Review on Microwave and Millimeter Filters Using MEMS Technology

Aline Jaimes-Vera[1], Ignacio Llamas-Garro[2], Alonso Corona-Chavez[2], Ignacio Zaldivar-Huerta[1]

[1] Electronics Department, [2] Large Millimeter Telescope, National Institute for Astrophysics, Optics and Electronics.
Luis Enrique Erro #1, Tonanzintla Puebla, Mexico. CP 72840
ajaimes@inaoep.mx

Abstract

Several different fabrication techniques and materials have been proposed for the realization of low loss high-Q micromachined filters or tunable filters. In this paper a review of several filters that have been proposed over the last years is presented, including a discussion of topologies and the structures used to make microwave filters.

1. Introduction

Filters play an important role in many RF/microwave applications. The electromagnetic spectrum is limited and has to be shared; filters are used to select or confine the RF/microwave signals within assigned spectral limits. Since the early stages of RF/microwave engineering, filters made by metallic rectangular or cylindrical waveguides have been commonly used, however they are heavy in weight, large in size, costly to manufacture and they do not allow an easy integration with monolithic integrated circuits. On the other hand planar circuits at millimeter wave frequencies suffer from high losses. Several alternatives have been proposed over the last years to achieve good performance filters and transmission lines using MEMS technology. Emerging wireless communications applications continue to challenge RF/microwave filters with ever more stringent requirements e.g. higher performance, smaller size, lighter weight, and lower cost. Depending on the requirements and specifications, RF/microwave filters may be designed as lumped element or distributed element circuits, they may be realized in various transmission lines structures, e.g. microstrip, waveguide cavities, coplanar, coaxial, stripline. And can be implemented using a variety of fabrication techniques.

In this paper we describe circuits used to make microwave and millimeter wave filters, as a review of the state-of-the-art related to microwave filters using MEMS technology. MEMS filters can be classified into Micromachined Filters and Tunable filters.

Micromachined filters can be classified into the following groups: Microstrip, coplanar, micromachined cavities, filters supported by membranes and coaxial. For tunable filters, switches or varactors have been integrated on a filter topology to achieve reconfigurability. This review is mainly focused on lumped and distributed element filters made using MEMS technology, and does not include the FBAR structure [1-3].

2. Micromachined filters

In this section a review of micromachined filters made using MEMS techniques is presented. Different transmission line structures and topologies have been proposed with a general objective of producing low cost micro/millimeter wave high performance devices. The filters are designed with different structures like cavities, coplanar, microstrip or coaxial transmission lines.

2.1. Micromachined cavity resonators and filters

A micromachined cavity presented in [4] exhibits an unloaded Q at X band of Q_0=506. The cavity is coupled by two microstrip lines through two slots. The two microstrip lines are gold electroplated with a total thickness of 7.5μm in order to minimize losses; the cavity is also metallized with a thickness of 2μm. This structure presents a high Q, using wafer bonding and metallized silicon cavities.

Fig.1 [5] shows a 10GHz filter constructed of slot coupled micromachined cavities on silicon. The simulated model has a bandwidth of 4% with an insertion loss of 0.9 dB at 10.02 GHz. The measured filter yields a 3.7% bandwidth with a deembedded insertion loss of 2dB at 10.01 GHz. The difference of loss is due to the CPW-microstrip transition and line lengths. The overall dimensions of the filter are approximately 5cm long x 3cm wide x 2600μm high. This design is lightweight, of compact size, and may be easily integrated into a monolithic circuit. A high Q filter constructed of these

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resonators yields high power handling capabilities as the surface currents are distributed over a large conductor area.

