Mathematical modeling and parameter analysis of quantum antenna for IoT sensor-based biomedical applications

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ABSTRACT

In this paper, an equivalent combination of series and parallel R-L-C high-pass filter circuit is derived for a nano (quantum) antenna for the Internet of thing (IoT) based sensors for speedy data or organ image displaying in medical line surgeries. The proposed method utilized the sample frequency behavior of characteristics mode to develop a fundamental building block that superimposes to create the complete response. The resonance frequency, input impedance, and quality factor have been evaluated along with basic and higher-order resonating modes. The relation between quality factor, bandwidth, resonance frequency, and selectivity for higher order, increases the quantum circuits in terms of increased order of a filter, quality factor, and odd and even harmonics factors. Therefore, the basic circuits derivation factor of frequency coefficients are expanded in terms of polynomials and then they are expressed as a simple rational function from which the basic circuit parameters are calculated. In this circuit input impedance of each circuit’s element is complex. The real part of input impedance depends on frequency, depending on the frequency positive or negative value of the resistor, and the imaginary part of impedance modelling an inductor or capacitor due to the value of frequency. At cutoff frequency 511 THz, z11 and VSWR parameters are 34 Ω and 1.11, respectively. The proposed quantum DRA is tested at 5 THz, 10 THz, and 500 THz by calculating the electrical parameters like R, L, C and model performance is quite good as compared to existing ones. The dynamic impedance is dependent on the skin effect and enhances the detailed discussion below. The utilization of optical or quantum DRAs is as optical sensors in biomedical engineering, speedy wireless communication, and optical image solutions. Analyte material has been used for monitoring frequency deviation.

Keywords: NDRA (QA); phasor model; resistor; inductor; capacitor; quality factor; dynamic impedance; MATLAB; HFSS software-based simulations

1. Introduction

The Internet of Things (IoT) is a rapidly growing network of interconnected devices that are designed to communicate with each other and share data. The integration of IoT technology with quantum antennas can result in significant improvements in the performance and efficiency of wireless communication systems[1].
These antennas are designed to operate using the principles of quantum mechanics, which allow for more efficient and precise transmission and reception of signals. Quantum antennas use quantum effects such as entanglement, superposition, and tunneling to enhance their performance and sensitivity. The Internet of Things (IoT) has been rapidly expanding into the healthcare sector and is becoming increasingly important in the monitoring of health conditions. It has the potential to revolutionize disease prevention and help improve patient outcomes. The IoT sensors can be used to monitor various parameters such as temperature, humidity, pressure, and vibration, and transmit this data wirelessly to a central system.

The analysis of any antenna and its structure with different parameters has to be known. It involves a large mathematical calculation that can be simplified by its equivalent RLC circuit\(^3\). In the current article, the HFSS NDRA model has been processed with its electrical equivalent circuit design\(^4\). An estimated equivalent RLC circuit pattern has been initiated\(^5\) that portrays the principal mode of propagation of the transmission line by utilizing a microstrip coupled slot. Lumped impedances have been attained precisely to narrate the function from source to end terminals. The reactive power due to the inductive and capacitive part is absorbed during excitation and termination while radiated waves are observed by the resistive part only. This methodology can be utilized for computing the input impedance of NDRA with microstrip-coupled loading\(^6,7\). The designing of NDRA equivalent circuits has been explained in very few research articles, as the maximum part of the research is convenient to the design of equivalent circuits of patch antenna\(^8\text{–}15\). For precise results of internal and load impedance of NDRA, the equivalent circuit representation is essential. The designed parameters of NDRA such as impedances and radiation fields have been represented in higher-order and fundamental resonating modes. Some other parameters like bandwidth, resonating frequency, and radiation field parameters have been calculated by utilizing an equivalent circuit model\(^15\). The frequency at which an object vibrates most readily is known as the resonance frequency. It is an object’s inherent vibrational frequency. Resonance frequency in electronics refers to the frequency at which a circuit resonates. A resonant circuit is one that may gradually release electrical energy that has been stored in an electric field (capacitor) or magnetic field (inductor). The values of a circuit’s components determine its resonance frequency. The design substrate describes the substance used to construct electronic circuits. The substrate supports the circuit mechanically and acts as an electrical insulator between the circuit’s several layers. Electric current flowing along a conductor’s surface is referred to as surface...
Surface current is significant in electronics because it can lead to unwelcome interference in circuits. By employing appropriate grounding methods and designing circuits with little electromagnetic interference, surface current can be reduced.

In this article, higher-order modes are analyzed exactly. The radiation pattern and the field nature of NDRA can be predicted by resonant modes circuit models. In this research article, a physical science-based circuit for resonant modes has been created straightforwardly in precise structure. It has an advantage analysis and synthesis of distinct NDRA structures. The concept of resonance provides an easier way to design the NDRA. This analytical approach of linking the Quantum DRA circuit models to its radiated fields is used in NDRA research initially. The light beam interacts and passes through the medium that has a collision with fundamental negatively charged particles and molecules of the material. The material medium is considered plasma which possesses the property of explicit permittivity, permeability, and conduction to propagate the EM waves in it at optical frequency.

The integration of IoT technology with quantum antennas has the potential to significantly improve the performance and efficiency of wireless communication systems. This can lead to a wide range of applications, including smart cities, healthcare, transportation, and industrial automation. The main motive for to design and analysis of the proposed quantum antenna for wideband (THz) frequency in the biomedical field is to reduce the signal transmission time with low power dissipation. The objectives of the paper are:

1) Understanding the designing analysis of proposed quantum antenna for wideband (THz) frequency in the biomedical field using HFSS microwave studio and MATLAB tools.

2) The proposed quantum antenna provides a wideband (THz) or low wavelength with low power dissipation, therefore, less number of surrounding tissues are damaged when used in biomedical applications.

3) The limitations associated with metals and all-dielectric-based structures antennas can be avoided by utilizing a quantum antenna.

4) The proposed quantum antenna becomes less sensitive toward temperature variations, less expensive, small in size and weight, low wavelength, low power dissipation, and less body tissue damage when used in biomedical applications like laser operations.

The paper is structured as follows: Sections 2 and 3 provide the interpretation and radiation theory related to a quantum antenna. Section 4 discusses the quantum DRA circuit and its analysis. Section 5 discusses the simulated results of the proposed antenna using MATLAB. Section 6 shares the results analysis and response tuning of the proposed antenna using HFSS software. Finally, the paper is concluded in Section 7.

