Chapter 10

Micro-Switch Design and Its Optimization Using Pattern Search Algorithm for Application in Reconfigurable Antenna

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Additional information is available at the end of the chapter

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Abstract

This chapter reports the design and optimization algorithm of metal-contact RF micro-switch. Various important evolutionary optimization techniques that can be used to optimize non-linear and even non-differentiable types of radio frequency (RF) circuit's problems are also reviewed. The transient response of the proposed switch shows displacement time (i.e., squeezed-film damping effect) of 5.0 μs and pull-in voltage varying from 9.0 to 9.25 V. Primarily, the switch exhibits insertion loss of 0.15 to 0.51 dB in on-position and isolation of 75.96 to 35.83 dB in off-position at 0.1–10 GHz. Also, the proposed RF switch equivalent circuit and layout are validated in ADS software which was earlier simulated in HFSS. A pattern search (PS) algorithm is used to optimize RF characteristics of the proposed switch after a brief review of the different optimization techniques. After optimization, the switch shows decrement in insertion loss and increment in isolation at 0.1–10 GHz. Further, two such optimized switches are introduced on the defected ground structure (DGS) antenna to make it reconfigurable in terms of frequency. Reconfigurable antenna (RA) is simulated using HFSS software and simulation results are verified by showing the mark of agreement with the fabrication results. The novelty in the proposed design is due to dual-band behavior and better resonance performance than antennas available in the literature. Attractions of proposed RA are its miniaturization and its utility in IEEE US S-(2.0–4.0 GHz) and C-(4.0–8.0 GHz) band.

Keywords: design optimization, microstrip antennas, RF microswitches, reconfigurable antenna, vehicular and wireless technologies

1. Introduction

There are various kinds of RF switches available that can be used along with microstrip antenna to achieve the reconfigurability. An RF MEMS metal-contact switch is an emerging technology that has replaced the semiconductor field-effect transistors (such as GaAs FETs), PIN diode switches/Schottky diodes and electromagnetic relays [1, 2]. The metal-contact MEMS switches are not only used in reconfigurable antenna structures but also in switching networks, satellite systems, filters and automated test equipments from 0.1 to 40 GHz applications [3].

MEMS RF switches demonstrate exceptional performance in upper range of frequency as compared to the traditional semiconductor RF switching microelectronics technology. The advantages of MEMS RF switches over semiconductor switches are batch fabrication (that involves lithography-based micromachining, fabricated on either quartz or automated mark high-resistivity Si or GaAs wafers), low insertion loss (around 0.2 dB), high isolation (around 70 dB), small off-state capacitances (2–4 femto Farads), high linearity and low power consumption (almost zero power). Also, metal semiconductor (MES)-FET switching in the cold-FET mode requires almost no control power. Some commercial cold-FETs can switch at 2.3 V [4–7].

Performance comparison of the various commercially available RF switches is shown in **Table 1**.

Despite all of the advantages discussed, MEMS switches also have some problems associated with them. The main issues at present are relatively low speed (around 3–40 μs), moderate voltage or high current initiative (electrostatic actuated switches require 5–80 V for consistent operation, whereas magnetic/thermal switches can be activated with 2–6 V but require 9–105 mA of current supply), reliability (0.2–4 billion cycles), high packaging cost and low power handling (<200 mW) and therefore, they are rarely commercially available [4, 7].

Optimization of MEMS switches had played a major impact in RF circuits [10–12]. The microstrip patch antennas (MSA) are preferred for wireless applications due to their low-profile

Parameter of switch characteristics	**MEMS**	**GaAs/metal semiconductor (MES)—field-effect transistor (FET)**	**PIN-diode**	**Electromechanical relay (EMR)**
Voltage (V)	10–75	3–5; 2.3 (commercial cold-FETs)	±2.5–5	3–2
Current (mA)	Almost zero	Almost zero	0–20	15–150
Power consumption (mW)	0.05–0.1 (negligible power consumption)	0.05–0.1; no power consumption in commercial cold-FETs	5–95	<380
Switching time	1–400 μs	1–120 ns	10–120 ns	>1 ms
Isolation in OFF condition (1–10 GHz) (in dB)	>45	15–25	>35	>40
Insertion loss in ON condition (1–10 GHz) (in dB)	0.05–0.2	0.4–2.5	0.3–1.2	<0.3

Table 1. Comparison of various electrostatic RF switches [4, 8, 9].

structure, easy to manufacture structure, wide and multiband behavior [13, 14]. Different techniques have been used to achieve multi-band operation for MSA. Some of the techniques employed variation in physical dimensions of feed line, modification of the effective length of antenna using slot, implementation of defected ground structure and use of the switching device within the antennas [15–17].

Further, the fabrication process of the RA is a difficult multi-layered task and an effective integration needs cautious planning for every single stage in the direction not to fade the proposed antenna's performance. Among those stages, the utmost critical procedures [4, 13] can be summarized in:

- *Release and fabrication procedure of the RF switch membrane*. Proper care must be required for this step; otherwise, stiction complications, membrane deformations and infatuation of sacrificial layer occur.
- *Patterning of DC bias transmission line*. It requires very well contact by means of the DC pad; otherwise, there are chances of leakage of RF energy through transmission line.
- *Patterning and the deposition of the thin film of dielectric material designed for the RF MEMS switches*. Imprecision all through this stage may cause either the major dielectric charge issues or the small break down voltage of the designing switches.

All the aforementioned issues can be avoided if the procedure is well organized; otherwise, it will affect the electromagnetic characteristics as well as input impedance of the antenna [4, 13].

