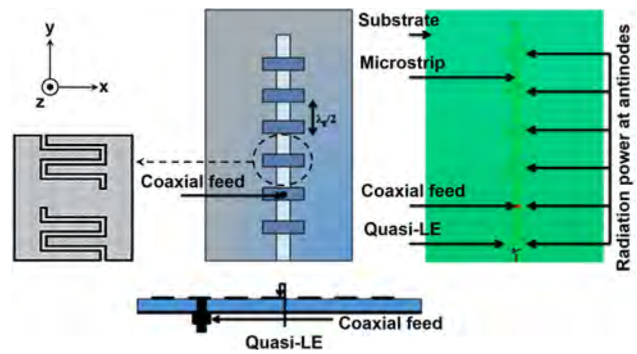


Figure 7: The quasi-LE resonator antenna array with a series-fed layout [17]

4.1 The Series-fed Array Layout

In a series-fed array configuration, the radiating elements connected in series tap of the power from a common source by allocating one of the antenna's input impedance as a load of the former. An unmatched transmission line and load arrangement cause some energy to reflect back down the microstrip to the source. Consequently, the interference of the incident and reflected power generates the standing waves on the transmission lines. Ultimately, the nodes and antinodes with minimum and maximum voltage/current are periodically produced along the microstrip from the load termination toward the generator, respectively [100–105].

In order to overcome these drawbacks and acquire a maximum radiation at every antinode, Olokede [17,20] utilized the current distribution pattern of a single element quasi-LE resonator to determine that the antinodes will duplicate at every half wavelength (λ) along the microstrip and concluded to design an antenna with the array elements positioned at every $\lambda/2$, Figure 7 [17]. The proposed six-element antenna footprint was excited by a coaxial feed and fed by a microstrip feeder. The distinguished properties of a coaxial feed probe excitation were utilized to gain an improved impedance match, bandwidth and reflection coefficient. Furthermore, the microstrip feeder arrangement ensured that the power is distributed uniformly to all the array elements for accomplishing linear polarization. As a result, the radiating components fruitfully combined the radiated power generated by the individual antenna element and eventually augmented the directive characteristics of these radiators in terms of sidelobe level, beam width, gain, and the like. The far-field radiation patterns of the quasi-LE resonator antenna for single element and array configurations were attained from the calculations reported in [17] and Equation (14), respectively [69,106–111].

$$AF = \frac{1}{m}\frac{\sin[m(k_0 d_y \sin\theta\cos\phi/2)]}{\sin[(k_0 d_y \sin\theta\cos\phi/2)]} \tag{14}$$

where AF is the array factor, m is the number of array elements, and d_y is the inter-element spacing.

4.2 The Corporate-fed Array Network

The radiating elements in a corporate-fed array arrangement are connected in parallel from a sole source. Their excitations can be controlled in any event by employing amplitude/phase shifters. Ultimately, this enables a broad assortment of patterns or beam scanning to be pioneered to the array. In addition, the parallel-fed array approach does not experience elevated mismatch losses and on that account affords a relatively wide bandwidth along with excellent design flexibility [91–93,112].

Contrariwise, triumphing miniaturization along with equal excitations present a challenge. The radiation from the feed line is another shortcoming which in due course vitiates the arrays' side lobe levels or cross polarization. Likewise, it is necessary to limit the losses attributable to the feed resistance, copper, dielectric, surface waves, radiation, mutual coupling and all that [113–116].

To this end, a quasi-LE resonator-based array design was reported, Figure 8 [19]. This model ensured that the antenna size was moderately reduced indeed after employing a corporate-fed network for excitation. Furthermore, the quality factor recorded was higher than that of overlay capacitors which typically occupies vaster area. The confirmation of more energy in the interdigital capacitor or inductor resulted into a narrow bandwidth characteristic. However, the radiation patterns and gain were witnessed to be suitable for long-range communications.

