Low-Loss, Broadly-Tunable Cavity Filter Operating at UHF Frequencies

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Abstract — A four-pole tunable filter has been demonstrated at UHF frequencies which tunes 300 MHz to 700 MHz and exhibits mid-band losses between 0.5 dB and 0.9 dB. This filter incorporates piezo-electric tuning of capacitively-loaded cavities and frequency-tailored input/output coupling networks to maintain good impedance match across more than an octave tuning band. The unloaded quality factor of the filter cavities range from 340-550. The filter has an output intercept point greater than +54 dBm and can handle power levels of +26 dBm.

Index Terms - Tunable circuits and devices, UHF circuits, cavity resonators, piezoelectric transducers, microwave filters.

I. INTRODUCTION

Tunable filters can lead to significant reductions in size and weight compared to using numerous fixed filters and switching networks. With fixed filters, cavity-based filters generally provide the lowest loss, as evidenced by the unloaded quality factors that range in the thousands at microwave frequencies. Thus, there has been significant research focused on building tunable microwave filters based on evanescent cavities that are tuned through capacitive loading [1,2]. These technology developments are also applicable to lower frequencies, such as UHF frequencies, where the electromagnetic spectrum is quite crowded and reconfigurable filtering networks can provide significant benefit. This paper explores the use of piezoelectrically-tuned evanescent cavities to create a broadly-tunable multi-pole filter with very low loss at UHF frequencies.

II. DESIGN AND CONSTRUCTION

Applications for UHF filtering generally require small relative bandwidths (<10%), low insertion losses (<2dB), and moderate power handling capabilities (> 20dBm). These features can be effectively implemented using capacitively-loaded coaxial cavity resonators. In such a cavity, a post is used to concentrate the electric field of the TE101 mode between the top of the post and the top cavity wall. This adds a capacitive loading which lowers the resonant frequency of the cavity. The concept is shown in Figure 1. To affect frequency tuning, the capacitive loading of the coaxial cavity is physically varied by mechanically moving the top surface of each cavity resonator toward or away from their respective center posts. This is accomplished using a flexible metal membrane and a piezoelectric actuator placed directly above, external to the filter cavity. The application of a bias voltage to the piezoelectric ceramic induces a strain in the actuator which causes the disc to change shape and deflect the metal membrane towards or away from the loading post. This method provides an effective means to manipulate the capacitive loading without introducing additional loss or nonlinear elements into the RF signal path.

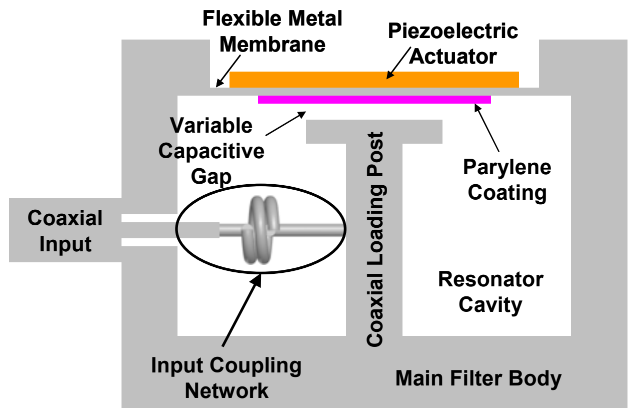

Figure 1 - Cross-section view of a capacitively-loaded cavity with a piezo actuator for mechanical deflection.

A 4-pole, tunable, coaxial cavity filter has been designed, fabricated and tested for operation at UHF frequencies. This filter makes use of four two-layer bending disk piezoelectric actuators (Piezo Systems T216-A4NO-373X). These actuators can be operated with either positive or negative bias, and are capable of up to ±120 µm of displacement at ±180 volts. To maintain as small of a volume as possible, adjacent resonators were loaded at opposing sides of the cavity. Figure 2 shows the fully-assembled 4-pole filter assembly.

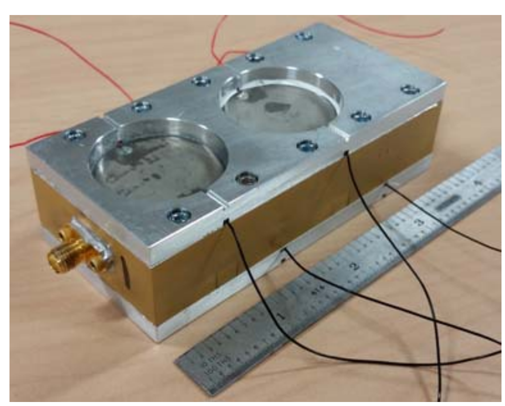

Figure 2 - Four-pole tunable filter at UHF frequencies.

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The assembly is 9.7 cm x 4.6 cm x 2.8 cm (excluding RF connectors) and weighs 244 grams. The filter body was fabricated from 6061 aluminum alloy and plated with nickel-copper-gold to enable soldering. The top and bottom surfaces of the cavity are composed of a cold-rolled aluminum sheet with a thickness of 75 µm. The non-movable portions of the cavities are supported mechanically by an aluminum frame. A thin layer (~9µm) of Parylene N is selectively deposited onto the movable aluminum membranes to prevent shorting to the top of the post, and to prevent breakdown at high RF power levels.