2. Interpretation of quantum antenna

With light amplification and stimulated emission of radiation (LASER) feed, the quantum antenna persists only with dynamic impedance at resonance as the input impedance (Z\text{in}). In this situation, this dynamic impedance depends on the optical frequency and Plank’s constant just as the dynamic impedance of classical DRA. With an increment in optical frequency above the resonating frequency (\omega_2), the dynamic impedance or the input impedance will be increased which follows the pattern as that of capacitor charging. It has been analyzed that the antenna’s bandwidth has also been increased with increment in optical frequency but its effect on the quality factor is reversed due to the proposed rectangular shape of a quantum antenna having of larger surface area than other shapes.
In the electrical equivalent circuit of a quantum antenna, the impedance has quite a low value when the frequency is increased highly, so the current $I_1$ maximizes correspondingly, which results in high power and signal strength\cite{28-31}. It also provides very high signal absorption and dispatching. Initially, when the circuit is tuned, the inductive branch current behaves as a surface current that depends on the area. This current is present due to the skin effect. In QA, both impedances (input as well as dynamic) depend on frequency. The actual power is only due to the real part of the input impedance and the non-real part has no contribution in useful power. Both reactive elements (inductor and capacitor) transfer power from one-half cycle to the other half cycle between themselves.

Such types of models are specially required for 5G applications due to very small power loss and high selectivity at larger frequencies\cite{32}. As the inductor or capacitor stores larger power than the dissipated power, therefore the quality factor will be very low, i.e., $Q = \frac{f_r}{\text{bandwidth}}$. The quality factor inversely depends on bandwidth, so the bandwidth will be very high. Finally, the bandwidth of an antenna gets improved which allows passing the of high-range signals. The expression of the formula for a resonant frequency of THz NDRA is given by Equation (1)\cite{33}.

$$f_r = \frac{c}{2\pi \sqrt{\epsilon_r}} \sqrt{\left(\frac{m \pi}{a}\right)^2 + \left(\frac{n \pi}{b}\right)^2 + \left(\frac{p \pi}{d}\right)^2} \quad \text{and}$$

$$Q = \frac{f_r}{f_r - f_l} = \frac{f_r}{\text{bandwidth}}$$ (1)

The terahertz frequency has the advantage of a smaller wavelength. Hence, the depth of signal penetration will be less as compared to microwaves. However, power input level variation results will be different. Terahertz frequency is nonionizing and non-invasive. THz imaging in biological applications is based on the differences in water content and physiological structural changes between abnormal and normal tissues observed. Change in power level may be used to capture images of layered tissue\cite{34}. This

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q$</td>
<td>Position vector</td>
</tr>
<tr>
<td>$P$</td>
<td>Time derivative moment vector</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Temperature</td>
</tr>
<tr>
<td>$P$</td>
<td>Average field energy in Gibb’s state</td>
</tr>
<tr>
<td>$a_k$</td>
<td>Annihilation and creation operators</td>
</tr>
<tr>
<td>$H$</td>
<td>Electromagnetic field</td>
</tr>
<tr>
<td>$z_q(\beta)$</td>
<td>Quantum partition function</td>
</tr>
<tr>
<td>$i(t)$</td>
<td>Current through shunt R-L-C circuit</td>
</tr>
<tr>
<td>$f_r$</td>
<td>Resonant frequency in Hz</td>
</tr>
<tr>
<td>$BW$</td>
<td>Bandwidth</td>
</tr>
<tr>
<td>$Z$</td>
<td>Impedance</td>
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<tr>
<td>$P$</td>
<td>Power</td>
</tr>
<tr>
<td>$Z_{in}$</td>
<td>Input impedance</td>
</tr>
<tr>
<td>$Q$</td>
<td>Quality factor</td>
</tr>
<tr>
<td>$Y_1, Y_2, Y_3$</td>
<td>Individual admittance of each DRA</td>
</tr>
<tr>
<td>$R_1, R_2, R_3$</td>
<td>Individual Resistance of each branch of DRA</td>
</tr>
<tr>
<td>$Z_d$</td>
<td>Impedance of DRA</td>
</tr>
<tr>
<td>$Z_l$ and $Z_{in}$</td>
<td>DRA load and input impedance</td>
</tr>
<tr>
<td>$X_1, X_2, X_3$</td>
<td>Individual capacitance of each branch of DRA</td>
</tr>
<tr>
<td>$Y_l$</td>
<td>Load admittance</td>
</tr>
<tr>
<td>$A$ and $B$</td>
<td>Real and imaginary parts of the input admittance $Y_{in}$</td>
</tr>
<tr>
<td>$</td>
<td>S_{11}</td>
</tr>
<tr>
<td>$E_{aps}$</td>
<td>Time-varying field</td>
</tr>
<tr>
<td>$Z_p$</td>
<td>Equivalent impedance of quantum DRA</td>
</tr>
</tbody>
</table>
can have better resolution results as compared to MRI with minimal investment. Terahertz device size shall be very small as compared to MRI. Dielectric behaves like a conductor at high frequency and conductor behaves like a dielectric. Biosafety is an important issue in sensing as the electron energy of the THz wave is low. Biomedical technology (tissue exhibits reflection and absorption properties that change dramatically with tissue characteristics), is used for medical and dental Imaging. Here, it has been demonstrated that the dielectric response of the cell can reflect particular water dynamics by THz spectroscopy. Table 1 shows the used symbols in mathematical modeling with their Nomenclature.

3. Nano dielectric resonator antenna (NDRA) radiation theory

\[ [q_a, p_b] = \frac{i\hbar}{2\pi} \delta(a, b) \]  (2)

where,

- \( q \) = Position vector
- \( p \) = Time derivative moment vector
- \( \beta = \frac{1}{kT} \), \( T \) = Temperature
- \( \rho = \frac{\exp(-\beta H)}{\tau_r(\exp(-\beta H))} \) average field energy in Gibb’s state = \( \rho \) is explained by \( \tau_r(\rho H) \) and \( \tau_r(\rho p_p) \).

