A 5-bit RF MEMS Switch Time Delay Line Shifter

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Abstract - A 5-bit radio frequency micro-electromechanical system (RF MEMS) true-time-delay (TTD) phase shifter operating over frequency ranges 6-12 GHz is designed and fabricated. The TTD phase shifter provides five delay bits: 2λ, 4λ, 8λ, 16λ, the biggest delay-bit time is 1680ps and the total time delay is 3255ps. The circuit uses twenty cantilever RF MEMS switches. The circuit is fabricated on four layers by using microwave multilayer printed circuit board technology (PCB). Measurements show that the return loss of every delay-bit is better than 12dB across the entire band and the insert losses are between -8dB and -10dB for all states. The circuit has high linearity of phase response across the entire band.

Index Terms—true-time-delay line (TTDL) phase shifter, micro-electromechanical system cantilever switch, RF MEMS switch time delay line (STDL) shifter, microwave multilayer printed circuit board.

1. Introduction

Recently, broadband electronically steerable array antennas have been rapidly developed and successfully employed in some applications, such as the broadband radar system, double-frequency-band radar and so on. Conventionally, ultra-broadband phased-array radars need a lot of wideband technologies, such as broadband phased-array antenna, reconfigurable switch-network, all kinds of broadband devices and so on.[1] especially broadband switch time delay line (STDL) shifter. STDL shifter is previously fabricated by employing the semi-conduction technology. But the non-linearity of PIN diodes limits the bandwidth of devices. Now RF MEMS switch is to implement STDL shifter which provides better performance than the array with the conventional semi-conductor technology in terms of (low) loss, (high) linearity, (flat) delay and (small) size. So MEMS STDL shifter meets the long delay and broadband performance.

Since 1998, the first RF MEMS shifter was reported numerous research efforts have been presented in the literature.[2][3] The kinds include switched line,[2] reflect-line,[3] quasi-lumped element approaches[3] and distributed transmission line.[4] However, RF MEMS time delay shifters are few, especially the large time delay shifters. In 2006, a 6-bit RF MEMS time delay circuit with 393.75ps total time delay was presented.[5] The circuit die size is 27mmx14mm. A fully packaged RF MEMS 4-bit, only 100ps-time-delay shifter was reported and its return losses are better than 8dB.[6] In 2008, a MEMS long time delay circuit in multi-layer liquid crystal polymer films was designed. Its true time delay components produce 0ps, 200ps, 400ps, and 600ps relative delays.[7] So far a most significant time delay bit of 16λ hasn’t been researched and presented yet.

In this paper, we present the fabrication and design of a large time delay circuit with 3255ps total time delay, and the most significant time delay of 1680ps over ranges 6-12GHz. Comparing with the time-delay of Ref [8], our delay is nearly three times and the size is only 25mmx4mm x2.5mm which comprises five bits (λ, 2λ, 4λ, 8λ and 16λ). The circuit which using 20 RF MEMS cantilever switches is distributed in four layers PCB. This paper presents the circuit fabrication, design techniques, simulated performance and experimental results.

2. The design of RF MEMS switch

(1) The theory of design

The sketch of 5-bit true-time-delay line (TTDL) shifter is shown in Fig.1. The time delay circuit is realized using 5-bit time delay sections (λ, 2λ, 4λ, 8λ and 16λ). Each section has four RF MEMS switches and two micro-strip transmission lines. MEMS switches are used to routing the input RF signal into transmission lines with the appropriate delay length. The time delay is obtained by switching a pair of MEMS switches to turn on any transmission line. The different line-length represents the different phase and the difference of two delay phases is the desired time delay. The time delay of each bit is given by Eq.1:

\[
\Delta \Phi = 2 \pi f \frac{\lambda}{v_p} \left( t_2 - t_1 \right)
\]

Where \( \lambda \) is wavelength of the RF signal, \( v_p \) is phase velocity, \( t_2 \) and \( t_1 \) are the lengths of delay line and reference line respectively. \( \Delta \Phi \) is the designed time delay.

Fig.1 The sketch of 5-bit RF MEMS TTDL shifter

The five bit sections are designed separately for the desired time delay and then combined. Our design provides the best balance among low-loss, a minimum return loss, flat delay response and circuit complexity of all states.

(2) 5-bit time delay shifter design

We design a 5-bit true-time-delay line (TTDL) shifter which including time delays of \( \lambda, 2\lambda, 4\lambda, 8\lambda \) and \( 16\lambda \), respectively. The shifter can produce 32 kinds of states time-delay. All bits are connected in series by means of two RF MEMS single-polo-double-throw switch (SPDT switch). By selecting different states of SPDT switch, 32 kind states of STDL shifter can be realized. At last the total time delay of 3255ps can be achieved. Rogers Duroid 5880 with
thickness of 250μm and εr of 2.2 has been chosen as the substrate. The lengths of delay lines are determined by Eq.1. The simulated results are shown in Fig.2. Both the input and output return loss for “0” states are less than 20dB, and both the input and output return loss for all “1” states are less than 17dB. For all combinations of “0” and “1” states, the input and output return losses for 32 states exceed 20dB over frequency ranges from 6GHz to 10.5GHz. Because of its complexity of curves, we don’t show them one by one.

3. Fabrications

The 5-bit MEMS STDL shifter circuit as shown in Fig.3 is distributed in four layers PCB by multilayer PCB laminating technology. First, the circuit is deposited on the dielectric laminate layer. All the MEMS switches are mounted on the first layer. Then the semi-solidified-plate is etched to the next ground layer. The two other laminate layers with alternating low and high temperatures are placed into a lamination press. Last plated through holes are formed to provide common ground layer interconnections. The 5-bit MEMS STDL shifter forms 25mm x 4mm x 2.5mm multilayer PCB.

4. The experiment results

The STDL shifter circuit was measured within 6-12GHz using a network analyser. The time delays of 32 states were measured. The measured time delays for five states of λ, 2λ, 4λ, 8λ, and 16λ are shown in Fig.4. All of the time delay errors for central frequency are less than 3.2ps. Delay errors can be corrected by adjusting the delay lines.

5. The experiment results

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Fig.2 The input and output return loss for all “0”/“1” states

Fig.3 The 5-bit MEMS STDL shifter and MEMS cantilever switch

The twenty MEMS switches in the circuit are metal-to-metal cantilever series switches. The switches are fabricated on 200μm-thick silicon substrate as shown in Fig.3. A layer of silicon oxide with 1-um-thickness is grown on the substrate. The size of switch is 1mm x 1.2mm x 0.4mm.

Fig.4 The measured time delays for five states

The return loss of all 32 delay states of circuit is shown in Fig.5. The return loss is better than 12dB across the entire band. The only exception is nearly 10dB at 12GHz. The insertion loss for five delay states (λ, 2λ, 4λ, 8λ, and 16λ) of the circuits is shown in Fig.6. The insertion loss is between 8dB and 10dB for 6-9GHz. The insertion loss is 14dB at high frequency of 12GHz. This is caused by using multilayer structures.

6. Conclusion

A five-bit RF MEMS time delay line shifter circuit has been demonstrated. The circuit achieves relative time delays of λ, 2λ, 4λ, 8λ, and 16λ, and the biggest time delays of 1680ps. Besides, the present time delay circuit possesses other advantages such as wideband, low loss, high linearity, flat delay, small size and easy fabrication.

References