Optimized Reconfigurable Electrically Small Planar Microstrip Patch Antenna Loaded with Metamaterial

Tanuj K. Garg¹, S.C.Gupta², S.S.Pattnaik³, Vipul Sharma⁴
¹³Department of Electronics & Communication Engineering, Gurukul Kangri University, Haridwar, India
²Department of Electronics & Communication Engineering, DIT, Dehradun, India
³Department of ETV, NITTTR, Sector-26, Chandigarh, India

Abstract-- In this paper, authors present an optimized reconfigurable electrically small planar microstrip patch antenna loaded with square shaped split ring resonator metamaterial with micro-splits. In this the length of SRR is optimized so that the loaded antenna resonant at a frequency that lies in frequency regime in which the isolated SRR shows the metamaterial properties. To achieve the frequency tunability, reactance of structure is changed by introducing micro-splits. These micro-splits are introduced by making RF MEMS switches ON/OFF. In all configurations, condition ka < 1 by Chu limit is satisfied as required for an ESA.

Index Terms-- Chu limit, Electrically small antenna, RF MEMS Switch, Micro-splits, Split ring resonator (SRR).

I. INTRODUCTION

Accurate design and optimal output are the demands of present day wireless industries. Nature inspired soft computing techniques such as Bacterial Foraging optimization (BFO), Particle Swarm optimization (PSO), Bio-geographic based optimization technique (BBO) etc are the upcoming optimization techniques of recent times which have drawn the attention of researchers. Also the advances in wireless industries demand an antenna which is not only being small in size but also are reconfigurable. So expectation is to design an optimized efficient reconfigurable electrically small antenna that can be easily integrated into the system.

How an antenna is defined as a small antenna? In 1947, Wheeler defined an antenna as electrically small if it occupies a volume of a sphere whose radius is a small fraction of free-space wavelength. This means that for an antenna to be electrically small (ESA) maximum dimension of an antenna should be less than λ/2π [1]. The relation can be expressed by following equation:

\[ \text{ka} < 1 \quad (1) \]

Where k= 2π / λ, λ is free space wavelength, ‘a’ is radius of sphere enclosing maximum dimension of an antenna.

In 1948, Chu derived a theoretical fundamental relationship between dimension of an antenna and antenna’s Quality factor. The relation is expressed as:

\[ Q_{\text{chu}} = \frac{1}{k \alpha} + \frac{1}{(k^2 \alpha^2)} \quad (2) \]

This is referred as Chu limit [2, 3].

From the inception of metamaterial (MTM), which is artificial material engineered with microscopic structures produce properties that may not be found in nature, drastic reduction in antenna dimensions have been reported [4-5]. In 2005, Ziolkowski and Erentok reported the efficient ESA by enclosing the dipole antenna in DNG or SNG metamaterial spherical shell [6]. In 2006, they pursued metamaterial based efficient ESA [7]. In 2007, Alici and Ekmel purposed electrically small SRR antennas in which SRR was excited by monopole antenna [8]. In 2010, Joshi JG et al. presented a planar metamaterial loaded electrically small patch antenna of size ka=0.775 by Chu limit. The antenna exhibits an impedance bandwidth of 512 MHz at resonant frequency of 9.51 GHz, has large radiation Quality factor 18.86 than minimum Q_{chu} = 3.43. Good impedance matching was achieved without incorporating any additional impedance matching network. In this the magnetic resonant frequency of isolated SRR is 5.0 GHz whereas the loaded patch antenna resonant at frequency is 9.51 GHz, which is different from magnetic resonant frequency of isolated SRR [9].

