DESIGN OF A 90^0 SWITCHED LINE PHASE SHIFTER FOR PHASED ARRAY ANTENNAS

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Abstract

Phase shifters are considered as the most vital subsystem for an antenna in any transceivers or RADARs. As the name suggests that, these components provide phase shift for the input signal, with respect to the reference signal at its output without any loss or modifications in the amplitude of input. In this work, an attempt has been made to design a 90^0 phase shifter based on switched line type. The phase shifter is designed to implement on a microstrip circuit type. The frequency considered for the operation is 1 GHz. Agilent's ADS (Advanced Design Simulation) software tool was used for designing and simulating the switched line phase shifter. The ADS software is widely used for designing and the simulation of microwave circuits and its components. Initially the circuit was designed with ideal switch models, which are readily available in ADS. Then independent single pole double throw switches were designed and simulated again. Parameters like return loss and insertion loss were considered as main parameters and then the designs were optimized to achieve the best possible return loss and insertion loss.

***Keywords** - Phase shifters, SPDT switches, Switched line.*

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1. INTRODUCTION

The phase of an electromagnetic wave of a given frequency can be shifted when propagating through a transmission line by the use of Phase Shifters [1]. In the field of electronics, it is often necessary to change the phase of the signals. RF and Microwave Phase Shifters have many applications in various equipments such as phase discriminators, beam forming networks, power dividers, linearization of power amplifiers and phase array antennas [2].

Phase Shifters can be separated into two categories: Reciprocal and Non-Reciprocal [3]. The reciprocal phase shifter is not directionally sensitive, which means that the phase shift in the direction of both transmit and receive is same. Therefore, with the of use reciprocal phase shifters, switching of phase states between transmit and receive is not required. On the other side with the use of a nonreciprocal phase shifter, switching of phase states between transmit and receive is required.

Optimal transmitting and receiving properties are required to be provided by the modern radio communication systems for an effective utilization of transmission channels. Thus focusing on the antennas, this requires electronically steerable radio patterns, that can be achieved by the phased array antennas [4]. One of the most important part of the phased array antennas are the phase shifters. Differential signal phase shift of antenna's will be determined by the phase shifters. "Switched-line Phase Shifter" [5] is one of the most important type of Phase Shifter based on the diodes and their phase shift corresponds to the length difference between two switched transmission lines [4]. Thus by changing the bias point of a pin-diode from forward to reverse direction and vice versa, the switching procedure is obtained. Digital-to-Analog conversion is not required because the phase shift can be controlled digitally with the use of this method.

2. MOTIVATION

In the area of applications like phased array antennas and communication antennas, there is a need of beam forming configurations for effectively having a directional radiation of electromagnetic waves. This can be achieved by using multiple antenna radiating elements with varied phase inputs of signal rather than using single element. In such cases the phase shifters come into play as the name suggests shifting the phase of the input signal to required amount. Also, in the Defence areas where RADARs are used to the great extent in finding the enemy's path and to detect early warnings of any threat, the RADAR system must itself be concealed from the enemies. So in such scenarios static radar with electronic beam steering offers more stealth compared to conventional mechanical beam steering RADARs. Due to these reasons an attempt has been made to study and design a 90^0 switched line phase shifter.

The objectives of this work is to design a 90^0 switched line phase shifter for phase shifting purpose and to design the circuit keeping in mind for implementation on micro strip line on a standard FR-4 substrate. For this we simulate and design its operation on Agilent's Advanced Design System software. Some of the specifications of the microwave 2-port device that were considered for the design are: Operating frequency of 1 GHz, Return loss better than 20 dB, Insertion loss ranging within -1 to 0 dB.

3. MICROSTRIP LINES

Microstrip transmission lines consists of a conductive strip of width "W" and thickness "t" and a wider ground plane, separated by a dielectric layer (a.k.a. the "substrate") of thickness "H" [6] as shown in the fig 1. Especially for microwave integrated circuits and MMICs, the most popularly used microwave transmission line is Microstrip and the major advantage of microstrip over stripline is that all active components can be mounted on top of the board.