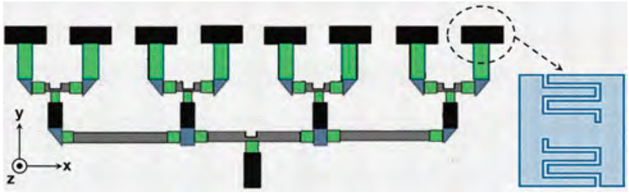


Figure 8: A corporate-fed network array of 8-quasi-LE resonators [19]

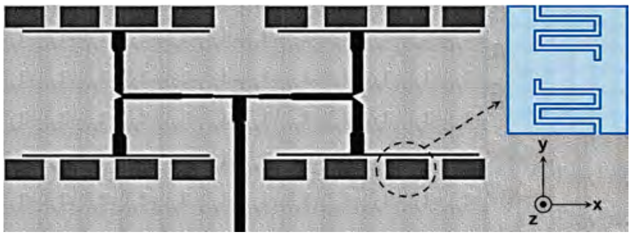


Figure 9: The 8×2 quasi-LE resonator-based array with a corporate-fed network [8]

Likewise, a novel non-radiating edge-fed two sub-arrays of quasi-LE resonators were fabricated to establish an improved operation in terms of efficiency, gain, bandwidth, and insertion loss. However, these advantages were accomplished when the arrangement along with its exact reflection was merged to form an 8×2 parallel array layout shared by a corporate feed, Figure 9 [8]. The inter-element spacing for these outlines was kept realistically large to inhibit the mutual coupling effect among the neighboring components or junctions. Besides, the complete configuration was fed using a power divider (Wilkinson) by the T-junction so as to split the 50Ω line in two and reach an identical proportion of phase or magnitude to the feed points [117]. The obligatory power distribution and the quantity of the feeds were determined by utilizing the calculations stated in [118].

In contrast, it has been highlighted in existing writings that the conventional T-shaped feed assembly has been incompetent because of the intrinsic losses at the disconnections. Experimental observations reported in [119–121] prove that a reduction in the input reflection coefficients can be accomplished with curved corners. For this reason, a hybrid-ring coupler confirms an attractive selection for the design of power divider between the radiating elements. In addition, it demonstrates as exceptional in beam-forming set-ups for the microstrip array antennas [122]. In this context, a quasi-semi hybrid-ring liked T-shaped feed was integrated with quasi-LE resonators to follow a footprint shown in Figure 10 [18]. The invent was successful in avoiding the needless losses associated with the disconnections as the curved geometry restricted the number of junctions. A few other benefits

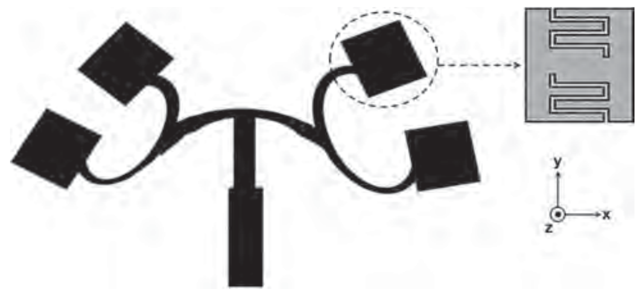


Figure 10: The 4-element quasi-lumped resonator antenna array with a corporate-fed model [18]

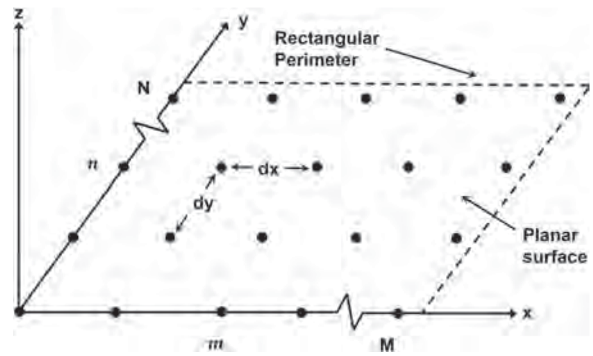


Figure 11: Two-dimensional planar array [86]

offered by this outline include superior functioning compared with the traditional corporate-fed system in terms of radiating elements' real estate capability, gain, and fabrication procedure.