K. M. Passino conceived BFO in 2002 [10]. BFO is based on the foraging behaviour of Escherichia Coli (E. coli) bacteria present in the human intestine. Bacterial Foraging is an optimization technique based on population search. The bacteria have four main mechanisms: chemotaxis, swarming, reproduction, and elimination-dispersal. When the bacteria meets favourable environment i.e. rich in nutrients and noxious free, it continues swimming in same direction. Otherwise it moves in different direction, this is called tumbling. Thus chemotaxis is achieved by swimming and tumbling of the bacteria. Let \( \theta^j \) (j, k, l) represents the position of \( j^{th} \) bacterium at \( j^{th} \) chemotactic, \( k^{th} \) reproductive, and \( l^{th} \) elimination-dispersal step. Then movement of the bacterium may be represented by following equation.

\[ \text{Received: } 12 \text{ January 2012, Revised: } 01 \text{ March 2012, Accepted: } 03 \text{ May 2012} \]

\[ \text{Website: www.ijetae.com (ISSN 2250-2459, ISO 9001:2008 Certified Journal, Volume 4, Issue 8, August 2014)} \]
\[ \theta^i(j + 1, k, l) = \theta^i(j, k, l) + \frac{C(i) \text{del}(i)}{\sqrt{\text{del}^2(i) \text{del}(i)}} \]  

(3)

Where \( C(i) \) is size of unit step taken in random direction, \( \text{del}(i) \) indicates a direction vector whose element lying between [-1,1].

If the \( i^{th} \) bacterium gets favourable environment, then it attract other bacterium and bacteria propagate with high bacterial density otherwise it repel other bacteria.

Let \( J_{\text{health}} \) represents the health of \( i^{th} \) bacterium after travelling \( N_i \) chemotactic steps can be evaluated by following equation.

\[ J_{\text{health}}^i = \sum_{j=1}^{N_i} J(j, k, l) \]  

(4)

Depending on the health of bacteria, half of the bacteria (which are least healthy) are eliminated while each of healthier bacterium splits into two. Thus making the population of bacterium constant.

To ensure that the bacteria do not trapped into local minima, some of the bacteria get eliminated and dispersed with probability \( P_{\text{ed}} \).

The Particle Swarm Optimization (PSO) is a population-based optimization method developed by Eberhart and Kennedy in 1995 [11-12]. It is inspired by social behaviour of bird flocking or fish schooling. Initially all the particles are dispersed with random positions and velocities. Each particle moves in search space according to their individual flying experiences and their interactions with neighbouring particles. Let the position of \( i^{th} \) particle in the swarm be \( x_{id}(t) \) and it is moving with velocity \( V_{id}(t) \). Then the position and velocity of particle is updated by the equations:

\[ V_{id}(t + 1) = V_{id}(t) + c_1 \text{ rand}( ) \times (\text{pbest} - x_{id}) \]  

\[ + c_2 \text{ rand}( ) \times (\text{gbest} - x_{id}) \]  

(5)

\[ x_{id}(t + 1) = x_{id}(t) + V_{id}(t + 1) \]  

(6)

Where \( t \) is current iteration, \( i \) is particle number, \( d \) is dimension of space, \( V_{id}(t) \) is velocity of \( i^{th} \) particle for d-dimension at \( t^{th} \) iteration, \( x_{id}(t) \) is the position of \( i^{th} \) particle for d-dimension at \( t^{th} \) iteration, \( c_1 \) and \( c_2 \) are acceleration constant, \( \text{rand}( ) \) is random number between \([0,1]\), pbest is local best and gbest is global best for d-dimension at \( t^{th} \) iteration. Convergence of PSO is faster. Equation (5) has three parts. The first part of the equation indicates the current velocity of the particle. The second part represents the cognition, which signifies that the particle is attracted by its own personal best position and moving towards it.

The third part refers to cooperation (social search), which represents that the particle is attracted towards global best position.

In this paper, the authors present the optimization of reconfigurable electrically small patch antenna loaded with metamaterial by using Intelligent Bacterial Foraging Optimization Algorithm (IBFOA) [13], which is hybridization of BFO and PSO soft computing technique, so that loaded antenna resonates in the same frequency regime in which SRR shows metamaterial properties (real value of refractive index is negative). Hybrid means soft fusion of various soft computing techniques to enhance the performances of presently available soft computing. Root mean square error between resonant frequency of loaded antenna and that of isolated SRR is taken as cost function. Minimum value of cost function signifies the favourable environment for bacterium.