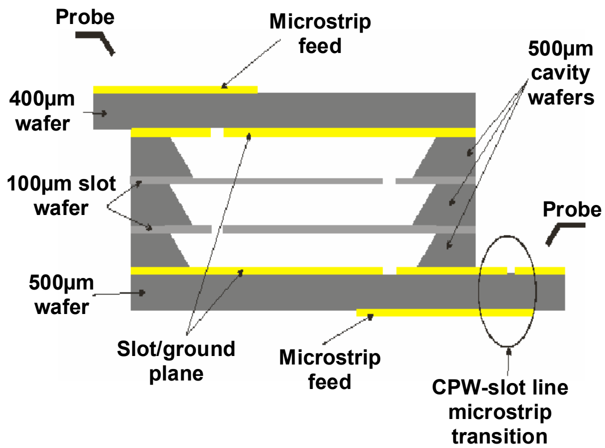


Fig 1. Side view of a three-cavity filter, taken from [5]

2.2. Coplanar

Figure 2 shows a third order, 5% fractional bandwidth coupled-line filter with a center frequency of 94GHz [6]. Insertion loss and return loss are 4 and 20 dB respectively for a center frequency of 91.5 GHz. Good agreement between theory and experimental results are obtained over a wide frequency band up to 110 GHz. Other filter topologies in wide and narrowband designs are presented in [6].

Other examples of coplanar transmission lines taken from literature include coplanar waveguides on silicon, where the silicon between conductors is etched away, to reduce substrate losses [7]. Coplanar waveguides obtained by lifting the edge of a conductor to obtain a large range of possible characteristic impedances are presented in [8]. Coplanar waveguides on a thin organic substrate can be found in [9]. Also in [10] a study on using silicon rich oxide (SRO) as a passivation layer is demonstrated. In [11] low loss coplanar transmission lines on low resistivity silicon substrates are presented.

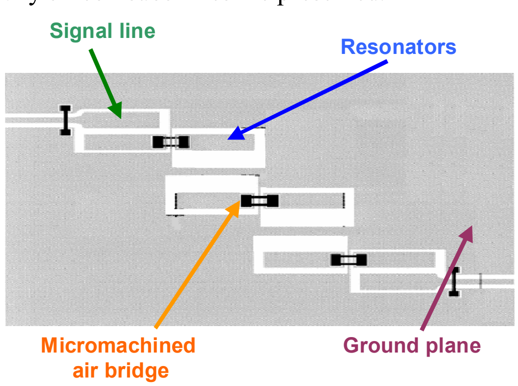


Fig 2. Layout of a coplanar 94 GHz central frequency, 5% fractional bandwidth, coupled-line filter, taken from [6]

2.3. LIGA planar transmission lines and filters

Fig 3 [12] shows a microstrip structure used in the design of X band microstrip stepped impedance lowpass and coupled resonator broadband bandpass filters.

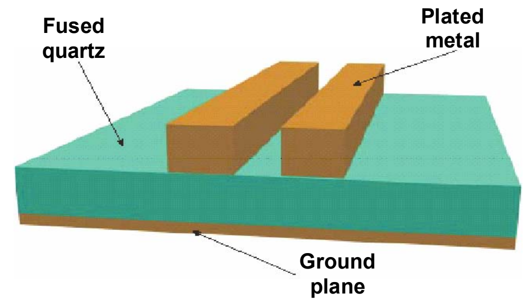


Fig 3. Two 200µm thick coupled LIGA microstrip lines, taken from [12]

In [12] lowpass and bandpass LIGA microstrip filter designs are presented with design frequencies of 10 and 14 GHz, the results are summarized as follows. A 14 GHz stepped impedance low pass filter with 200µm thick conductors was designed with a 3dB cutoff frequency of 13.4 GHz, and an attenuation of 20dB at 17.1 GHz. The minimum insertion loss for the filter is -0.15 dB at 8.07 GHz, the low pass filter topology is shown in fig 4. A coupled line Butterworth bandpass filter design in LIGA, using the same 200µm thick conductor geometry has been developed, in which quarter wavelength parallel-line sections with two open circuits ports were used as coupling elements. The filter is centered at 10GHz with four coupling elements having a 40% fractional bandwidth. By using tall conductors using LIGA process, stronger coupling coefficients between transmission line resonators can be achieved, compared to conventional thin metallizations.