4.3 The In-phase-fed Array Network

A planar array incorporates finite sized identical antennas ($m \times n$) arranged in a definite manner and fed by a suitable feed network, Figure 11 [86]. The signal radiates, reflects or scatters between these radiators depending on its power, reflection coefficients, and electrical phase created by the propagation delay among the elements. This technique excels in providing high directivity along with multiple features like beam steering in two planes, digital beamforming and the rest [86–88,95,98,123–126]. Hence, a quasi-LE resonator arrangement was incorporated with an innovative feed network to develop an efficient planar design, Figure 12 [16]. The array pattern involved four rectangular frames of 5×5 each. Whereas, the feed network encompassed four coaxial probes to excite the entire array by means of proximity coupling from the neighboring elements. This excitation was contributed by the capacitance generated because of the fringing field patterns from the four lattices. These fringing fields were equally responsible for inducing the current in other nodes and thereby

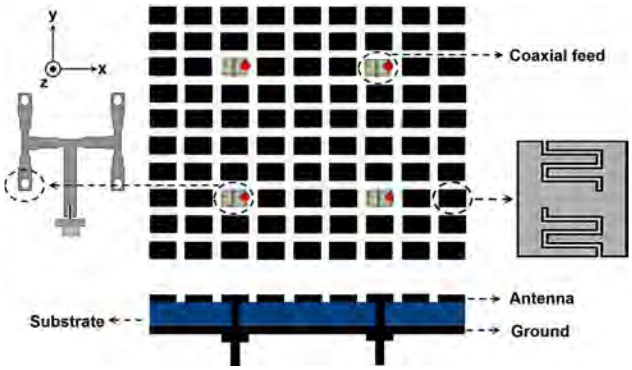


Figure 12: An in-phase-fed network array of 9 × 10 quasi-LE resonators [16]

bear a resemblance to active elements. Moreover, vias were introduced across each radiating element to conclude with additional parallel inductance. Consequently, a combination of capacitance and inductance fashioned the resonant chamber. The C and L values were determined from Equation (4) stated in [127]. The benefits of employing this method include upgraded gain, diminished back radiation, and an accurate match between the antennas and the feeds.

In summary, this complete section communicated about the various array networks and feed mechanisms utilized by the researchers previously to obtain novel designs of the quasi-LE resonator antennas. These arrangements offered better performance compared with the conventional microstrip antennas in terms of miniaturization, gain and so forth.

5. THE TYPICAL RADIATION PATTERNS OF THE QUASI-LUMPED ELEMENT RESONATOR ANTENNAS

The graphical representation of the antenna emission properties as a function of space plays a vital role of describing how the radiating elements receive energy [128–131]. Therefore, this section aims to demonstrate the typical radiation patterns of the quasi-LE resonator antennas, Figure 13 [12,16]. It is evident from the directional behavior of the configuration that the radiation components are reasonably acceptable. Likewise, a similar outcome has been observed in all the quasi-LE resonator antennas constructed over the years [8,13–14,17–20].

6. THE EDGE-FED QUASI-LUMPED ELEMENT RESONATOR ANTENNA

In [12], Ain *et al.* analyzed the effects of center-fed quasi-LE antennas' physical sizes on the resonant frequencies.

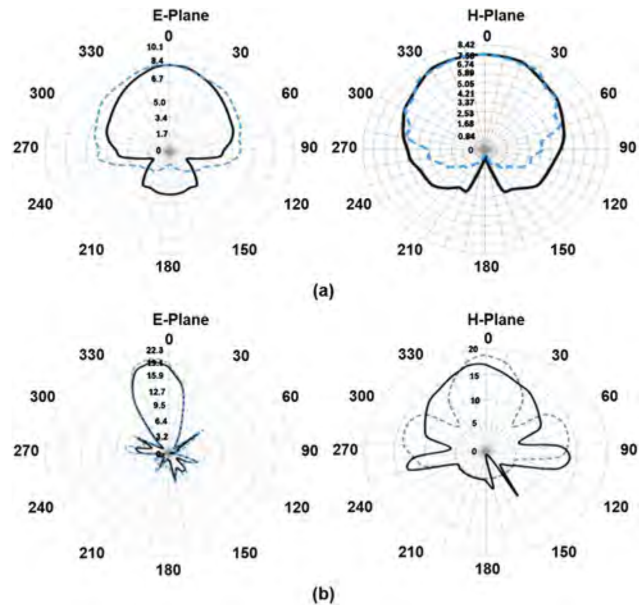


Figure 13: Radiation patterns of the quasi-lumped element resonator antennas: (a) Single element design [12] and (b) array configuration [16]