III. DESIGN OF FILTER COUPLING

A crucial aspect of any multi-pole tunable filter design is achieving the desired coupling between multiple filter cavities. As the filter changes frequency, especially when tuning over broad frequency ranges, it is imperative that dispersive coupling elements be crafted to exhibit the desired filter response. Frequency dependent coupling networks can be employed to maintain a good return loss, constant bandwidth, or whatever important filter characteristic is required over the tuning range. In this case, the input/output coupling network was designed to maintain a good impedance match and the inter-resonator couplings were allowed to vary naturally. Ideally, maintaining a constant return loss across frequency requires the external coupling coefficients to be constant. Tapping from the RF connector into the input or output post is largely capacitive and, as a result, the coupling coefficient increases dramatically with increasing frequency. To counteract this behavior, a series inductance was introduced into the coupling network to flatten the coupling with increasing frequency. An illustration of this external coupling network is shown in Figure 1.

As a check, the coupling coefficients of the input and output coupling networks were extracted from measured group delay measurements using a VNA. These values are plotted in the graph of Figure 3 along with ideal, uncompensated, and overcompensated coupling coefficients. Note the measured values deviate the furthest from the ideal values at the upper end of the tuning range. Inspection of the return losses across the tuning band corroborate this observation.

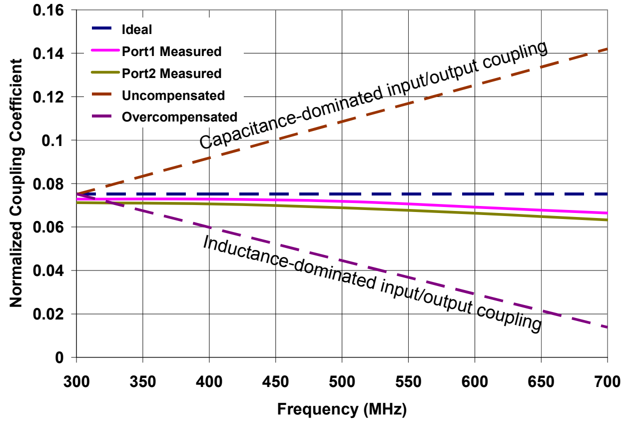

Figure 3 - Measured input/output coupling coefficients of frequency-tailored coupling networks.

The application driving this filter design did not require a constant bandwidth across the tuning range, therefore, no attempt was made to control this characteristic. However, the method employed here to control the impedance match across the tuning band could be extended to maintain a prescribed bandwidth.

IV. LINEAR CHARACTERIZATION

Insertion Loss/Return Loss - The filter's passband was tuned and measured at 50 MHz increments from 300 MHz to 700 MHz, over an octave of tuning. Loss measurements were made on an HP8510C vector network analyzer (VNA) using an SOLT calibration. A graph demonstrating the composite passband responses of the filter is shown in Figure 4. Losses range from 0.9 dB at 300 MHz to about 0.7 dB at 700 MHz, with a lowest loss of about 0.5-0.6 dB at mid-band. Also illustrated in Figure 4 is the filter return loss (impedance match) results across the tuning bandwidth. These results demonstrate a reasonably consistent 9-15 dB minimum return loss across the tuning band, with all four poles visible in the response. As previously discussed, the input and output coupling utilizes frequency-dependent elements to achieve a uniform return loss across the tuning range. The results from the Figure 4 are captured in Table 1 for clarity.

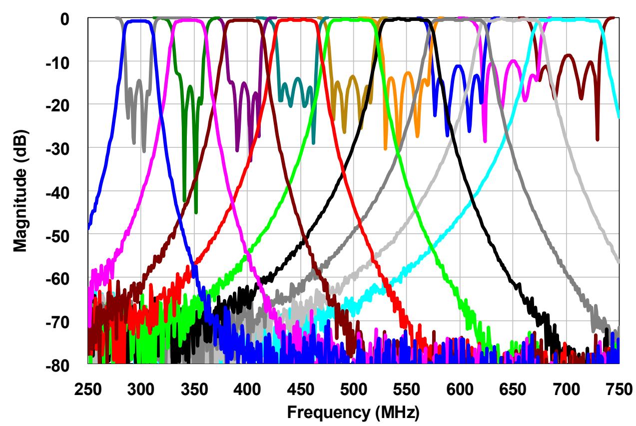

Figure 4 - Multi-pole tunable UHF filter response

Table 1 - Multi-pole Tunable Filter Response

Fo (MHz)	BW (MHz)	IL_0 (dB)	IL_{MAX} (dB)	RL_{MIN} (dB)
300	23.8	0.9	2.1	14.6
350	27.7	0.7	2.0	13.0
400	31.5	0.6	1.7	13.0
450	34.9	0.6	1.2	12.8
500	39.6	0.6	1.3	13.6
550	44.2	0.5	1.5	11.9
600	48.4	0.6	1.2	11.1
650	54.0	0.7	1.5	9.3
700	60.2	0.7	1.7	8.7

One of the most important metrics for a microwave filter is the unloaded quality factor. For this filter, the average unloaded quality factors, extracted from the filter measurements, ranges from 340 to 550.

