IJICT International Journal of Information & Communication Technology

ITRC

Volume 3- Number 2 - March 2011 (19-25)

Optimization and Fully-Distributed Analysis of Single-Pole Single-Throw Traveling Wave Switchesat Millimeter Wave Frequency Band

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Received: November 27, 2010 - Accepted: January 29, 2010

Abstract—**In this paper, a fully distributed model for a single pole single throw traveling wave switch is introduced and important parameters of the switch such as insertion loss, isolation, and reflection coefficient are presented based on the lossy transmission line model of switch. The results of fully distributed model are compared with the semi-distributed model's results and have good agreement with them. By applying the fully distributed model and calculating various switch's parameters as a function of the switch length and operating frequency, the optimum switch length and operating frequency are obtained versus the parameters of switch, especially the reflection coefficient and isolation in OFF and ON conditions.**

Keywords-Distributed structure, single pole single throw (SPST) switch, traveling wave switch (TWSW), lossy transmission line model, semi-distributed model.

I. Introduction

Nowadays, the demand for millimeter wave applications such as high-speed wireless LAN systems, radar systems is growing rapidly and also there is a huge demand for microwave circuits to operate at higher and higher frequency to achieve larger bandwidth. On the other hand, there has been an enlarged demand for microwave integrated circuit application at higher frequencies caused by low fabrication cost and better operation at further frequencies.

In communication and radar systems, switches play a fundamental role to control the flow of RF signal in transmitters and receivers. In the above-mentioned applications, broadband switches with high power transfer capability and high switching speed, have a serious duty in realization of low-cost communication systems.

Given the wide range of applications involving millimeter wave circuits in high speed communication and the important role played by distributed switches in communication systems, there has been a huge amount of research carried out on various microwave switches to improve switch performance. Toward this end, there has been some research to improve parameters such as insertion loss and isolation. In multiple millimeter wave applications, various switch structures are reported in the literatures [1]-[6].

In [1], performance of a single pole single throw traveling wave switch is analyzed with a lossy transmission line model. A single pole double throw traveling wave switch using fully distributed FET has been developed and discussed in [2]. [3] indicates a switch structure, which has a shunt structure in connection with a quarter wavelength transformer. The switches designed with this type of structure have an insertion loss less than 1.5 dB and isolation greater than 25 dB in the frequency range from 59 GHz to 61 GHz. Another structure involves a series FET in parallel with an inductor. Such a switch has an insertion loss of 1.6 dB and an isolation of 20 dB at 94 GHz [4]. The parallel LC resonance structure, a capacitive stub and an inductor line, is another microwave switch structure. A switch made in this structure has an insertion loss of 3.9 dB and an isolation of 41 dB at 60 GHz [5]. Yet another switch circuit has the series-shunt structure using the ohmic electrode sharing technology (OEST). Such a switch has an isolation of more than 20.6 dB and an insertion loss of less than 1.64 dB; these structures have been presented and discussed in [6].

In this paper, first a fully distributed model of a single pole single throw traveling wave switch is introduced. The results of fully distributed model are compared with the sliced model's results. These results have a good agreement with each other. By adjusting the length of the switch, the optimum length to gain proper insertion loss, isolation, reflection coefficient and wide bandwidth is presented and discussed.

II. Circuit Structure

The schematic of a Single Pole Single Throw (SPST) Traveling Wave Switch (TWSW) is shown in Fig. 1. The gate voltage (Vg) controls the transfer of signal through the drain transmission line. In distributed switches, the switch's length is comparable to the wavelength of the maximum frequency of the circuit, so the wave transmission in this structure cannot be ignored. Therefore, lump modeling cannot analyze distributed structures. Instead, distributed modeling should be applied for the analysis of these elements.

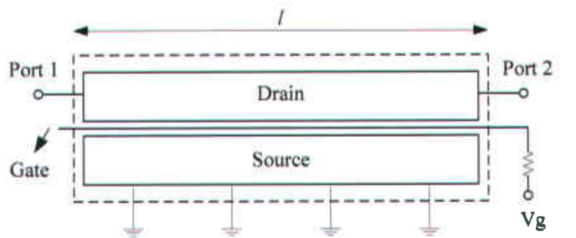

Fig. 1. Schematic of Single Pole Single Throw (SPST) Traveling Wave Switch (TWSW).