In IBFOA properties of PSO is utilized to find the corresponding positions of bacteria in predefined search space. By doing so, the search space became narrow. Thus reduce the computational time. The difference between resonant frequency of loaded antenna and isolated SRR for different values of \( L_{\text{SRR}} \) (Length of SRR) are calculated and placed randomly in search space of PSO. Then PSO is used to find nearest values of \( L_{\text{SRR}} \). These values are fed to BFO search space. The step size \( C(i) \) is not constant, its value varies with respect to swim length of bacteria during swimming and remains constant during tumbling.

II. DESIGN

In this design, the rectangular microstrip patch antenna is loaded with planar square shaped split ring resonator with micro-splits as shown in figure 1.

![Figure 1: Structure of rectangular microstrip patch antenna loaded with planar SRR with micro-splits.](image-url)
The dimensions of rectangular microstrip patch antenna are: length $L = 4$ mm, width $W = 0.5$ mm. The patch antenna is excited by coaxial feed at (-1.7 mm, -3.7 mm). The dimensions of square Split ring resonator structure are: Width of each ring is $w = 0.2$ mm, the separation between inner and outer rings is $s = 0.2$ mm, split width in each ring is $g = 0.2$ mm. Two additional micro-splits are also placed in outer ring at 0.35 mm distances on both side of main split. The width of each micro-split is 0.05 mm. $L_{SRR}$ is length of SRR, which is to be optimized. The square split ring resonator with micro-splits is placed at 0.2 mm distance from the microstrip patch antenna. The structure is designed on RT Duriod 5880 substrate having relative permittivity $\varepsilon_r = 2.2$ and thickness $h = 3$ mm. The RF MEMS switches are implemented by absence and presence of metal strip. The ON position of RF MEMS switch is implemented by presence of metal strip, whereas OFF position of RF MEMS switch is implemented by absence of metal strip. The structure is designed and simulated by using Ansoft HFSS simulator, finite element based electromagnetic mode solver.

To show the physical properties of the designed square SRR structure with micro-splits, the structure was placed in two port waveguide formed by a pair of both perfect magnetic conductor (PMC) walls in $z$-direction and perfect electric conductor (PEC) walls in $y$-direction. The whole structure is excited by an electromagnetic wave with propagation vector in $x$- direction. By using software $S$ parameters are calculated and effective permeability is extracted by using effective parameter retrieval method [14].

III. ANALYSIS AND DISCUSSION

The magnetic resonant frequency of isolated SRR is calculated for different values of $L_{SRR}$ by using mathematical equations given in [15].

The unloaded microstrip patch antenna was analysed and it was found that microstrip patch antenna resonates at frequency 27 GHz. The return loss characteristic of unloaded microstrip patch antenna is shown in figure 2.

Figure 2: Return Loss ($S_{11}$) of unloaded microstrip patch antenna.

Figure 3 shows the real value of refractive index of un-optimized isolated SRR with $L_{SRR} = 4$ mm, which is equal to the length of patch antenna. The isolated SRR shows metamaterial properties in the frequency regime 4.7 GHz- 4.9 GHz and 5.2 GHz- 5.4 GHz.

The microstrip patch antenna is loaded with SRR with $L_{SRR} = 4$ mm, the antenna resonant at frequency 8.90 GHz, as shown in figure 4 which is different from frequency regime in which isolated SRR shows metamaterial properties. The loaded antenna has a gain of 1.5982 dB (Figure 5).

To optimize the design, first we train a neural network for loaded antenna for different values of $L_{SRR}$ while keeping other parameters fixed. Then by using hybrid optimization technique IBFOA [13], we optimize the value of $L_{SRR}$ for which loaded antenna resonant in frequency regime in which isolated SRR shows metamaterial properties. Optimized value of $L_{SRR}$ obtained by IBFOA optimization technique comes to be 2.84 mm, at which loaded antenna resonant in frequency regime in which isolated SRR shows metamaterial properties. To check this, simulation is performed. Figure 6 shows the real value of refractive index of optimized isolated SRR with $L_{SRR} = 2.84$ mm. The isolated SRR shows metamaterial properties in the frequency regime 7.7 GHz- 9.9 GHz.
The microstrip patch antenna is now loaded with optimized SRR (without any additional micro-split) with $L_{\text{SRR}} = 2.84 \text{ mm}$, the antenna resonant at frequency 9.20 GHz and 9.70 GHz, as shown in figure 7. The loaded antenna resonant in same frequency regime in which isolated SRR shows metamaterial properties. This enhanced the gain of loaded antenna. The loaded antenna now has a gain of 1.9952 dB (Figure 8). To show the reconfigurability of loaded antenna, the loaded antenna is considered with SRR with Left (when switch S1 is in OFF state and S2 is in ON state), Right (when switch S1 is in ON state and S2 is in OFF state) and Both (when switch S1 and S2 are in OFF state) micro-splits.