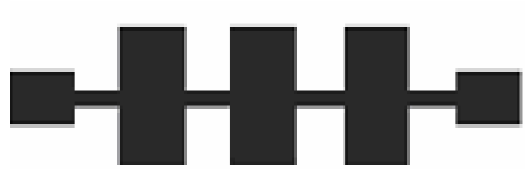
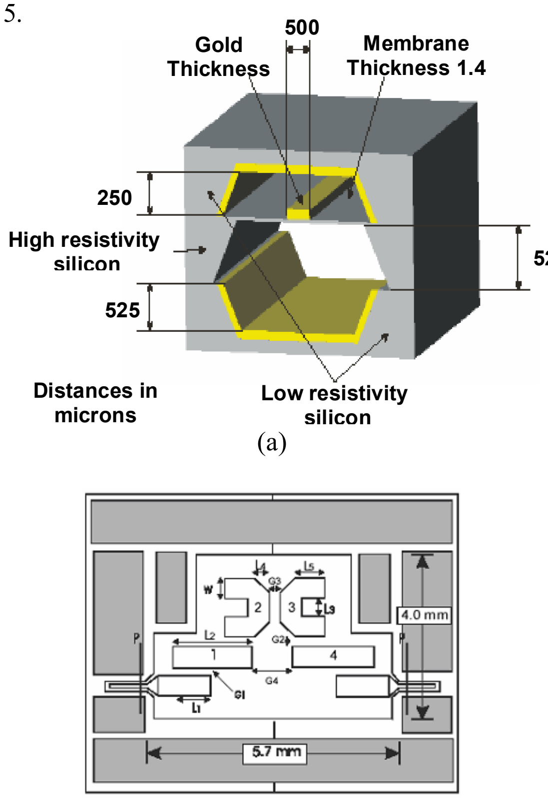


Fig 4. Layout of the low pass filter using 200µm thick nickel conductors, taken from [12]

2.4. Membrane and microstrip filters

High performance membrane filters at 37 and 60 GHz are presented in [13], the filters consist of a 3.5% fractional bandwidth two pole Chebyshev filter with transmission zeros having a 2.3 dB port to port insertion loss. Also in [13] a 2.7% and 4.3% bandwidth four and five pole Chebyshev filters at 60GHz exhibiting an insertion loss of 2.8 and 3.4 dB respectively are demostrated. The design of an 8% fractional bandwidth quasi elliptic filter at 60 GHz exhibiting an insertion loss 1.5 dB is also presented. The measured unloaded Q of these resonators is between 400 and 500 at the frequencies of interest. The layout and structure of the 8% fractional bandwidth quasi elliptic filter is presented in Fig 5.



(b)

Fig 5. Layout and structure of the four-pole membrane quasi elliptic filter taken from [13], (a) micromachined membrane structure, (b) microstrip filter topology

A planar diplexer integrated on a single silicon substrate is presented in [14], the diplexer channels have a Chebyshev response and have a 5% and 6.5% relative bandwidth at 28 and 31 GHz respectively. This design consists of two capacitively coupled bandpass filters with one port shared between the filters. The receive and transmit band filters have four and three poles respectively, both having a 0.1 dB passband ripple. The measured unloaded Q of one resonator is 460 at 29GHz. The diplexer outer dimensions are 1.5cm x 1.6cm x 1.4mm thick. The insertion loss is 1.4 dB for the 28GHz band and 0.9 dB for the 31GHz band, including all transition effects. The measured isolation is better than -35dB across the receive band, and better than -50 dB in the transmit band.

A silicon micromachined filter for flip chip mount using a using a BCB membrane is proposed in [15]. Experimental results of a two pole 30GHz, 4% fractional bandwidth filter with a resonator unloaded quality factor of 602 is presented. The filter exhibited an insertion loss of 1.8 dB. In [16] a low loss inverted microstrip line using BCB and silicon wafers is presented and a filter demonstrated using structure. In [17] a membrane supported filter using organic SU8 package was used to form microstrip resonators.