In semi-distributed modeling, the device is divided into N slices, which lump modeling is reliable for each segment. If the number of slices approaches infinity, then the semi-distributed analysis changes to fully-distributed modeling. The equivalent slice model of TWSW is shown in Fig. 2.

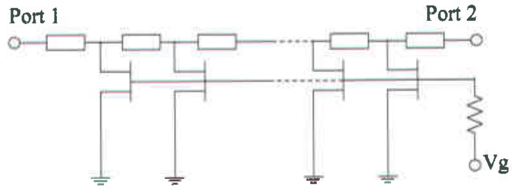

Fig. 2. Slice or semi-distributed model of TWSW.

III. Lossy Transmission Line Model

In distributed model of switch, by using the small-signal equivalent circuit as seen from drain terminal based on the FET model and the transmission line model of drain terminal, based on the control voltage (Vg) applied to gate, the lossy transmission line model of switch is resulted (Fig. 3).

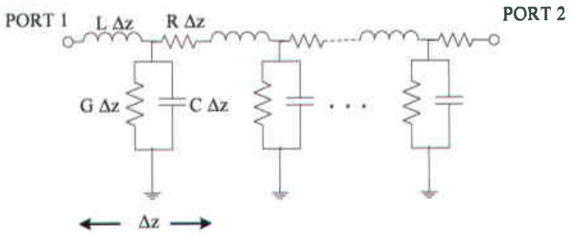

Fig. 3. The lossy transmission line model of TWSW.

Parameters of the transmission line model are combination of the equivalent admittance of the FET which is seen from Drain terminal and Drain TL parameters. The primary parameters of TL model are expressed as:

$$\begin{cases} R = R_{TL} \\ L = L_{TL} \\ C = C_{TL} + C_{FET}(V_g) \\ G = G_{FET}(V_g) \end{cases} \quad (1)$$

The secondary parameters of the transmission line, i.e., γ and Z, are calculated based on the primary parameters and are represented as [2]:

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \quad (2)$$

$$Z = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \quad (3)$$

Therefore, according to the controlling voltage (Vg), the secondary parameters of the switch are derived as:

$$\gamma = \alpha + j\beta \quad (4)$$
$$= \sqrt{(R_{TL} + j\omega L_{TL})(G_{FET}(V_g) + j\omega(C_{TL} + C_{FET}(V_g)))}$$

$$Z = \sqrt{\frac{R_{TL} + j\omega L_{TL}}{G_{FET}(V_g) + j\omega(C_{TL} + C_{FET}(V_g))}} \quad (5)$$

In these equations, R_{TL}, L_{TL} and C_{TL} are the series resistance and inductance and shunt capacitance of the drain transmission line per unit length, C_{FET} and G_{FET} are the shunt capacitance and conductance of the equivalent admittance of FET seems from Drain per unit length respectively. The values of C_{FET} and G_{FET} are dependent on status of the switch and controlling voltage. The series resistance R_{TL} is caused by the skin effect and is proportional to the square of frequency. R_{TL} can be expressed as [1]:

$$R_{TL} = \chi\sqrt{f} \tag{6}$$

The lossy transmission line model of the switch can be represented as a two port network (Fig.4).

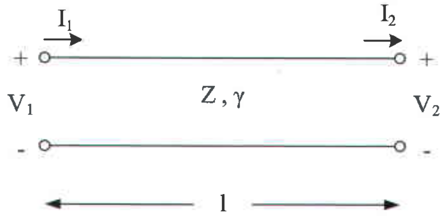

Fig. 4. Consider TWSW as a two port network.

The transmission matrix (ABCD Matrix) of switch is shown as:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cosh\gamma\ell & Z\sinh\gamma\ell \\ \frac{1}{Z}\sinh\gamma\ell & \cosh\gamma\ell \end{bmatrix} \tag{7}$$

Using the ABCD Matrix and the convergence of ABCD to scattering matrix, the S-parameters of the switch are derived as [2]:

$$S_{11} = \frac{(Z^2 - Z_0^2)\sinh\gamma l}{2ZZ_0\cosh\gamma l + (Z^2 + Z_0^2)\sinh\gamma l} \tag{8}$$

$$S_{21} = \frac{2ZZ_0}{2ZZ_0\cosh\gamma\ell + (Z^2 + Z_0^2)\sinh\gamma\ell} \tag{9}$$

