Integrated RF MEMS Phase Shifters with Constant Phase Shift

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Abstract — **In this paper, fully integrated RF MEMS phase shifters with low insertion loss, narrow frequency band, and constant phase shift are designed, fabricated, and characterized for mobile satellite broadcasting/communication systems. The fabricated phase shifters are comprised of CPW lines, short/open ended-stubs, and RF MEMS capacitive shunt switches. The constant phase shift can be obtained by optimizing the length of the open-ended stub and the short-ended stub. The fabricated 3-bit phase shifter has insertion loss of avg. -2.0 dB, return loss of min. -10dB, and phase error of avg. 2.0°, respectively. The utilized RF MEMS switches are operated at between 15 and 20 volts.**

I. INTRODUCTION

Phase shifter is widely used as a core component in the phased-array antennas systems, radar systems, and telecommunication systems. As the conventional FET-based phased shifter has high insertion loss and cost [1, 2], RF MEMS phase shifters have recently been developed to enhance the performance characteristics and to reduce the cost. The reported RF MEMS phase shifters are follows: low-loss distributed phase shifters for true time delay [3], X-band reflection type low-loss phase shifters [4], and Ka-band switched line phase shifters [5]. Although these RF MEMS phase shifters have much lower insertion loss than p-i-n diode or FET-based phase shifters, they have much higher actuation voltage, inclined slope of phase shift proportional to the frequencies, and wide frequency band characteristics. Thus, most of the reported RF MEMS phase shifters have been applied for passive phased array antennas in radar and military communication systems.

In this paper, integrated RF MEMS phase shifters with lower insertion loss compared to the FET-based phase shifter, narrow frequency band, and constant phase shift is realized for active phased array antenna in mobile satellite broadcasting/communication systems.

II. DESIGN

The previously reported RF MEMS phase shifters with short-ended stub and the RF MEMS switches could not have both good return loss and constant phase shift simultaneously due to their trade-off characteristics. In this paper, the open-ended stub is added onto the previously reported the RF MEMS phase shifter in order to obtain both good return loss and constant phase shift.

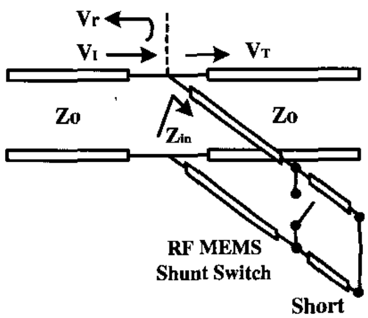

Fig.1. A schematic drawing of a phase shifter with short-ended stub with variable susceptance by using the RF MEMS switch.

Fig. 1 shows a schematic drawing of a phase shifter with short-ended stub. The transmitted voltage wave, V_T can be related with the incident voltage wave, V_I by the following equation (1).

$$V_T = V_I * (\frac{4}{4+b^2})^{1/2} * \exp\{-j \tan^{-1}(\frac{b}{2})\} \quad (1)$$

Where the normalized susceptance, b of short-ended stub can be defined as:

$$b = \frac{Z_o}{im(Z_{in})} \quad (2)$$

Thus, the phase shift, $\Delta\phi$ between the incident voltage wave, V_I and the transmitted voltage wave, V_T can be expressed by using the equation (3).

$$\Delta\phi = \tan^{-1}(b/2) \quad (3)$$

If normalized susceptance, b is changed by actuating the RF MEMS switch, the phase shift can be rewritten by

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using the equation (4).

$$\Delta\phi = \Delta\phi_{SWITCH\text{-}ON} - \Delta\phi_{SWITCH\text{-}OFF} \quad (4)$$

For the proposed phase shifter is being used in mobile satellite broadcasting/communication systems, it should have the constant phase shift, $\Delta\phi$ at the operating frequency band.

For obtaining the better return loss characteristics, the resonant frequencies of one bit phase shifter are better to be placed symmetrically on a center frequency, w_o as shown in Fig 2, when the RF MEMS switches are on and off.

