ANALOG RF MEMS ATTENUATOR WITH PZT ACTUATORS

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ABSTRACT

This paper reports on a voltage controlled, analog RF MEMS attenuator with lead-zirconate-titanate (PZT) actuators. Fabrication utilizes a PZT on silicon-on-insulator (SOI) material stack. The RF MEMS device demonstrated attenuation of up to 26.0 dB at 2.0 GHz and 9.3 dB at 25.0 GHz. Bias voltage varied from 0.0 V to 14.5 V dc. At 0.0 V the minimum insertion loss ranged from fractions of a dB at low frequencies to 1.16 dB at 25 GHz. This device can be used as part of a beam forming network for phased antenna arrays. Example of an 8 element linear antenna array was considered for $\cos^2$ and Taylor (-20dB) excitation distributions.

INTRODUCTION

RF attenuators are an essential part of beam forming networks, test equipment and almost any complex RF systems. There is a big body of experimental work and a variety of technologies have been used to build attenuators.

Classical devices were built with waveguide circuits. Some of the proposed concepts, such as the water loaded waveguide described in [1], were rather exotic. More conventional designs were studied as well [2]. These attenuators have very good RF performance, but tend to be bulky and relatively complicated to manufacture. Adjustment of the attenuation, when possible, was usually accomplished by either manual tuning or with the use of electric motors.

Hybrid solutions based on printed transmission lines and solid-state devices have become available [3], [4]. They offered more compact design and electronic control of the attenuation. Despite being a major advancement in size and weight reduction, these circuits still relied on significant lengths of transmission lines and were relatively large in size. Reference [3] is a typical example of this type of circuits.

The search for more compact solutions and the advances in semiconductor technologies led to the development of monolithic integrated attenuator circuits [5], [6]. These components feature a reduced area and precision voltage control of the attenuation. At the same time, semiconductor solutions require special attention to linearity and uniformity of the attenuation. The attenuation function is still carried out by multiple components operating together as part of the IC.

The ultimate reduction of component count per attenuation function can be achieved with MEMS technologies. In these solutions it is possible to accomplish variable attenuation of the signals using a single mechanical device. MEMS implementation of attenuators is well established in optics [7]. Mirrors, shutters and controlled misalignment of optical fibers can provide attenuation of the optical signals. The dynamic range of these systems is very high and the optical coupling can be controlled over many orders of magnitude. A recent overview of radar technology [8], however, pointed out that MEMS attenuators are still being investigated thoroughly in the RF communication and radar portion of the spectrum.

This work provides initial results for an analog reflection type MEMS attenuator in the 100 MHz to 25 GHz frequency range. The device is fabricated in PZT on SOI MEMS technology. Analog voltage controlled attenuation is achieved with moderate actuation voltages (maximum of 14.5 V). The continuous attenuation control, broad bandwidth, moderate actuation voltage and small size of the reported circuit highlight RF MEMS devices

as compelling candidates for attenuator solutions in the RF/microwave frequency range.

In this paper, the underlying MEMS fabrication technology will be described first. Then, the device design, operation and measured results will be reported. Finally, we will discuss the utility of the analog RF MEMS attenuator as a beam forming component for an eight element linear antenna array. To evaluate the device performance against the array requirements, as a function of frequency, uniform, $\cos^2$ and Taylor (-20 dB side lobes) excitation distributions will be compared.

FABRICATION

Detailed fabrication process flow of the PZT-on-SOI technology is presented in Figure 1. The process starts with an SOI wafer with a device layer of 4 μ m thick and a buried oxide thickness of 0.1 μ m.

Figure 1. Process flow for fabrication of RF MEMS attenuator.

The actuator materials were deposited next, consisting of a 200 nm thermal silicon dioxide (SiO_2) coating, a sputtered titanium thin film annealed to form 33 nm titanium dioxide, a 100 nm sputtered platinum (Pt) film, chemical solution deposited PZT with a Zr/Ti ratio of 52/48 and a thickness of 1000 nm, and 50 nm layer of sputtered platinum as shown in Fig. 1a.