As the values of C and G change in the ON and OFF states, the secondary parameters γ and Z change; thus the scattering parameters are dependent on the status of switch. The FET parameters, i.e. C_{FET} and G_{FET} are determined based on the Curtice 2 equivalent model of FET. The nonlinear elements of this model are expressed as [7]:

$$I_{ds}(V_{gs}, V_{ds}) = \beta(V_{gs} - V_{T0})^2(1 + \lambda V_{ds})\tanh(\alpha V_{ds})$$

$$C_{gs} = C_{gs0} \times \left(1 - \frac{V_{gs}}{V_{bi}}\right)^{-1/2} \tag{10}$$

$$C_{gd} = C_{gd0} \times \left(1 - \frac{V_{gd}}{V_{bi}}\right)^{-1/2}$$

The parameters of Curtice 2 model of FET for 100μm TWSW are shown in Table I.

Table I
Curtice 2 model's parameters for 100μm TWSW

Parameter	Value
β	0.0162 A/V^2
α	1.3 V^{-1}
λ	0 V^{-1}
V_{T0}	-2.35 V
C_{gs0}	12 fF
C_{gd0}	5.915 fF
C_{ds}	17.745 fF
V_{bi}	0.85 V

The diagrams of G_{FET} and C_{FET} versus V_{gs} for 100μm TWSW are shown in Figs. 5 and 6. The status of switch is controlled by the applying gate voltage. The switch transfers the signal through drain TL in ON state. In the OFF state, the switch behaves as short circuit and reflected the input signal and prevents from transmission of RF signal.

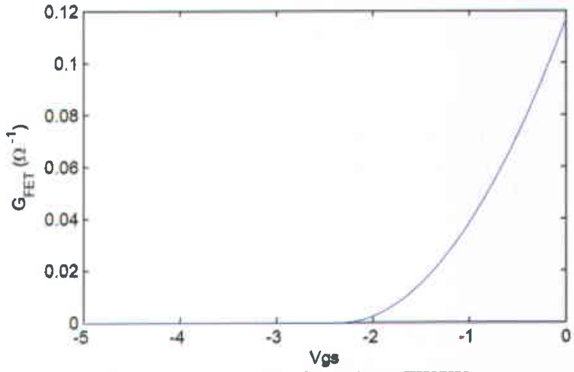

Fig. 5. G_{FET} versus V_{gs} for 100 μm TWSW.

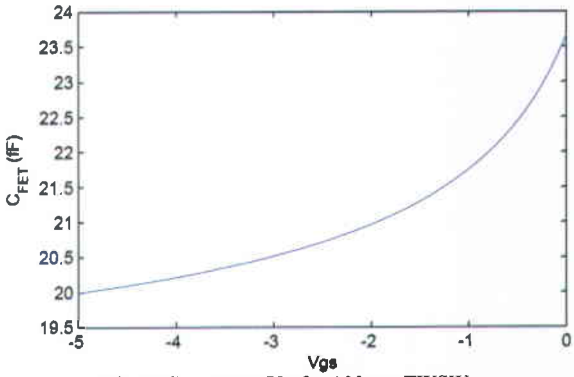

Fig. 6. C_{FET} versus V_{gs} for 100 μm TWSW.

The parameters of a Drain's transmission line for 100μm TWSW is listed in Table II [1]. Using the parameter values for 100 μm FET, the values of R, L, C and G per unit length are calculated.

Table II
Drain's TL parameters for 100 μm TWSW

Parameter	Value
χ	3.15×10^{-6} Ω/Hz$^{1/2}$
L_{TL}	40 pH
C_{TL}	7 fF

IV. Analysis Of Lossy Transmission Line Model

In this section, by using the scattering parameters S_{11} and S_{21}, the behavior of a 600 μm TWSW is studied versus control voltage and operating frequency. These parameters are shown in Figs. 7 and 8.

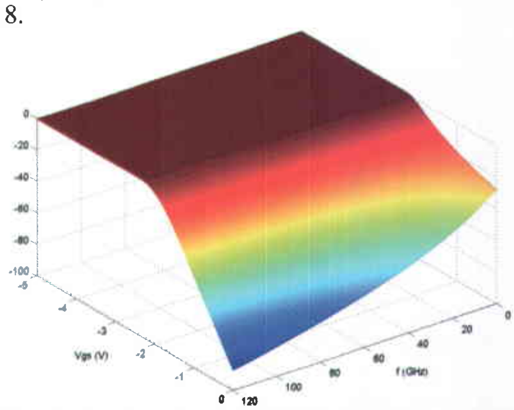

Fig. 7. Calculated S_{21} (dB) for 600 μm TWSW versus Control Voltage (V_{gs}) and operation frequency.