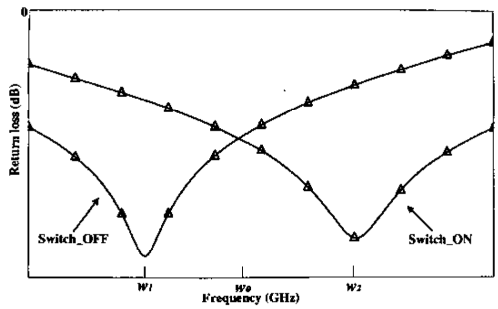


Fig.2. Optimized return loss characteristics of one-bit phase shifter.

The resonant frequencies, w_1 and w_2 of the phase shifter can be related to the reactance of short-ended stub as shown in the equation (5).

$$1/im(Z_{in}) = 0\Big|_{w=w_1\ \&\ w_2} \quad (5)$$

From the equation (5), the condition to obtain the best return loss over the operating frequency band can be expressed by using the following equation (6).

$$\frac{w_1 + w_2}{2} \approx w_o \quad (6)$$

Thus, the proposed RF MEMS phase shifters are optimally designed by using the above equations (4, 6). Fig. 3 shows a schematic drawing of the proposed phase shifter with 11.25°of phase shift. The phase shift can be obtained by the electrical length of the open-ended and short-ended stubs called as l_1, l_2, and l_3. Firstly, the initial length of the l_1, l_2, and l_3 is obtained as 580 um, 2100 um, and 0um at 11.7GHz by simulation, respectively. The electrical length results in 11.25°- phase shift at 11.7 GHz as shown in Fig. 4. But the slope of phase shift is also increased proportional to the frequencies. To obtain constant phase shift, the electrical length, l_3 of open-ended stub is increased to 500um and the electrical length l_2 of short stub is decreased to 1600um. Fig. 4 shows simulated results of the phase shift of the phase shifter with and without the open-ended stubs. The constant phase shift is obtained by adding the open-ended stub.

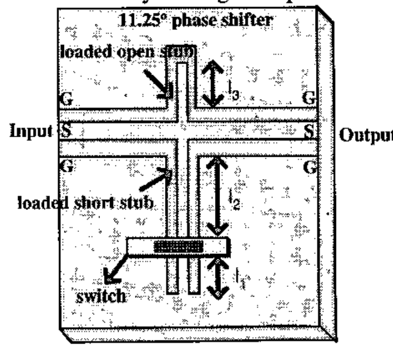


Fig.3. A schematic drawing of the proposed phase shifter with 11.25°-phase bit with the open-ended stub, the short-ended stub, and the RF MEMS capacitive shunt switch.

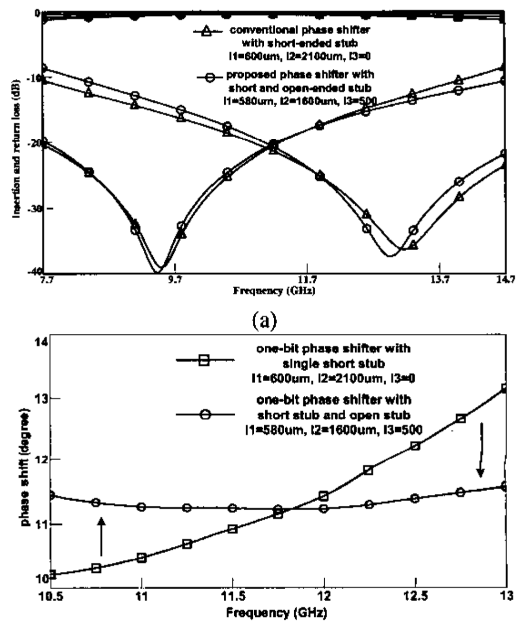


Fig.4. Simulated characteristic results of 11.25° phase shifter with and without open stub: (a) insertion and return losses, (b) phase shift

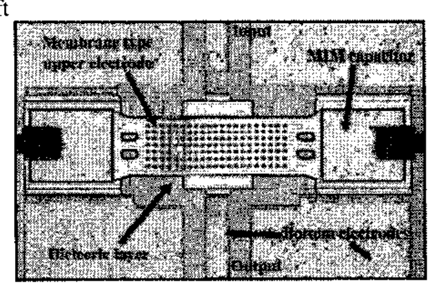


Fig.5. The photomicrograph of the fabricated RF MEMS capacitve shunt switch.