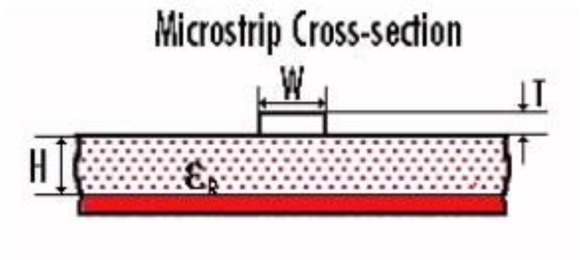

Fig 1 Microstrip line

The design equations associated for the design of microstrip lines is given as

For, $\left(\frac{W}{H}\right) \geq 1$

$$\varepsilon e = \frac{\varepsilon+1}{2} + \frac{\varepsilon-1}{2}\left(\frac{1}{\sqrt{1+12\left(\frac{H}{W}\right)}} + 0.04\left(1-\left(\frac{H}{W}\right)\right)^2\right). \qquad (1)$$

Where ε is substrate permittivity and ε_e is effective permittivity.

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon e}\left[\frac{W}{H}+1.393+\frac{2}{3}\ln\left(1.444+\frac{W}{H}\right)\right]}\ ohms. \qquad (2)$$

Where Z_0 is characteristic impedance.

From the equations 1&2, for the specification of using FR-4 substrate that carries permittivity of 4.8 and also considering the market availability of 0.06 in standard thickness substrate, we perform the calculations. So H = 0.06 in = 1.5 mm W=3 mm.

The values are assumed, so that the W/H ratio is more than 1 for design and simplification of calculation. Below is the table 1 representing microstrip line dimensions for ease of understanding the iterations carried out to get proper values of W and H for 50 ohms characteristic impedance.

Table.1. Microstrip line dimensions

W(mm)	H(mm)	W/H	Permittivity	Z_0(ohms)
3	1.5	2	3.618	46.98
3	1	3	3.75	36.133
1.8	1	1.8	3.586	50.044

Thus the final dimensions taken are depicted in the below fig 2.

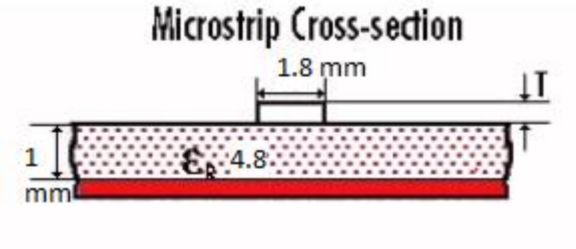

Fig.2 Microstrip line dimensions

4. PHASE SHIFTERS

Phase shifters find numerous applications in testing and measurement systems, but the most significant use is in phased array antennas. Where the antenna beam can be steered in space by electronically controlled phase shifters.

There are basically three types of PIN diode phase shifters:

- Switched line,
- Loaded line, and
- Reflection.

The basic schematic of switched-line phase shifter is shown in the below fig 3, which is the most straightforward type using two, Single Pole Double Throw (SPDT) switches to route the signal flow between one of two transmission lines of different length. The differential phase shift between the two paths is given by the equation 3.

$$\Delta\Phi=\beta(l_2 - I_1) \qquad (3)$$

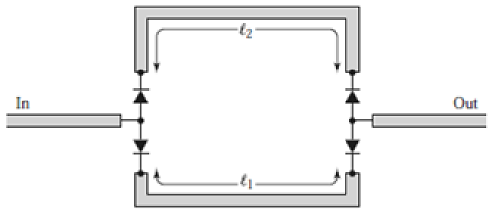

Fig.3. Basic schematic of switched line phase shifter

Where, β is the propagation constant of the line. If the transmission lines are TEM (or quasi-TEM, like micro strip), this phase shift is a linear function of frequency which implies a true time delay between the input and output ports. The insertion loss of the switched line phase shifter is equal to the loss of the SPDT switches plus line losses. The switched-line phase shifter is usually designed for discrete binary phase shifts of $\Delta\varphi$= 180◦, 90◦, 45◦, etc.

5. DESIGN AND IMPLEMENTATION

Advanced Design System (ADS) [7] is an electronic design automation software system developed by Agilent EEsof EDA a unit of Agilent Technologies now formally called as Keysight Technologies. It provides an integrated design environment to designers for RF electronic products such as mobile phones, pagers, wireless networks, satellite communications, radar systems, and high-speed data links.

