Modeling of Novel Modulated Helix Induction MEMS Switch on Time-Domain

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Abstract. In order to apply micro/nano technologies and Radio Frequency Micro/nano-Electro-Mechanical System (MEMS/NEMS) technologies in the Radio Frequency (RF) field to manufacture miniature, high isolation, low insertion loss, good linear characteristic and low power consumption microwave switches. Through analysis of electronics and mechanics of the RF switch, a novel MEMS helix induction modulated switch which working on 9GHz–20GHz is presented in this paper. The actuation voltage, insertion loss and isolation of the switch are 12V, 0.89dB@9.5GHz, 31.4dB@9.5GHz respectively. The alternating direction implicit finite-difference time-domain (ADI-FDTD) method for a full three-dimensional (3-D) wave presented is used for modeling and analyzing the micromachine switch for the first time. The numerical method is unconditionally stable. The limitation of the maximum the time-step size of the method does not depend on the CFL condition, but rather on numerical errors. Therefore, the time-step size can be arbitrarily set within numerical errors when this method is used. It is more efficient than the conventional finite element method (FEM) in terms of the central processing unit time if the size of the local minimum cell in the computational domain is much smaller than the other cells and the wavelength. Associated with practical model, Mur’s superabsorbing boundary condition was developed. Numerical simulation results are compared with those using the FEM and theoretic computation. It has been demonstrated that, with this technique, space discretization with only a few cells per wavelength gives accurate results, leading to a reduction of CPU computation time and improvement of computation efficiency.

1. Introduction
With the rapid development of modern radar, satellite communication and wireless communication systems, there has been much research work on RF MEMS/NEMS switches now [1, 2]. It is very important elements for composing the other RF MEMS/NEMS devices, such as variable capacitors, filters, phase shifters, resonances and configurable antenna, etc. Compared with conventional switches used widely in microwave and monolithic microwave integrated circuits(MMICs) such as P-i-n(PIN) diodes and field-effect transistor (FET) switches, the RF MEMS/NEMS switches offer high isolation, high frequency, good Q-factor, low return loss, low insertion loss and power consumption. But there still exists many problems which need to be solved, for example, MEMS switch driven by static has high actuation voltage, it makes against microwave integration. Because of conversion of open to shut adopting mechanics, the response rate of the MEMS switch is slower than
conventional switches, it is only microsecond. Because of static friction, conglutination, weariness of mechanic structure, the reliability and natural life of the MEMS switch are not as good as conventional PIN or FET switches. Through the general analysis of electricity and mechanics characteristics of the MEMS switches, A novel MEMS helix induction modulated switch working on 9GHz～20GHz is presented in this paper. The actuation voltage, insertion loss and isolation of the one circle helix structure switch are 12V, 0.89dB@9.5GHz, 31.4dB@9.5GHz, respectively.

Simulation of the MEMS switch mainly adopted Agilent ADS and HFSS soft etc. up to now there is no report about using the time-domain methods. The finite-difference time-domain (FDTD) method [3] is widely used for solving problems related to electromagnetism. As the tradition FDTD method is based on an explicit finite-difference algorithm, the Courant-Friedrich-Levy (CFL) condition must be satisfied when this method is used. Therefore, a maximum time-step size is limited by minimum cell size in a computation domain. In this paper, we first adopted the method of the alternating direction implicit finite-difference time-domain (ADI-FDTD) method [4] for a full three-dimensional (3-D) wave to Yee’s staggered cell to analyze and simulate the MEMS switch. The numerical method is unconditionally stable and is not dissipative [4,5]. Therefore, the time-step size can be arbitrarily set when this method is used. The limitation of the maximum the time-step size of the method does not depend on the CFL condition, but rather on numerical errors. Associated with practical switch model, Mur’s superabsorption boundary conditions are used in this paper. Numerical results manifested that the 3-D ADI-FDTD method was more efficient than the conventional finite element method (FEM). It consumedly reduced the CPU computation time.