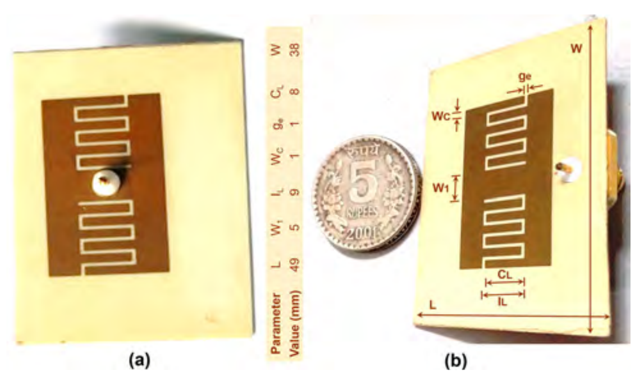


Figure 14: The fabricated quasi-LE resonator antennas with (a) center-feed and (b) edge-feed

They concluded that by utilizing this method, the radiating elements can be designed according to the anticipated specifications. In addition, experimental results of two distinct quasi-LE resonator models were presented to prove that the antennas occupying dissimilar areas can operate at the same frequency. Therefore, to validate these findings and check the effects of edge-feeding, it was decided to develop two quasi-LE resonator antennas (center-fed and edge-fed) with a cross section of approximately 500 mm^2 for 5.8 GHz applications. More precisely, the antennas were fabricated on RO4003C substrate with dielectric permittivity 3.38 and thickness 0.813 mm. Figure 14 illustrates the constructed antennas and their finalized parameter values.