The following procedure is used for the design of a 90 degree switched line phase shifter for the simulation:

- Initially started with design of suitable microstrip line dimensions based on availability from market so widely available substrate FR-4 was chosen with 1mm of thickness.
- Corresponding microstrip line design equations were employed to come up with width of the line.
- Based on basic schematics of switched line phase shifter a design consisting of measured width for the microstrip line and line difference for phase shift was carried out.
- The above mentioned design was completed using ideal SPDT switch that was available inbuilt in ADS tool.
- Its return loss and insertion loss were taken down after the simulation and plotted.
- Then a design of SPDT switch was performed using the specifications of already available discrete electronic component of PIN diode that is vital for switch design.
- The PIN diode MA4PH301 from MAcom technologies was used as reference for the new switch design where the actual PIN diode's specifications were fed into the ADS tool for further analysis.
- The corresponding circuitry for the SPDT switch was designed along with required DC blocking capacitors and chokes to operate at a frequency of 1 GHz.
- Further optimizations were done on the values of RF chokes and DC blocking capacitors using repeated simulations using ADS inbuilt optimization tool.
- Finally the return loss and insertion loss values were plotted and readings were recorded.

Design of Basic Phase Shifter

As a first step in modelling, the standard switched line phase shifter has been modelled in ADS with the dimensions line difference of 3.423 cm. The analysis setup has been made for the frequency range 500 MHz -1.5 GHz. Return loss parameters are simulated. The simulated return loss is better than 30 dB at the 1 GHz frequency. The phase shifter modelled in ADS and simulated return loss is shown in fig 4 and 4.1 respectively.

The figure 4 shows the basic design of switched line phase shifter using ADS's inbuilt SPDT switch and note that two options like S parameter simulation for return loss and insertion loss and transient simulation block for time domain results is seen and the phase shift of output waveforms are also employed.

The fig 4.1 indicates the ideal values observed for the design of phase shifter to give a phase shift of 90 degrees. As seen in circuit diagram the ideal SPDT switched employed, so the graph gives a quite linear curve in either cases delivering good return loss more than 30 dB and good insertion loss maintained at less than 1 dB.

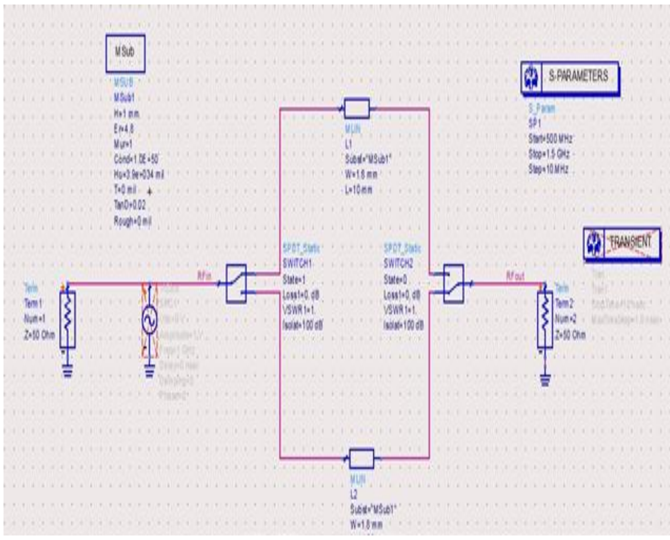

Fig. 4 Switched line phase shifter model on ADS

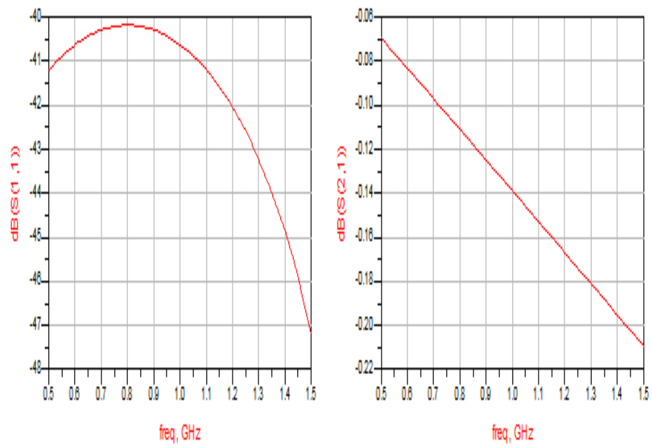

Fig 4.1 Switched line phase shifter return loss(left) and insertion loss(right)

Design of Phase Shifter Based on Real SPDT Switch

As a second step in modeling, the standard switched line phase shifter for 90 degrees was designed again using real design based on PIN diodes whose part number is MA4PH301-146 from MA com technology. The design of SPDT switch involved usage of two of those PIN diodes. The PIN diode's specifications like reverse voltage, minimum operating frequency, total capacitance, series resistance and delay time was entered in ADS tool to customize the given PIN diode for modeled SPDT switch is depicted in fig 5 below.