The motivation of this research work is a great effort put in emerging RF-switch-based-reconfigurable antenna designs and procedures capable of facing specific challenges such as low power consumption, simplicity, robustness as well as small size. The scope of this work describes a two-way application: (a) design of an electrostatic actuated metal-contact cantilever beam switch and (b) development of a grid-based numerical optimization method based on pattern search (PS) technique. Further, some important nature-inspired-optimization algorithms and numerical-based-optimization algorithms are also studied that can be helpful to improve complex RF circuits like switches and antennas. The design of cantilever beam microswitch is identified for applications in microwave multiband reconfigurable antennas. A novel approach of PS optimization method is used here to optimize the isolation, insertion and return loss of metal-contact microswitch. Finally, all the above-mentioned procedure is combined together that creates a slot-dual frequency band reconfigurable antenna configuration.

2. Review of some important optimization techniques

Optimization refers to maximizing or minimizing the objective function or fitness function. In today's scenario, the evolutionary optimization techniques that can be used to optimize even non-differentiable and non-linear types of problems are most commonly used. These techniques are based on intensifying the search (w.r.t. neighborhood) and diversifying the range (of solutions). Some of these significant algorithms will be discussed in this section:

Particle Swarm Optimization (PSO): PSO [18, 19] is a population-based and swarm-intelligence-based evolutionary optimization technique motivated by the flocking of the birds and the schooling of the fishes. The solution of the problem is represented as a particle and the parameters of the solution are represented as 'position, velocity, local best position and global best position' of the particle. All the positions achieved are evaluated by a kind of fitness function to represent how well the design criterion (e.g., switch design or antenna design criterion) is satisfied. The process terminates after a pre-specified number of iterations. This technique is very simple and fast because of being based on intelligence and learning. But the quality of results may not be so good because of being based upon a random process.

Genetic Algorithm (GA): GA [19] is a population-based evolutionary optimization technique motivated by the natural evolution process. The solution of the problem is represented as a chromosome and the parameters of the solution are represented as genes. The problem is initialized by the population of chromosomes. The best chromosomes are selected (that act as parents) using an appropriate fitness function (for example, in switch design, the solution parameter may be the insertion loss or isolation as in our case). These parents then generate the offspring using 'crossover' and 'mutation'. Last step is elitist replacement scheme that compares all the individuals in the population and the offspring. The program terminates after a designated number of iterations. It can be applied to a wide range of simple as well as complex problems. But it may be time-consuming sometimes to find an optimum solution.

Ant Colony Optimization (ACO): ACO [20] is another population-based and swarm-intelligence-based evolutionary optimization technique motivated by the foraging behavior of the social ants. The solution of the problem is represented as a pheromone deposited by the ants in going toward and back from the food source and the parameters of the solutions are represented as the concentration of the pheromone. The other ants follow the route at which pheromone concentration is higher. The food may be called as the desired condition, for example, in switch optimization using ACO, some particular range of the insertion loss or isolation may be the desired conditions. This technique is very fast and efficient because of being based on intelligence and learning. But sometimes it yields the local optimum solution because this technique updates the pheromone according to the current best path.

Firefly Algorithm (FA): FA [21, 22] is one more population-based and swarm-intelligence-based evolutionary optimization technique motivated by the short and rhythmic flashing patterns of the swarming fireflies. Fireflies are the glowworms that can produce the natural light (with its intensity proportional to its hunger) to attract victim. For example, in switch design context, this technique may be used to compute the optimum weights and positions of the switches for the optimum design. This technique converges very fast and it is based on intelligence and learning. But there is no provision of the memory to memorize the situation that remained better than the present.

Cuckoo Search (CS): CS [21, 23] is another population-based and swarm-intelligence-based evolutionary optimization technique motivated by the hatching behavior of cuckoo species. The female cuckoo chooses a nest to lay the eggs where the host has just laid its own eggs. In this technique, each egg in the nest corresponds to a solution while each cuckoo egg corresponds to a new solution. Keeping the best nest corresponds to the best objective. This quality optimization technique may be used to optimize many of the parameters in switch design. It is a simple, robust and easy to converge method. But the parameters of this approach cannot be changed that results into less efficiency.

Bat Algorithm (BA): BA [21, 24] is one more population-based and swarm-intelligence-based evolutionary optimization technique inspired by the echolocation nature of the microbats. They use echolocation to detect their prey even in the whole darkness, that is, they transmit a sound pulse and listen to the echo bouncing back from the surrounding objects. For example, locations of the switches in a reconfigurable antenna may be optimized using this technique. This technique becomes more optimum with the increase in population size and it is based on intelligence and learning. But it has somewhat low convergence accuracy.

Artificial Bee Colony Optimization (ABC Optimization): ABC algorithm [25] is another popular population-based and swarm-intelligence-based evolutionary optimization technique inspired by the behavior of honeybee in food foraging. In this technique, solution to the optimization problem is indicated by the position of a food source while the solution quality (or fitness) is indicated by the food source. Each employed bee corresponds to one food source (i.e., one solution). An onlooker bee selects source of food depending on the probability value associated with the food source. If a food source (i.e., solution) cannot be improved further, the scout bee helps to generate new solutions randomly. For example, this algorithm may be effectively used to tag the switch design problems. It provides the clarity and errors in case of optimal solutions, but it has not been so widely used for solving the real-life problems.

Galaxy-based Search Algorithm (GbSA): GbSA [26] is a new evolutionary algorithm that has come into existence only a few years back. In this technique, the movement of solution is spiral from randomly generated initial solution (initial solution is commonly assumed to be at the core of galaxy) and the arm of galaxy moves spirally to search the surrounding until it finds a better solution. The algorithm is very optimal, but it needs to be used for many of the applications in the future.