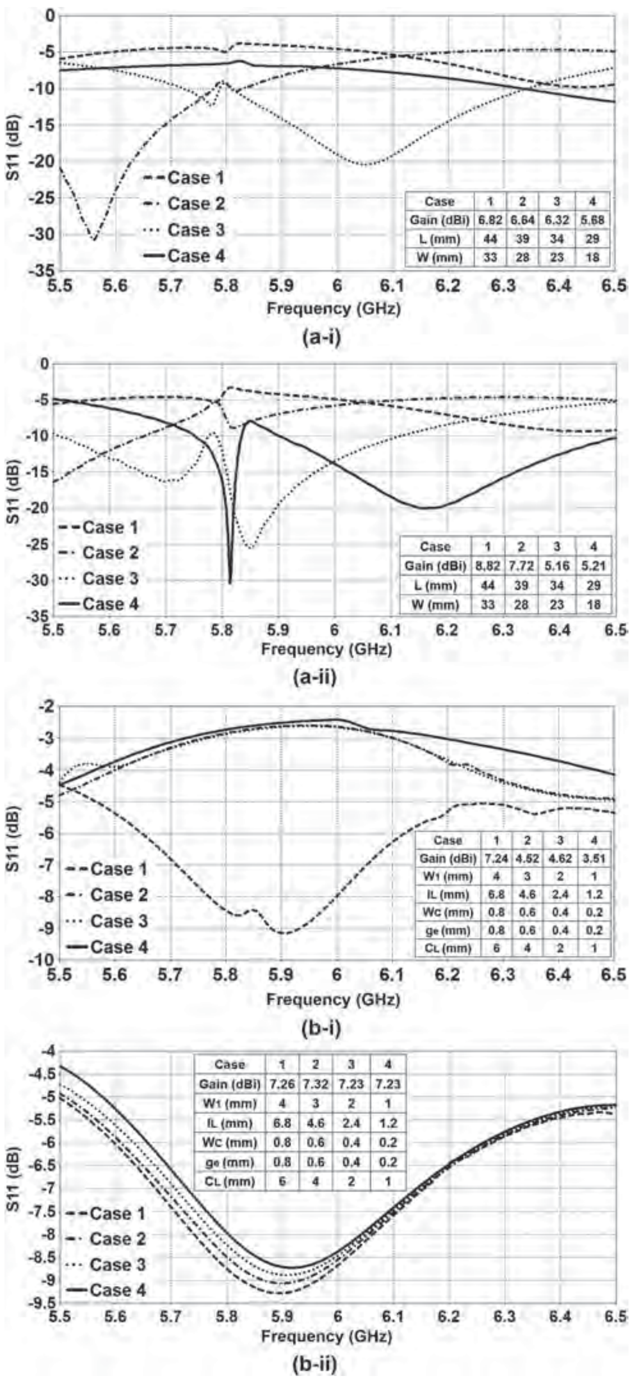


Figure 15: Parametric simulation studies for deciding (a) the ground plane extents of the antenna with (i) center-feed or (ii) edge-feed and (b) the design of quasi-LE resonator with (i) center-feed or (ii) edge-feed

The initial design parameters of the antennas were determined from Equations (3–13). However, these systems recorded poor bandwidth and gain values, Figure 15 (a-i and a-ii) Case 4. To overcome these shortcomings, the size of the ground plane was increased while keeping the quasi-LE resonator's dimensions constant, Figure 15 (a-i and a-ii) Case 1, 2 and 3 [132–134].

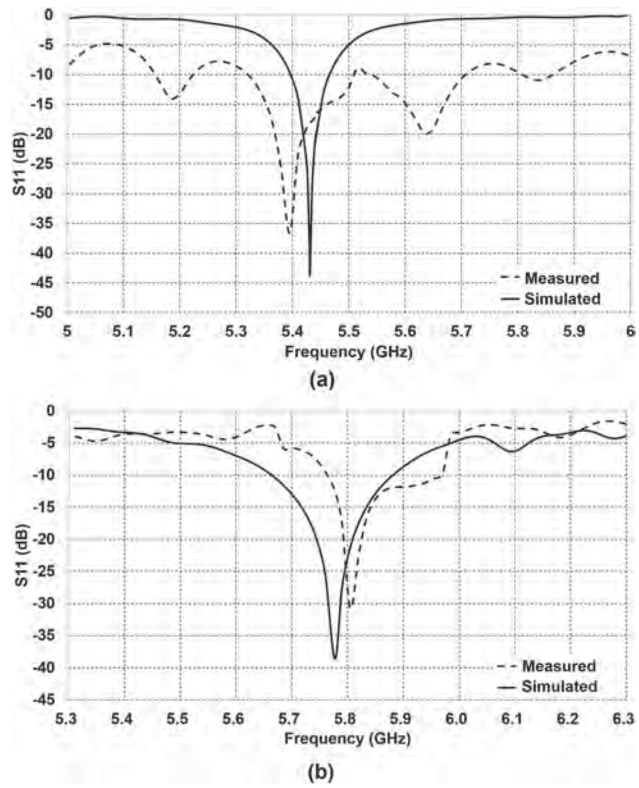


Figure 16: Simulated and measured S-parameters of the quasi-LE resonator antenna with (a) center-feed and (b) edge-feed

The precise values for these models were decided by utilizing the parameter sweep function of CST Microwave Studio simulation software, Figure 15 (b-i and b-ii) [68]. Ultimately, the combined area of the design was considered as 1862 mm^2.

The constructed center-fed antenna showed return loss value of −36.66 dB at 5.39 GHz and covered the frequencies of 5.32 GHz to 5.51 GHz, Figure 16(a). Similarly, the fabricated edge-fed prototype demonstrated S11 value of −38.60 dB at 5.8 GHz with 225 MHz bandwidth, Figure 16(b). At resonant frequency, a gain of 8.32 and 8.05 dBi was acquired for the center-fed and edge-fed arrangements, respectively. Moreover, both the configurations operated with an efficiency value of more than 90%. Figure 17 illustrates the simulated and measured radiation patterns of the quasi-LE resonator antenna with center-feed and edge-feed.