The complete schematic of Switched line phase shifter for 90 degrees phase shift is shown in the fig 6a and 6b. As it can been seen that there are 4 PIN diodes used 2 each for an SPDT switch and corresponding DC blocking capacitors and RF chokes. The circuit diagram is split into two part for better understanding, as single diagram is large in dimension on a single page.

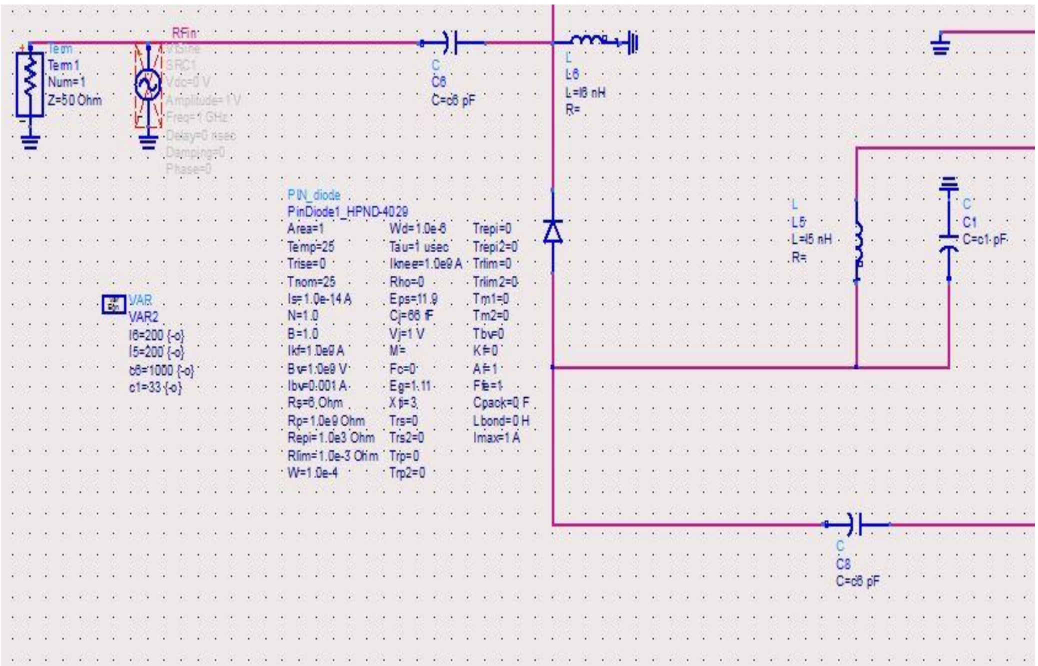

Fig 5 SPDT switch using PIN diode with specifications

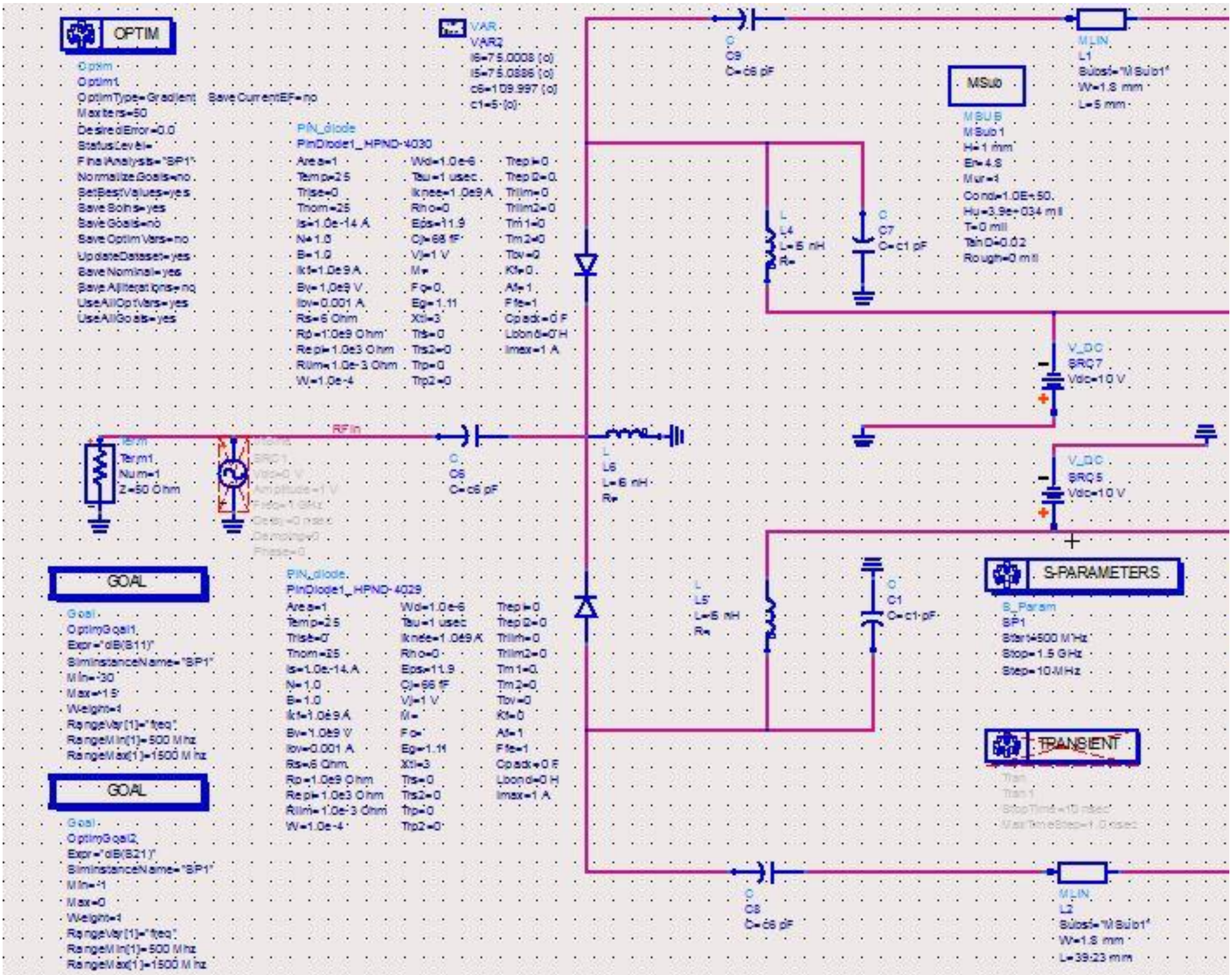

Fig. 6a Final circuit schematic

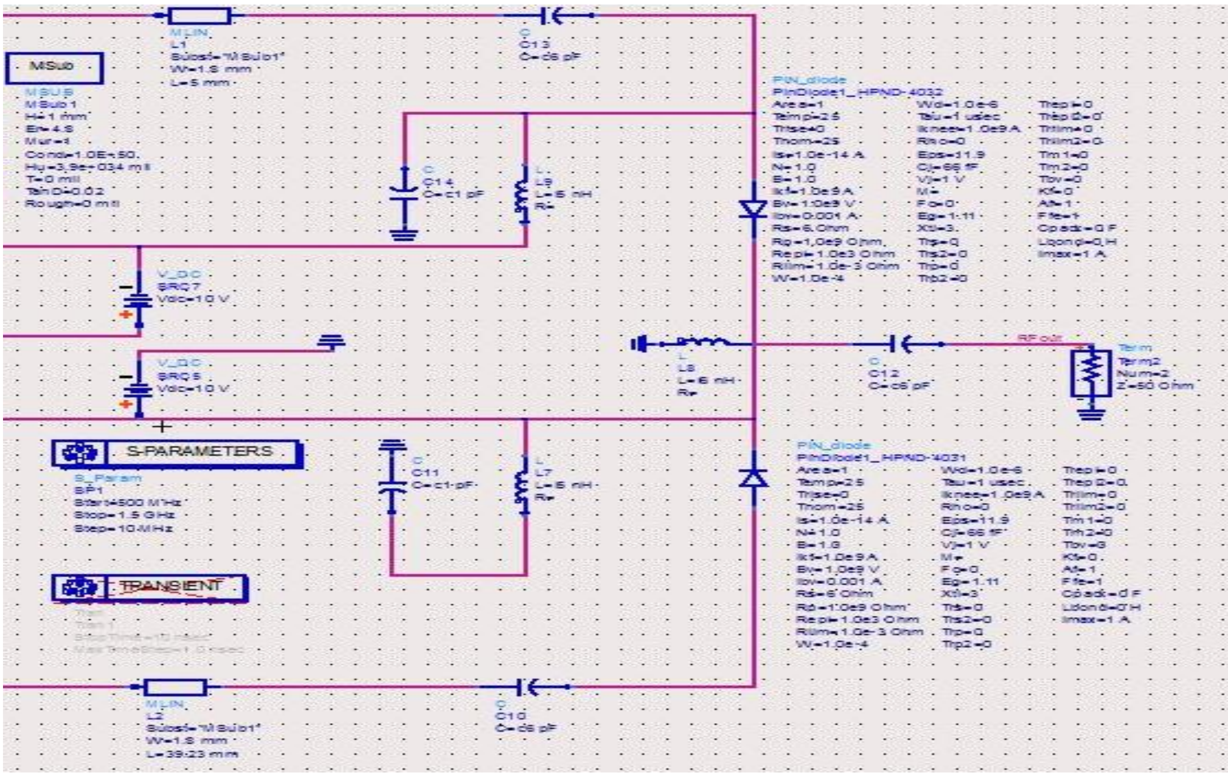

Fig.6b. Final circuit schematic

Next the results based on S parameters are summarized and got an -21.22 dB of return loss and 0.806 dB of insertion loss which were the targeted specification and performance to achieve at the beginning. The wave forms are shown in fig 7 which chows steep dip at 1 GHz of frequency for return loss and an insertion loss less than 1 dB at the targeted frequency.

