FUNDAMENTAL AND OVERTONE ALUMINUM NITRIDE DUAL MODE RESONATOR FILTERS

R.H. Olsson III and M.R. Tuck

Sandia National Laboratories, Albuquerque, New Mexico, USA

ABSTRACT

This paper reports post-CMOS compatible aluminum nitride dual mode resonator filters that realize 4th order band-pass filters in a single resonator device. Dual mode filters at 106 MHz operating in their fundamental mode are reported with insertion losses as low as 5.5 dB when terminated with 150 Ω . A notching technique is demonstrated for varying the 3 dB bandwidth of these filters from 0.15 to 0.7%, overcoming a significant limitation of previous work. Dual mode filters operating at their 5th and 10th overtones are reported scaling the operating frequencies of this class of device to 0.55 and 1.1 GHz.

INTRODUCTION

Aluminum nitride (AlN) MEMS filters are a promising technology for the miniaturization of RF communication systems [1-3]. The small size and single chip integration of filters operating from 1 MHz to several GHz enable real time spectrum analyzers and multi-channel software defined radios with greatly reduced size and power consumption. These applications require banks of greater than 100 filters, placing added emphasis on small size and a minimum number of devices. Dual mode filters, which realize a 4th order band-pass filter in a single device, are ideal for such applications. AlN dual mode filters were first reported at 23 MHz in [4] and later scaled to 108 MHz utilizing the ring device in Fig. 1 [3]. It was demonstrated in [3] that varying the ratio, R/W , changes the separation between the two resonant modes shown in Fig. 2 that comprise the dual mode filter and thus the filter bandwidth. This technique, however, was limited and the minimum separation between the two resonant peaks could only be reduced to 0.3%. Due to the high-Q of these devices, large peak separations result in excessive pass-band ripple (PBR) even with large resistive filter terminations. Furthermore, it is often desirable in spectrum analyzer and RF communications applications to reduce filter bandwidth to improve sensitivity. Utilizing a notching technique [5] the resonant peak separation for the dual mode filters has been reduced to less than 0.1%, resulting in low insertion loss (< 7dB), low termination impedance (150 Ω) filters with bandwidths as small as 0.15% and no PBR.

In order to address the applications outlined above it is necessary that the dual mode MEMS filter technology be able to cover the VHF (30-300 MHz) and UHF (0.3-3 GHz) frequency range. Scaling the dual mode filter in Fig. 1 to higher frequencies while operating in the fundamental mode requires a subsequent reduction in resonator width, W , which increases the filter impedance due to the smaller transduction area. While this increased impedance can be compensated by a subsequent increase in ring radius, R , this results in an excessively large filter area. It was demonstrated in [3] that operating an AlN ring resonator in overtone modes scales the operating frequency while maintaining a constant device size and impedance. This technique has been applied to dual mode filters where operation at the 5th and 10th overtones has scaled these filters to 550 and 1080 MHz, the highest frequency dual mode filters reported to date. These overtone filters can function as a 2, 3, or 4-port networks corresponding to single-ended, single-ended-to-differential (balun), or fully differential operation, which can be used to improve the rejection of out-of-band signals and spurious modes.

Figure 1: Fundamental dual mode AlN MEMS filter with bandwidth controlling notches and 4-anchors.

Figure 2: Anti-symmetric, *Mode(0)*, and symmetric, *Mode(1)*, resonant modes that comprise the dual mode filter shown for a 2-anchor filter.