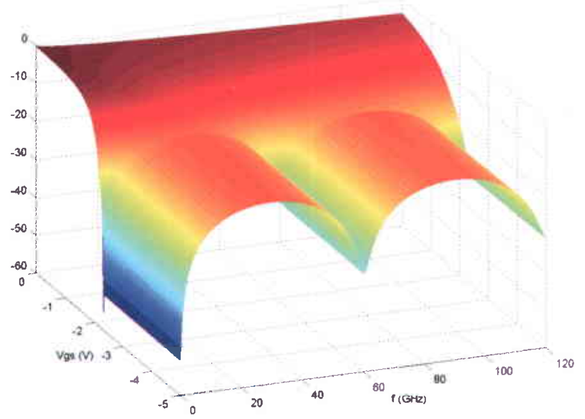

Fig. 8. Calculated S_{11} (dB) for 600μm TWSW in various Control Voltage (V_{gs}) and operation frequency.

In Fig. 9, the division of operating area is shown. The domain is divided to ON, OFF and transient regions based on the amplitude of S_{21}(dB) in that regions.

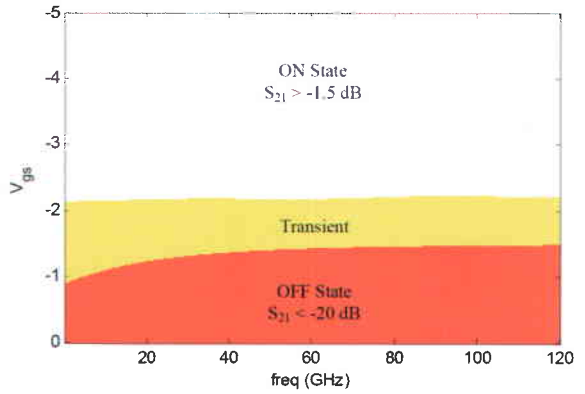

Fig. 9. Defined the ON and OFF region for 600 μm TWSW based on the S_{21} (dB).

In the ON state, S_{21}(dB) > -1.5dB, the switch passes the signal with low insertion loss, and in the OFF region, S_{21}(dB) < -20dB, the switch isolates the input and output terminates, and prevent the flow of RF signal. In the transient area, the behavior of TL is not suitable to act as a switch and must be prevented from operating in this region, thus the ON and OFF control voltages are selected as far as possible from the transient region, and the control voltage are selected as:

$$\begin{cases} V_{gs}(ON) = -5v \\ V_{gs}(OFF) = 0v \end{cases} \tag{11}$$

According to Figs. 7 and 8, in the ON state, V_{gs}=-5v, the signal transfers through the transmission line and reflected signal is low. In the OFF states, V_{gs}=0v, the switch prevents the transfer of signal and behaves like a short circuit and reflected a high ratio of incident signal.

In the next part of this section, the performance of a 600 μm TWSW is studied in ON and OFF states with fully distributed analysis, by applying the scattering parameters. The results are compared with the semi-distributed analysis of switch to validate. In sliced analysis, the switch structure is dividing into 20 equal slices each with a 30 μm length. These results are shown in OFF and ON status in Figs. 10 and 11.

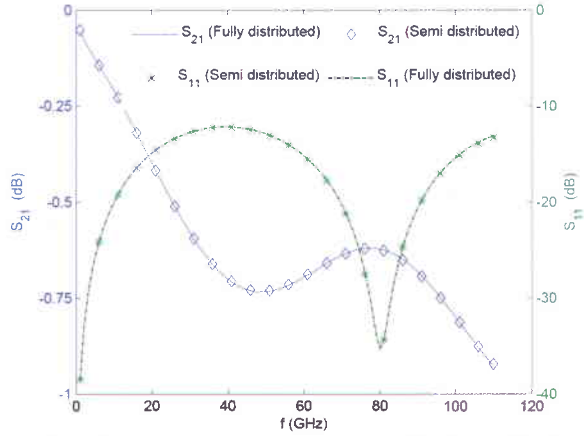

Fig. 10. Calculated insertion loss and reflection coefficient for 600μm TWSW in ON state using scattering parameters and sliced modeling.