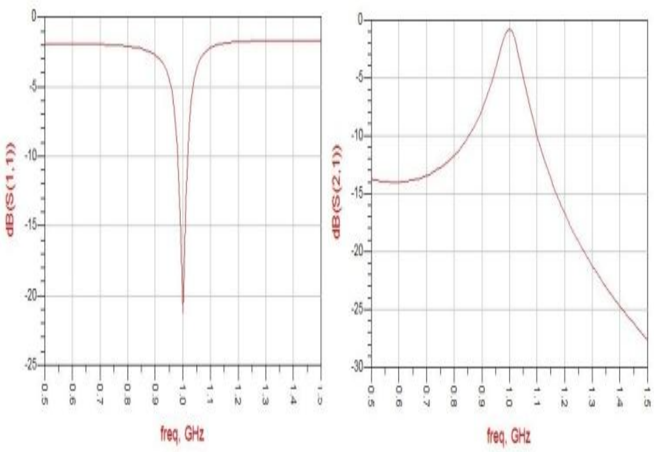

Fig.7 Final Switched line phase shifter return loss (left) and insertion loss (right)

And a diagram of tabulated values observed throughout the simulation is as shown in the table 2 and is given for reference based on which the graphs are displayed above.

Table.2. Tabulated values from simulation for return loss (left) and insertion loss (right)

freq	S(2,1)
500.0 MHz	-13.748 / -81.217
510.0 MHz	-13.808 / -81.570
520.0 MHz	-13.861 / -81.917
530.0 MHz	-13.905 / -82.260
540.0 MHz	-13.943 / -82.597
550.0 MHz	-13.973 / -82.932
560.0 MHz	-13.995 / -83.264
570.0 MHz	-14.010 / -83.594
580.0 MHz	-14.017 / -83.923
590.0 MHz	-14.017 / -84.251
600.0 MHz	-14.008 / -84.580
610.0 MHz	-13.992 / -84.911
620.0 MHz	-13.967 / -85.243
630.0 MHz	-13.934 / -85.579
640.0 MHz	-13.892 / -85.919
650.0 MHz	-13.841 / -86.263
660.0 MHz	-13.781 / -86.614
670.0 MHz	-13.712 / -86.972
680.0 MHz	-13.633 / -87.338