2.5. A high Q millimeter wave dielectric resonator

A high performance micromachined millimeter wave dielectric resonator circuit on silicon has been demonstrated in [18], in which an appropriate coupling between two coplanar lines and a dielectric resonator have allowed the achievement of loaded quality factors ranging from 400 to 2400 at 35 GHz, with transmission levels ranging from -5 to -14 dB. The structure is shown in Figure 6. With this structure the possibility of obtaining a high Q at millimeter waves is demonstrated using dielectric resonators.

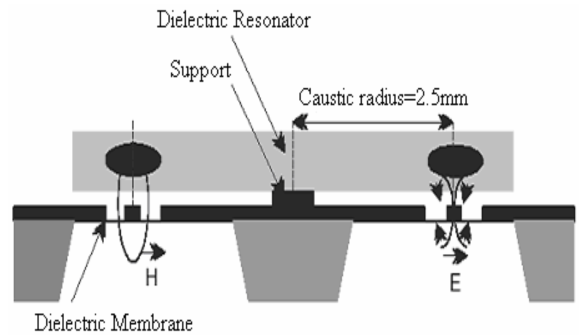


Fig 6. A dielectric resonator at millimeter waves, taken from [18]

2.6. Coaxial

The structure in [19, 20] is a suspended coaxial line. The coaxial center conductor is held by λ/4 stubs connected to the metal side walls (outer conductor) of the coaxial line, avoiding dielectric loss in a completely shielded structure. This line shows a Q_0 of about 210, at 29.75 GHz. This transmission line has been made by laser micromachining, and also its fabrication with SU8 has been devised, where SU8 allows complex structures to be realized compared to silicon.

A dielectric filled coaxial transmission line is presented in [21]. This coaxial line has potential operation in the terahertz region, and is MMIC compatible; it presents the possibility of having no crosstalk between adjacent lines, which enables denser IC design using a compact transmission line. The square coaxial transmission line had a measured loss of 1.5 dB/mm at 35 GHz using a 4 micron width centre conductor, and a predicted loss of 3dB/mm at 1THz using a 10 micron width center conductor.

The structure in Figure 7 [22], consists of a monolithic surface micromachined half-coaxial transmission line on a

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quartz substrate. A thick sacrificial layer is used to form the half coaxial cavity and then removed leaving a 100µm air propagation media between conductors. The unloaded quality factor for this structure is 153 at around 32 GHz for a fully monolithic planar transmission line.

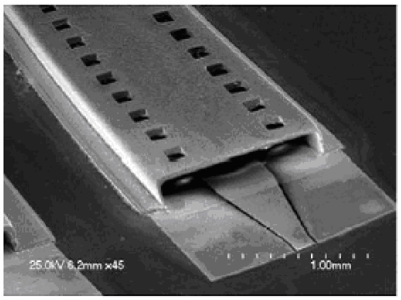

Fig 7. Half coaxial transmission line, taken from [22]

In Figure 8 [23] a narrowband suspended coaxial transmission line filter with air propagation medium is presented. The design consists of a 4-pole, 4% fractional bandwidth band pass filter centered at 9GHz, consisting of four capacitively coupled self supported coaxial line resonators.