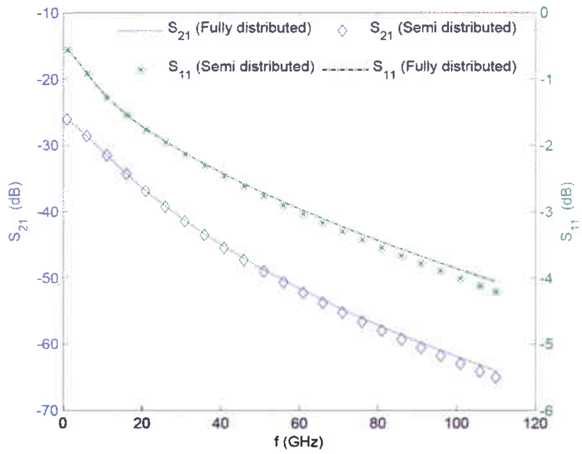

Fig. 11. Calculated isolation and reflection coefficient for 600 μm TWSW in OFF state using scattering parameters and semi-distributed modeling.

As seen in Figs. 10 and 11, the results of the fully distributed model and sliced model are in close agreement with each other in ON and OFF status and the fully distributed model is validated.

In the last part of this section, the behavior of switch is studied as a function of the length of switch and operating frequency. According to Figs. 12 and 13, in OFF state, the reflection coefficient is better in small length and isolation is closer to desired value in large switch length; therefore, a tradeoff between these parameters needs to be done. As the reflection coefficient changes are negligible, the isolation is chosen as the principal parameters in OFF state.

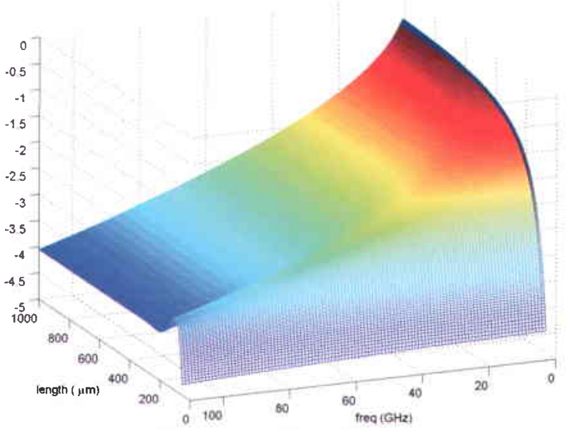

Fig. 12. S_{11} (dB) in OFF state.

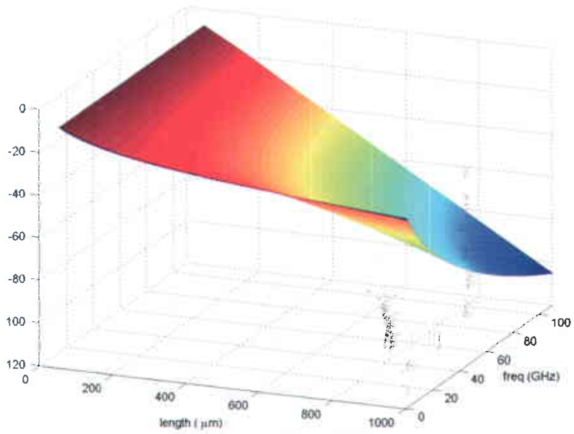

Fig. 13. S_{21} (dB) in OFF state.

Figs. 14 and 15, indicate that the insertion loss is satisfactory in the ON state, thus the reflection coefficient is the main parameter in the ON state. Thus, the important parameters in optimization of TWSW are isolation (S_{21}(OFF)) and reflection coefficient in ON state (S_{11}(ON)).

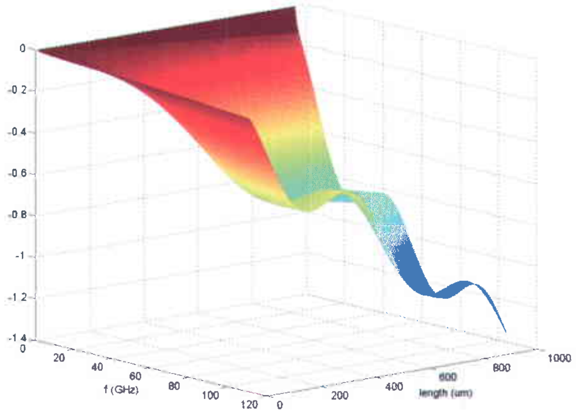

Fig. 14. S_{21} (dB) in ON state.