690.0 MHz	-13.543 / -87.715
700.0 MHz	-13.443 / -88.103
710.0 MHz	-13.332 / -88.504
720.0 MHz	-13.210 / -88.920
730.0 MHz	-13.075 / -89.353
740.0 MHz	-12.927 / -89.805
750.0 MHz	-12.766 / -90.280
760.0 MHz	-12.590 / -90.781
770.0 MHz	-12.399 / -91.310
780.0 MHz	-12.192 / -91.873
790.0 MHz	-11.967 / -92.474
800.0 MHz	-11.724 / -93.119
810.0 MHz	-11.460 / -93.815
820.0 MHz	-11.175 / -94.571
830.0 MHz	-10.865 / -95.396
840.0 MHz	-10.530 / -96.302
850.0 MHz	-10.167 / -97.306
860.0 MHz	-9.772 / -98.425
870.0 MHz	-9.343 / -99.683
880.0 MHz	-8.876 / -101.111
890.0 MHz	-8.367 / -102.746
900.0 MHz	-7.812 / -104.641
910.0 MHz	-7.206 / -106.863
920.0 MHz	-6.544 / -109.500
930.0 MHz	-5.822 / -112.676
940.0 MHz	-5.039 / -116.556
950.0 MHz	-4.198 / -121.365
960.0 MHz	-3.318 / -127.396
970.0 MHz	-2.437 / -135.002
980.0 MHz	-1.634 / -144.519
990.0 MHz	-1.039 / -156.050
1.000 GHz	-0.806 / -169.136
1.010 GHz	-1.037 / 177.374
1.020 GHz	-1.701 / 164.851