FUNDAMENTAL DUAL MODE FILTERS

A photo of the fundamental dual mode filter is shown in Fig. 1. The filter was fabricated using the process detailed in [3] which achieves highly oriented AlN films (rocking curve full-width-half-maximum of 1°) necessary for constructing low impedance filters. For the fundamental mode filters reported here, the bottom oxide thickness in [3] has been increased to 0.6 μm in an ongoing effort to achieve passive temperature compensation. The dual mode filter in Fig. 1 has small internal notches that change the coupling stiffness between the drive and sense halves of the ring resulting in a decrease in the separation between *Mode(0)* and *Mode(1)* in Fig. 2 and filter bandwidth. The measured results from four dual mode filters with radius, $R = 140\mu\text{m}$, width, $W = 40\mu\text{m}$, 2-anchors and notching, N , of 0, 2, 3 and 4 μm are shown in Fig. 3. Utilizing notching the resonant peak separation can be changed by nearly an order of magnitude providing the ability to design dual mode filters in the 0.1% to 1% bandwidth range. The measured and modeled (ANSYS finite element model) peak separations are shown in Fig. 4, demonstrating good agreement between the theoretical and experimental results. Since the impedance of each dual mode filter is approximately 150 Ω , that termination impedance was chosen for all the filters for comparison. The measured results of the dual mode filters with different amounts of notching are shown in Fig. 5 and a close-up

Figure 3: Measured transmission of dual mode AlN filters with an outer radius, R , of $140 \mu\text{m}$, width, W , of $40 \mu\text{m}$, 2-anchors and internal notching of 0, 2, 3, and 4 μm . Notching decreases the peak separation from 613 kHz to 87.5 kHz.

Figure 4: Measured and predicted peak separation vs. notching.

Figure 5: Measured transmission of dual mode AlN filters with, $R = 140 \mu\text{m}$, $W = 40 \mu\text{m}$, 2-anchors and internal notching of 0, 2, 3, and 4 μm when terminated with 150Ω . The PBR is reduced to below 3 dB for all notched filters.

of the filter pass-bands are shown in Fig. 6. The ripple of each filter with notching is reduced to below 3 dB while the unnotched filter ripple is nearly 10 dB. While further increases in the termination impedance will continue to reduce the ripple, impedance increases are limited to a maximum of 800Ω by the 1.8 pF shunt transducer and pad capacitance of the device. The wide bandwidth response of a dual mode filter is shown in Fig. 7 demonstrating greater than 50 dB of stop-band rejection. Since the motivation of this work is to construct single-chip filter banks it is important that the frequency spacing between filters be well

Figure 6: Close-up of the filter pass-bands from Fig. 5.

Figure 7: Wideband frequency response of the dual mode filter.

controlled and that the crosstalk between filters be low. Shown in Fig. 8 is the response of a bank of four dual mode filters located on the same $1.7 \times 0.7 \text{ mm}$ die, all with radius, $R = 140 \mu\text{m}$, notching, $N = 3 \mu\text{m}$, 4-anchors, and widths, W , varying from 40.25 to $41 \mu\text{m}$ in $0.25 \mu\text{m}$ increments for a filter bandwidth of 250 kHz and a center-to-center frequency spacing of 600 kHz. The increase in termination impedance to 200Ω (compared to the 150Ω in Fig. 5) is needed to offset the slight decrease in Q for the 4-anchored filters compared to those with 2-anchors. Also shown in Fig. 8 is the crosstalk between physically adjacent filters spaced $300 \mu\text{m}$ apart and frequency adjacent filters physically located $500 \mu\text{m}$ apart. It can be seen in Fig. 8 that the filter bandwidths and frequency spacings are well controlled and that the crosstalk between filters is well below the filter stop-band rejection. Table 1 summarizes the performance of the notched fundamental dual mode filters and filter bank.

Figure 8: Frequency response and crosstalk performance of a 4-element, single-chip dual mode filter bank.

Table 1: Fundamental dual mode filter performance.

R (μm)	W (μm)	N (μm)	Termination Impedance (Ω)	Insertion Loss (dB)	Center Frequency (MHz)	3 dB Bandwidth (kHz)	Pass-band Ripple (dB)	20 dB Shape Factor
140	40	0	150	6.2	105.4	744	9.6	1.8
140	40	2	150	5.5	105.6	381	2.7	2.6
140	40	2	200	5.2	105.6	394	1.7	2.6
140	40	3	150	6.8	105.7	288	0.7	3.2
140	40	4	150	6.8	105.8	156	0	4.5
140	40.25	3	200	7.7	103.4	260	0	3.1
140	40.5	3	200	7.6	104.0	252	0	3.2
140	40.75	3	200	7.4	104.6	240	0	3.5
140	41	3	200	7.3	105.2	244	0	3.5