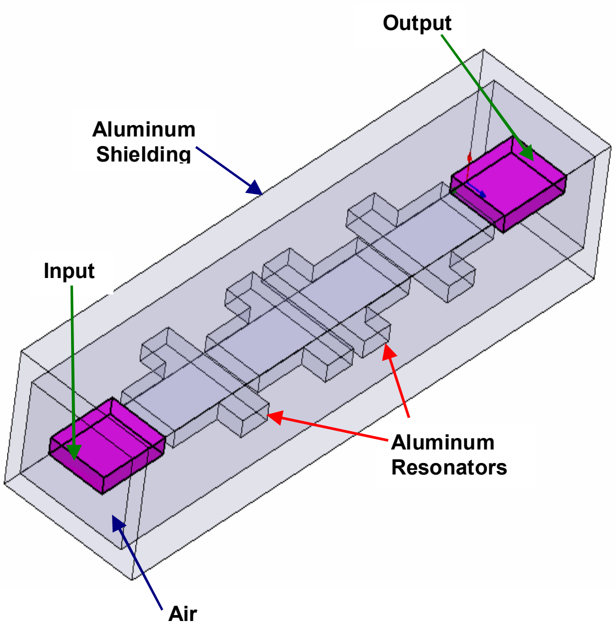

Fig 8. Filter structure using free standing metallic resonators, taken from [23]

3. Micromachined tunable filters

Micromachined tunable filters present circuit reconfigurability, e.g. the frequency of the passband or rejection band can be varied by adjusting its components. MEMS switches or varactors have been integrated on filter topologies to achieve reconfigurability. There are two different types of frequency-tuning methods for MEMS filters: analog and digital. Analog tuning is made with MEMS varactors and provides continuous frequency variation between 5-15%. Digital tuning is made with MEMS switches, where discrete center frequencies and wide tuning ranges of 20-60% are possible [24]. Also MEMS switches can be used to switch between transmission line resonators of different lengths to provide more than one filter center frequency.

3.1. Tunable filters using MEMS varactors

A micromachined tunable filter at X band is presented in [25]. The filter uses membrane technology as in [13, 14] to produce a stripline filter. The filter is tuned via conventional varactors at the end of the resonators. The varactors were measured to have a capacitance variation of 1.8pF to 1.1pF. The tuning range was approximately from 5.5 to 10.5 GHz, with an insertion loss of about 5dB. The insertion loss and the out of band rejection were degraded, caused by a bad contact between ground planes.

Another micromachined tunable filter is reported in [26], shown in fig 9 where MEMS variable capacitors are integrated on two filter topologies in order to tune filter center frequency. Two bandpass filters are presented, one with two poles made with lumped elements and one with two poles made with distributed elements. Both are designed at Ka band. With applied bias, the center frequency shift is in the range of 1.1 GHz (4.2%) for the lumped element filter, and 0.8 GHz (2.5%) for the distributed element filter. These tunable filters use cantilever type MEMS variable capacitors. With the application of DC bias voltage on the cantilevers, the electrostatic force between the two plates reduces the distance between them, resulting in a capacitance increase. The lumped element filter was designed to have a 4.7% fractional bandwidth, a 0.5dB ripple and a center frequency of 26.8 GHz. The distributed element filter was designed to have a 8.5% bandwidth, a 0.5 dB ripple and a center frequency of 30.6 GHz.

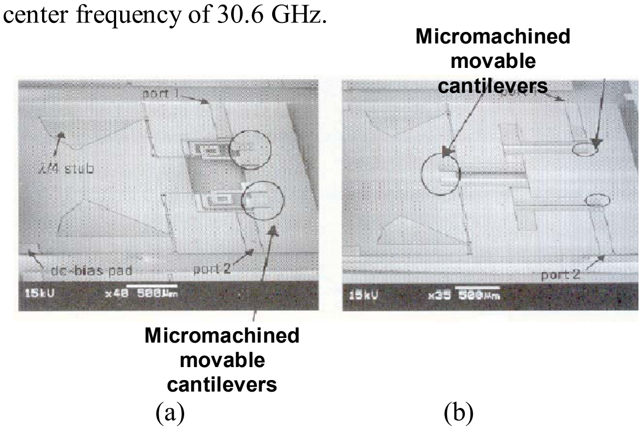

Fig 9. Micromachined tunable filters, taken from [26] (a) Two pole lumped element filter (3.4 x 2.9mm), (b) Two pole distributed element resonator filter (4.1 x 3.4mm)

In [27] a differential wide band tunable filter on a glass substrate using digital capacitor banks is presented. The filter provides continuous central frequency tuning in 16 states. The filter has a tuning range of 44% with very fine resolution, and return loss better than 16 dB for the whole tuning range. The relative bandwidth of the filter is 5.1±0.4% over the tuning range and the size of the filter is 5mm x 4mm. The insertion loss is 4.1 and 5.6 dB at 9.8 and 6.5 GHz, respectively.

