Design and Multiphysics Analysis of Low-Loss 60-GHz SPNT RF-MEMS Switches

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Abstract — A design of a capacitive-shunt RF-MEMS switch for 60-GHz ISM-band application is proposed and analyzed. A 0/1-level RF-MEMS packaging technique is used here where via technologies are needed to pass the RF signal through the sealed package. The analysis and characterization of the RF-MEMS switch system include the solder bumps and vias in addition to the switch and the substrate losses in the 60-GHz frequency band. In this condition, a SP9T switch system still exhibits low insertion loss, i.e. around 1.5 dB. The isolation for the 60-GHz ISM band (i.e. 57-66 GHz) is better than 25 dB. Further, the impedance bandwidth is larger than 20 GHz which means that the switch can also be used for V-band applications. This proposed RF-MEMS switch system is suitable for various applications, such as antenna sectoring, signal routing, and phase shifting. This switch can also be improved to realize a NPNT RF-MEMS switch.

I. INTRODUCTION

RF microelectromechanical systems (MEMS) switch increases its popularity since last two decades [1]. It is because of its higher performance than p-i-n diode and field-effect transistor (FET) switches [2]. In this paper, a high performance SPNT switch based on the capacitive-shunt RF-MEMS is designed and analyzed.

In the application of switched-beam antenna, the uniform performance for different output ports of the RF-MEMS switch ensures the uniform performance for different scan direction of the antenna array. Moreover, the advantages of utilizing this switch system for realizing the mentioned application are its less complexity, less losses in the switching section (e.g. compared to Butler matrix network in [3]), and no scan blindness (e.g. compared to phased-array approach). Further, the proposed RF-MEMS switch system is also suitable for realizing various functions, a.o. signal routing and phase shifting.

II. RF ANALYSIS AND DESIGN OF THE SPNT RF-MEMS

A. RF Analysis

Basically, the RF-MEMS switch has two different types, namely the ohmic-series switch and the capacitive-shunt switch. The capacitive-shunt switch is suitable for millimeter-wave applications because its capacitance is low in the up state (e.g. 10-50 fF). Unlike the ohmic-series switch, no induction and resistance in the up-state beam position may exist owing to no contact metal needed. A low reflection coefficient can be obtained because of the low capacitance as expressed in [2]:

\[ |S_{11}|^2 = \frac{\omega^2 C_u Z_0^2}{4}, \]

where \( C_u \) is the up-state capacitance, \( Z_0 \) the characteristic impedance, and \( \omega \) the angular frequency. Especially at millimeter-wave frequencies, \( C_u \) should be designed to have a low or close to zero value to minimize the reflection coefficient. The equivalent circuit of this switch is depicted in Fig. 1.

\[ |S_{21}|^2 = \begin{cases} \frac{4}{\omega^2 C_u^2 Z_0^2} & \text{for } f \ll f_0 \\ \frac{4\omega^2 C_u^2 Z_0^2}{Z_0^2} & \text{for } f = f_0 \\ \frac{4\omega^2 C_u^2 Z_0^2}{Z_0^2} & \text{for } f \gg f_0 \end{cases} \]

where \( f_0 = 1/(2\pi\sqrt{LC_d}) \). Further, \( L \) is the inductance, and \( R_s \) is the series resistance. It can be clearly observed that at the resonant frequency \( f_0 \) the isolation is independent of the down-state capacitance and is limited by the series resistance of the beam material. This series resistance has to be low enough to give a high isolation at the resonant frequency. Clearly from (2), the resonant frequency of the capacitive-shunt MEMS switch is determined by the LC product.

A thin silicon nitride (Si$_3$N$_4$) is deposited on the conductor strip to prevent the short contact between two electrodes. Consequently, the capacitance of the MEMS
NPNT RF-MEMS switch. The quarter-wave transformer implemented, while 1-level Sapphire (Al2O3) modeled as a mechanical spring, with an equivalent mass of the beam is reduced by 60%.

