

# Frequency Reconfigurable $K_u$ -Band Miniaturized Planar Antenna for Satellite Communication and its Circuit Modelling

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**Abstract:** This work highlights the design and development of a  $K_u$ -band reconfigurable planar antenna on Silicon substrate. Capacitive type shunt RF-MEMS switch is implemented to achieve the frequency re-configurability. Bulk and surface micromachining both processes have been implemented in this single architecture. Effect of micromachining along with other fabricated aspects has been modelled in terms of lumped equivalent circuit elements. Simple approach of modelling paves the way to decipher the mystery of device physics without introducing any mathematical complications. A linearly polarized patch antenna with microstrip feeding shows the frequency reconfigurability of around 200 MHz (14.3 GHz to 14.5 GHz) in the  $K_u$ -band is the focus of this modelling aspect. Finally, a comparative study has been concluded which summarizes the results obtained from circuit modelling and full-wave analysis. It validates the adopted approach throughout the entire work.

**Keywords:** RF MEMS switch; reconfigurable antenna; electrical modelling

## 1. Introduction

With the advent of multiple switching technologies<sup>1,2</sup>, modern communication system demands portable, compact, light weight and multi feature circuits. In case of RF (Radio Frequency)/wireless communication, reconfigurability characteristics play a key role in realization of whole system. The term 'reconfigurable' is coined for antenna engineering in terms of either frequency or polarization or directivity. In contrast to the earlier versions, modern antennas have become smarter enough in terms of efficient usage within a very limited resource with a very economical way. Implementing various switching technologies, these smart antennas show excellence in performance with bare minimum foot-prints and associate circuitry. From the last decade, micro-electro mechanical system (MEMS) is getting utmost importance for realization of efficient switching circuit with its unique features. It offers multiple promising characteristics, like-minimum insertion loss, light weight, no harmonic distortion, zero DC power consumption, almost linear characteristics etc. Compared to existing technologies for implementing switching operations, MEMS seems to be superior in nature<sup>3-5</sup>. With the modified version of standard micro-fabrication process, MEMS technology leads to the superior device performances. Additionally, two micromachining (bulk and surface)<sup>6-10</sup> methods are conventionally adopted in MEMS which are of unique characteristic. Along with design exercises, antenna using MEMS technology needs extra efforts in fabrication process, which ultimately results in a superior antenna using standard CMOS (Complementary Metal Oxide Semiconductor) process.

Present work discusses about electrical modelling of a miniaturized MEMS based reconfigurable Ku-band antenna. With the help of capacitive type shunt switches; this antenna changes its operating frequency from 14.5 GHz to 14.3 GHz. The said antenna exhibits its linear polarization behaviour with a peak gain of around 4.8 dBi within 844 MHz bandwidth for more than 90% radiation efficiency over high resistivity ( $\rho > 8 \text{ k}\Omega\text{-cm}$ ,  $\tan \delta = 0.01$ ) silicon substrate. Bulk and surface micromachining both have been implemented in this antenna structure. Current research work proposed an equivalent circuit model of this compact antenna, which basically decrypts the insight device physics. Each circuit elements represents the physical phenomenon happening in this MEMS-based antenna module. Following section describes it in detail.

## 2. Circuit Modelling

Though microstrip antenna offers numerous advantages<sup>11-14</sup>, but dates back it is suffering from various demerits<sup>15, 16</sup>. MEMS technology has come as a blessing to the antenna engineers, which can alleviate these disadvantages in a very efficient way<sup>17-20</sup>. Gain, bandwidth and finally radiation efficiency can be improved significantly with MEMS process for this microstrip antenna structure. Present work describes a Ku-band antenna, whose performance can be reconfigured suitably with the use of MEMS-switch. Operating frequency of this antenna varies from 14.5 GHz to 14.3 GHz. RF-switch here basically alters the effective electrical length of this antenna. Geometry of the proposed antenna is shown in Fig. 1 (a), with all detailed dimensions as mentioned in Table 1. Cross-sectional diagram of the antenna (Fig.1 (b)) reveals the application of MEMS-technology in antenna structure. This antenna is targeted over 675 $\mu\text{m}$  thick high resistive silicon (HRS) substrate ( $\rho > 8 \text{ k}\Omega\text{-cm}$ ,  $\epsilon_r = 11.7$ ,  $\tan \delta = 0.01$ ). Beneath the patch, a silicon membrane of 26  $\mu\text{m}$  thickness is made, except the feed portion to elevate the gain and radiation efficiency of the antenna as compared to its standard printed versions. Details about the designing can be found in reference<sup>21</sup>.