In [24] a wide band tunable filter on a glass substrate is presented, having a center frequency ranging from 12 to 18 GHz (40% tuning range). Capacitor banks have been used to load the CPW resonators to reduce their effective length and make them tunable in a very wide frequency range. The coplanar waveguide filter has a return loss better than 10dB for the whole tuning range. The relative bandwidth of the filter is 5.7±0.4% over the tuning range and the size of the filter is 8mm x 4mm. The insertion loss is 5.5 and 8.2 dB at 17.8 and 12.2 GHz respectively.

3.2. MEMS Switches

In [28] a monolithic, low-power reconfigurable bandstop filter operating at 8, 10, 13, and 15 GHz is presented. The filter is based on microstrip lines, developed on a high-resistivity silicon substrate. The filter is based on microstrip radial stubs that provide different reactance at different resonant frequencies, selected using MEMS switches. The tuning range of the fabricated filter is 7 GHz (8-15 GHz), which is about 60% of the mid-band frequency. The pass-band insertion loss was found to be at around 0.5 dB. MEMS switches can be used to enlarge resonators by connecting transmission lines of different lengths, to achieve different centre frequencies in a discrete way [29].

In [30] the performance of MEMS metal switches were investigated at a wide temperature range, the study is aimed at the integration of MEMS switches with superconducting microwave circuitry. Measurements were carried out using a cryogenic probe station for frequencies up to 20 GHz. The results show a 50% increase in the actuation voltage and a decrease in the percentage of operational switches as the temperature was reduced from room temperature to 10 K. Isolations and insertion losses at low temperatures were similar to room temperature values. A metal switch used for this study is shown in Fig. 10. The switches consist of two electrostatically actuated nickel pads and a small central gold plated nickel RF contact pad, to form a direct contact switch over a coplanar line.

4. Conclusion

In this paper a review of microwave and millimeter wave filters using MEMS technology has been presented. Structures and filters proposed over the last years have been classified and a discussion on several designs has been given, with the objective of presenting an overall view of the field.

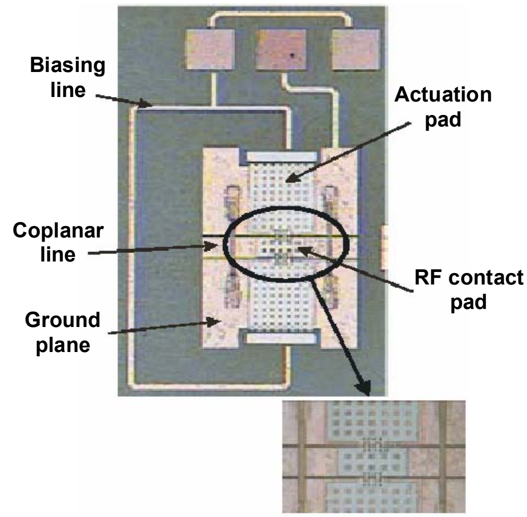

Fig 10. Photograph of the metal switch, taken from [30]