Finally, the MEMS component behaves like a RLC circuit with negligible R and L. Thereby, the up-state capacitance, \( C_u \), is given in [4]:

\[
C_u = \frac{1.4 \varepsilon_0 A}{h_0 + \frac{t_{550}}{t_{551}}}
\]  

where \( C_u \) is assumed to be 40% larger than the parallel plate value due to fringing fields. \( A \) is the area of the electrode under the beam. From RF perspective, it is the area of the signal strip under the beam. Furthermore, the down-state capacitance, \( C_d \), is given by:

\[
C_d = R_A \frac{\varepsilon_0 \varepsilon_r A}{t_{550}}
\]  

where \( C_d \) is assumed as for the parallel plate value and there is no influence due to surface roughness \( R_A \) of the dielectric. In reality, the dielectric surface is not flat. In this case, \( R_A \) can be defined as e.g. 0.65.

**B. SPNT RF-MEMS Design**

The 0/1-level packaging technique is employed to provide full-solution of the RF-MEMS design (see Fig. 2(a)). 0-level Liquid Crystal Polymer (LCP) is implemented, while 1-level Sapphire (Al2O3) is utilized for the laminate of the MEMS. LCP has relative permittivity \( (\varepsilon_r) \) of 3.16 and loss tangent \( (\delta) \) of 0.002. Sapphire has relative permittivity \( (\varepsilon_r) \) of 9.4 and loss tangent \( (\delta) \) of 0.000158. The diameter of the solder ball is 60 \( \mu \)m whereas the through-Sapphire-via has the diameter of 36 \( \mu \)m.

In Fig. 2(b), the structure of the SP3T RF-MEMS is shown. It can easily be developed further into SPNT or NPNT RF-MEMS switch. The quarter-wave transformer is extensively used for realizing a good matching.

**III. ELECTROMECHANICAL ANALYSIS OF THE RF-MEMS**

The fixed-fixed membrane in this switch type is modeled as a mechanical spring, with an equivalent spring constant \( k \). This \( k \) is given by [5]:

\[
k = 32Ew \left( \frac{1}{l} \right)^3 \left( \frac{27}{4\pi} \right) + 8\sigma(1-v)w \left( \frac{1}{l} \right), \left( N/m \right)
\]  

where \( E \) is the Young’s modulus, \( \sigma \) the residual stress, and \( v \) the Poisson ratio of the beam material. \( l \) and \( w \) are the dimensions of the beam as depicted in Fig. 2. \( t \) is the thickness of the beam. The effective mass of the beam is [4]: \( m = 0.4plwt \). \( p \) is the mass density of the beam material. Because the beam is fixed at both ends, the mass of the beam is reduced by 60%.

![Fig. 2. Structure of the RF-MEMS capacitive-shunt switch: (a) 0/1-level RF-MEMS packaging, (b) SP3T or basic switch element, (c) SP5T, (d) SP7T, and (e) SP9T on the CPW transmission line. All dimensions are in mm. \( f_0 = 61 \) GHz.](image-url)
To collapse the switch to the down-state position, the pull-down voltage ($V_p$) is given by [4]:

$$V_p = \frac{a k b^2}{27 e A}$$  \hspace{1cm} (6)

where $h_0$ is the initial height of the beam. Moreover, the bias voltage necessary to hold down the voltage ($V_h$) is given by:

$$V_h = \frac{2k(h_0 - t_{m})H_{m}}{e A}$$  \hspace{1cm} (7)

Therefore, the switching time ($t_s$) is defined as [5]:

$$t_s = \frac{V_p}{\sqrt{h_0/k/m}}$$  \hspace{1cm} (8)

where $V_p$ is the drive voltage and $\sqrt{h_0/k/m}$ is actually the resonant frequency of the beam.

In this design, the 1.5µm-thick MEMS beam is made of aluminum, and the copper metal traces are used to realize the CPW transmission line. The summary of the material parameters for electromechanical analysis is shown in Table I.