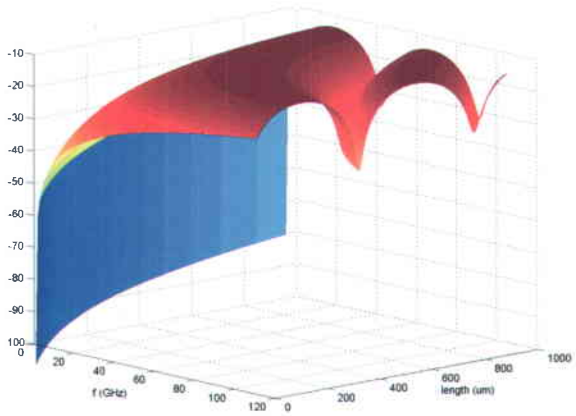

Fig. 15. S_{11} (dB) in ON state.

V. Optimization Of Switch Performance

The scattering parameters of the switch, i.e., S_{11} and S_{21}, are functions of the length of drain transmission line. In this section, S_{11} and S_{21} are calculated at various frequencies and switch lengths, and the optimum switch length is achieved based on desired isolation and reflection coefficient.

S_{11} and S_{21} as a function of frequency and switch length in OFF and ON states are illustrated in Figs. 12-15. Figs. 16 and 17 indicate the frequency and length domain division based on isolation and reflection coefficient in the ON state. Fig. 18 displays the composition of two figures.

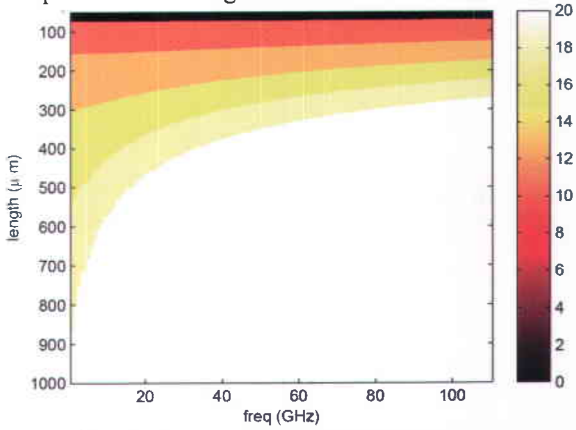

Fig. 16. Division of domain based on S_{21} (OFF).

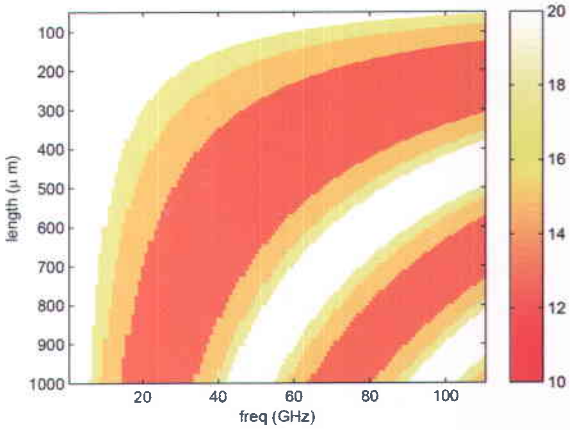

Fig. 17. Division of domain based on S_{11} (OFF).

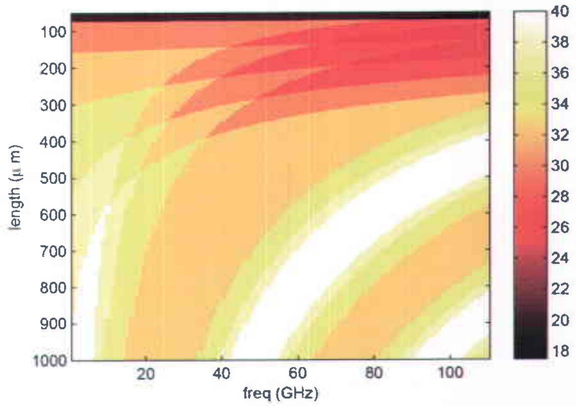

Fig. 18. The combination of two divisions of domain.