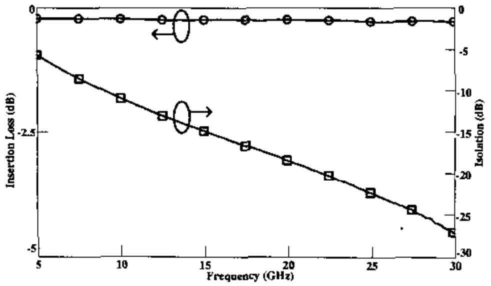


Fig.6. Measured insertion loss and isolation characteristics of the fabricated RF MEMS capactive shunt switch.

Fig. 5 shows the RF MEMS capacitive shunt switch composed of a bottom electrode for signal path, a dielectric layer, and movable top electrode. The fabricated RF MEMS switch has an insertion loss of –0.26dB at 30 GHz and an isolation of –20dB at 30 GHz when a bias voltage of 15 - 20 V is applied, as shown in Fig. 6.

III. FABRICATION

Fig. 7 shows fabrication sequence of the proposed one and three-bit RF MEMS phase shifters. Ground and transmission lines are formed by lift off techniques on a GaAs substrate and aluminum nitride as an insulating layer is deposited and patterned on top of the transmission line. The resistive line is deposited and patterned. Plating molds for post and CPW transmission lines are formed. A seed metal is deposited and the molds are then filled with electroplated gold. Movable top electrode is formed by photolithography and wet-etching technique.

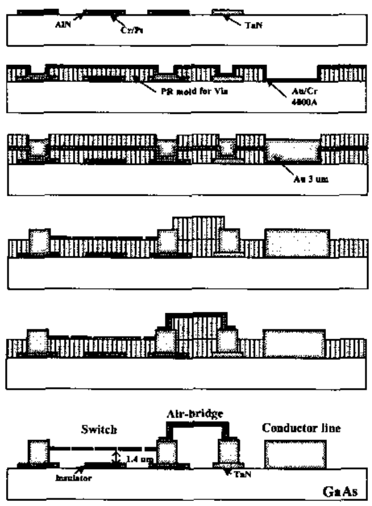


Fig.7. Fabrication sequence of the proposed RF MEMS phase shifters with constant phase shift.

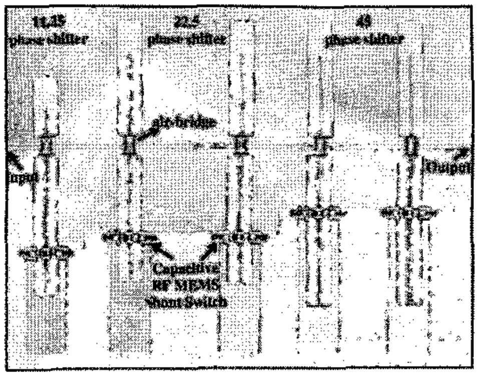


Fig.8. Photomicrograph of the fabricated 3- bit RF MEMS phase shifter with constant phase shift.

Plating molds for air-bridge are then formed and gold is electroplated. After selectively removing the photoresist and the seed metal layer, the movable top electrode is released by etching the sacrificial layer using plasma etcher. Fig. 8 shows a photograph of the fabricated three-bit phase shifter. As shown in Fig. 8, each one-bit phase shifter has 11.25°, 22.5°, and 45°-phase shift, and they are cascaded through CPW transmission line. Resistive DC-bias lines with resistance of 20~40Kohms are used to isolate DC and RF signals, and 20pF of MIM capacitors are utilized to ground RF signal in series with RF MEMS switches. Actual size of the fabricated three-bit RF MEMS phase shifter is 5.0 mm x 5.0mm.

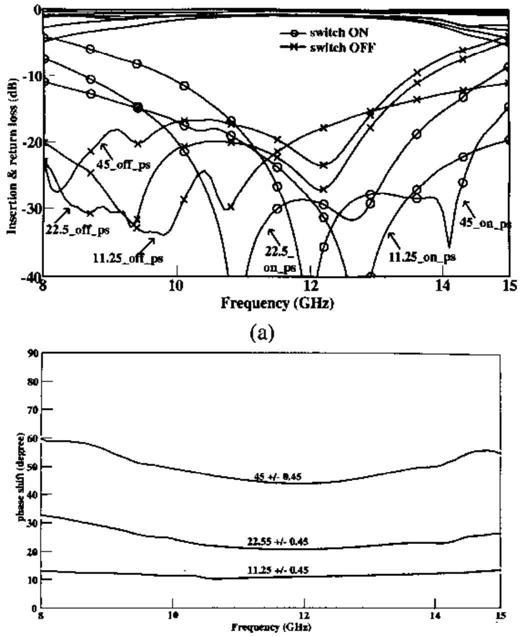
IV. MEASUREMENTS AND DISCUSSIONS

A. ONE-BIT RF MEMS PHASE SHIFTERS

Table I. Comparison of measured performance characteristics of the fabricated one-bit Phase Shifters.

