Distributed RF-MEMS Circuits

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ABSTRACT

Distributed RF-MEMS transmission lines are created by periodically placing RF-MEMS switches along a high-impedance transmission line. This scheme allows the parasitic capacitance of the switch to be designed as a loading capacitance on the transmission line such that the loaded line impedance is close to 50 Ω. By appropriate design, these distributed lines are capable of operating as analog or digital phase shifters with excellent performance from X-band to W-band. In addition, the distributed RF-MEMS transmission lines are also capable of implementing high-isolation switches with broad bandwidths.

INTRODUCTION

The field of RF-MEMS has grown rapidly over the last decade due to its tremendous potential to greatly enhance the performance of existing circuits such as phase shifters and switches, as well as the promise of new capabilities for low-loss tuning. One of the circuit topologies being explored for capitalizing on the inherent broad bandwidth of the basic RF-MEMS capacitive switch is the distributed transmission line. Using this methodology, distributed switches and phase shifters have been built that demonstrate tens of gigahertz bandwidth centered from X-band to W-band. These circuits have numerous applications including electronically scanned arrays, adaptive amplifiers, and integrated spectrometers.

DISTRIBUTED RF-MEMS TRANSMISSION LINES

The low parasitics of RF-MEMS make it fairly easy to implement 2-bit and 4-bit switched-line phase shifters from X-band to Ka-band [1][2]. These phase shifters have demonstrated excellent performance with an average insertion loss at 10 GHz of 0.6 dB for a 2-bit and 1.2 dB for a 4-bit design. However, at higher frequencies it becomes much more difficult to implement this switched-line design due to the increased reactance of the parasitic capacitance from the switch.

One method for implementing phase shifters at higher frequencies is to design the parasitic capacitance of the RF-MEMS switch into the transmission line. This can be done by starting with a high impedance transmission line and periodically loading the line with the RF-MEMS switches. An example of this approach is given in Fig. 1. By appropriately choosing the RF-MEMS switch dimensions and the periodic spacing of the beams, the loaded transmission line impedance can be reduced from the initial high impedance, Z_o, to a loaded impedance given by [3]:

$$Z_l = \sqrt{\frac{L_t}{C_t + C_b/s}} \tag{1}$$

where L_t and C_t are the per unit-length inductance and capacitance of the unloaded high-impedance transmission line and C_b and s are the RF-MEMS switch capacitance and periodic spacing, respectively. In addition to altering the transmission-line impedance, the phase velocity is also decreased due to the capacitive loading and is given by [3]:

$$v_l = \frac{1}{\sqrt{L_t\left(C_t + C_b/s\right)}} \tag{2}$$

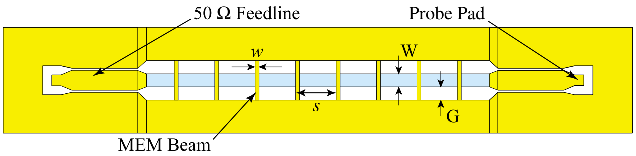


Figure 1: High-impedance CPW line periodically loaded with RF-MEMS switches to produce a 50 Ω line.

This effect on the phase velocity produces a slow-wave transmission line with a phase velocity that can be below that of the dielectric substrate, and therefore without radiation loss [4].

Such a periodic transmission line will operate over a broad frequency range from DC up to the point where the guided wavelength begins to approach the spacing of the switches. As this frequency is approached, the loaded transmission-line impedance becomes increasingly more reactive, producing a corresponding increase in the reflection loss. The frequency at which the loaded line becomes entirely reactive is termed the Bragg frequency and is approximated by [5]:

$$f_{Bragg} = \frac{1}{\pi s \sqrt{L_t \left(C_t + C_b/s \right)}} \tag{3}$$

In addition to these approximations, an equivalent circuit has been developed to model the effect of the periodic placement of RF-MEMS switches along the transmission line. As can be seen in Fig. 2, the circuit model accurately predicts the behavior of the distributed line as the Bragg frequency is approached [3]. The equivalent circuit model has been used in the design of distributed RF-MEMS transmission-lines up to 120 GHz with excellent results [7].