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6. References

[1] S.V. Krishnaswamy, J. Rosenbaum, S. Hortwitz, C. Yale, and R.A. Moore, "Compact FBAR filters offer low-loss performance", *Microwaves RF,* pp127-136, September 1991
[2]R. Ruby and P. Merchant, "Micromachined thin film bulk acoustic resonators", *Proc. 1994 IEEE Int. Frequency Control Symp.,* Boston, MA, June 1-3, 1994, pp 135-138
[3] Sang-Ho Kim, Jae-Sung Lee, Hyun-Chul Choi, and Yong-Hyun Lee, "The fabrication of thin-film bulk acoustic wave resonators employing a ZnO/Si composite diaphragm structure using Porous silicon layer etching", *IEEE electron device lett.,* Vol. 20, No.3, March 1999
[4] John Papapolymerou, Jui-Ching Cheng, Jack East and Linda P.B. Katehi, "A Micromachined High-Q X-band resonator", *IEEE Microwave and guided letters,* Vol. 7, No. 6, June 1997
[5] Lee Harle and Linda P.B. Katehi, "A vertically integrated micromachined filter", *IEEE transactions on microwave theory and techniques,* Vol. 50, No.9, September 2002
[6] Eric Rius, Gaetan Prigent, Henry Happy, Gilles Dambrine, Samuel Boret, and Alain Cappy, "Wide- and narrow-band bandpass coplanar filters in the W-frequency band", *IEEE transactions of microwave theory and techniques,* Vol.51, No.3, March 2003, pp 784-791
[7] Katherine Juliet Herrick. Thomas A. Schwartz and Linda P.B. Katehi, " Si-micromachined coplanar waveguides for use in high-frequency circuits", *IEEE Transactions on microwave theory and techniques*, Vol. 46, No.6, June 1998, pp 762-768

[8] Jae-Hyoung Park, Chang-Wook Baek, Sanghwa Jung, Hong-Teuk Kim, Youngwoo Kwon and Yong-Kweon Kim, “Novel micromachined coplanar waveguide transmission lines for application in millimeter-wave circuits” *Jpn. J. Appl. Phys.,* Vol.39, Part I, No. 12B, December 2000, pp 7120-7124

[9] Wai Y. Liu, D. Paul Steenson and Michael B. Steer, “Membrane-supported CPW with mounted active devices”, *IEEE Microwave and wireless components letters*, Vol. 11, No. 4, April 2004

[10] J.A. Reynoso-Hernandez, Raul Rangel-Rojo, I. Zaldivar, L.E. Sanchez, and M. Herrera, “Influence of the SRO as passivation layer on the microwave attenuation losses of the CPW’s fabrication on HR-Si, IEEE Microwave and wireless lett., Vol. 13, No.12, December 2003, pp 508-510

[11] Happy Henri, Six Gonzague, Vanmackelberg Matthieu, Cappy Alain and Dambrine Gilles. “Ultra low loss transmission lines on low resistivity silicon substrate” *IEEE MTT-S Digest,* 2000, pp 1809-1812

[12] Theodore L. Willke and Steven S. Gearhart, “LIGA micromachined planar transmission lines and filters” *IEEE transactions on microwave theory and techniques,* Vol. 45, No. 10, October 1997

[13] Pierre Blondy, Andrew R. Brown, Dominique Cros and Gabriel M. Rebeiz, “Low loss micromachined filters for millimeter wave communication systems”, *IEEE transactions on microwave theory and techniques,* Vol. 46, No.12, December 1998, pp 1181-1184

[14] Andrew R. Brown and Gabriel M. Rebeiz, “A high performance integrated K-band diplexer”, *IEEE transactions on microwave theory and techniques,* Vol. 47, No.8, August 1999

[15]M. Chatras, P. Blondy, D. Cros, O. Vendier and J.L. Cazaux, “A surface-mountable membrane supported filter” *IEEE Microwave and Wireless Components Lett.* Vol. 13, No.12, Dec. 2003, pp 535-537

[16] Kazuaki Takahashi, Ushio Sangawa, Suguru Fujita, Michiaki Matsuo, Takeharu Urabe, Hiroshi Ogura and Hiroyuki Yabuki, “ Packaging using micromechanical technologies and planar components” *IEEE Transactions on microwave theory and techniques*, Vol. 49, No. 11, November 2001, pp2099-2104