Harmony Search (HS): HS [27, 28] is a population-based evolutionary optimization algorithm (mainly used for solving the reliability problems) motivated by the nature of music. This method may convert the harmony of music into optimization. Just like music in which a particular note is played to have the pleasing harmony, a particular value is created in each decision variable to have the best possible optimum value. Like the judgement of quality of music by the pitch function, judgement of the quality of the decision variable is done by the fitness function. This technique does not need any initial value for the optimization, but it performs well only for a single objective function.

Biogeography-Based Optimization (BBO): BBO [29] is a population-based evolutionary algorithm working on migration and mutation. The algorithm is based on the principles of emigration and immigration between the habitats. A habitat with high value of habitat suitability index (HSI) has high emigration rate and low immigration rate and vice versa. In this technique, each habitat corresponds to a solution, that is, high value HSI habitat corresponds to a good quality solution and vice versa. As an example, BBO technique may be used for the optimization of post-parameters in antenna design or switch design. This method is fast and free from any assumptions. Moreover, good solutions are retained. But the system using only migration and mutation may not converge to the global optimum.

Differential Evolution (DE): DE [30] is another population-based evolutionary computational algorithm for the optimization. It uses a differential operator to create a new solution. This algorithm has been widely used in the design and synthesis of antenna as well as switches. The main difference between DE and GA is the use of same operators but in the different ways. In this method, the selection step is implemented after the mutation and crossover steps and involves both the parents as well as offspring. This method is good in diversification, but it has somewhat less accuracy.

Simulated Annealing (SE): SE [31] is an evolutionary probabilistic optimization technique motivated by the annealing process in solids. It is a technique without any memory. This algorithm is based on the trajectory of the search path. In this technique, a material is heated above melting point and then is cooled gradually to the ambient temperature to generate a larger crystalline solid with minimum energy probability distribution and minimum metallic defects. Most of the times, this is done in a lot of iterations. This technique can efficiently be used for the global optimization of the different parameters in switch design. It is good even for quite unordered data and it has very good global optimality. But there is a trade-off between the computational speed and quality of the solution.

Invasive Weed Optimization (IWO): IWO [32] is an evolutionary optimization technique inspired by the colonization of the invasive weeds. Each invading weed grows to a flowering weed and generates new weeds. These new weeds again grow to the flowering weeds and this process goes on and on and at last, maximum number of weeds is spread over the field. Now, only those weeds having good fitness can survive to generate new weeds. Each individual (i.e., a set having a value of each optimizing variable) is represented by a seed while any individual after evaluating its fitness is represented by a plant. As an example, this technique can be applied easily for the reconfigurable antennas by the positions of the switches. This technique shows a very high stability, but there is a further scope of improvement in the rate of success of this technique.

Pattern Search (PSearch or PS) Optimization: PSearch (or PS) Optimization [10, 33] is a very efficient, non-random and direct (i.e., does not require any information about the gradient of the fitness or objective function) optimization tool (especially with regard to multi-objective optimization in antenna design or microswitch design) for searching the minima of a function which is not necessarily differentiable or even continuous. This optimization strategy is comparatively faster than the other discussed algorithms. The algorithm searches a collection of points (called mesh having some specified pattern and constant size) surrounding the current point until a point is found in that mesh where the fitness or objective function value is less than its value (in case of minimization) at the current point. Thereafter, this new point acts as current point and once again starts searching the neighborhood points to obtain a new optimized point in the next iteration of the algorithm. If there is no point on mesh where the objective function value is lower than its value at the current point, then this

Feature → technique ↓	**Inspired by**	**Time for convergence/ optimization**	**Accuracy**	**Suitability**
Particle swarm optimization [18, 34]	Flocking behavior of birds	Little bit more time (because of overhead)	Average	Even for complex problems
Genetic algorithm [19, 34]	Natural evolution	Little bit more time (because of overhead)	Good	Even for complex problems
Ant colony optimization [20]	Behavior of social ants	Less time	Average	Even for complex problems
Firefly algorithm [21, 22]	Flashing behavior of the fireflies	Less time	Good	Even for complex problems
Cuckoo search [21, 23]	Hatching behavior of cuckoo	Quite less time	Good	Even for complex problems
Bat algorithm [21, 24]	Echo behavior of bats	Little bit more time (because of being fallen into local optimization sometimes)	Average	Even for complex problems
Artificial Bee colony optimization [25, 35]	Behavior of honeybee in food foraging	Less time	Good	Even for complex problems
Harmony search [27, 28]	Nature of music	Less time	Average	For simple problems
Biogeography-based optimization [29, 36]	Distribution of plants and animals in habitats	Less time	Good	Even for complex problems
Differential evolution [30, 37]	Natural laws concerned with the evolution of the individuals	Less time	Average	Even for complex problems
Simulated annealing [31, 38]	Annealing process in solids	Higher time	Good	Even for complex problems
Invasive weed optimization [32, 39]	Colonization of the invasive weeds	Little high	Low	Even for complex problems
Pattern search optimization [10, 33]	Searching around mesh	Less time	Good	Even for complex problems

Table 2. Comparison of important optimization techniques.

algorithm will reduce the size of mesh so as to search around the current point with more persistence and hence to find the minimum with more accuracy.

A very brief comparison of these optimization techniques has been discussed in **Table 2** (more experiments need to be done for GbSA as it has not been used in so many cases).

A very brief review of the advantages and disadvantages of the different optimization techniques discussed above can be shown in **Table 3**.

In this research work, PSearch algorithm will be used for the synthesis and optimization of the switch because of its speed, reliability and accuracy. Although PSearch is a much faster method of reaching the acceptable results, but it can be improved more by selecting the different search directions depending upon the objective function to be minimized.