ANALOG PHASE SHIFTERS

The distributed RF-MEMS transmission line is most easily used as a phase shifter by applying a single control voltage between the center conductor and ground plane of the CPW line using an external bias tee. As the bias is increased the shunt capacitance of the RF-MEMS switch is increased, thus increasing the capacitive loading of the transmission line. This increased loading lowers the impedance as well as the phase velocity as seen from (1) and (2). It is this change in phase velocity that allows the distributed line to operate as a true time-delay phase shifter. This type of continuously variable phase shifter has been demonstrated at 60 GHz with 4 dB insertion loss for 360° phase shift and at 100 GHz with 5 dB insertion loss for 360° phase shift [7].

The critical limitation in the performance of the analog phase shifter is the inherent instability in the electrostatically actuated RF-MEMS switch. Theoretically, an electrostatically actuated RF-MEMS switch is capable of achieving a capacitance ratio of 1.5 before becoming unstable and collapsing onto the center conductor. However, with a single bias voltage controlling many switches, one switch is bound to collapse before the others due to slight variations in the mechanical properties of the various switches. Thus, in practice the capacitance ratio that can be achieved with an analog type distributed RF-MEMS phase shifter is limited to 1.2 [6]. The impedance change for this capacitance ratio is relatively small and does not significantly affect the return loss of the distributed line. Thus, by increasing the capacitance ratio, it is possible to further increase the phase shift for a given length distributed phase shifter while keeping the insertion and return loss reasonably constant.

DIGITAL PHASE SHIFTERS

This need for an increased capacitance ratio leads to the design of a digital type distributed RF-MEMS phase

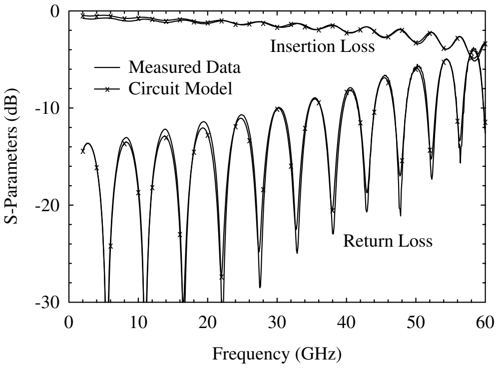


Figure 2: Measured and modelled data of a 98 Ω CPW line ($W = G = 100$ μm on quartz) with 60 μm wide beams spaced 640 μm apart. The Bragg frequency is approximately 70 GHz [6].

shifter [8]. This design requires a slightly more complicated design since the typical capacitance ratio for a RF-MEMS switch is 80-100 [9]. Such a large change in the loading capacitance will produce a similarly large change in the loaded-line impedance producing unwanted reflections. Therefore, the RF-MEMS switch is placed in series with a small capacitance that is on the order of the up-state switch capacitance. In the upstate, the total shunt capacitance loading the transmission line is the series combination of the RF-MEMS capacitor and the fixed capacitor. While in the down-state, the RF-MEMS capacitor greatly increases so that the small fixed capacitor dominates the series combination, thus limiting the shunt loading capacitance ratio.

Design of the digital type distributed RF-MEMS phase shifter must account for the large impedance change that can occur. In fact, the design of the loading capacitance is dictated by the desired return loss over the operating range of the phase shifter. Using this approach, the phase shift per unit length of line is found to be:

$$\Delta\phi = \frac{\omega Z_o}{v_{po}}\left[\frac{1}{Z_{lu}} - \frac{1}{Z_{ld}}\right] \tag{4}$$

where Z_o and v_{po} are the impedance and phase velocity of the unloaded transmission line, while Z_{lu} and Z_{ld} are the loaded-line impedance in the up-state and the down-state respectively. Therefore, it is seen that as the up and down-state impedances are separated farther apart, the phase shift that can be achieved for a fixed length of line increases. However, the return loss will also increase.

If a maximum return loss of -10 dB for the phase shifter is desired, then the up and down-state impedances can be designed as 69 Ω and 36 Ω respectively. However, this will only be useful for a 1-bit design. To implement a 2-bit or 4-bit phase shifter with a total return loss of -10 dB, each individual section must be designed with a return loss of better than -15 dB. This requirement limits the up and down-state impedances to 60 Ω and 42Ω respectively [8].