Theoretical and practical analysis has already been described in [12] for designing the center-fed quasi-LE resonator antennas. This section aimed to substantiate these findings by presenting simulation and measurement outcomes of a center-fed quasi-LE resonator antenna with unique dimensions. We conclude it should

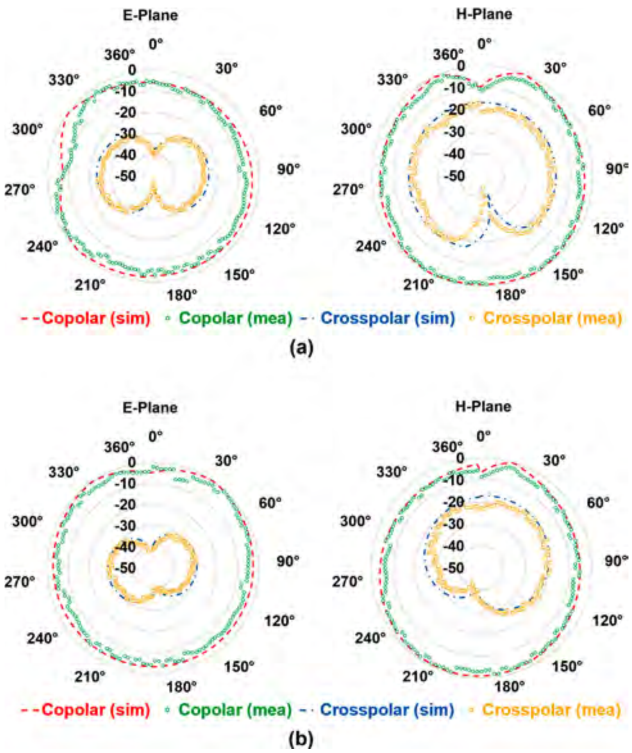


Figure 17: Simulated and measured radiation pattern of the quasi-LE resonator antenna with (a) center-feed and (b) edge-feed

be possible to construct the radiating elements for different frequency bands by employing this method. Moreover, we demonstrated that increased bandwidth and gain values are associated with both larger ground plane and edge-feeding. This ultimately indicates the existence of another method of improving the quasi-LE resonator antenna's performance.

7. PERFORMANCE OF THE QUASI-LUMPED ELEMENT RESONATOR CONFIGURATIONS

7.1 Pros

Preliminary, considering the definition of quasi-LE which states that their extents are much minute than the wavelength; the mutual coupling effects experienced between closely placed radiating components are more minor in contrast to the distributed elements [133–139]. The compact dimensions also enable smaller amplitude or phase variations. At microwave frequencies, high-impedance lines possessing inductive characteristics along with associated shunt capacitance are typically employed. This ultimately compromises the gain-bandwidth product of the circuit. Engagement of lumped inductors with much lower parasitic capacitance outcomes in to a broader bandwidth. All of these factors can ultimately reduce the costs drastically.

Table 2 displays the findings of various methods embraced for developing an antenna for 5.8 GHz band. Parameters including reflection coefficient, bandwidth, gain and efficiency for all the quasi-LE resonator models in addition to a few recently designed microstrip antennas were reported for the assessment. Also, the fabricates were segmented on the basis of the type of design for better perception. The quasi-LE-based paradigms demonstrate premium in terms of miniaturization along with reasonable gain and efficiency.

7.2 Cons

The realization of quasi-LEs at millimeter wave frequencies is possible by maintaining the component dimensions much smaller than the operating wavelength. However, when its extent becomes further enormous, the components report with unwanted associated parasitic for instance inductance, resistance and capacitance. Additionally, the parasitic reactance become too substantial and thereby results into spurious resonances and more extensive loss. Therefore, the analytical methods are not precise enough to calculate the quasi-LE's performance perfectly.