Classically, we get

\[ \frac{\rho}{\tau_r(\rho H)} = 0. \]

\( a_k = \frac{a_k+i p_k}{\sqrt{2}} \) annihilation and creation operators \( a_k^* = \frac{a_k-ip_k}{\sqrt{2}}, k = 1, 2, 3 \ldots \ldots \)

\[ [a_k, a_m^*] = \frac{h}{2\pi} \delta(k, m) \] Heisenberg commutation relation

Electromagnetic field = \( H = \frac{1}{2} \sum_{k=1}^{N} a_k^* a_k + \frac{N\hbar}{4\pi} \) field energy quantum states or eigenstates of \( H|n \geq n_1, n_2, n_3 \ldots \ldots n_N >, n_1, n_2, n_3 \ldots \ldots \ n_N = 0, 1, 2, 3 \ldots \)

\[ H|n \geq \frac{h}{2\pi} (\sum_{k=1}^{N} a_k^* a_k + n_1 + n_2 + \ldots \ldots + n_N) \]

Now, the Quantum \( a_k \) in the Gth state is

\[ \exp\left(-\frac{\beta N \hbar}{4\pi}\right) < n|a_k \exp\left(-\frac{\beta \hbar}{2\pi} \sum_{m} a_m^* a_m\right) (n \geq \exp\left(-\frac{\beta N \hbar}{4\pi}\right) \sum_{m} \exp\left(-\frac{\beta \hbar}{2\pi} \sum_{m} n_m\right) \delta(n, m - e_k) = 0 \]

Here, \( e_k = [0, 0, \ldots \ldots, 0, 1, \ldots, 0] \), \( \tau_r(p_p^2 \exp(-\beta \hbar)) = -\frac{1}{2\tau_r(\rho H)}(\frac{\beta \hbar}{2\pi} \sum_{k=1}^{N} a_k^* a_k e^{-\beta \hbar}) \frac{z_q(\beta)}{z_c(\beta)} \]

\[ z_q(\beta) = Quantum \ partition \ function = \frac{1}{2\tau_r(\beta)} \tau_r \left[ (a_k^* a_k + \frac{h}{4\pi}) \exp(-\beta \hbar) \right] \]

\[ z_c(\beta) \] quantum part.

4. Quantum DRA circuit and analysis

Analysis of series and parallel combination of circuit parameters of Quantum DRA has been provided to calculate current \( I(t) \), resonating frequency \( (f_r) \) impedance \( (Z) \), power \( (P) \), and bandwidth (BW)\( ^{35,36} \).

\[ \tau_r(\rho H) \]

\[ \tau_r(\rho p_p) \]
**NDRA (Nano DRA) impedance (Z\textsubscript{in})**

Equivalent circuits of nano (quantum) antenna.

![Electrical equivalent impedance circuit of the quantum antenna.](image)

When initial excitation is provided, the voltage drops across the parallel combination of impedance \(Z_2\) and \(Z_3\) is equal and some voltage drop across the impedance \(Z_1\) as shown in Figure 1, but the current is divided between impedance \(Z_2\) and \(Z_3\) due to their different values as shown in Equation (3).

\[
Z_2 = R_2 + j\omega L_2; \quad I_2 = \frac{V}{Z_2} \quad \text{and} \quad Z_3 = R_3 - \frac{j}{\omega C_3}; \quad I_3 = \frac{V}{Z_3}
\]  

(3)

The value of \(Z_2\) and \(Z_3\) changes due to variable frequency terms in \(Z_2\) and \(Z_3\). The value of impedance \(Z_2\) and \(Z_3\) will be equal at a particularly high frequency which results in equal current flow. But it remains equal for a very short instant as it persists only for a particular high frequency. The occurrence of this incident is due to the Dirac-de lta function. The frequency at which equal current is observed in parallel impedances \(Z_2\) and \(Z_3\) is known as a first tuning frequency. But at this time, the currents \(I_2\) and \(I_3\) in impedance \(Z_2\) and \(Z_3\) individually have equal magnitude but opposite phases to each other. So, its resultant will be zero and the all-current flows through the impedance \(Z_1\) alone, which is expressed as \(Z_1 = R_1 - \frac{j}{\omega C_1}\) (\(Z_1\) is frequency dependent)\cite{37}. When the frequency gets higher, the value of the impedance \(Z_1\) is decreased to a low value which results in a huge amount of current and power. Under this condition, \(Z_1\) is considered as a dynamic impedance of the circuit as the impedance depends only on \(Z_1\). This impedance depends on the frequency and having characteristics of exponentially increased function similar to the charging of a capacitor. The current in \(Z_1\) depends on a voltage drop across \(Z_1\) and given by \(i_i = \frac{dv_i}{dt}\) as \(dt\) is quite small, so the higher current results in large bandwidth. This current \(i_i\) is called as surface or displacement current.

In Figure 1, \(X_1 = -\frac{1}{\omega C_1}, \quad X_2 = \omega L_2\) and \(X_3 = -\frac{1}{\omega C_3} \)

Input impedance \(Z_{\text{in}} = Z_1 + Z_2\|Z_3 = Z_1 + \frac{Z_2Z_3}{Z_2+Z_3}\)

where,

\[
Z_1 = R_1 + jX_1, \quad Z_2 = R_2 + jX_2\quad \text{and} \quad Z_3 = R_3 + jX_3
\]

\[
Z_{\text{in}} = R_1 + jX_1 + \frac{(R_2+X_2)(R_3+X_3)}{R_1+jX_1+R_2+jX_2+R_3+jX_3} = R_1 + jX_1 + \frac{R_2R_3-X_2X_3+j(X_2R_3+R_2X_3)}{R_2+R_3+j(X_3+X_2)}
\]

\[
=R_1 + jX_1 + \frac{(R_2R_3-X_2X_3)(R_2+R_3)+(X_2R_3+R_2X_3)(X_3+X_2)+j((R_2+R_3)(X_2R_3+R_2X_3)-(X_2+X_3)(R_2R_3-X_2X_3))}{(R_2+R_3)^2+(X_3+X_2)^2}
\]

\[
Z_{\text{in}}(\text{real part}) = R_1 + \frac{(R_2R_3-X_2X_3)(R_2+R_3)+(X_2R_3+R_2X_3)(X_3+X_2)}{(R_2+R_3)^2+(X_3+X_2)^2}
\]

(4)
\[ Z_{in}(\text{imaginary part}) = \left[ X_1 + \frac{(R_2 + R_3)(X_2R_3 + R_2X_3) - (X_3 + X_2)(R_2R_3 - X_2X_3)}{(R_2 + R_3)^2 + (X_3 + X_2)^2} \right] \] (5)

To obtain the resonance condition, the imaginary part of an input impedance must be zero[38]. \( Z_{in} = Z_{in}(\text{real part}) + Z_{in}(\text{imaginary part}) \).