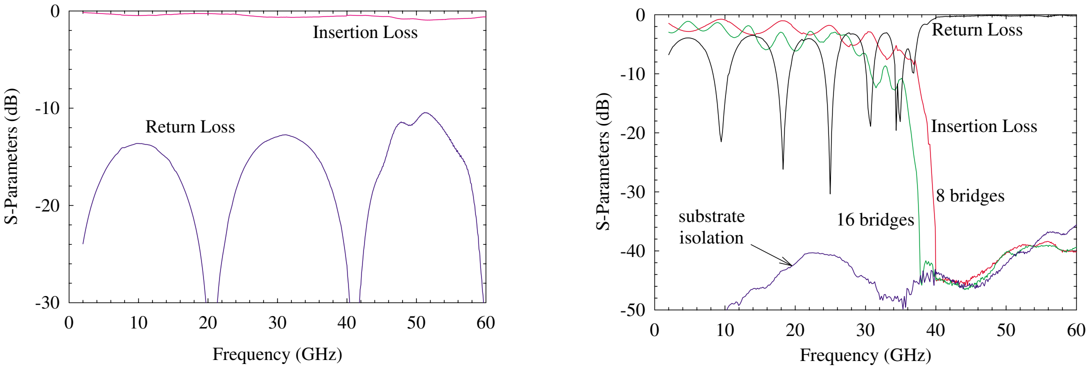
In order to capitalize on the increased phase shift per unit length offered by the digital type distributed phase shifter, it is critical that the small capacitor placed in series with the RF-MEMS switch not introduce significant loss. Several implementations of the series capacitor have been explored as detailed by Table 1. As can be seen, the SiN metal-insulator-metal (MIM) capacitor introduced significant loss. This is not surprising considering the very small required capacitance and thus small dimensions resulting in a high series resistance and low Q capacitor. What is somewhat surprising is that the metal-air-metal (MAM) series capacitor with a CPW based distributed line out-performs the radial stub series capacitor with a microstrip based distributed line. This is due to the Q of the radial stub being limited to 75-95 while the MAM capacitor has a very high Q of 400 at 10 GHz. Thus, the low insertion loss of the loaded line is maintained when using a MAM capacitor with a CPW based distributed line.

Table 1: 2-bit X-band phase shifter performance for different series capacitors.

Transmission line	Series capacitor	Performance	Reference
CPW	SiN MIM	4 dB	[10]
Microstrip	Radial Stub	3 dB	[10]
CPW	MAM	1.2 dB	[11]

HIGH ISOLATION SWITCH CIRCUITS

In addition to the impedance and phase velocity of the distributed RF-MEMS transmission line being lowered as the loading capacitance is increased, the Bragg frequency is also lowered. When the distributed line is operated as a phase shifter, the change in loading capacitance is limited such that the lowering of the Bragg frequency does not produce a large effect. However, the distributed transmission line functions as a high-isolation switch when the loading capacitance is allowed to increase by a large amount ($C_{max}/C_{min} > 10$) such that the Bragg frequency moves down into the frequency of operation. Above the Bragg frequency the distributed line appears to be purely reactive such that the magnitude of the reflection coefficient is very nearly one. Figure 3 gives the measured performance of a distributed RF-MEMS transmission line operated in this mode. With the switch in the up-state, the insertion loss has a maximum of 0.6 dB from 40 to 60 GHz. With the switch in the down-state, the isolation is better than -35 dB from 40 to 60 GHz and is primarily limited by the radiation of the feedlines (Fig. 1) through the substrate [6].



(a) (b)

Figure 3: Distributed RF-MEMS transmission line with 8 beams operated as a switch in the (a) up-state and (b) down-state. The capacitance ratio for this measurement is 12.

CONCLUSION

The distributed RF-MEMS transmission line enables RF-MEMS switches to be used for phase shifters and high-isolation switches at frequencies where traditional lumped-element designs suffer from the parasitic capacitance of the switch. Measured results have demonstrated analog phase shifter with 4 dB insertion loss at 60 GHz and 5 dB insertion loss at 100 GHz for 360° phase shift. Digital phase shifters have demonstrated increased performance over the analog versions with 1.2 dB insertion loss at X-band and 2.2 dB insertion loss at V-band for 2-bit phase shifters. High-isolation switches have also been demonstrated with better than 35 dB isolation from 40-60 GHz and less than 0.6 dB insertion loss.

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