Filter Rejection - This tunable filter was designed to provide a 4-pole Chebyshev response, achieving a rejection that is 44 dB down at 15% above and below the center frequency. This filter achieves those goals throughout the tuning range, with an ultimate rejection greater than 65 dB from DC to 1 GHz. The rejection of the filter remains better than 65 dB down at least through 8 GHz, where the waveguide cavities begin propagating and the loading posts are separated by one-half wavelength, enabling parasitic passband return responses.

V. NONLINEAR CHARACTERIZATION

Small-signal Nonlinearity - At small signal levels, third-order intermodulation products are important because the undesired spurs occur very close to the desired signals. This nonlinearity is most appropriately characterized by the third-order intercept point. For characterization of the tunable filter, a standard intermodulation test setup was used [3] consisting of two RF sources (Wavetek 2500 and Agilent N5171B), two amplifiers (WJ 6202-051T), and two circulators (various models depending on frequency) combined in a Wilkinson power combiner (Merrimac PDM-20-1100) and applied to the tunable filter, with the output products viewed on a Agilent E4402B spectrum analyzer.

The intermodulation measurements were made at the lowest and highest frequencies of the filter tuning range. The filters were tested with two tones separated by 2 MHz separation in frequency with output power levels ranging from 0 to 4 dBm. At 300 MHz the filter yielded an output intercept point (OIP3) of +54 dBm. At 700 MHz, measurements yielded an OIP3 of 57 dBm. Afterwards, the measurement system itself was measured for nonlinearity, yielding an IP3 of +57 dBm at 300 MHz and +59 dBm at 700 MHz. Since the IP3 of the measurement system was only a few dB higher than that of the filter measurements, the measured OIP3 of the tunable filter should be equal to or better than the measured +54 dBm and +57 dBm levels.

Power Handling - Fixed frequency filters are generally limited in power handling by breakdown mechanisms associated high RF fields within the filter [4]. However, filters utilizing flexible cavity membranes (driven by MEMS or piezoelectric actuators) often have other phenomena that impact their operation at more moderate power levels [5,6]. In this case, high circulating RF voltages create an electrostatic force sufficient to deflect the movable membrane. We observe this phenomena by measuring the small-signal response of the filter on a VNA under varying power levels at mid-band (500 MHz). The measurements were made with the HP 8510C VNA, a amplifier (WJ 6202-051T) with 23 dB gain and >25 dBm output power over the UHF frequency range, and a variety of 3-, 6-, and 10-dB attenuator pads. Figure 5 demonstrates the measured filter passband response at input power levels ranging from 0 dBm to 26 dBm. It is apparent that as the power level increases, the filter response begins shifting towards lower frequencies (approximately 2.2 MHz or 0.44% at +26 dBm). By and large, the filter passband response stays intact but shifts slightly lower in frequency with increasing power level.

In piezoelectrically-controlled filters, strain gauges are often used to quantify the precise position of the individual actuators, and thus their tuning positions. It is believed that these in situ sensors will sense changes in membrane position caused by RF power levels which detune the filter to lower frequencies. Thus, the same resonator frequency sensing mechanism that is used to set the tuning of the filter can be used to correct for the shift in filter frequency at moderate RF power levels. This shift can be compensated by throttling back the actuator bias voltages, thus maintaining the desired filter response. To check this theory, the shifted response at 26 dBm was re-tuned by making small adjustments to the piezo actuator bias voltages. These adjustments negated the effects of the power-induced frequency shift.

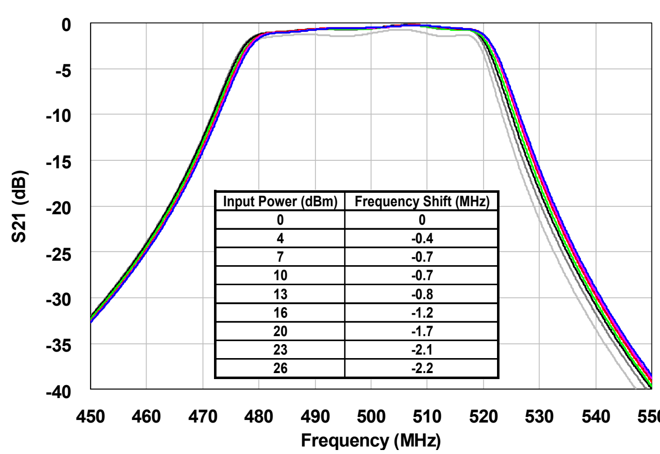

Figure 5 - Shift in filter response with power level.

VI. CONCLUSIONS

A four-pole tunable filter has been demonstrated that achieves greater than an octave tuning range with less than 1 dB mid-band loss at UHF frequencies. The filter successfully incorporated inductive input/output coupling to maintain a good return loss across the tuning range and an unloaded quality factor > 340. Characterization of filter nonlinearities demonstrate an intercept point > +54 dBm and power handling of at least 26 dBm.

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