OVERTONE DUAL MODE FILTERS

In order to scale the dual mode filter architecture and its advantages of ultra-small size, a minimum number of devices for manufacturability, variable bandwidth and excellent stop-band rejection to higher frequencies without increasing size or insertion loss overtone operation is employed. It was demonstrated in [3] that through appropriate top Al electrode patterning on a single ring resonator that overtones can be selectively transduced and higher frequencies can be achieved without increasing motional impedance or device footprint. The 5th overtone dual mode filter (4-anchors) shown in Fig. 9 utilizes this technique to scale the 4th order fundamental dual mode filter in Fig. 1 to 550 MHz. The mode shapes in Fig. 2 now appear as overtones as shown in Fig. 10 (2-anchors), with the symmetric mode occurring at lower frequency. Overtone operation also allows for 3-port (balun) or 4-port (fully differential) dual mode filters. The measured 2 and 3-port frequency response of a 5th overtone dual mode filter with radius, $R = 140 \mu\text{m}$, width, $W = 40 \mu\text{m}$, notching, $N = 4 \mu\text{m}$, and 2-anchors is shown in Fig. 11. Inside the filter bandwidth S31 and S41 are 180° out-of-phase while transmission outside the filter bandwidth is dominated by capacitive feed-through placing S31 and S41 in phase. Thus, subtracting S41 from S31, which forms a single-ended-to-differential converter or balun, improves the stop-band rejection by 16 dB while reducing the insertion loss by 3 dB due to the increased transduction area. Further increases in stop-band rejection can be achieved utilizing fully differential operation as shown in Fig. 12, where the frequency response of two 5th overtone dual mode filters with 3 and 4 μm of notching are presented. The notching technique demonstrated above for the fundamental dual mode filters can be used to control the bandwidth of overtone dual mode filters. As was the case for the fundamental

Figure 9. Fully differential 5th overtone dual mode AlN filter.

Figure 10: Symmetric, Mode(0), and anti-symmetric, Mode(1), resonant modes that comprise the 5th overtone dual mode filter.

Figure 11: Frequency response of a 5th overtone dual mode filter when operated as a 2 and 3 port network. Ports 3 and 4 are 180° out of phase in the filter pass-band and in phase outside the pass-band. Subtracting the outputs to form a balun reduces insertion loss by 3 dB and increases stop-band rejection by 16 dB.

Figure 12: Fully differential frequency response of the 5th overtone dual mode filter with 3 and 4 μm bandwidth controlling notches.

Table 2: Performance of 5th and 10th overtone dual mode filters with radius, $R = 140 \mu\text{m}$, and width, $W = 40 \mu\text{m}$.

Over-tone	# of ports	N (μm)	# of anchors	Insertion Loss (dB) @ 50 Ω	Center Frequency (MHz)	3 dB Bandwidth (kHz)	PBR (dB)	20 dB Shape Factor	Stop-band Rejection (dB)	Min. Off-Overtone Rejection (dB)
5th	2	4	2	23.5	544	875	0	2.9	32	22
5th	3	4	2	19.4	544	875	0	2.6	48	35
5th	4	4	2	21.4	544	875	0	2.5	58	49
5th	4	3	2	22.7	543	688	0	3	56	47
5th	4	2	4	22.7	559	813	0	2.7	57	62
5th	4	0	4	24.7	559	625	0	3.5	55	60
10th	2	0.5	4	41.1	1084	750	0	-	9	0
10th	3	0.5	4	39.1	1084	750	0	9.2	20	24
10th	4	0.5	4	39.2	1084	750	0	11.8	24	46
10th	4	0.5	4	39.8	1084	1500	0	4.4	24	46

mode devices, notching has a much larger effect on the frequency of the anti-symmetric mode, controlling the bandwidth by moving it closer or further in frequency from the symmetric mode which is comparatively constant with notching. The wideband response of the 5th overtone dual mode filter is shown in Fig. 13 for 2, 3, and 4-port operation, where balun and fully differential configurations not only improve the stop-band rejection by 16 and 26 dB, but also the rejection of lower overtones by 13 and 27 dB. Table 2 summarizes the results for the 5th overtone dual mode filters and presents additional data on 10th overtone dual mode filters operating at 1.1 GHz.