[17] J.E. Harriss, L.W. Pearson, X. Wang, C.H. Barron and A.V.Pham, “Membrane-supported Ka band resonator employing organic micromachined packaging” *IEEE MTT-S Digest,* 2000, pp 1225-1228

[18] B. Guillon, D. Cros, P. Pons, K. Grenier, T. Parra, J.L. Cazaux, J.C. Lalaurie, J. Graffeuil and R. Plana, “Design and realization of high Q millimeter wave structures through micromachining techniques”, *IEEE MTT-S Digest,* pp 1519-1522, 1999

[19] I. Llamas–Garro, M.J. Lancaster, and P.S. Hall, “Air filled square coaxial transmission line and its use in microwave filters”, *IEE proc. On microwaves antennas and propagation,* Vol. 152, No.3, June 2005, pp 155-159

[20] K. Jiang, M.J. Lancaster, I. Llamas-Garro and P. Jin, “SU-8 Ka-band filter and its microfabrication” *Journal of Micromechanics and Microengineering,* Vol. 15, August 2005, pp 1522-1526

[21] Jennifer A Bishop, Majid M. Hashemi, Kursad Kiziloglu, Lawrence Larson, Nadir Dagli, Umesh Mishra, “Monolithic coaxial transmission lines for mm-wave ICs” *high speed semiconductor devices and circuits, Proceedings IEEE/Cornell conference on advanced concepts,* 5-7 August 1991, pp 252-260

[22] Ignacio Llamas-Garro, Yongsung Kim, Chang-Wook Baek, Yong-Kweon Kim, “A Monolithic Surface Micromachined Half-Coaxial Transmission Line Filter”. *IEEE transactions on microwave theory and techniques (to appear, December 2006 issue)*

[23] Jaimes-Vera Aline, Llamas-Garro Ignacio, Corona-Chavez Alonso, Zaldivar-Huerta Ignacio[1] “Compact Air-filled High-Q Coaxial Filters Using Micromachined Free Standing Structures” ICED 2006, November 21-23, 2006, Veracruz, Mexico.

[24] Kamran Entesari and Gabriel M. Rebeiz, “A 12-18 GHz Three pole RF MEMS tunable filter”, *IEEE transaction on microwave theory and techniques,* Vol.53, No.8, August 2005

[25] Andrew R. Brown and Gabriel M. Rebeiz, “Micromachined micropackaged filter banks and tunable bandpass filters”, *IEEE wireless communications conference,* Proceedings 11-13, August 1997, pp 193-197

[26] Hong-Teuk Kim , Jae-Hyoung Park, Yong-Kweon Kim and Youngwoo Kwon, “Millimeter wave micromachined tunable filters”, *IEEE MTT-S Digest,* pp 1235-1238, 1999

[27] Kamran Entesari and Gabriel M. Rebeiz, “A differential 4-bit 6.5-10 GHz RF MEMS tunable filter”, *IEEE transaction on microwave and techniques,* Vol.53, No.3, March 2005

[28] Guizhen Zheng, and John Papapolymerou, “Monolithic reconfigurable bandstop filter using RF MEMS switches” *International Journal of RF and Microwave Computer-Aided Engineering,* Vol. 14, No. 4, July 2004, pp 373-382

[29] Erwan Fourn, Arnaud Pothier, Corinne Champeaux, Pascal Tristant, Alain Catherinot, Pierre Blondy,Gérard Tanné, Eric Rius, Christian Person, and Fabrice Huret , “MEMS switchable interdigital coplanar filter”, *IEEE transaction on microwave theory and techniques,* Vol.51, No. 1, January 2003, pp 320-324

[30] Hieng Tiong Su, Ignacio Llamas-Garro, Michael J. Lancaster, Martin Prest, Jae-Hyoung Park, Jung-Mu Kim, Chang-Wook Baek, and Yong-Kweon Kim, “performance of RF MEMS switches at low temperatures” *Electronics Letters*, Vol. 42, No. 21, October 2006, pp. 1219-1220.