IV. SIMULATION RESULTS

A. High-Frequency Analysis

The 3D electromagnetic simulator CST Microwave Studio (MWS) is used to perform the full-wave analysis of the switch structure. In Fig. 3, the S-parameters of SP9T switch are illustrated. The signal path is switched to port 4 in this result. The obtained insertion loss ($S_{21}$) has included the loss contribution from the solder bumps and vias in addition to the switch and the substrate loss at 61 GHz. Every solder bump contributes 0.114dB loss whereas every via contributes 0.07dB loss. Each RF-MEMS itself only contributes 0.06dB loss. The substrates (LCP and Sapphire) contribute 0.95dB loss for the taken path as illustrated in the surface current animation in Fig. 4.

The obtained isolation for most of the inactive ports is better than 25 dB. Both obtained insertion loss and isolation promise improvements from the design in [6]. The 10dB-impedance bandwidth covers almost the whole V-band frequencies in this SP9T. Multiple dips in the $S_{11}$ trace are caused by coupled resonant circuits consisting of three basic switch elements.

As mentioned earlier, Fig. 4 illustrates the surface current. Air bridges are applied around the junction to obtain an equipotential between surrounding ground strips. The grounding vias have to be carefully positioned around the signal via to ensure a proper matching.

In Fig. 5, the S-parameters of the SP9T RF-MEMS switch for different switched signal paths are illustrated. It can be observed that the uniform performance is retained for different cases. The insertion loss for all the cases is approximately less than 2 dB from 57 - 66 GHz ISM band. The identical group delay is obtained with variation less than 5 ps for the frequency band.

The identical performances for each switched path allow the realization of the switched-beam antenna, e.g. for radar and commercial applications at 60 GHz. Moreover, similar performances are also observed in SP3T, SP5T, and SP7T RF-MEMS switches.

A minor difference in $S_{11}$ results (i.e. larger dips for the black trace) between signal paths switched to port 2 and port 3 results from the non-uniformity of the junction performance between the straight and perpendicular path.
B. Electrostatic and Mechanical Analyses

In this section, the electrostatic and mechanic problems of this RF MEMS design are investigated using CST MPhysics Studio. To analyze these problems, the material properties from Table I are incorporated.

The DC voltage (\(V_{dc}\)) has to be defined which will actuate the aluminum beam through actuation pads right under that beam as shown in Fig. 6. The zero displacement area is the area nearby the beam holder where no beam’s deformation exists.

The actuation pads are connected to a simple biasing network in the bottom part of the 1-level substrate. From (8), 90 \(V_{dc}\) results in 7.6-\(\mu\)N electrostatic force and thus 5.4-\(\mu\)s fast switching time. The residual stress, \(\sigma_r\), is approximated as zero when the aluminum beam is etched on the ground substrate. This zero approximation is possible since the beam structure always returns to the initial position (when it is not actuated) owing to the fixed position of the etched beam holder. This switching time is an acceptable value for a MEMS switch [2]. The resulting beam displacement of 2.82 \(\mu\)m suffices to create a contact between two electrodes since the initial height of the beam is 2 \(\mu\)m.

From the analysis, it follows that the capacitance ratio (\(C_d/C_u\)) is approximately 32 which is an acceptable value (20 < \(C_d/C_u\) < 100) for a design of the MEMS switch [2].

V. Fabrication

Fabrication processes start with the deposition of the metal layers, i.e. copper and/or gold, on the Sapphire wafer using evaporation method. The layers are patterned using the mask and etched to create the CPW lines. The Plasma-Enhanced Chemical Vapour Deposition (PECVD) can be used to deposit the Si\(_3\)N\(_4\) on the metal layer [7]. The sacrificial layer is employed here where the aluminum will be deposited on to form the MEMS beam. The XLIM lab in [8] and DIMES lab at TU Delft can accommodate the fabrication processes.

VI. Conclusion

The high-performance SPNT RF-MEMS switch based on the capacitive-shunt switch has been designed. The analysis of the switch system which includes the solder bumps, vias, and RF-MEMS switches in addition to the substrate losses in the 60-GHz frequency band still results in low insertion loss, i.e. around 1.5 dB for SP9T. The isolation is better than 25 dB, and this SPNT switch exhibits a wideband performance. Uniform performances are observed for different switched signal paths. The proposed RF-MEMS switch is suitable for applications, such as antenna sectoring/switching, signal routing, and phase shifting.

REFERENCES