At resonance frequency imaginary part of \( Z_{in} = 0 \),

\[ R_2R_3X_2 + R_2^2X_2 + R_3^2X_2 + R_2R_3X_3 - (R_2R_3X_2 - X_2^2X_3 + R_2R_3X_3 - X_2^2X_2) + X_1[(R_2 + R_3)^2 + (X_3 + X_2)^2] = 0, \]

\[ R_2^2X_3 + R_3^2X_3 + X_2^2X_3 + X_2^2X_2 + X_1(R_2^2 + R_3^2 + 2R_2R_3 + X_2^2 + X_3^2 + 2X_2X_3) = 0, \]

\[ (R_2^2 + X_2^2)(X_1 + X_3) + (R_3^2 + X_3^2)(X_1 + X_2) + 2X_1(R_2R_3 + X_2X_3) = 0. \]

Putting the value of \( X_1, X_2 \) and \( X_3 \).

\[ \left( \omega L_2 \frac{1}{\omega C_1} \right) \left( \frac{R_2^2}{\omega^2 C_3^2} + \frac{1}{\omega^2 C_3^2} \right) + \left( -\frac{1}{\omega C_1} \right) \left( \frac{R_2^2}{\omega^2 C_3^2} + 2\omega^2 L_2^2 \right) - \frac{2}{\omega C_1} \left( R_2R_3 - \frac{L_2}{C_3^2} \right) = 0 \]

\[ \left( \frac{\omega^2 L_2 C_1 - 1}{\omega C_1} \right) \left( \frac{R_2^2 \omega^2 C_3^2 + 1}{\omega^2 C_3^2} \right) + \left( \frac{1}{\omega C_1} \right) \left( \frac{R_2^2}{\omega^2 C_3^2} + 2\omega^2 L_2^2 \right) - \frac{2\omega^2}{\omega C_1} \left( R_2R_3 - \frac{L_2}{C_3^2} \right) = 0 \]

\[ \frac{\omega^4 L_2 C_1 R_2^3 C_3^2 - 1 + \omega^2 (L_2 C_1 - R_2^2 C_3^2)}{C_1 C_3^2} + \omega^4 L_2^2 \left( -\frac{1}{C_1} \right) \left( \frac{R_2^2}{C_1} + \frac{1}{C_3} \right) + \omega^2 R_2^2 \left( -\frac{1}{C_1} \right) \left( \frac{R_2^2}{C_1} + \frac{1}{C_3} \right) - \frac{2\omega^2}{C_1} \left( R_2R_3 - \frac{L_2}{C_3^2} \right) = 0 \]

\[ \omega^4 \left[ L_2 R_2^3 - L_2^3 \left( \frac{1}{C_1} + \frac{1}{C_3} \right) \right] + \omega^2 \left[ L_2 \frac{R_2^2}{C_3^2} - R_2^2 \left( \frac{1}{C_1} + \frac{1}{C_3} \right) - \frac{2}{C_1} \left( R_2R_3 - \frac{L_2}{C_3^2} \right) \right] - \frac{1}{C_1 C_3^2} \left( R_2R_3 - \frac{L_2}{C_3^2} \right) = 0 \]

\[ \omega^4 [A] + \omega^2 [B] - C = 0 \]

Comparing the above two equations after this where \( A, B, \) and \( C \) are: \( A = L_2 R_2^3 - L_2^3 \left( \frac{1}{C_1} + \frac{1}{C_3} \right), B = \frac{L_2}{C_3^2} - \frac{R_3^2}{C_3^2} - R_2^2 \left( \frac{1}{C_1} + \frac{1}{C_3} \right) - \frac{2}{C_1} \left( R_2R_3 - \frac{L_2}{C_3^2} \right), \) and \( C = \frac{1}{C_1 C_3^2} \). Solution of this equation we assume \( \omega^2 = p \),

\[ p^2 [A] + p [B] - C = 0, p = \frac{-B \pm \sqrt{B^2 + 4AC}}{2A} \]

where \( \omega^2 = p, \omega = \sqrt{\frac{-B \pm \sqrt{B^2 + 4AC}}{2A}} \)

\[ \begin{pmatrix} -1 & \frac{L_2}{C_3^2} - \frac{R_3^2}{C_1} - R_2^2 \left( \frac{1}{C_1} + \frac{1}{C_3} \right) - \frac{2}{C_1} \left( R_2R_3 - \frac{L_2}{C_3^2} \right) \\ \frac{L_2}{C_3^2} - \frac{R_3^2}{C_1} - R_2^2 \left( \frac{1}{C_1} + \frac{1}{C_3} \right) - \frac{2}{C_1} \left( R_2R_3 - \frac{L_2}{C_3^2} \right) \end{pmatrix} \pm \sqrt{\frac{2 \left( L_2 R_2^3 - L_2^3 \left( \frac{1}{C_1} + \frac{1}{C_3} \right) \right) \left( \frac{1}{C_1 C_3^2} \right)}{2 \left( L_2 R_2^3 - L_2^3 \left( \frac{1}{C_1} + \frac{1}{C_3} \right) \right)}} \]

(6)
The derived formula of input impedance shows its dependency on circuit parameters such as resistance, inductance, capacitance, and resonating frequency\[^{[39]}\].

\[
Z_{in} = f(R, L, C, \omega)
\]

\[
Z_{in} = Z_{in \text{ real}}(\omega) + Z_{in \text{ imaginary}}(\omega)
\]

(7)

In dynamic resonator antenna (DRA), the non-imaginary part of the impedance is independent of frequency so the input impedance can be written as:

\[
Z_{in} = Z_{in \text{ real}} + Z_{in \text{ imaginary}}(\omega)
\]

\[
Z_{in \text{ real}} = f(\omega)
\]

\(Z_{in \text{ real}}\) implies the real part of input impedance alone.

But in NDRA (QA), the real part is frequency dependent that can be given as: \(Z_{in \text{ real}} = \text{resistance} = f(\omega)\).

This frequency-dependent resistance is additionally referred to as a dynamic resistance of the circuit\[^{[40]}\].

\[
Z_d = R_1 + \frac{(R_2 R_3 - \frac{L_2}{C_3})(R_2 + R_3) + (\omega L_2 R_3 - \frac{R_2}{\omega C_3})(\omega L_2 - \frac{1}{\omega C_3})}{(R_2 + R_3)^2 + (\frac{\omega L_2 - \frac{1}{\omega C_3}}{\omega C_3})^2}
\]

(8)

Putting the value of \(X_1 = \frac{1}{-\omega C_1}\), \(X_2 = \omega C_2\) and \(X_3 = \frac{1}{-\omega C_3}\) in above equation:

\[
Z_d = R_1 + \frac{(R_2 R_3 - \frac{L_2}{C_3})(R_2 + R_3) + (\omega^2 L_2 R_3 C_3 - R_2)(\omega^2 L_2 C_3 - 1)}{(R_2 + R_3)^2 + (\frac{\omega^2 L_2 C_3 - 1}{\omega C_3})^2}
\]

\[
Z_d = R_1 + \frac{(R_2 R_3 - \frac{L_2}{C_3})(R_2 + R_3) + (\omega^2 L_2 R_3 C_3 - R_2)(\omega^2 L_2 C_3 - 1)}{(R_2 + R_3)^2 + (\frac{\omega^2 L_2 C_3 - 1}{\omega C_3})^2}
\]

\[
Z_d = R_1 + \frac{(R_2 R_3 - \frac{L_2}{C_3})(R_2 + R_3) + (\omega^2 L_2 R_3 C_3 - R_2)(\omega^2 L_2 C_3 - 1)}{(R_2 + R_3)^2 + (\frac{\omega^2 L_2 C_3 - 1}{\omega C_3})^2}
\]

(9)

\[
Z_d = f(\omega) \text{ or } R_{in} = f(\omega)
\]

In the alternative method, there are two resonant mode presents in this circuit. In another way to explain in the below circuit.