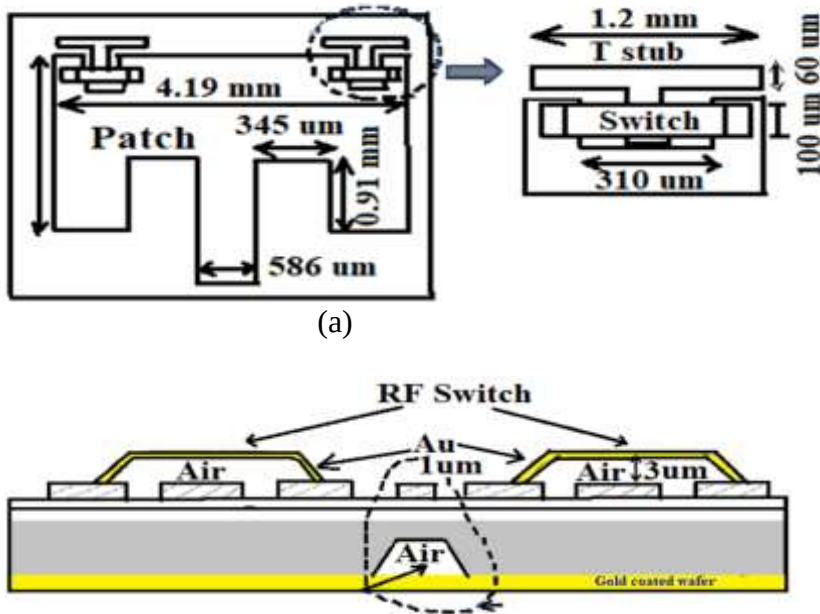


**Figure 1.** (a) Geometry and (b) Cross sectional view of MEMS-based reconfigurable antenna<sup>21</sup>

The dimensions of the micro-machined patch dimension are calculated using the following equations<sup>21</sup>

$$(2.1) \quad W = \frac{c}{2 * f_r * \sqrt{\frac{\epsilon_{reff} + 1}{2}}},$$

$$(2.2) \quad L = \frac{c}{2 * f_r * \sqrt{\epsilon_{reff}}},$$

where,  $W$  and  $L$  are the width and length of the micro-machined antenna,  $f_r$  is resonant frequency,  $\epsilon_{reff}$  is effective dielectric constant of the substrate, and  $c$  is velocity of the light in vacuum. Taking the optimized membrane thickness as  $30\mu\text{m}$ , the length and width of patch over the cavity come out as  $4.19\text{ mm}$  and  $2.27\text{ mm}$ , respectively.

Electrical model of the antenna is shown in Fig. 2. Single frequency microstrip fed patch antenna can be modelled as a tank circuit (parallel RLC network). This tank circuit is responsible for radiating the EM-energy by exhibiting its  $TM_{10}$  mode. The frequency of the resonance is mainly governed by its reactive network i.e. inductance ( $L_{10}$  or combination of  $L_{10}$  and  $L'_{10}$ ) and capacitance ( $C_{10}$ ). Resistance ( $R_{10}$ ) of the circuit dictates the operational bandwidth of antenna. Frequency reconfigurability can be achieved by implementing a switch in between  $L_{10}$  and  $L'_{10}$ . Switch decides the change of centre frequency ( $f_0$ ) from  $14.5$  to  $14.3\text{ GHz}$ .

**Table 1** Dimension of proposed antenna

| Parameters                        | Values                   |
|-----------------------------------|--------------------------|
| Length of the switch membrane     | $310\text{ }\mu\text{m}$ |
| Width of the switch membrane      | $100\text{ }\mu\text{m}$ |
| Thickness of the switch membrane  | $0.5\text{ }\mu\text{m}$ |
| Pull down voltage                 | $30\text{ V}$            |
| Material used for switch membrane | Gold                     |
| Initial Air-gap height            | $3\text{ }\mu\text{m}$   |