Optimization technique	**Advantages**	**Disadvantages**
Particle swarm optimization [18, 40]	1. Particles preserve the good solutions (memory characteristic) 2. Each member is involved in the exploitation of the solution space	1. Quality of results may not be too good as the guided random process is the basis 2. Very sensitive to the tuning of parameters
Genetic algorithm [38]	1. Very useful for the large or/and unknown search space 2. Solution becomes more and more optimal with passage of time	1. Solution is prone to fall in local optimum if the fitness (cost) function is not properly defined 2. Not a very good technique for the constraint-based optimization
Ant colony optimization [38]	1. Adaptable to real time changes 2. Has property of distributed computing	1. Convergence is difficult to prove in many cases 2. Solution may fall into local optimum in a few cases
Firefly algorithm [22]	1. High speed and performs good even at high levels of noise 2. Performs better with the increase in population size	1. Unable to get rid of local optima while doing local search (in a very few situations) 2. Unable to preserve the good solution (no memory)
Cuckoo search [23, 41]	1. Tendency to be trapped in local optimum is very very less and hence faster than the other methods 2. Easier to implement as it depends upon population and probability only	1. Little less efficiency because of inability to change parameters 2. Number of iterations required may be quite large
Bat algorithm [24, 42]	1. Very efficient even for the multi-constraint problems 2. Can be used to derive many algorithms by changing some of its parameters	1. Little less convergence accuracy 2. Not so good for the multi-dimensional problems because of fast initial convergence
Artificial Bee colony optimization [35]	1. Can intensify and diversify the search quite effectively 2. Gives optimum results in reasonable time	1. Is yet to prove its worth in so many real-life applications 2. Some mathematical justifications are yet to be done in this technique
Harmony search [43, 44]	1. Does not need any initial value resulting in convergence to a global optimum in a much better way 2. Parameters need not to be fine tuned	1. Mainly useful only for a single objective function 2. Very poor in case of local search
Biogeography-based optimization [45]	1. Has high diversity resulting in a good solution 2. Preserves the good solutions (memory characteristic)	1. Less efficient in exploitation of the solution 2. Sensitive to the tuning of some parameters
Differential evolution [30, 37]	1. Efficient memory utilization 2. Can easily be implemented in parallel	1. Large computation needed to reach the optimal solution 2. Less accurate
Simulated annealing [38]	1. Ability to approach the global optimal solution in most of the cases 2. Simple to code even for the complicated and unordered data/problems	1. Very much time-consuming because the fitness function needs more computation 2. Parameters have to be very much fine-tuned

Optimization technique	Advantages	Disadvantages
Invasive weed optimization [32, 39]	1. Allows all plants to take part in reproduction 2. Shows high stability and good convergence	1. Little scope of improvement in the success rate of this algorithm 2. Is yet to prove its importance in many real-life situations
Pattern search optimization [10, 33]	1. Very fast and reliable method 2. Very accurate method as the mesh size may be reduced to search around the point with higher resolution	1. Wrong selection of starting point may result in sticking around local minima

Table 3. Advantages and disadvantages of important optimization techniques.

3. Switch design and analysis

Initially, metal MEMS switch is analyzed with the help of software coventorware. RF MEMS switches in terms of multi-Physics properties have been studied, designed and simulated for RA design. The multi-Physics characteristics for MEMS switches generally include the squeeze film damping effect/displacement time, activation/pull-in voltage, electrostatic force and on-off capacitance ratio.

The lumped/equivalent circuits of aforementioned MEMS switch are generated by using Advanced Design System (ADS) software with the help of Hspice model. After generation of lumped elements, the mathematical analysis and verification of post-processing simulation results of switches are performed. Further, the ANSYS high frequency structure simulator (HFSS) software is used to find out the electromagnetic (EM) characteristics of MEMS switch. In case of switch, the important EM post-parameters like insertion loss (IL), return loss (RL) and isolation are studied. This software provides the in-built optimization tools which are also considered to optimize the EM results.

Proposed MEMS switch here moves at one end in the downward direction and is fixed at other end of the beam. The cantilever beam makes a metal contact with the transmission line as it moves in down direction in response of electrostatic actuation. When beam metal part connects the two ports of transmission line, switch is called in ON position and when beam metal part disconnects the two ports of transmission line, the switch is called in OFF position [46]. The presented MEMS resistive switches are different according to their beam shapes and metal contact areas.

Figure 1 shows 3D view of the metal-contact RF microswitch implemented on silicon substrate of area 272 × 118 μm^2 and thickness 48 μm. The cantilever beam is made of gold and silicon nitrate of thickness 0.2 μm. A 0.5-μm-thick dimple is used to make metal to metal contact and to separate the cantilever beam from actuation pad in down-position.

The equivalent R-L-C circuit of proposed switch in on-position and off-position are shown in **Figure 2**. The circuit model of metal-contact microswitch is used to extract the *C, R* and *L* equivalent parameters of the switch. There are a number of circuit elements which represent the physical part of the proposed microswitch [47]. Here in **Figure 2a**, R_4 = 3.98 ohm represents a value of line resistor; L_2 = 0.63 nH, a value of line inductor of the cantilever