Figure 9 (blue curve) shows the return loss ($S_{11}$) of patch antenna loaded with square SRR with left micro-split. The loaded patch antenna resonant at frequency 9.30 GHz and 9.90 GHz, with -10 dB bandwidth of 680 MHz and a gain of 2.0751 dB (Figure 10). Figure 9 (Red curve) shows the return loss ($S_{11}$) of patch antenna loaded with square SRR with right micro-split. The loaded patch antenna resonant at frequency 9.40 GHz and 9.90 GHz, with -10 dB bandwidth of 750 MHz and a gain of 2.085 dB (Figure 11). Figure 9 (Brown curve) shows the return loss ($S_{11}$) of patch antenna loaded with square SRR with both micro-split. The loaded patch antenna resonant at frequency 9.30 GHz and 10.00 GHz, with -10 dB bandwidth of 820 MHz and a gain of 2.0557 dB (Figure 12).
Thus we get frequency tunability. The wavelength of loaded structure is 32.61 mm (without micro-splits), 32.26 mm (with Left micro-split), 31.91 mm (with Right micro-split) and 32.26 mm (with both micro-splits). Therefore ka values for loaded structure is 0.682, 0.689, 0.697 and 0.689 respectively; which satisfies the condition ka < 1 that means purposed antenna structure is an electrically small antenna (ESA).

![Figure 7: Return Loss (S11) of loaded microstrip patch antenna with square SRR without any additional micro-splits after optimization.](image)

![Figure 8: Gain of loaded microstrip patch antenna with square SRR without any additional micro-splits after optimization.](image)

![Figure 9: Return Loss (S11) of loaded microstrip patch antenna with square SRR with Left, Right and Both micro-splits after optimization.](image)

Using equation (2) minimum Quality factor (chu limit) is calculated for the purposed antenna $Q_{chu} = 4.62$ (without micro-splits), 4.51 (with left micro-split), 4.39 (with right micro-split), and 4.51 (with both micro-splits); whereas the radiation Quality factor $Q_{rad} (= f_r / B.W)$ for purposed ESA is 16.14, 13.68, 12.53, 11.34 respectively, which is quite large than $Q_{chu}$.

Large bandwidth and high gain suggest that patch antenna is perfectly matched with square SRR. So there is no requirements of additional matching networks like reactance and resistive matching network, quarter wave transformer, capacitive loading.

![Figure 10: Gain of loaded microstrip patch antenna with square SRR with left micro-split after optimization.](image)
In this paper, optimized reconfigurable electrically small planar microstrip patch antenna loaded with square shaped split ring resonator metamaterial with micro-splits is presented. By using IBFOA we optimized the design so that loaded antenna resonant at frequency in the frequency regime in which isolated SRR shows metamaterial properties. So that optimized design had greater gain. By introducing micro-splits and hence changing the reactance of structure, frequency tunability has been achieved. These micro-splits are implemented by using RF MEMS switches and thus the number of micro-splits is considered by making RF MEMS switches ON/OFF.

In all configurations, condition $ka < 1$ by Chu limit is satisfied as required for an ESA. The resonant frequency of optimized loaded structure shifted from 9.20 GHz (No additional Gap) to 9.30 GHz (Left Gap) or to 9.40 GHz (Right Gap) and to 9.30 GHz (Both Gaps). Thus we get frequency tunability by making RF MEMS switches ON/OFF. The proposed antenna finds its application in multi-band mobile communication, handheld devices, body area network (BAN) due to its miniaturized size, good bandwidth and high gain.

Acknowledgment

The authors sincerely express their gratitude to Director, National Institute of Technical Teachers’ Training and Research (NITTTR), Chandigarh, India for support.

REFERENCES

