Low-Loss Bandpass RF Filter Using MEMS Capacitance Switches To Achieve A One-Octave Tuning Range And Independently Variable Bandwidth

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***Abstract* — We demonstrate a low insertion loss (1.5dB) tunable two-pole bandpass radio frequency filter with a tuning range of one octave (812-1752 MHz). It is also tunable in band width, with 3dB-bandwidths of 7 to 42% being achieved. The circuit used consists of two fixed high quality factor toroidal inductors mounted on a printed circuit board next to a fused-quartz substrate on which were fabricated the MEMS (Micro-Electro-Mechanical System) capacitance switches. Five arrays of MEMS elements, with a total of 34 MEMS bridges, are used on this chip. Each array is independently addressable in a four-bit scheme to permit well matched, independent tuning of the center frequency and bandwidth.**

I. Introduction

Many radio frequency communication systems require highly sensitive receivers. However, it is difficult to simultaneously maintain selectivity and sensitivity with conventional technology in the presence of interference. Strong interfering signals can significantly degrade the performance of a receiver. Interference can blind the receiver by saturating the low-noise amplifier (LNA) or force a receiver to reduce its sensitivity to avoid detecting unwanted signals. Low-loss, narrow-band preselector filters placed before the LNA can improve the receiver sensitivity by rejecting interfering signals thus avoiding their deleterious effects. Such a filter must have very low loss in order to maintain the designed receiver noise figure. An important part of the solution to this problem are tunable, low-loss bandpass and/or bandstop (notch) filters.

Previously, Goldsmith and coworkers [1] have tested MEMS tunable bandpass filters that have tuned in center frequency from 806-917 MHz and 110-160 MHz, with insertion losses of 6-7 and 3-5 dB, respectively. Peroulis et al.[2] have tested a filter that uses MEMS to achieve two bandpass states, one at 15 GHz and the other at 30 GHz. Jung et al.[3] have used MEMS tuning elements to construct a resonator that tunes from 23.5 to 25 GHz. Our own MEMS switch work has its origin in the MEMS cantilever beam of H.C. Nathanson et al.'s resonant gate transistor at what was then the Westinghouse Research Laboratory and is now a part of Northrop Grumman [4] The current fabrication technique we use is taken from airbridge technology developed to reduce stray capacitance on MMICs.

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II. Experiment

Our MEMS capacitance switch is conceptually similar to those previously mentioned. It consists of a bottom electrode covered by a dielectric film and separated from the upper electrode by an air gap. When sufficient voltage is applied between the lower and upper electrode, the bridge snaps down to come into contact with dielectric, switching from a low to a high capacitance state. The precise details of our MEMS bridge are considered proprietary. However, we can state that the main conducting elements are gold, with a thin film dielectric layer. Following MMIC airbridge technology, a sacrificial layer initially separates the dielectric/bottom electrode from the air bridge until release.

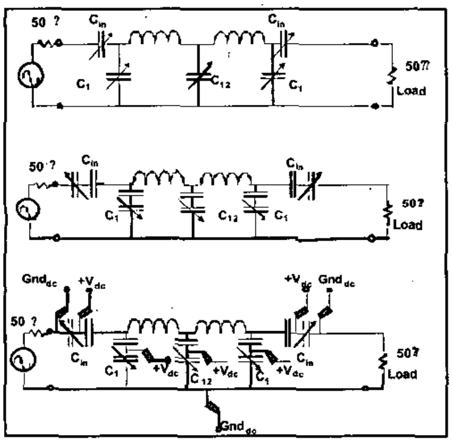

Figure 1. Upper: Schematic layout of the basic 2-pole circuit. Middle: With the required blocking/defining capacitors drawn in a one-bit scheme. The actual device implemented for this work consisted of four-bits in parallel for each array. Lower: With the addition of the resistors to choke off the RF in the DC control lines.