Phase bit	Insertion loss	Return loss	Phase Shift
11.25°	Max. 0.38dB	Min. 20dB	11.25° ± 0.45°
22.5°	Max. 0.88dB	Min. 20dB	22.5° ± 0.45°
45°	Max. 0.92dB	Min. 20dB	45° ± 0.45°

The fabricated the RF MEMS phase shifters were measured by using GSG probes and HP 8510C network analyzer. Fig.9 shows performance characteristics of the fabricated 1-bit RF MEMS phase shifters. Insertion loss, return loss, and phase shift were also tabulated in Table1. The insertion losses of the 11.25°, 22.5°, and 45° phase shifters are -0.38 dB, -0.88 dB, and -0.92 dB, respectively. The return losses are better than –12 dB in operating frequency ranged 10.7 ~12.75GHz. The insertion losses of the phase shifters were slightly degraded in order to obtain the constant phase shift.

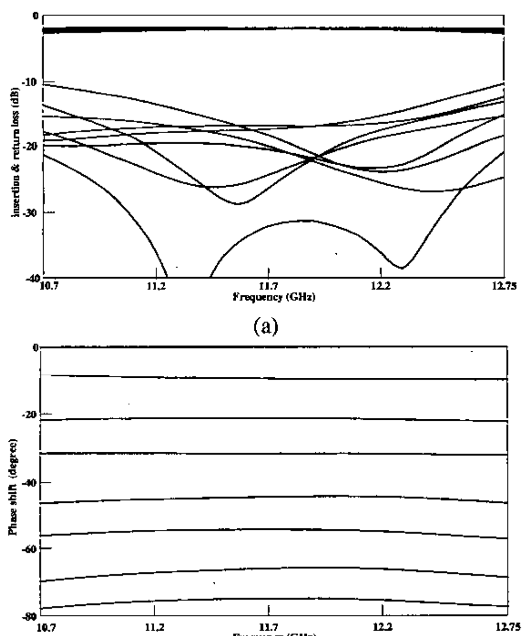


(a)

(b)

Fig.9. Measured performance characteristics of the fabricated RF MEMS 1-bit phase shifters with 11.25°, 22.5°, 45°- phase bit: (a) insertion and return losses and (b) phase shift

B. THREE-BIT PHASE SHIFTER



(a)

(b)

Fig.10. Measured performance characteristics of the fabricated three-bit RF MEMS phase shifter: (a) insertion and return losses (b) phase shift

Table II. Comparison of simulated and measured results of the fabricated 3-bit RF MEMS phase shifter

Parameters	Simulation	Measurement
Insertion loss	Avg. -1.8 dB	Avg. -2 dB
Input Return loss	Min -10dB	Min. -10dB
output Return loss	Min -10dB	Min. -10dB
Phase error	Avg. 1 °	Avg. 2°

As shown in Fig. 10 and Table 2, simulated insertion loss, return loss, and phase error of the three-bit MEMS phase shifter are well agreed. In our knowledge, the measured phase error and actuation voltage are the lowest values in the previously reported RF MEMS phase shifters.

V. CONCLUSION

Integrated RF MEMS phase shifters with constant phase shift are designed, fabricated, and characterized. The fabricated 3-bit phase shifter comprised of open-ended stubs, short-ended stubs, and the MEMS capacitive shunt switches has low insertion loss, high return loss, narrow frequency band, and constant phase shift. The open-ended stubs are used for obtaining the constant phase shift with small phase errors. The fabricated three-bit RF MEMS phase shifter has insertion loss of avg. -2.0dB, return loss of Min. -10dB, and phase error of avg.2.0°. These results show the strong potential of the fabricated RF MEMS phase shifters with constant phase shift for mobile satellite broadcasting/ communication systems.

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