---

**Figure 2.** Electrical equivalent admittance circuit of a quantum antenna.
\[ X_1 = -\frac{1}{\omega C_1}, X_2 = \omega L_2 \text{ and } X_3 = -\frac{1}{\omega C_3} \]
\[ Y_1 = Y_2 + Y_3, \quad Y_1 = \frac{1}{R_2 + j\omega L_2} + \frac{1}{R_3 + j\omega L_3} \]
\[ Y_t = \frac{1}{R_2 + j\omega L_2} + \frac{1}{R_3 - j\omega C_3}, \quad Y_t = \frac{R_2 - j\omega L_2}{R_2 + j\omega L_2} + \frac{R_3 + j\omega C_3}{R_3 - j\omega C_3} \]
\[ Y_t = \frac{R_2}{R_2^2 + \omega^2 L_2^2} + \frac{R_3}{R_3^2 + \frac{1}{\omega^2 C_3^2}} + j \left[ \frac{1}{\omega C_3} \right] \left( \frac{R_2}{R_2^2 + \omega^2 L_2^2} \right) - \frac{\omega L_2}{R_2^2 + \omega^2 L_2^2} \]
\[ Y_t = (G_t + jB_t) \]
\[ Y_T = Y_1 + Y_T = Y_1 + (G_1 + jB_1) \]
\[ Y_T = \frac{1}{R_1 - j\frac{\omega C_1}{\omega^2}} + (G_1 + jB_1), \quad Y_T = \frac{R_1 + j\frac{\omega C_1}{\omega^2}}{R_1^2 + \frac{1}{\omega^2 C_1^2}} + (G_1 + jB_1) \]
\[ Y_T = \left( \frac{R_t \omega^2 C_1^2}{R_t^2 \omega^2 C_1^2 + 1} + G_t \right) + j \left( B_t + \frac{1}{R_1^2 + \frac{1}{\omega^2 C_1^2}} \right) \]

For the first resonating mode susceptance (imaginary part) of \( (Y_t) = 0 \), i.e., \( B_t = 0 \)
\[ \frac{\omega C_3}{R_3^2 \omega^2 C_3^2 + 1} - \frac{\omega L_2}{R_2^2 \omega^2 L_2^2} + \frac{\omega C_1}{R_2^2 \omega^2 C_1^2 + 1} = 0, \quad \frac{C_3}{R_3^2 \omega^2 C_3^2 + 1} - \frac{L_2}{R_2^2 + \omega^2 L_2^2} + \frac{C_1}{R_1^2 + \omega^2 C_1^2 + 1} = 0 \]

After solving this equation, the value of \( \omega_r \)
\[ \omega_r = \sqrt{\frac{-\left( \frac{L_2}{C_2} - \frac{R_2}{C_2} \left( \frac{1}{C_1} + \frac{1}{C_3} \right) - \frac{2}{C_1} \left( R_2 R_3 - \frac{L_2}{C_3} \right) \right) \pm}{2 \left( \frac{L_2^2 R_3^2 - L_2^2 \left( \frac{1}{C_1} + \frac{1}{C_3} \right) \frac{1}{C_1 C_3} \right)} \}
\]

Quality factor (\( Q \)) = \( 2\pi \times \frac{\text{maximum energy stored per cycle}}{\text{power dissipated per cycle}} \).

To analyze series circuit: \( Z = R + jX \ldots \ldots = R + j(X_k - X_c) \ldots \), \( Q = \frac{|X_1|}{R} = \frac{|X_2|}{R} \ldots \ldots \)

But for analysis of parallel circuit, \( Y = G + jB = G + j(B_c - B_k), \quad Q = \frac{|B_1|}{G} = \frac{|B_2|}{G} \). According to this,
\[ Z_{in} = R_{in} + jX_{in} = Z_{in}(\text{real}) + Z_{in}(\text{imaginary}) \]
Quality factor ($Q$) = \[
\frac{R_2 X_3 + X_2^2 X_3}{(R_2 + R_3)^2 + (X_2 + X_3)^2}
\]

\[
Q = \frac{R_2 X_3 + X_2^2 X_3}{(R_2 + R_3)^2 + (X_2 + X_3)^2}
\]

\[
Q = \frac{R_2 X_3 + X_2^2 X_3}{(R_2 + R_3)^2 + (X_2 + X_3)^2}
\]

\[
Q = \frac{R_2 X_3 + X_2^2 X_3}{(R_2 + R_3)^2 + (X_2 + X_3)^2}
\]

\[
Q = \frac{R_2 X_3 + X_2^2 X_3}{(R_2 + R_3)^2 + (X_2 + X_3)^2}
\]

\[
Q = \frac{R_2 X_3 + X_2^2 X_3}{(R_2 + R_3)^2 + (X_2 + X_3)^2}
\]

Multiplying $\omega^2$ numerator and denominator:

\[
Q = \frac{-\omega^2 R_2^2 - \omega^2 L_2^2}{\omega^2 C_3^2}
\]

\[
Q = \frac{-\omega^2 R_2^2 - \omega^2 L_2^2}{\omega^2 C_3^2}
\]

The phasor representation of equivalent circuit of QA (Figure 3) is shown in Figure 4.