The upper portion of Fig. 1 shows a schematic of the idealized circuit. It is a two pole filter using two fixed inductors and five tunable capacitor arrays. Each array consists of a four-bit set of MEMS capacitance switches, where each bit is DC separated from its neighbor by a blocking capacitor, shown schematically in the middle of Fig. 1 as a one-bit device for clarity. The DC control lines are brought in between the blocking capacitor and the MEMS capacitor (Fig. 1 lower) where isolation of the RF from the DC leads is accomplished by use of a thin film resistor going to each element.

Morphing the circuit of Fig. 1 to fit onto a 4.1mm x 4.1mm chip is shown schematically in Fig. 2. This places the two inductors at right angles, reducing

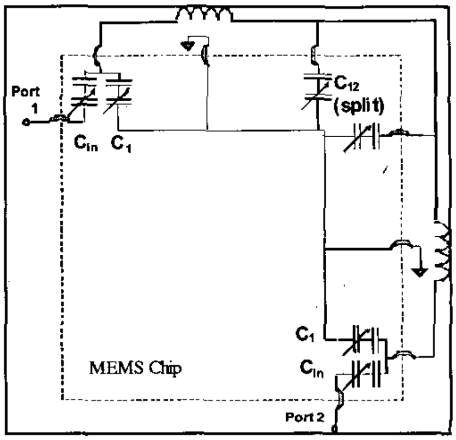

Figure 2 . The circuit schematic morphed to accommodate fabrication on the MEMS chip. For clarity only one-bit is shown and the isolating resistors are not drawn.

cross-coupling, and allows for a more compact layout. Fig. 3 shows an optical non-contact profilometer scan of one of our chips after the sacrificial layer was released, oriented as per Fig. 2. The MEMS chip is bonded into the milled out pocket of a printed circuit board which contains the two toroidal inductors and the DC control I/O. (See the photo of Fig. 4.) Our choice in using wire wound toroidal inductors is based on their high Quality Factor (Q). The Q's for our inductors are typically 200.

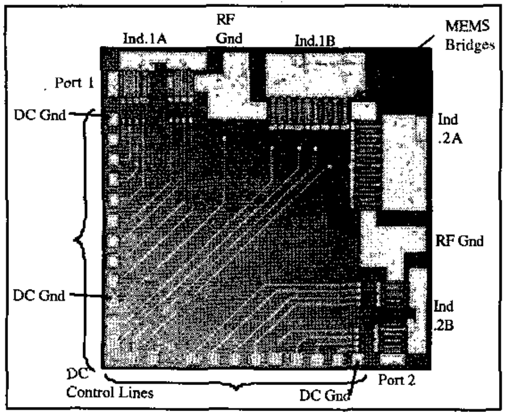

Figure 3. Optical non-contact profilometer scan of a fabricated MEMS chip. All 34 of the MEMS air bridges have air gaps as denoted by their red color.

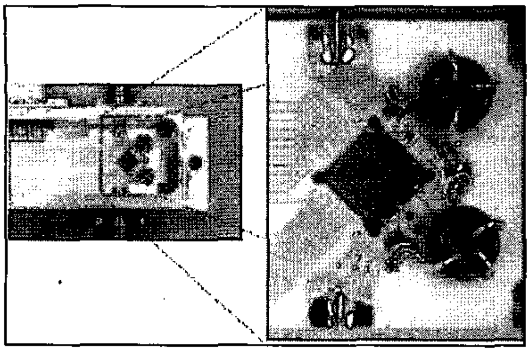

Figure 4. Photograph of the tunable filter. In the center is the 4mm x 4mm MEMS chip, flanked by the two toroid inductors. RF port 1 is at the top and port 2 at the bottom. The DC control lines approach the chip from the left. The size of this package has not been optimized. The reader will notice that the 25-pin micro-D connector used for the DC I/O dominates the package size, and that a single toroidal inductor is as large as the entire five array four-bit MEMS chip.