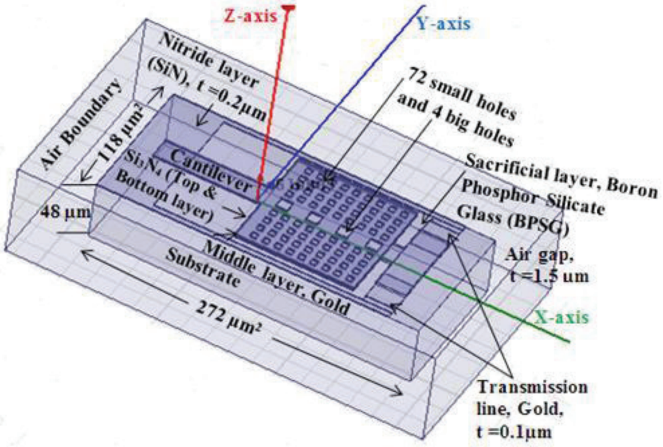
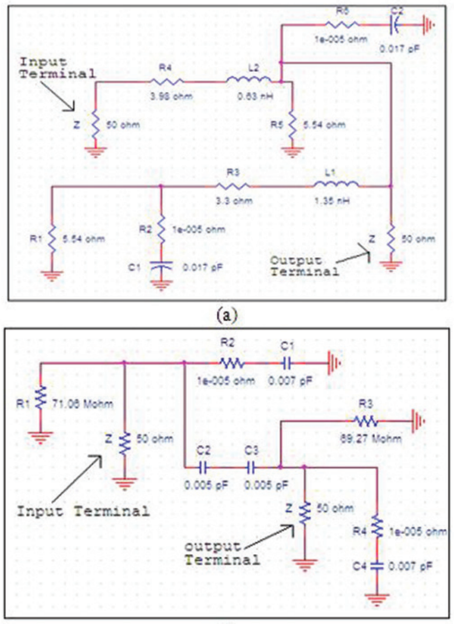


Figure 1. 3D layout of metal contact microswitch (in coventorware software).

beam. Further, $R_3 = 3.3$ ohm, contact resistance value; $L_1 = 1.35$ nH, contact inductance value; and $C_1 = C_2 = 0.017$ pF, the shunt coupling capacitance value. The rest of the shunt resistors ($R_1 = 5.54$ ohm, $R_2 = 1\text{e-}005$ ohm, $R_5 = 5.54$ ohm and $R_6 = 1\text{e-}005$ ohm) represents the losses effect due to the holes at higher frequencies. In off-state position of the switch (as shown in **Figure 2b**), $C_4 = 0.007$ pF represents a series switch capacitance value.

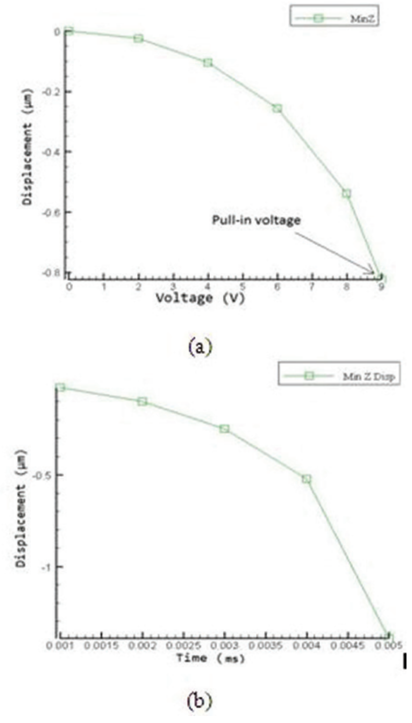
After solving equivalent circuit, at a given solution frequency, the impedance in ON position is equal to $Z_{eq} = R_{sw} + iwL_s = 3.98 + 2.52i$ (in ohm) and in OFF position, the capacitance value calculated is $C_c = 2.74$ femto-Farad. These values are useful to define the insertion loss and isolation. Except the characteristics impedance, other circuit values are permitted to vary the isolation and insertion loss results calculations [48]. Here the actual equivalent circuit of proposed structure was generated by using HSPICE model file. The HSPICE file from HFSS was exported in



(a)

(b)

Figure 2. Equivalent R-L-C circuit of metal-contact MEMS switch in (a) on-position (b) off-position.

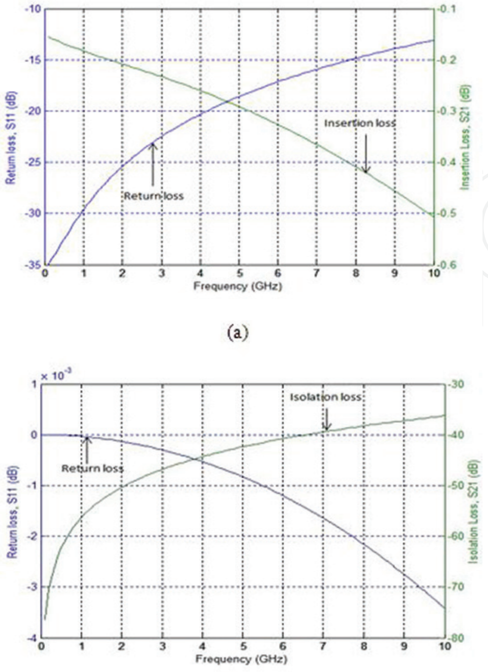


(a)

(b)

Figure 3. (a) Normalized gap height/displacement (in z-direction) versus applied voltage (pull-in voltage characteristics) and (b) transient response of switch.

Advanced Design System (ADS) software to validate the results through equivalent circuit and layout approach. The generated lumped LCR model of switch in ADS was simulated again by setting 50 ohm impedance at input and output terminal for the verification of post-electromagnetic parameters and further comparison shows similar results as generated by HFSS.



(a)

Figure 4. (a) Simulated S-parameter (insertion loss and RL) of switch in on-state and (b) simulated S-parameter (isolation and RL) of switch in off-state (S_{11} and S_{21}).