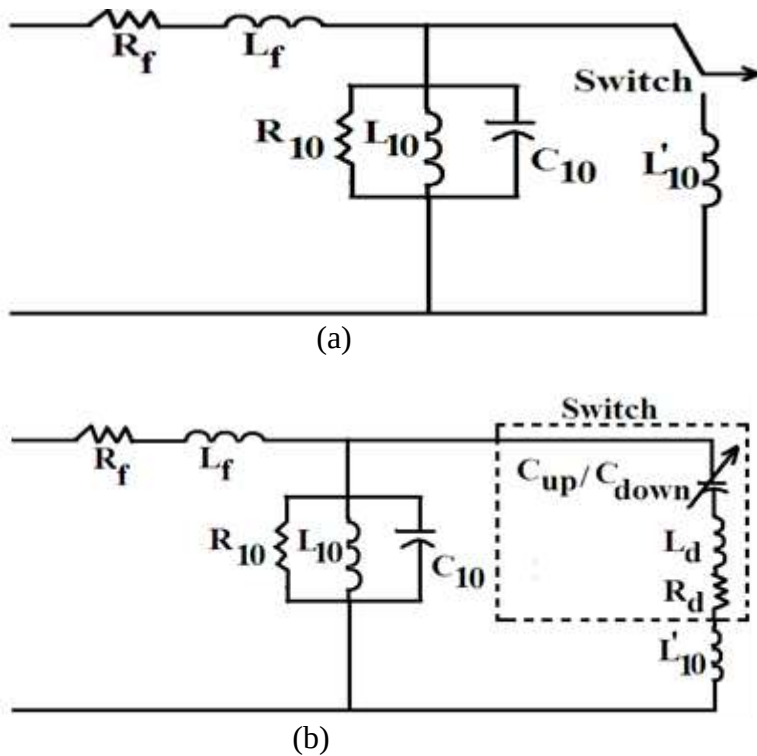


**Figure 2.** Proposed electrical model of the reconfigurable antenna

From the physical layout of this antenna (Fig.1), it can be inferred that the RF-switches use add-on structure with the main radiating element i.e. T-shaped stub. When this stub structure gets included with the main radiating element, the overall electrical length is increased, and thus operating frequency of antenna gets reduced.

Microstrip feed ( $50\ \Omega$ ) can be thought of as a series combination of  $R_f$  and  $L_f$ . Finite conductance values of the used metallization layer is expressed in terms of  $R_f$  and the conduction current crowding effect is symbolised with the help of  $L_f$ . Amount of stored electromagnetic energy within the cavity resonator (patch antenna) can be altered dynamically with the change of states of RF-MEMS switch. With the application of electrostatic force or DC actuation voltage, it shows two different states as ON/OFF or in other words UP/DOWN states. This RF-switch can be modelled as equivalent RLC-circuit, which has been used in this antenna structure, as shown in Fig. 2 (b).

Switch is represented by a two state capacitor<sup>1,5,22</sup>, whose capacitance changes from a low-value (in UP state,  $C_{up}$ ) to a high value (in DOWN state,  $C_{down}$ ). Ratio between these ( $C_{Down}/C_{UP}$ ) is known as figure-of merit(FOM) of the structure, which dictates the quality of switching operation. Additionally, in down state, while the signal and ground plane touch each other, at that time a huge amount of current crowding phenomenon occurs, which is represented by  $L_d$  and  $R_d$ . From the Fig. 2 (b), it is clear that when the switch is closed, then the overall inductance becomes a parallel combination of  $L_{10}$  and  $L'_{10}$ , which shifts the  $f_0$  at 14.3 GHz.

The values of all circuit elements of the whole electrical model after optimization are summarized in Table II. Finally, a conclusive comparison is drawn (Fig.3) between the data obtained from this proposed model and full wave analysis or 3D simulation. From this graphical data presentation, it can be inferred that the resonance behaviour of the MEMS based reconfigurable antenna has been clarified well with the help at circuit parameters. Small deviations between these two approaches are attributed because of different algorithms are applied by two unlike computational electromagnetic platforms.