DISCUSSION AND CONCLUSIONS

Fundamental and overtone dual mode filters that realize a 4th order band-pass filter in a single device have been demonstrated at 100, 550, and 1085 MHz. A notching technique has been developed capable of controlling the bandwidth of these filters between 0.1 and 1%. Banks of dual mode filters around 100 MHz have shown excellent bandwidth and frequency spacing control and the crosstalk between filters is below the filter stop-band rejection. When scaled to overtone operation, these filters demonstrate higher than expected insertion loss. The 106 MHz fundamental dual mode filter with 4 μm of notching in Fig. 3 and the 544 MHz, 5th overtone fully differential dual mode filter with 4 μm of notching in Fig. 12 both have 0.16% bandwidth. The insertion loss of the 106 MHz filter at 50 Ω is 12.7 dB and is expected to be 3 dB higher in the 544 MHz filter due to the 25% reduction in transduction area (the input signal is divided between in^+ and in^- from Fig. 9) if the quality factor, Q , of the resonant

modes are the same for the two filters. The measured insertion loss of the 5th overtone filter, however, is 21.4 dB, 5.7 dB higher than expected and increases slightly for the filter with 3 μm of notching and decreased bandwidth of 688 kHz. It is suspected that resonator Q is being reduced at higher frequencies by the tapered sidewall of the AlN etch. AlN resonators measured at frequencies in excess of 1 GHz often exhibit two closely spaced resonant peaks due to the AlN taper. This particularly degrades the insertion loss of the 1.1 GHz 10th overtone filters due to their narrow bandwidth and high operating frequency. On going work in realizing a vertical AlN sidewall should significantly reduce dual mode filter insertion loss at higher frequencies. A path has been demonstrated for the realization of miniature, single device, 4th order filters covering the VHF and UHF frequency range for real time spectrum analysis and cognitive radio applications.

ACKNOWLEDGEMENTS

The authors would like to thank the Microelectronics Development Laboratory staff at Sandia National Laboratories including Jim Stevens and Craig Nakakura for AlN process development. This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. Sandia National Laboratories is a multiprogram laboratory operated by the Sandia Corporation, Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

REFERENCES

- [1] G. Piazza, P. J. Stephanou and A. P. Pisano, "Single-Chip Multiple Frequency ALN MEMS Filters Based On Contour-Mode Piezoelectric Resonators," *Journal of Microelectromechanical Systems*, 16, 2, pp. 319-328, (2007).
- [2] D. J. D. Carter, J. Kang, D. White and A. E. Duwel, "Fabrication and Measurement of an IC-Compatible GHz-Range Piezoelectric Longitudinal Bar Resonator," *Proc. of the Solid-State Sensor, Actuator, and Microsystems Workshop*, (2004), pp. 254-257.
- [3] R. H. Olsson III, J. G. Fleming, K. E. Wojciechowski, M. S. Baker and M. R. Tuck, "Post-CMOS Compatible Aluminum Nitride MEMS Filters and Resonant Sensors," *Proc. IEEE Frequency Control Symposium*, (2007), pp. 412-419.
- [4] P. J. Stephanou, G. Piazza, C. D. White, M. B.J. Wijesundara and A. P. Pisano, "Piezoelectric Aluminum Nitride MEMS Annular Dual Contour Mode Filter," *Sensors and Actuators A*, 134, pp. 152-160, (2007).
- [5] G. K. Ho, Personal Communication, June 2007.

Figure 13: Wideband response of a 5th overtone dual mode filter. Utilizing balun and fully differential operation reduces feed-through of lower overtones by 13 and 27 dB.