The phasor representation of equivalent circuit of QA (Figure 3) is shown in Figure 4.

\[
V_{R_2} = I_2 R_2 = I_2 R_2 \angle 0^0, \quad V_{X_2} = I_2 X_2 = I_2 \omega L_2 \angle 90^0
\]
\[
\begin{align*}
V_p &= \sqrt{V_{R2}^2 + V_{X2}^2}, V_{R3} = I_3 R_3 = I_3 R_3 \angle 0^0 \\
V_{X3} &= I_3 X_3 = \frac{i}{\omega C_3} \angle -90^0, V_p = \sqrt{V_{R3}^2 + V_{X3}^2}
\end{align*}
\]

For the parallel combination \( V_{PZ2} = V_{PZ3} \),
\[
\sqrt{V_{R2}^2 + V_{X2}^2} = \sqrt{V_{R3}^2 + V_{X3}^2}, \sqrt{I_2^2 R_2^2 + I_2^2 X_2^2} = \sqrt{I_3^2 R_3^2 + I_3^2 X_3^2}
\]

\[
I_2 \sqrt{R_2^2 + X_2^2} = I_3 \sqrt{R_3^2 + X_3^2}, I_2 \sqrt{R_2^2 + \omega^2 L_2^2} = I_3 \sqrt{R_3^2 + \frac{1}{\omega^2 C_3^2}}
\]

At the resonance mode \(|I_2| = |I_3|\) and squaring both sides,
\[
R_2^2 + \omega^2 L_2^2 = R_3^2 + \frac{1}{\omega^2 C_3^2}, \omega_{r1}^4 L_2^2 C_3^2 - (R_2^2 - R_3^2) \omega_{r1} C_3^2 + 1 = 0
\]

\[
\omega_{r1} = \sqrt{\frac{(R_2^2 - R_3^2)C_3^2 + \sqrt{(R_2^2 - R_3^2)^2 C_3^4 - 4L_2^2 C_3^2}}{2L_2^2 C_3^2}}.
\]

By solving the parallel impedances \( Z_2 \) and \( Z_3 \) into an equivalent impedance \( Z_P \), Figure 3 can be represented as shown in Figure 5.

**Figure 5.** Modified electrical equivalent impedance circuit of a quantum antenna.

\[
\begin{align*}
V_l &= V_1 - V_p, V_{R1} = I_1 R_1 = I_1 R_1 \angle 0^0 \\
V_{X1} &= I_1 X_1 = I_1 \frac{1}{\omega C_1} \angle -90^0, V_p = I_1 Z_P = I_1 Z_P \angle 90^0
\end{align*}
\]

At the particular frequency, \( V_{Z1} = V_p \) and arises another mode of resonance frequency:
\[
I_1 Z_P = I_1 Z_1, Z_P = Z_1, \frac{1}{Y_1 + Y_2} = Z_1
\]

After this solution of resonance frequency:
\[
\omega_{r2} = \sqrt{\frac{L_2 R_2^2 R_3^2 (\frac{1}{C_1} + \frac{1}{C_3}) - \frac{2}{C_1} (R_2 R_3 - L_2^2) \frac{1}{C_3}}{2(\frac{L_2^2 R_3^2 - L_2^2 (\frac{1}{C_1} + \frac{1}{C_3})}{C_1 C_3})}}.
\]
\[ Z_{in} = Z_1 + Z_p, \quad Z_{in} = Z_1 + \frac{1}{Y_p} = Z_1 + \frac{1}{Y_2+Y_3} \]

\[ Z_{in} = R_1 + jX_1 + \frac{1}{Y_p} = R_1 + jX_1 + \frac{1}{r_2 + jx_2} + \frac{1}{r_3 + jx_3} \]

\[ Z_{in} = R_1 + jX_1 + \frac{1}{Y_p} = R_1 + jX_1 + \frac{r_2 - jx_2}{r_2^2 + x_2^2} + \frac{r_3 - jx_3}{r_3^2 + x_3^2} \]

\[ Z_{in} = R_1 + jX_1 + \frac{1}{Y_p} = R_1 + jX_1 + \frac{r_2}{r_2^2 + x_2^2} + \frac{r_3}{r_3^2 + x_3^2} - j \left( \frac{x_2}{r_2^2 + x_2^2} + \frac{x_3}{r_3^2 + x_3^2} \right) \]

\[ Z_{in} = R_1 + jX_1 + \frac{1}{Y_p} = R_1 + jX_1 + \frac{A + JB}{A^2 + B^2} \]

where,

\[ A = \frac{r_2}{r_2^2 + x_2^2} + \frac{r_3}{r_3^2 + x_3^2} \quad \text{and} \quad B = \frac{x_2}{r_2^2 + x_2^2} + \frac{x_3}{r_3^2 + x_3^2} \]

\[ Z_{in} = R_1 + jX_1 + \frac{1}{Y_p} = R_1 + jX_1 + \frac{A + JB}{A^2 + B^2} = Z_{inv} + Z_{ inva} \]

The classical DRA can be analyzed by its equivalent series RLC circuit\(^{[41]}\). The research done till now explains that the dynamic electrical concept of classical DRA is freelance from an operational frequency in the range of microwave spectrum and planks constant. But the laser-fed quantum antenna doesn’t have such type of observations. The formulation and calculation of dynamic impedance of QA the above observations are analyzed through mathematical reduction and simulation in HFSS software for its modeling. The shunt branch impedance \( Z_2 \) and \( Z_3 \) are tuned to take it in an optical frequency range such that \( |Z_2| = |Z_3| \), the resonance condition is obtained but both of these impedances are in opposite phases. So, the whole circuit of a quantum antenna can be represented by impedance \( Z_1 \) which is a series combination of resistor and capacitor. As the angular resonant frequency depends on the values of inductance and capacitance \( \omega r_1 \propto \frac{1}{L_2C_3} \). Thus, by changing their values, we can modify the bandwidth of the circuit. If there is a further increment in the value of \( \omega r_1 \), the quantum antenna circuit reacts as a series combination RLC\(^{[42]}\). So, it is obvious that another resonant frequency \( (\omega r_2) \) is achieved due to the tuning between \( Z_1 \) and the resultant of parallel impedance \( Z_P \) that is a parallel combination of \( Z_2 \) and \( Z_3 \).

The expression of \( (\omega r_2) \) shows that there is an effect of the values of \( R_2, R_3, L_2, C_1, \) and \( C_3 \) on it. But, the foremost impact on \( (\omega r_2) \) is of the value of \( C_1 \). So, if \( C_1 \) is increased, the resonating frequency \( \omega r_2 \) would increase accordingly.

The nano-antenna circuit acts as a filter due to zero circuit output for a domain of frequency and finite output for a specific range of frequency\(^{[43]}\). So, there is existence 1 stage 2 mode only in a nano-antenna circuit. However, for the higher stage, odd and even harmonics of \( \omega \) will be increased.