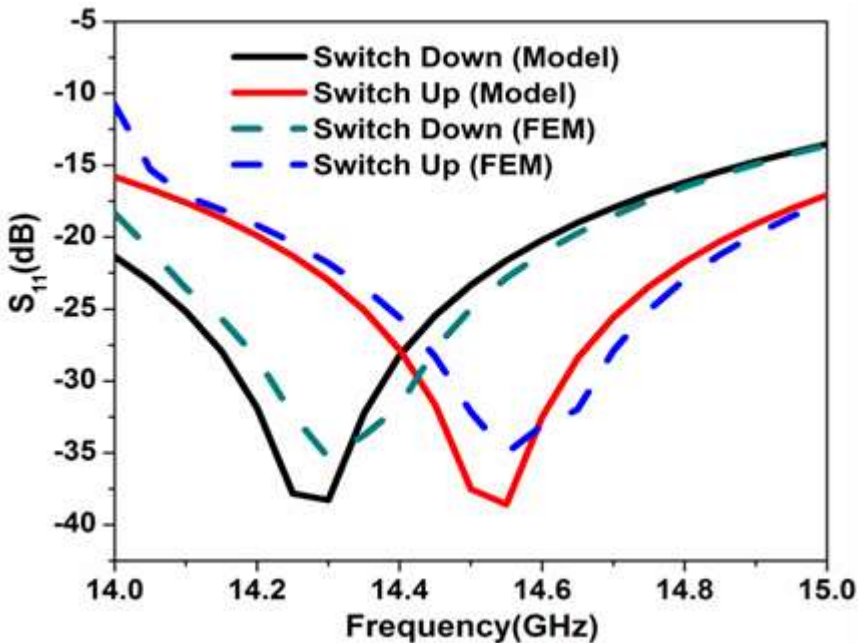


Figure 3. Comparison of FEM data and circuit model data

**Table 2** Parameters values of equivalent circuit of proposed antenna

| Parameter | Values       | Parameter  | Values          |
|-----------|--------------|------------|-----------------|
| $R_f$     | $1\ \Omega$  | $C_{up}$   | $28.5\ pF$      |
| $L_f$     | $1\ fH$      | $C_{Down}$ | $2.076\ fF$     |
| $R_{10}$  | $50\ \Omega$ | $L_d$      | $7.622\ pH$     |
| $L_{10}$  | $0.124\ nH$  | $R_d$      | $0.035\ \Omega$ |
| $C_{10}$  | $1\ pF$      | $L'_{10}$  | $3.72\ nH$      |

The far-field radiation pattern of the reconfigurable antenna is shown in Fig.4. It shows a stable directive pattern in the broadside fashion, consisting few numbers of grating/minor lobes. Circuit modelling has been implemented in a very easy way. This is the merit of the work.

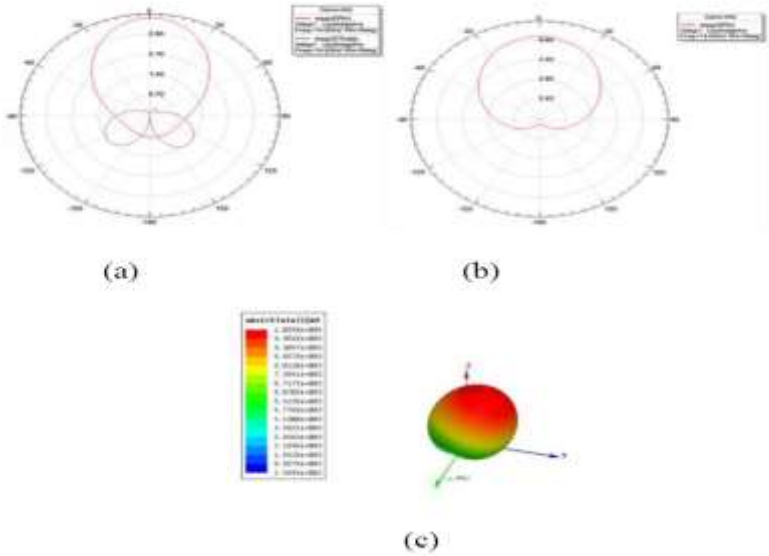


**Figure 4.** Radiation Pattern of the antenna when (a) Switch is up (b) when Switch is down (c) 3D pattern

**3. Conclusion**

Proposed electrical modelling of the MEMS based antenna demystifying the insight device physics of the structure in a very simple manner without applying any unwanted mathematical jugglery. Concept of frequency reconfigurability for the antenna problem has been explained here in a very efficient way. Antenna and switch both have been modelled separately and for the actual device these are integrated. Significance of each circuit elements have been explicitly discussed in this article. The

adopted approach paves the easiest way for beginners of this field from scratch prior to its 3D-complicated model creation and optimization. This way it becomes a time saving as well as an efficient way to decode the device physics. Comparison of the model data with the results obtained from full-wave analysis validates well the proposed circuit model.

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