7.3 Recommendations

In engineering, the discipline of the antenna has enjoyed an extremely fruitful period during the past several decades. Responsible for its accomplishment have been the technical advances in certain novel antennas, for instance microstrip, array, multiple elements, and the like. An enormous influence in the success of radiating elements has been the innovations in computer architecture and technology.

Even though a confident level of maturity has been accomplished, there are several problems to be worked out. The innovative miniaturized footprint suitable for the modern devices along with enhanced performance characteristics is until now a most challenging problem. However, quasi-LE resonator can be integrated with much architecture to develop patterns for the wireless networks. Moreover, the realization of high-performance miniature quasi-LE based designs working at 28 GHz or 5G applications should be considered [140–149].

The quasi-LE models should be analyzed by electromagnetic simulation or measurement procedures because the parasitic reactance is an integral portion of the element and their properties can be included in the design. Utilizing novel materials for the antennas represent another

Table 2: Comparison of antenna design methods at 5.8 GHz.

Reference	Configuration	Design	$\|S_{11}\|$ (dB)	BW (MHz)	Gain (dBi)	Efficiency (%)	Area (mm^2)	Height (mm)	Substrate
This work	Quasi-LE Resonator (C-F)	SE	−36.66	190.00	8.32	98.29	1862.00	0.81	RO4003C
	Quasi-LE Resonator (E-F)	SE	−38.60	225.00	8.05	98.50	1862.00	0.81	RO4003C
[12]	Quasi-LE Resonator	SE	−21.24	370.00	9.40	94.23	32.48	0.81	RO4003C
[13]	Quasi-LE Resonator	SE	−50.97	340.00	9.38	N/A	32.48	0.81	RO4003C
[14]	Quasi-LE Resonator	SE	−50.00	430.00	6.96	N/A	32.48	0.81	RO4003C
[150]	Circular Patch Rectenna	SE	−18.00	200.00	4.17	75.00	600.00	1.60	FR-4
[151]	Square Spiral Patch	SE	−17.00	1520.00	N/A	N/A	400.00	1.00	FR-4
[152]	Asymmetric Double U-Slot	SE	−24.00	780.00	4.20	N/A	320.00	1.56	FR-4
[153]	Fabry-Perot	SE	−18.00	750.00	15.50	N/A	10,404.00	30.00	$\varepsilon_r = 4.4/9.2/4.5$
[154]	Circular QMSIW	SE	−30.00	210.00	4.88	89.40	361.00	1.57	RT5880
[155]	Elliptical-Shaped Monopole	SE	−26.00	1080.00	1.70	N/A	1520.00	1.00	FR-4
[156]	Folded-Slot Active Tag	SE	−23.00	900.00	2.38	N/A	117.70	1.60	FR-4
[157]	Dielectric Patch Resonator	SE	−10.00	1000.00	7.20	N/A	179.73	7.76	RT5880
[158]	Disc-Based Design	SE	−30.00	950.00	7.16	75.00	1225.00	1.60	$\varepsilon_r = 3.67$
[159]	V-Shaped Slits	SE	−22.00	200.00	1.26	85.00	72.27	1.34	FR-4
[160]	Microstrip Slot	SE	−28.00	1500.00	N/A	N/A	400.00	0.80	FR-4
[161]	Reconfigurable Slot	SE	−19.00	1290.00	2.50	75.00	675.00	0.80	RO4350B
[162]	CPW-Fed Monopole	SE	−35.00	1350.00	2.18	N/A	650.00	1.00	FR-4
[163]	Coplanar Monopole	SE	−25.00	3000.00	3.25	82.00	357.50	1.60	FR-4
[164]	Planar Monopole	SE	−16.00	200.00	4.00	N/A	732.00	1.50	RO4003
[165]	Fractal Monopole	SE	−25.00	3130.00	3.50	N/A	395.13	1.50	FR-4
[166]	Superconductor	SE	−25.80	2580.00	5.95	92.68	412.09	0.50	$LaAlO_3$
[19]	Quasi-LE Resonator	AR	−50.01	190.00	16.20	60.70	429.00	0.08	RO4003C