For the primary stage of the filter, 1st and 2nd mode resonating parameters such as \( f_c \) are calculated. Considering Figure 6, the input excitation and output response are represented by \( X_i \) and \( X_o \).
Applying the Laplace transform

\[ Z_5 = \omega_0^2 s^2 + 1, \quad Z_6 = R_6 + sL_6 \] and \[ Z_7 = \omega_0^2 s^2 + 1 \]

where,

\[ Z_p = \frac{Z_2Z_3}{Z_2 + Z_3} \]

\[ X_o(s) \]

\[ X_i(s) \]

\[ \frac{X_o(s)}{X_i(s)} = \frac{1}{1 + \frac{Z_p}{Z_2 + Z_3}} = \frac{1}{1 + \frac{(R_4sc_1 + 1)(R_2s + 2)sc_3+1)}{Z_2Z_3}} \]

\[ \frac{X_o(s)}{X_i(s)} = \frac{1}{1 + \frac{s^3R_4C_1L_2C_3 + s^2(R_3C_2 + R_2C_1C_3(R_2 + R_3)) + R_3C_4s^2 + 1}{s^3R_3C_1L_2C_3 + s^2(R_2C_1 + R_2C_3C_1C_3) + R_3C_4s^2}} \]

Put \( s = j\omega \), the transfer function will be:

\[ X_o(j\omega) = \frac{1}{1 + \frac{-\omega^2(R_2C_3 + R_1C_1C_3(R_2 + R_3)) + j(\omega R_4C_1 - \omega^3R_1C_1L_2C_3)}{-\omega^2(R_2C_3 + R_2C_1C_3(R_2 + R_3)) + j(\omega R_4C_1 - \omega^3R_1C_1L_2C_3)}} \]

The characteristics and behavior of QA as the acceptor or rejector circuit are described by Equation (14). It behaves as an acceptor circuit (band-pass filter) and a rejector circuit (band rejects filter)\[44\].

Different operating modes can be calculated by simplifying the transfer function as:

\[ \frac{X_o(j\omega)}{X_i(j\omega)} = \frac{1}{1 + \frac{a + b\omega}{c + d\omega^2}} \]

where,

\[ a = 1 - \omega^2(L_2C_3 + R_1C_1C_3(R_2 + R_3)) \]
\[ b = R_1C_1\omega - \omega^3R_1C_1L_2C_3 \]
\[ c = -\omega^2(L_2C_3 + R_3R_2C_1C_3) \]
\[ d = (\omega R_4C_1 - \omega^3R_1C_1L_2C_3) \]

At high response of transfer function \( b - d = 0 \) and \( a + c = 0 \).
Applying this condition, there will be two modes generated at different frequencies

\[(R_1 C_1 \omega - \omega^3 R_1 C_1 L_2 C_3) - (\omega R_2 C_1 - \omega^3 R_3 C_1 L_2 C_3) = 0\]

And the 2nd condition is

\[1 - \omega^2 (L_2 C_3 + R_1 C_1 C_3 (R_2 + R_3)) - \omega^2 (L_2 C_3 + R_2 R_3 C_1 C_3) = 0\]

\[\omega_1 = \sqrt{\frac{R_1 C_1 - R_2 C_1}{R_1 C_1 L_2 C_3 - R_3 C_1 L_2 C_3}}\]

\[\omega_2 = \sqrt{\frac{1}{L_2 C_3 + R_2 R_3 C_3 + (L_2 C_3 + R_1 C_1 C_3 (R_2 + R_3))}}\]

The bandwidth of nano-antenna:

\[(BW) = \frac{(\omega_2 - \omega_1)}{\frac{1}{\sqrt{L_2 C_3 + R_2 R_3 C_3 + (L_2 C_3 + R_1 C_1 C_3 (R_2 + R_3))}} - \frac{R_1 C_1 - R_2 C_1}{R_1 C_1 L_2 C_3 - R_3 C_1 L_2 C_3}}\]

As per the above discussion, the input impedance is only the function of the non-imaginary part of \(Z_{in}\)

\[Q = \frac{\omega_2 - \omega_1}{\sqrt{L_2 C_3 + R_2 R_3 C_3 + (L_2 C_3 + R_1 C_1 C_3 (R_2 + R_3))}}\]

\[\sqrt{R_1 C_1 L_2 C_3 - R_3 C_1 L_2 C_3}\]

5. MATLAB simulation results

The simulation results are presented as follows:

Figure 7. Simulated graph of all parameters of QA at \(R_1 = 3530\ \Omega, R_2 = 3560\ \Omega,\) and \(R_3 = 3590\ \Omega.\)
Figure 8. Simulated graph of all parameters of QA at $R_1 = 1000 \, \Omega$, $R_2 = 1035 \, \Omega$, and $R_3 = 1065 \, \Omega$.

Figure 9. Simulated graph of all parameters of QA at $L_2 = 1210e^{-6} H$, $C_1 = 25e^{-15} F$, $C_3 = 143e^{-15} F$, $R_1 = 3530 \, \Omega$, $R_2 = 3560 \, \Omega$, and $R_3 = 3590 \, \Omega$. 
Figure 10. Simulated graph of all parameters of QA at $L_2 = 1210 \times 10^{-6}$H, $C_1 = 25 \times 10^{-15}$F, $C_3 = 143 \times 10^{-15}$F with $R_1 = 1000 \ \Omega$, $R_2 = 1035 \ \Omega$, and $R_3 = 1065 \ \Omega$.

Figures 7–10 show the simulation plot of all parameters of QA at distinct values of $L_2$, $C_1$, $C_3$, $R_1$, $R_2$ and $R_3$.

Figure 11. Simulated graph of all parameters of QA.

Table 2 indicates the approximate values of equivalent circuit parameters of QA at $\omega = 5$ THz.
Table 2. Calculated values of circuit elements after synthesis of QA at 5 THz.

<table>
<thead>
<tr>
<th>Frequency (THz)</th>
<th>$\omega$</th>
<th>$R_1$ (kΩ)</th>
<th>$R_2$ (kΩ)</th>
<th>$R_3$ (kΩ)</th>
<th>$L_2$ (mH)</th>
<th>$C_1$ (µF)</th>
<th>$C_3$ (µF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3.530</td>
<td>6.899</td>
<td>4.955</td>
<td>1210 × 10^{-3}</td>
<td>25 × 10^{-4}</td>
<td>143 × 10^{-4}</td>
<td></td>
</tr>
</tbody>
</table>

Figure 12. Simulated graph of all parameters of QA.

Table 3 represents the approximate values of equivalent circuit parameters of QA at $\omega = 10$ THz.

Table 3. Evaluated values of QA circuit parameters after synthesis at 10 THz.