The mechanical movement depends on spring constant of designed beam structure and lower spring constant is required for better switch operation [49]. At pull-in voltage (V_p = 9.1 V), an electrostatic force is generated between actuation and beam electrode. As a result, beam metal-part makes a contact with transmission line and RF signal passes through this path. The plots of V_p and squeezed-film damping effect in the form of displacement time (t_s) are shown in **Figure 3**. The simulated S-parameters from 0.1 to 10 GHz are shown in **Figure 4**. In ON-position, the insertion and return losses (RL) are 0.15 to 0.51 dB and 34.94 to 13.10 dB, respectively. In OFF-position, the isolation is 75.96 to 35.83 dB.

4. Pattern search optimization method for RF switches

A PS method [33] searches set-points around the existing point, observing for unique where the experimental value of the cost function is lesser than the value at the existing point. The insertion, isolation and RL of presented microswitch in on-off condition are optimized using PS method. These parameters were improved by varying the physical dimensions (width and length) of transmission lines as shown in **Figures 5** and **6**. The substrate thickness and cantilever dimensions are already optimized during the designing process of the RF switch. Here, the problem statement and objective function are by varying structure dimensions of RF microswitch of transmission line to find the maximum transmission from Wave Port 1 to Wave Port 2 (S21 = >1), define the cost function to be –mag (S(WavePort2, WavePort1)) at some specific frequency. The physical dimensions for optimization purpose must be limited so as to avoid the overlarge size as compared with the substrate area, so the restricted limits are set as (20 μm ≤ (L = length) ≤ 45 μm) and (5 μm ≤ (W = width) ≤25 μm), respectively. During optimization analysis, the target is set to identify maximum condition to achieve aforementioned cost function in both on and off position.

Table 4 summarizes the optimized S-parameters of metal-contact switch at 5 GHz. The PS optimization takes six and eight iterations in on and off-positions to optimize the S-parameters with simulation time of 39 and 38 min, respectively. The minimum cost function is achieved in

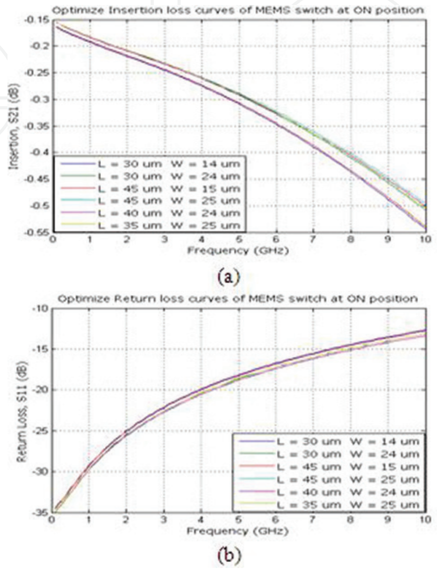


Figure 5. Optimized results at on-position of switch: (a) insertion and (b) return loss.

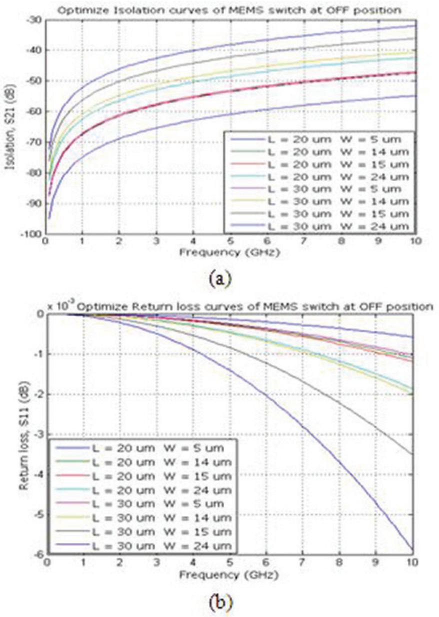


Figure 6. Optimized results at off-position of switch: (a) isolation and (b) return loss.

S-parameters	Without optimization (dB)	With PS optimization (dB)
Insertion loss	−0.32	−0.26
RL in down-state	−17.89	−19.85
Isolation	−41.95	−60.90

Table 4. S-Parameters of MEMS switch at 5 GHz.

fourth iteration in on position and sixth iteration in off position. The optimized value of length and width in on-position is 45 and 25 μm and in off-position of switch is 20 and 5 μm. It has been observed from optimized results that there is major improvement in isolation, reasonable return loss and minor improvement in insertion loss. This is because that PS algorithm follows

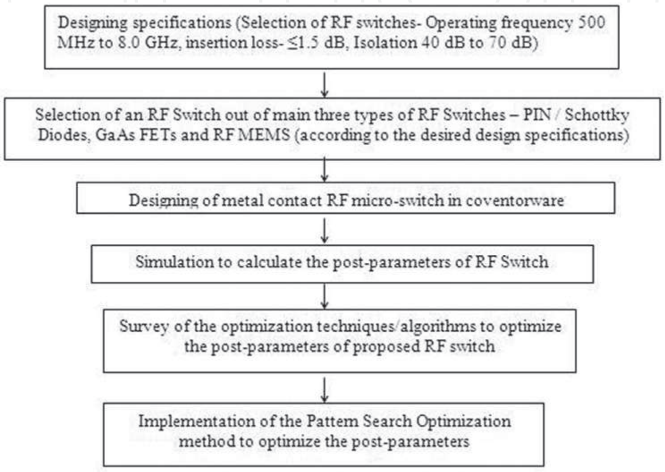


Figure 7. Flow diagram of designing and optimization approach of RF switches.

the designing equations for antenna analysis not includes the transmission line effect and consequently, they are only useful for comparison with simulated data under restricted conditions.

The design approach of RF switches (as discussed in Section 3) with their optimization approach (as discussed in this section) may be shown in the form of flow sequence in **Figure 7**.