[18]	Quasi-LE Resonator	AR	−26.19	100.00	10.97	N/A	227.46	0.81	RO4003C
[17]	Quasi-LE Resonator	AR	−31.81	242.00	12.17	N/A	2400.00	0.81	RO4003C
[16]	Quasi-LE Resonator	AR	−34.00	190.00	19.79	69.18	9600.00	0.85	RO4003C
[20]	Quasi-LE Resonator	AR	−50.97	340.00	N/A	N/A	239.67	0.81	RO4003C
[8]	Quasi-LE Resonator	AR	−35.00	330.00	12.80	N/A	273.80	0.81	RO4003
[8]	Quasi-LE Resonator	AR	−39.00	370.00	16.90	N/A	547.60	0.81	RO4003
[167]	HIS-EBG Reconfigurable	AR	−20.07	110.00	7.83	N/A	4900.00	1.60	FR-4
[168]	Spiral Split Ring Resonator	AR	−25.00	700.00	7.00	N/A	185.64	1.48	FR-4
[169]	Split Ring Resonator Patch	AR	−22.00	610.00	5.70	N/A	189.77	1.48	FR-4
[21]	Rectenna Patch	AR	−49.00	200.00	8.93	73.39	184.94	1.60	FR-4
[170]	Dual-Diode Rectenna	AR	−22.00	232.00	6.38	76.00	N/A	0.51	RT5880
[171]	SIW Rectenna	AR	−33.00	100.00	6.90	61.49	1722.00	0.80	PTFE
[172]	Sequential Phase Network	AR	−30.00	1750.00	8.20	N/A	2025.00	1.60	FR408
[146]	Wide-Slot Rectenna	AR	−20.00	2000.00	6.40	62.00	43,255.00	0.80	Teflon
[173]	Microstrip Quasi Yagi	AR	−35.00	970.00	10.00	80.00	3600.00	1.50	$\varepsilon_r = 2.55$
[174]	Yagi-Uda Patch	AR	−33.00	213.00	7.50	N/A	3888.00	1.60	$\varepsilon_r = 2.2$
[175]	E-Shaped Monopole	ME	−18.00	N/A	2.90	90.00	1330.00	0.80	$\varepsilon_r = 2.2$
[176]	Printed Monopole	ME	−27.00	1180.00	2.50	94.00	796.50	0.80	FR-4
[177]	Back-To-Back Monopole	ME	−18.00	N/A	4.86	N/A	750.00	0.80	FR-4
[178]	F-Shaped Monopole	ME	−38.00	1100.00	2.80	N/A	780.00	1.60	FR-4
[179]	Metamaterial	ME	−26.20	1040.00	2.14	71.00	1000.00	1.60	FR-4
[180]	Unit Cell Radiators	ME	−18.00	2840.00	5.00	86.00	8100.00	1.60	FR-4

Note: C-F = Center-Fed; E-F = Edge-Fed; SE = Single Element; AR = Array; ME = Multiple Element; BW = Bandwidth; N/A = Not Available

approach to offer multiple prospects for the system performance.

8. CONCLUSIONS

This article was authored with the attempt to present the readers an outline of the investigation that has been carried out in quasi-LE resonator antenna technology for 5.8 GHz applications. Their history or modeling procedures were summarized and utilized to fabricate an antenna with unique dimensions. Approximately all of the major developments of quasi-LE resonator antennas were briefly discussed. It is evident from the various publications addressed in this manuscript that the quasi-LE resonator antennas can be modeled to suit modern compact telecommunications devices. Furthermore, these antennas can be further studied for fruitful employment in different frequency bands. The literature review proves that all the quasi-LE resonator antennas utilized same radiating element design and substrate properties. Therefore, further investigation can be performed on distinct quasi-LE resonator outlines with different dielectric constants to suit the necessities of the consumers. Additionally, their performance can be enhanced by exercising materials with distinct permittivity. Addressing the above-mentioned problems will make the quasi-LE resonator antenna a better alternative for upcoming wireless applications.

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