2. Modulated helix induction mems switch

The layout of the modulated helix induction switch designed and its equivalent circuit in this paper is shown in Figure 1. In equivalent circuit, the CPW represents coplanarity wave-guide transmission line.

Figure 1. modulated helix inductance switch (a) planform (b) equivalent circuit.

|     |  |  |  |  |  |  |  |  |
|-----|---|---|---|---|---|---|---|---|
| N   | \(L_s/\text{pH}\) | \(R_s/\Omega\) | \(C_s/\text{pF}\) | \(C_{on}/\text{pF}\) | \(C_{off}/\text{pF}\) | \(L_b/\text{pH}\) | \(R_b/\Omega\) |
| 1   | 82.4 | 0.52 | 0.08 | 0.05 | 3.0 | 3.0 | 0.15 |
| 2   | 391.1 | 1.22 | 0.25 | 0.05 | 3.0 | 3.0 | 0.11 |
| 3   | 1059 | 1.86 | 0.52 | 0.05 | 3.0 | 3.0 | 0.08 |

C represents variable capacitor of the micromechanic switch. \(R_b\) and \(L_b\) represent the equivalent resistance and induction of the part of beeline girder upper electrode respectively. \(L_s\), \(R_s\) and \(C_s\)
represent the equivalent induction, resistance and capacitor of the part of helix structure upper electrode respectively. Through optimization design, the width of the CPW signal line is 196μm, and apart from the ground 120μm. The total size of the switch is about 900μm×1100μm. Al (thickness is 1.2μm) was selected as upper pole, the height of air cavity is 3μm, Si3N4 wafer (thickness is 300nm) was selected as the substrate medium of the switch. Computed equivalent circuit parameters with one, two and three circle helix structure of the switch are shown in Table 1.

3. 3-D ADI-FDTD algorithm

For \( E_x \) component, the numerical formulation of the ADI-FDTD method for a full 3-D wave is presented as follows. The electromagnetic field components are arranged on the cells in the same way as that using the conventional FDTD method. These formulations are available for homogeneous lossless medium and for using nonuniform cells. The calculation for one discrete time step is performed using two procedures.

First procedure, we can obtain the modified equation for \( E_x^{n+1/2} \) component by Maxwell equations:

\[
\begin{align*}
-\eta_1 E_x^{n+1/2}(i+1/2, j, k) + \frac{\varepsilon}{\Delta t} E_y^{n+1/2}(i+1/2, j, k) - \eta_3 E_z^{n+1/2}(i+1/2, j, k) & = \frac{\varepsilon}{\Delta t} E_x^n(i+1/2, j, k) \\
+\left[H_y^n(i+1/2, j, k) - H_y^{n+1/2}(i+1/2, j, k-1/2)\right]/\Delta y & -\left[H_y^n(i+1/2, j, k+1/2) - H_y^{n+1/2}(i+1/2, j, k+1/2)\right]/\Delta y \\
+\frac{\Delta t}{\mu} [E_x^n(i+1, j, k-1/2) - E_x^n(i, j, k-1/2)]/\Delta x & -\frac{\Delta t}{\mu} [E_x^n(i+1, j, k+1/2) - E_x^n(i, j, k+1/2)]/\Delta x \\
\end{align*}
\]

where

\[
\eta_1 = \frac{\Delta t}{\mu(\Delta x)^2}, \eta_2 = \varepsilon \Delta t, \eta_3 = \frac{\Delta t}{\mu(\Delta z)^2}
\]

In the same way, we can obtain the modified equation for \( E_y^{n+1/2} \) and \( E_z^{n+1/2} \) components.