<table>
<thead>
<tr>
<th>Frequency (THz)</th>
<th>$\omega$</th>
<th>$R_1$ (kΩ)</th>
<th>$R_2$ (kΩ)</th>
<th>$R_3$ (kΩ)</th>
<th>$L_2$ (mH)</th>
<th>$C_1$ (µF)</th>
<th>$C_3$ (µF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>3.53</td>
<td>1.875</td>
<td>3.9803</td>
<td>1210 × 10^{-2}</td>
<td>25 × 10^{-4}</td>
<td>143 × 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>3.53</td>
<td>3.881</td>
<td>4.131</td>
<td>1210 × 10^{-2}</td>
<td>129 × 10^{-4}</td>
<td>145 × 10^{-4}</td>
<td></td>
</tr>
</tbody>
</table>

Figure 13. Simulated graph of all QA parameters.
Table 4 shows the approximate values of equivalent circuit parameters of QA at $\omega = 500$ THz.

<table>
<thead>
<tr>
<th>Frequency (THz)</th>
<th>$R_1$ (k$\Omega$)</th>
<th>$R_2$ (k$\Omega$)</th>
<th>$R_3$ (k$\Omega$)</th>
<th>$L_2$ (mH)</th>
<th>$C_1$ (µF)</th>
<th>$C_3$ (µF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>3.53</td>
<td>9.999</td>
<td>10.558</td>
<td>$1210 \times 10^{-2}$</td>
<td>$129 \times 10^{-4}$</td>
<td>$145 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

$fr = \frac{c}{2\pi\sqrt{\varepsilon_r}} \sqrt{\left(\frac{\pi a}{n}\right)^2 + \left(\frac{\pi b}{n}\right)^2 + \left(\frac{\pi d}{n}\right)^2}$

From the study and analysis of Figures 7–13, it is clear that for a classical antenna, the frequency is generally in the GHz range but at the same time the dynamic impedance and its magnitude are also increased. Its effect the quality factor proportionally, so the bandwidth will be reduced. That’s why such type of antenna has a limited range of signals while the nano DRA or quantum DRA operates at terahertz frequency due to which dynamic impedance decreases and magnitude of the impedance is also decreased that shows a decrement in quality factor but the increment in bandwidth. That’s why such types of antenna are used for a wide range of signals. The mathematical analysis of quantum DRA in this article is a novel work that has not been presented in earlier studies.

The linear permittivity of a homogenous substance in free space is referred to as relative permittivity $\varepsilon_r$ (also known as dielectric constant, although it is depreciated and refers to the static, zero frequency relative permittivity).

$$Q = \frac{f_r}{f_{n-f_1}} = \frac{fr}{\text{bandwidth}} = \frac{1}{\Delta f} = \frac{X}{\text{ESR}} = \frac{1}{\tan \delta}$$ equivalent series resistance (ESR).

6. Designing procedure and formulation of quantum DRA

Designing of quantum rectangular DRA

The perspective view of quantum rectangular DRA using HFSS is shown below:

Figure 14. Quantum rectangular DRA.
**Figure 15.** Simulated plot between reflection coefficient and frequency.

**Figure 16.** Simulated plot between input impedance and frequency.

**Figure 17.** Simulated plot between VSWR and frequency.
Figure 18. Radiation pattern quantum rectangular DRA.

Figure 19. 3D polar plot quantum rectangular DRA.
The design, dimensions, and radiation pattern of THz rectangular DRAs, along with $S_{11}$, $Z_{11}$, VSWR, and other antenna radiation patterns have been obtained in Figures 14–18. Figures 19–22 show the graph of gain, axial ratio and polarization ratio versus frequency respectively. These can provide wider bandwidth
and fast data rate. Terahertz DRA can be used for optical communication. It provides a new opportunity for fast communication systems. The equivalent circuit of terahertz DRA has already been explained in this article. For proper working of any antenna, the frequency must be less than −10 dB. The comparative study of proposed quantum DRA with respective to existing is shown in Table 5.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Title</th>
<th>Operating frequency /bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pan et al.[50]</td>
<td>Compact quasi-isotropic dielectric resonator antenna with small ground plane</td>
<td>189 THz–194 THz</td>
</tr>
<tr>
<td>Kumar[51]</td>
<td>A compact graphene based nano-antenna for communication in nano-network</td>
<td>55 THz frequency with a peak gain of 5.47 dB</td>
</tr>
<tr>
<td>Kavitha et al.[52]</td>
<td>Graphene plasmonic nano-antenna for terahertz communication</td>
<td>30 THz frequency with a peak gain of 3.52 dB</td>
</tr>
<tr>
<td>Proposed nano DRA</td>
<td>Mathematical modeling and parameter analysis of quantum antenna for IoT sensor-based biomedical applications</td>
<td>511 THz frequency with good performance</td>
</tr>
</tbody>
</table>

7. Conclusion

In this paper, parameters like dynamic impedance ($Z_d$), quality factor, and input impedance ($Z_{in}$) of NDRA (QA) have been formulated and calculated by its electrical equivalent circuit that is a series and parallel sequence of resistor, inductor, and capacitor. The calculated and simulated results for different parameters are shown. Under tuning conditions, it has been ascertained that dynamic impedance is decreased with an increase in THz frequency (511 THz) which results in a decrement in power losses, therefore it requires less power for signal transmission. Due to low power dissipation, there is low-temperature variation, and due to this less number of body tissues are damaged when used in biomedical applications just like laser operation. The integration of IoT technology with quantum antennas has the potential to significantly improve the performance and efficiency of wireless communication systems. Therefore, this research article on NDRA (QA) circuits can facilitate developers in sensible realization for bioscience and medical applications and the results have been validated at 5 THz, 10 THz and 500 THz. Quantum antenna is very high bandwidth and high dissipation factor (D.F), can be used for sensors and wide band antennas for high-speed communications applications. Simulation results based on optical DRAs have been included along with equivalent R, L, C circuit and MATLAB based mathematical analysis.

Author contributions

Conceptualization, RK (Ram Krishna) and RSY; methodology, RK (Ram Krishna); software, RK (Ram Krishna) and RK (Ravinder Kumar); validation, RK (Ram Krishna), RSY and HS; formal analysis, RK (Ram Krishna); investigation, RK (Ram Krishna); resources, RK (Ram Krishna) and AKR; data curation, RK (Ram Krishna); writing—original draft preparation, RK (Ram Krishna) and HS; writing—review and editing, RK (Ram Krishna) and HS; visualization, RK (Ram Krishna); supervision, RSY; project administration, RK (Ram Krishna), RSY and NG; funding acquisition, AKR and RK (Ram Krishna). All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

References