The top Pt, PZT, and bottom Pt are then patterned using argon ion-milling, see Fig. 1b. To access the bottom Pt, a via is patterned into the PZT by ion-milling followed by a wet etch of the residual PZT using $\text{H}_2\text{O}:\text{HCl}:\text{HF}$ (2:1:0.05), see Fig. 1c. The SiO_2 is then etched using reactive ion etching (RIE) followed by a Si deep reactive ion etch (DRIE) of the device Si layer and another RIE of the buried oxide, see Fig. 1d. Next, a 150 nm protective coating of alumina is deposited by atomic layer deposition. The Al_2O_3 is then patterned with a reactive ion etch to open access to the contact areas of the PZT actuator as well as the bottom of the DRIE etch trench, see Fig. 1e. The co-planar waveguide (CPW) transmission lines consisted of a tri-layer of Cr/Pt/Au (20/20/730 nm) and were deposited by electron beam evaporation and patterned via lift-off, see Fig. 1f. In order to control the switch contact surfaces, specific contact materials were deposited on the contacting pads. The contact metallurgy was a bi-layer of Au/Ru (400/100 nm) and was deposited by electron beam evaporation and patterned via lift-off. Next, a sacrificial layer of photoresist is deposited and patterned to define the gap for air bridges and contact cantilevers. A 2 μm thick gold air bridge layer is then deposited via electron beam evaporation and patterned using lift-off. Afterwards, the resist layer is removed by an oxygen plasma followed by a wet clean in dimethyl sulfoxide solution. Finally, a short reactive ion etch of the native oxide in the bottom of the DRIE trench is performed in a fluorinated plasma followed by a xenon difluoride etch to fully release the piezoelectric actuator composite, see Fig 1g.

MEASURED RESULTS

PZT and PZT-on-SOI technology [9], [10] were used to fabricate a variety of MEMS devices and circuits. An optical image of the fabricated analog RF MEMS attenuator is shown in Figure 2.

Figure 2. Optical image of analog RF MEMS attenuator.

The MEMS structure is placed in a coplanar waveguide transmission line. The wide line in the middle of Figure 2 is the signal conductor, while the two lines at the top and bottom of the figure are part of the RF ground plane. The transmission line is designed to have a 50Ω characteristic impedance in the metal/dielectric stack of the technology. RF signals are input in the device from the left side, go through the MEMS attenuator, and exit through the output port on the right hand side. Mechanical motion is accomplished by the use of two PZT actuators; these are the structures with release holes, placed in the dielectric gap of the RF transmission line. A bias voltage is applied to the PZT capacitors through gold air-bridges located on the anchored side of the actuators (right side of Fig. 2). On the released end of each actuator is a movable beam that mechanically couples them together. The beam extends in a U shape and wraps around the actuators. The top surface of the beam is metalized and serves dual purpose. Under the crossover with the transmission line it forms the bottom movable plate for the coupling capacitors. At the end of the U shape extensions it connects to the ground plane and provides an electrical short circuit for the RF signals.

Two capacitors are formed between bridges in the RF signal line and the movable short to ground. As the actuators change the spacing between the two electrodes of the capacitors, the coupling of the RF signal to ground is changed and different levels of attenuation can be achieved between the input and the output ports. The RF frequency was swept from 100 MHz to 25 GHz and Figure 3 shows the response of the attenuator for different actuation voltages.

The 14.5 V state determines the maximum attenuation when the two plates of the variable capacitor are in contact, while the 0 V state represents maximum separation and respectively minimum attenuation.

Figure 3. Frequency response of the analog MEMS attenuator for different actuation voltages. The trace for 0 V is the top most one. As the voltage increases, the attenuation is increased and the bottom most trace shows response for 14.5 V.

These two states constitute a MEMS switch. The rest of the states, which are of particular interest for a variable attenuator, show continuous coverage between the “open” and “closed” conditions.

Piezoelectric devices generate displacement proportional to the voltage applied across the PZT film (not the contact gap), hence they are capable of continuous gap control. Exact numbers of the measured attenuation, for select frequencies, are given in Table 1. Below 2 GHz, the attenuation range is from 0.5 dB to more than 26 dB. At 25 GHz the maximum attenuation is reduced to 9.3 dB. Also, the response is quite frequency independent for attenuation levels of up to ~ 7 dB, with frequency dependency becoming clearly expressed for higher attenuation levels.

LINEAR ANTENNA ARRAY

One of the possible applications for continuously tunable RF MEMS attenuators is in beam forming networks for antenna arrays. Schematic representation of an eight element linear antenna array is shown in Figure 4.

Figure 4. Schematic diagram of beam forming network. Components included are - antenna elements, phase shifters, attenuators and power divider.

The concept of beam steering is relatively straightforward. Input RF power is divided equally among all branches of the beam forming network. In each branch, the amplitude and phase of the radiated signals can be adjusted. The desired outcome is that the main lobe beam width, radiation direction, side lobe levels, nulls locations, etc., can be controlled fast and efficiently through electronic means. Usually, the attenuator, phase shifter and possibly a power amplifier constitute the ‘antenna module’ for a transmitting array radiator. They are placed behind the individual radiating element and it is desirable for the components to be compact in size and light weight.