Table III is suggested for optimization. The domain is separated based on the value of S_{11}(ON) and S_{21}(OFF), and finally the region that has the highest value is chosen as the optimum zone.

Table III
The division of domain by mapping the value and weight to the regions, based on S_{21}(OFF) and S_{11}(ON).

Value	S_{21} (OFF)	S_{11}(ON)
20	S_{21} (OFF) ≤ -30 dB	S_{11} (ON) ≤ -20 dB
17.5	S_{21} (OFF) ≤ -25 dB	S_{11} (ON) ≤ -17 dB
15	S_{21} (OFF) ≤ -20 dB	S_{11} (ON) ≤ -14 dB
12.5	S_{21} (OFF) ≤ -15 dB	S_{11} (ON) ≤ -11 dB
10	S_{21} (OFF) ≤ -10 dB	S_{11} (ON) ≤ -8 dB
0	S_{21} (OFF) ≥ -10 dB	S_{11} (ON) ≥ -8 dB

Considering the acceptable range of parameters and the classification of the domain, the optimum region is achieved from Fig. 18. Three light regions have reflection coefficient in ON state less than -20 dB and isolation more than 30 dB, therefore according to operating frequency the best optimum region is chosen. For example, the optimum length of switch to achieve the biggest bandwidth is 800 µm at 60 GHz. The scattering parameters of 800 µm TWSW in ON and OFF states are shown in Figs. 19 and 20.

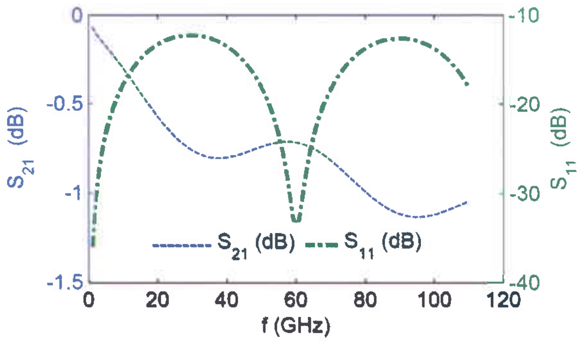

Fig. 19. The insertion loss and reflection coefficient for 800 µm TWSW in ON state.

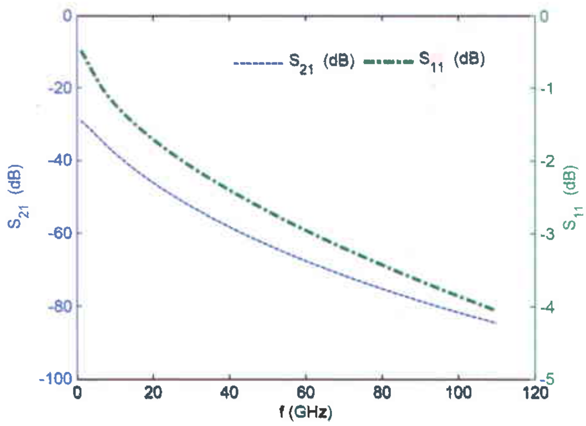

Fig. 20. The isolation and reflection coefficient for 800 µm TWSW in OFF state.

As it can be observed in Figs. 19 and 20, the switch has a small insertion loss in wide frequency range in the ON state and a proper isolation in the OFF state, in which case switch almost does not transfer any signal through drain transmission line and behaves like a short circuit and reflects RF signal. Of course, different considerations in practice decrease this bandwidth, but altogether the distributed structure is ideal for reaching wide bandwidth.

VI. Conclusion

With growing operating frequencies and as the switch lengths are becoming comparable with wavelength; lump modeling cannot describe the behavior of structures properly. Therefore, the requirement for fully distributed modeling with consideration of wave transmission in the structure is becoming obvious. Also, because of the wave transmission effects, the operation of the switch is intensely related on the frequency and structure dimensions. Therefore, the effect of distribution, the length of switch has an important effect on the behavior of the system. The switch parameters have been calculated versus frequency and switch length, and given acceptable values for the parameters, the optimum length of switch has been achieved.

Acknowledgment

The authors wish to acknowledge the Iran Telecommunication Research Center (ITRC) for supporting this research.

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