freq	S(1,1)
500.0 MHz	-1.938 / -171.131
510.0 MHz	-1.935 / -171.501
520.0 MHz	-1.931 / -171.864
530.0 MHz	-1.928 / -172.223
540.0 MHz	-1.926 / -172.578
550.0 MHz	-1.924 / -172.930
560.0 MHz	-1.922 / -173.279
570.0 MHz	-1.921 / -173.627
580.0 MHz	-1.921 / -173.974
590.0 MHz	-1.920 / -174.322
600.0 MHz	-1.921 / -174.670
610.0 MHz	-1.921 / -175.020
620.0 MHz	-1.923 / -175.373
630.0 MHz	-1.924 / -175.730
640.0 MHz	-1.926 / -176.092
650.0 MHz	-1.929 / -176.460
660.0 MHz	-1.932 / -176.835
670.0 MHz	-1.936 / -177.218
680.0 MHz	-1.940 / -177.611
690.0 MHz	-1.946 / -178.015
700.0 MHz	-1.951 / -178.433
710.0 MHz	-1.958 / -178.865
720.0 MHz	-1.966 / -179.314
730.0 MHz	-1.975 / -179.783
740.0 MHz	-1.985 / 179.726
750.0 MHz	-1.996 / 179.210
760.0 MHz	-2.009 / 178.666
770.0 MHz	-2.023 / 178.088
780.0 MHz	-2.040 / 177.474
790.0 MHz	-2.059 / 176.816
800.0 MHz	-2.081 / 176.109
810.0 MHz	-2.106 / 175.344
820.0 MHz	-2.135 / 174.512
830.0 MHz	-2.169 / 173.602
840.0 MHz	-2.209 / 172.600
850.0 MHz	-2.257 / 171.489
860.0 MHz	-2.313 / 170.247
870.0 MHz	-2.382 / 168.846
880.0 MHz	-2.465 / 167.253
890.0 MHz	-2.570 / 165.421
900.0 MHz	-2.701 / 163.291
910.0 MHz	-2.871 / 160.782
920.0 MHz	-3.094 / 157.785
930.0 MHz	-3.397 / 154.147
940.0 MHz	-3.819 / 149.650
950.0 MHz	-4.430 / 143.976
960.0 MHz	-5.355 / 136.646
970.0 MHz	-6.833 / 126.876
980.0 MHz	-9.374 / 113.051
990.0 MHz	-14.257 / 89.173
1.000 GHz	-21.222 / 4.563
1.010 GHz	-13.221 / -69.120
1.020 GHz	-8.477 / -92.358

6. CONCLUSIONS AND FUTURE SCOPE

Successfully modelled the 90 degree switched line phase shifter using own design of SPDT switch at 1 GHz operating frequency. Return loss obtained were well within the target values namely -21.22 dB and insertion loss less than 1 dB in magnitude where we got 0.806 dB. Valuable insight on design using Agilent's ADS tool was gained and technically understood the methods and procedures for optimizing the microwave circuits. Future scope will include the designed schematic can be implemented practically on further optimizations using discrete components on a circuit board.

The discrete components can be converted to stub elements and radial stubs to make it friendly to implement in the form of microstrip circuitry and further optimizations can be processed to reduce the complexity and size.

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