Attenuators play a role in adjusting the amplitude of the radiated signals. Creating a non-uniform amplitude distribution (excitation pattern) along the aperture of the array affects the side lobes level of the radiation pattern, the beam width of the main lobe and the gain of the array. There are number of excitation patterns that have been adopted for beam control.

We will consider three of them. Uniform distribution is usually used as a reference for comparison. It provides a narrow main lobe but the peak of the first side lobe is only 13 dB lower than the main one.

Taylor distribution is commonly used because one can specify the maximum acceptable side lobes level. In this paper we consider a -20 dB level for the side lobes. Cosine squared ($\cos^2$) is another distribution targeted at reducing the side lobes level. It uses a more aggressive taper. Consequently, the side lobes are reduced more at the expense of some broadening of the main beam and gain reduction. Plots of the radiation patterns calculated based on all three excitation distributions are shown in Figure 5.

Table 1. Attenuation in dB at different actuation voltages and frequencies.

Freq. (GHz)	Actuation Voltage (V)												
	0	0.5	1.5	2	2.5	3	3.5	4.5	6.5	7.5	8.5	10.5	14.5
0.1	0.13	0.14	1.09	3.33	5.01	6.21	7.46	10.48	12.61	15.42	18.19	20.12	27.06
5.0	0.60	0.50	1.40	3.56	5.21	6.33	7.54	10.58	12.27	14.66	16.65	17.92	20.63
10.0	0.76	0.62	1.49	3.65	5.21	6.34	7.49	10.11	11.57	13.28	14.47	15.07	16.03
15.0	0.91	0.75	1.61	3.75	5.28	6.33	7.39	9.66	10.75	11.85	12.48	12.75	13.05
20.0	1.04	0.85	1.74	3.81	5.28	6.28	7.22	9.04	9.81	10.46	10.76	10.86	10.90
25.0	1.16	0.91	1.77	3.82	5.21	6.09	6.97	8.32	8.90	9.27	9.38	9.40	9.30

Figure 5 Radiation patterns of 8 element linear array for different amplitude distribution .of the signals between individual radiating elements.

The attenuation for every element (both $\cos^2$ and Taylor distributions) is listed in Table 2. Comparing the required attenuation levels from Table 2 with the demonstrated performance of the RF MEMS attenuator from Table 1 allows the following conclusions to be drawn: 1) Uniform distribution can be accomplished with the lowest loss state of the attenuator and the worst case insertion loss penalty will be 1.16 dB at 25 GHz. At lower frequencies the introduced loss is significantly less. 2) Taylor distribution with side lobe peaks suppressed to -20 dB can be realized in the whole frequency range from 100 MHz to 25 GHz.

Table 2. Radiating element attenuation in dB for 8 element array.

element #	$\cos^2$	Taylor
1	18.4	9.0
2	7.4	4.0
3	2.2	1.3
4	0.0	0.0
5	0.0	0.0
6	2.2	1.3
7	7.4	4.0
8	18.4	9.0

3) Cosine squared distribution can be supported from 100 MHz to 7 GHz. The broad band performance and low loss of the RF MEMS attenuator exceeds the capabilities of waveguide and hybrid attenuators and rivals the solid state solutions. At the same time the RF MEMS attenuator is very competitive in terms of size, weight and consumed DC power. The presented MEMS attenuator has adequate performance for use in beam forming networks.

CONCLUSIONS

An analog RF MEMS attenuator with PZT actuators was presented. The device was fabricated using PZT-on-SOI technology. It demonstrated minimum insertion loss of 0.13 dB

and 1.16 dB for frequencies of 100 MHz and 25 GHz, respectively. In the same frequency range, the maximum attenuation was 27.06 dB and 9.3 dB. Continuous voltage controlled attenuation was achieved for all states between the above two extremes. The attenuation function is achieved with a single MEMS device featuring compact size and with maximum DC voltage of 14.5 V. The analog RF MEMS attenuator was evaluated for use in linear antenna array beam forming network. It was found that uniform distribution can be achieved with minimum insertion loss in broad frequency range (100 MHz-25GHz). Taylor distribution with -20 dB peak level of the antenna pattern side lobes can also be supported across the entire frequency range. The more aggressive $\cos^2$ excitation distribution can be supported from 100 MHz to 7 GHz.

Overall, the proposed analog RF MEMS attenuator with PZT actuators has superior frequency performance compared to waveguide and hybrid solutions and has very competitive size, weight and power consumption, compared to solid state attenuators.

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