5. Defected ground slot reconfigurable antenna

Figure 8 shows the geometry of our proposed defected ground slot antenna which consists of feed-line, patch element and two RF micrometal-contact switches. The antenna was designed on Rogers 4350 substrate of thickness 0.762 mm, relative permittivity $\varepsilon_r = 3.66$ and dielectric loss tangent 0.004. **Table 5** shows all the dimensions of antenna. The positions of switches S_1 and S_2 on antenna were set in a way to operate antenna in dual band. To find the best location of switches on microstrip antenna, the parametric analysis was carried in HFSS software [11, 12].

The proposed RA fabrication and testing set-up broadly contain five different sections which include defected ground planar antenna, RF switches with biasing circuit and voltage regulated power supply to on/off the desired RF switches, vector network analyzer (VNA) and anechoic chamber. The resistive RF microswitch selected for the antenna is same as designed and optimized in this article. For proof of concept, its equivalent RF switches (CSWA2-63DR+) having almost similar isolation and matching of 50 ohm was considered. Although small variation in results are noticed in ON-position of switches at antenna, as compared to simulated results, this is just because of different insertion loss value of tested switch. It consumes very low power (in μW) and typical supply current range is 18 μA. Further, the RF switch used here has operating bandwidth lying from 0.5 to 6.5 GHz. A separate laminate sheet of

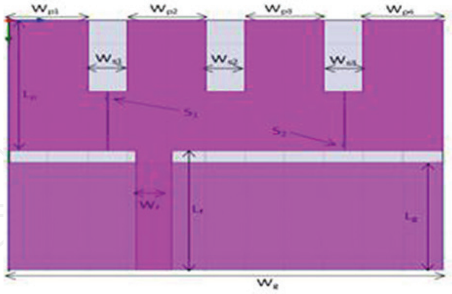


Figure 8. Dual band slot antenna with two metal-contact MEMS switches.

Parameters	**Lf**	**Wf**	**Lg**	**Wg**	**Lp**	**Wp1**
	10	1.8	9	22	11	4
Parameters	**Wp2**	**Wp3**	**Wp4**	**Ws1**	**Ws2**	**Ws3**
	4	4	4	2	2	2

Table 5. Antenna dimensions (in mm).

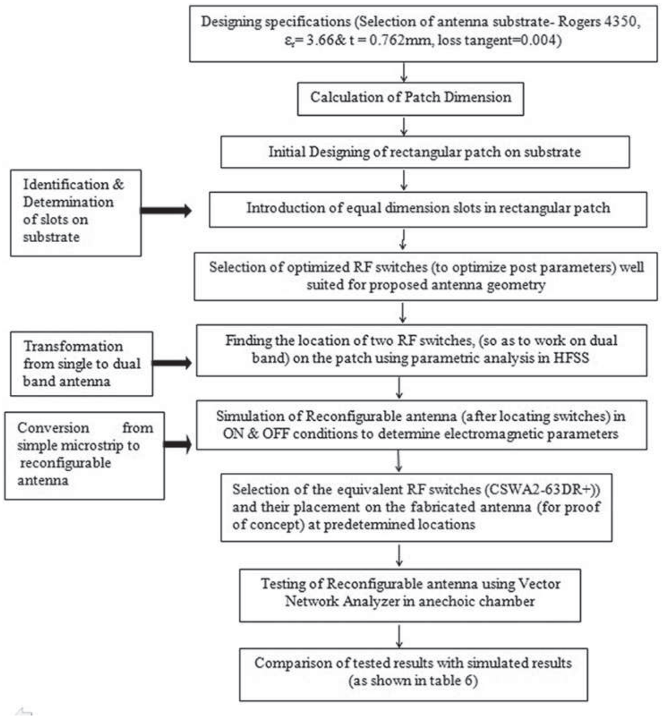
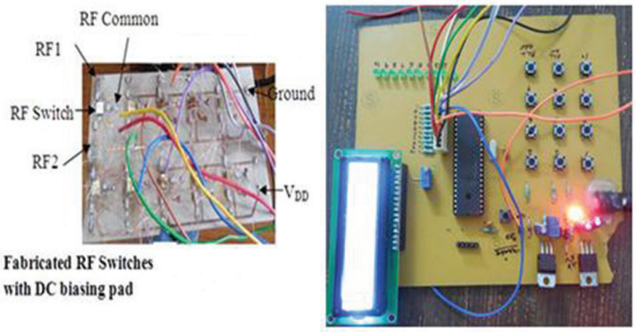


Figure 9. Flow diagram of designing approach of reconfigurable antenna.

Roger RO4350 with same substrate thickness (0.762 mm) as that of defected ground antenna was used for integration of RF switches.

The design approach of reconfigurable antenna (as discussed in this section) may be shown in the form of flow sequence in **Figure 9**.

Figure 10 shows the laminate sheet that consists of 10 RF switches and only two switches (*S*1-*S*2) were used in this work. This PCB carries the DC bias lines and pads that were designed for further connection with antenna as well to the power supply. The gold-plated SMA connector of 50 ohm was used at terminal RF1, RF2 and RF common which further connected to defected ground antenna through excellent quality thin copper wires having diameter 0.025 mm. Each RF switching circuit consists of a RF switch and three equal valued capacitors (47 pF) for blocking DC. The highly stable on-chip capacitor dielectrics C0G (NP0) ceramics was



Fabricated RF Switches with DC biasing pad

Power supply circuit for operational Switches

Figure 10. Prototype of RF switches PCB and regulated power supply circuit.