III. Results

Application of a DC voltage of 25V caused the bridges to snap shut. With five four-bit arrays that are independently addressable there are over 1 million possible states. Only a small subset of these produce the desired bandpass response. In Fig. 5 we show one octave tuning from 860 to 1750 MHz, with an insertion loss of 1 dB and a return loss of 13 dB. Our widest

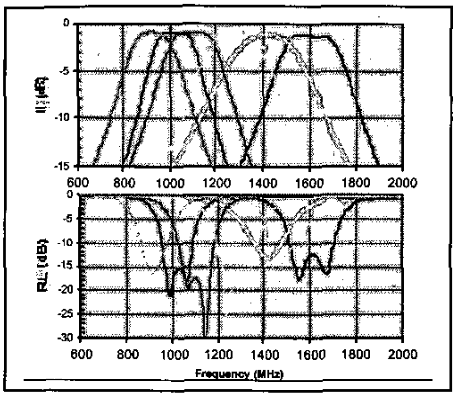

Figure 5. Insertion loss and Return loss of the filter, demonstrating a series of settings achieving a full octave of tuning range.

bandpass filters have a 3dB relative bandwidth of 42%, and the narrowest 7%. While full octave coverage is possible with moderate and wide bandwidth choices, the limitation to just four bits (16 positions) in the central coupling capacitor (C_{12} in Fig. 1) creates good narrow bandpass filters at some positions (IL of 1.9dB) but also forces gaps in coverage. Increasing the number of bits is an obvious solution.

It is also possible to select a constant center frequency and vary the bandwidth. In Fig. 6 we show four bandpass filter states all centered at 1300 MHz, with 3dB bandwidths that vary from 9 to 40%. The wider bandwidth filters have a low insertion loss and good return loss figure. A drop in insertion loss peak is noticed for the narrowest filter. The narrowest band in Fig. 6 also shows an extra peak in insertion loss. This is of unknown origin but seems to occur only for the larger values of the coupling capacitor C_{12}, and is always at

−15dB or bettter and is well removed from the primary pass band.

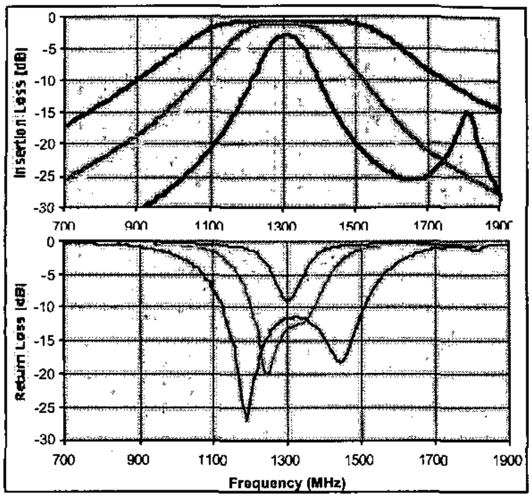

Figure 6. Insertion loss and Return loss of the filter, demonstrating a series of settings achieving narrower and broader pass bands at the same center frequency.

When two 10 dBm tones are placed into the widest pass bandwidth settings (40%), the third order intercept was typically +38 dBm. Narrower settings resulted in lower third order intercepts, with the lowest intercept of 29-33 dBm occurring for the narrowest (7%) filter settings. It is conjectured that the Q of the filter boosts the internal voltage across the MEMS bridge and makes it more sensitive to the input power, narrower filters having higher Q's. Placing one tone inside the pass band and examining the harmonic tone showed it to be at an impressive +82 dBm (limited only by the test instrumentation).

When switching from all-off to all-on filter settings at atmospheric pressure, the RF response has a 10%-90% rise of 8 μs, with a latency time of about 10 μs before that transition. The all-on to all-off 90%-10% response time is 7 μs, but the latency time is less than 1 μs. It is conjectured that the bridge releases quickly from the dielectric. At c. 5 Torr abs. the switching time is about 2 μs for both filter-on and filter-off. There is a latency of about 8 μs for the filter-on time, which would need to be factored into driver circuitry, involving a "think ahead" for accurate high speed filter switching.

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