Second procedure, the modified equation for \( E_x^{n+1} \) component by Maxwell equation:

\[
\begin{align*}
-\phi_1 E_x^{n+1}(i+1/2, j-1, k) + \phi_2 E_x^{n+1}(i+1/2, j, k) - \phi_3 E_x^{n+1}(i+1/2, j+1, k) & = \frac{\varepsilon}{\Delta t} E_x^{n+1/2}(i+1/2, j, k) \\
+\left[H_y^{n+1/2}(i+1/2, j, k+1/2) - H_y^{n+1/2}(i+1/2, j, k-1/2)\right]/\Delta y & -\left[H_y^{n+1/2}(i+1/2, j, k+1/2) - H_y^{n+1/2}(i+1/2, j, k-1/2)\right]/\Delta y \\
+\frac{\Delta t}{\mu} [E_x^{n+1/2}(i+1, j-1/2, k) - E_x^{n+1/2}(i, j+1/2, k)]/\Delta x & -\frac{\Delta t}{\mu} [E_x^{n+1/2}(i+1, j+1/2, k) - E_x^{n+1/2}(i, j-1/2, k)]/\Delta x \\
\end{align*}
\]

where

\[
\phi_1 = \frac{\Delta t}{\mu(\Delta y)^2}, \phi_2 = \varepsilon \Delta t, \phi_3 = \frac{\Delta t}{\mu(\Delta y)^2}
\]

the modified equation for \( E_y^{n+1} \) and \( E_z^{n+1} \) component can be obtained accordingly. By solving these simultaneous linear equations, we can get the values of the electric-field components at the time of \( n+1 \). Thereafter, we can get the values of the magnetic-field components at the time of \( n+1 \).

Since the simultaneous linear equations such as (1) and (3) can be written in a tridiagonal matrix form, and from formula (2) and (4), we can find that their coefficients on the left-hand side satisfy strict superiority on the cross. The 3-D ADI-FDTD algorithm is unconditionally stable.

In microwave circuit analysis, Gauss impulse is generally selected as an excitation for smoothness in time domain and easy spectrum width setting. The width of gauss pulse is \( T=20ps \), Assume that the time delay \( t_0=3T=60ps \), the response value of the frequency domain can be calculated by Fourier-transforming the time domain value. Associated with practical switch model, Mur’s superabsorption boundary conditions [6] are used in this paper.
The computed curves based computation domain $100 \times 120 \times 50$ and $\Delta x = \Delta y = 10\mu m$, $\Delta z = 0.08\mu m$, $\Delta t = 1.5ps$. For one, two and three circle helix structure switch, the simulation results through ADI-FDTD algorithm are shown in Figure 2 respectively. From Figure 2, we can find the simulation results through ADI-FDTD method are in good agreement with theoretic computed results (see Table 1). Figure 3 and Figure 4 are return loss for one circle helix structure switch with on or off state. The drifts between the theoretic value and the computed value by using ADI-FDTD and FEM(HFSS soft) are about 1.45%and 1.01% respectively. The CPU computation time of the ADI-FDTD method is 85 minutes, but the CPU computation time of the FEM is 1200 minutes. It efficiently reduces the computation time (only 7% for HFSS soft). Within numerical errors, we can select more long the time-step, so that saving more CPU time.

![Figure 2](image2.png)

**Figure 2.** ADI-FDTD Simulation of isolation about modulated helix inductance switch.

![Figure 3](image3.png)

**Figure 3.** Results of computed and simulated with switch on.

![Figure 4](image4.png)

**Figure 4.** Results of computed and simulated with switch off.
4. Conclusion
A modulated helix induction MEMS switch has been presented in this paper, its size approaches micrometer level. It performs excellently especially in miniaturization. ADI-FDTD method was used to model the structure of the switch. The algorithm of the method is unconditionally stable. Thus, the limitation of the maximum time-step size does not depend on the CFL condition, but rather on numerical errors. The fact that there is a good agreement between the ADI-FDTD computed value, FEM computed value and theoretic computed value manifests that the 3-D ADI-FDTD method is more efficient than the conventional FEM method. It efficiently reduced the CPU time.

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