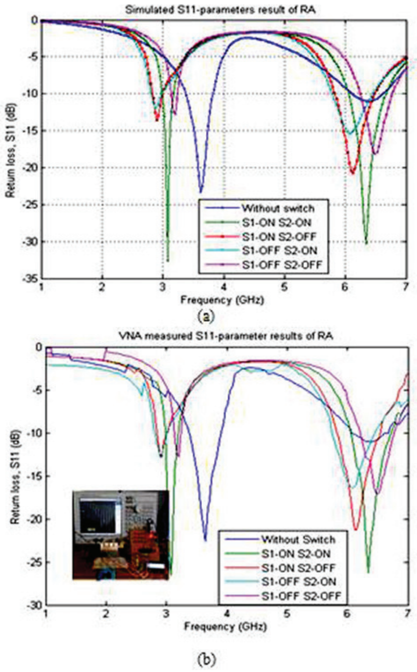


Figure 11. Comparison of simulated and measured RL of proposed RA.

used for biasing circuit. A variable DC regulated power supply producing 1.3–4.92 V was designed to activate RF switches as shown in **Figure 10**.

The electronics switches were integrated on power supply PCB which activates the desired RF switches through 40 pin Atmel microcontroller. The measurements of RA electromagnetic characteristics were done with the help of Agilent Technologies E5071C in an anechoic chamber. The two RF switches provide four possible switching states, that is, on-on, on-off, off-on and off-off. The testing result shows that in on-on state, antenna demonstrates best resonance performance as shown in **Figure 11** and **Table 6**.

Switch-state	**Resonating freq. (GHz)**		**RL (S_{11}) in dB**		**Bandwidth (MHz)**	
	Simulated	**Measured**	**Simulated**	**Measured**	**Simulated**	**Measured**
Antenna without switch	3.62	3.58	−23.29	−22.50	300	294
S$_1$-ON	3.08	3.06	−32.54	−27.20	121	118
S$_2$-ON	6.34	6.40	−30.25	−26.32	392	384
S$_1$-ON	2.89	2.85	−13.58	−12.92	151	148
S$_2$-OFF	6.13	6.08	−20.75	−21.10	392	386
S$_1$-OFF	2.87	2.86	−11.98	−12.55	181	178
S$_2$-ON	6.09	6.14	−15.37	−15.18	573	569
S$_1$-OFF	3.17	3.20	−12.50	−13.10	90	88
S$_2$-OFF	6.49	6.50	−18.12	−16.78	271	266

Table 6. Comparison of S-parameter results of antenna with and without RF switches.

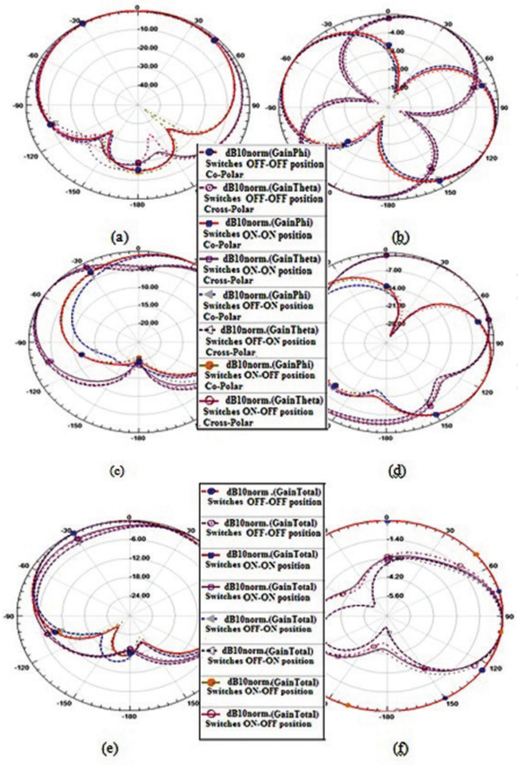


Figure 12. Measured normalized co-polar, cross-polar and total gain radiation patterns in E-plane and H-plane for the reconfigurable antenna at different switching configuration (a) XZ-plane (phi = 0), (b) XY-plane (theta = 0), (c) YZ-plane(phi = 90), (d) gainPhi and gainTheta (theta = 90), (e) gain total (phi = 0, theta = 90) and (f) gain total (theta = 0, theta = 90).

Radiation pattern characteristics—The measured radiation pattern performances for the RA at different switching configuration plotted above are included next. Measured normalized relative power patterns, that is, YZ-, XZ- and XY- cut patterns are shown in **Figure 12a–d** at solution frequency 4 GHz are obtained. The combined magnitude of the electric field components in the desired polarization is shown next in **Figure 12e–f**. A figure-eight pattern in XY-plane (as shown in **Figure 12b**) signifies a dipole type of radiation pattern. Reconfigurable antenna as expected achieved fairly normalized omni-directional patterns. From 3D radiation pattern plot, it has been observed that the antenna behaves directional in the elevation plane and non-directional in the azimuth plane. Further, considering all four possible configurations (on and off) of the switches on antenna, the RA was showing well-behaved linearly polarized characteristic as axial ratio (E_y/E_x) is above one at theta equal to zero.

6. Conclusions

In this chapter, initially a metal-contact microswitch for application of reconfigurable defected ground antenna has been presented, simulated and optimized. Further, the circuit model of RF switch has also been used to extract the capacitance, resistance and inductance parameters by using ADS to validate insertion loss and isolation results. For optimization of S-parameters, pattern search (PS) optimization algorithm has been used after reviewing many of the commonly used optimization techniques. After PS optimization, the RF switch shows significant improvements in insertion loss and isolation at 0.1–10 GHz. Further, the proposed metal-contact microswitch when introduced on defected ground slot antenna and fabricated antenna showed dual-band characteristics as well as reduction in size. From wireless industrial application point of view, the proposed compact reconfigurable antenna with RF switches aiming towards the future wireless miniature devices is suitable for IEEE S- and C-bands. In other words, the proposed reconfigurable antenna finds suitable applications in vehicular and wireless technologies.

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