Coupled-line RF MEMS Filters for Millimeter-wave Applications

Stepan Lucyszyn [1], Kenichi Miyaguchi [2], Ian D. Robertson [3] and Hong W. Jiang [1]
[1]Department of Electrical and Electronic Engineering, Imperial College London, UK
[2]Mitsubishi Electric Corporation, Kamakura, Japan
[3]School of Electronic and Electrical Engineering, University of Leeds, UK
[1]s.lucyszyn@imperial.ac.uk

Introduction

Millimetre-wave transmission lines suffer from high insertion losses when integrated with low resistivity silicon substrates. Inverted-microstrip has received relatively little attention. It is widely employed for antenna applications and as a transmission line for flip-chip monolithic microwave integrated circuits (MMICs). A few papers have investigated its use in micromachined form [26-30]. Takahasi *et al.* [27] demonstrated a 25 GHz dual-mode ring-resonator filter over a bulk-micromachined cavity, having less than 1 dB loss and an 8% bandwidth. Martoglio *et al.* [30] demonstrated a silicon/glass inverted microstrip filter at 29 GHz with 2.2 dB loss and 28% bandwidth. All these results have been collated for comparison in Table I. The structure investigated in this paper is a form of inverted microstrip that is, unlike the work by Takahasi *et al.* and Martoglio *et al.*, specifically for millimeter-wave operation because of the use of RF-coupled cantilevers.

Micromachined Filter Concept, Design and Measurements

A simplified isometric view of the proposed inverted-microstrip filter is illustrated in Fig. 1. It can be seen that the RF coupled-line approach is employed, since distributed-element lines minimize the problems associated with unwanted resonances found with lumped-element filter implementations at high millimeter-wave frequencies. Moreover, in order to reduce parasitic capacitances and ohmic losses associated with the use of low-cost silicon substrates, almost all the supporting silicon is removed, to leave free-standing metal cantilevers. The resulting air-filled cavity, which runs the whole length of the filter, can support unwanted modes that can also couple energy into the silicon substrate unless measures are taken to avoid this.

The total length for the 60 GHz 3-resonator filter (without including the two 2,330 μm long RF port feed structures) is 4,970 μm. An SEM view of the lower substrate for the 110 GHz filter can be seen in Figure 2, before assembly.

Figure 3 show a comparison of the passband insertion and return loss performances for the 76.5 GHz filter, using both LRRM (including the measurement of the lossy feed lines) and TRL (having reference lines at the filter itself) calibration methods. The TRL data clearly shows that the minimum insertion losses of the filters are as low as 0.54 dB for the 77 GHz filter; impedance matching is excellent. It is also evident, however, that even with precision micromachining techniques filters suffer from impedance mistuning. A significant contribution of this work is therefore the demonstration of MEMS tuning and this will now be introduced.

978-1-4244-2642-3/08/$25.00 ©2008 IEEE

RF MEMS Resonator Measurements

The tuning of an individual 60 GHz half-wavelength 2-port resonator, having parallel-coupled cantilevers, was achieved by applying a tuning voltage via the vector network analyzer's (VNA's) bias tees. Figure 4(a) shows the measured return loss of the resonator (with TRL calibration) as the bias voltage at both ports was varied from 0 V to 32 V. Using simple beam theory, Cu cantilevers have a calculated snap-down voltage of approximately 200 V. It should be noted that the measurements were restricted to a maximum bias potential of 32 V, by the VNA bias tees' safe operation limit. Figure 4(b) shows a plot of the corresponding resonant frequency vs. tuning voltage. As expected, the resonant frequency increases slightly as the feed line is deflected upwards towards the ground plane, reducing the amount of coupling.

Conclusions

When compared to traditional approaches for implementing millimeter-wave filters, intended for silicon integration, the use of CPW, conventional-microstrip and TFMS lead to unacceptably high losses. This paper has described a novel silicon micromachined RF-coupled cantilever inverted-microstrip millimeter-wave filter technology. Here, low insertion losses have been demonstrated with 3rd order filter implementations, designed for operation at 60 GHz and 76.5 GHz. From this work, it is believed that the technology proposed can be adapted for tunable RF MEMS applications.

Acknowledgements: This work was supported in part by the U.K. Engineering and Physical Science Research Council, under Contract GR/S57013/01; in part by the European Union's Network of Excellence *AMICOM*, under Contract FP6-507352; and in part by Mitsubishi Electric Corporation, Kamakura, Japan.

References

[1] K. Takahashi, S. Fujita, U. Sangawa, A. Ono, T. Urabe, S. Takeyama, H. Ogura and H. Yabuki, "K-band receiver front-end IC integrating micromachined filter and flip-chip assembled active devices", *IEEE MTT-S Int. Microwave Symp. Dig.,* vol. 1, pp. 229-232, Jun. 1999.

[2] K. Takahashi, U. Sangawa, S. Fujita, M. Matsuo, T. Urabe, H. Ogura and H. Yabuki, "Packaging using microelectromechanical technologies and planar components", IEEE *Tran. on Microwave Theory and Tech.*, vol. 49, no. 11, pp. 2099-2104, Nov. 2001.

[3] L. S. Lopez, and T. M. Weller, "A low-loss quartz-based cross-coupled filter integrated onto low-resistivity silicon", *IEEE Tran. on Microwave Theory and Tech*., vol. 52, no. 8, part 1, pp. 1809-1812, Aug. 2004.

[4] M.-L. Ha and Y.-S. Kwon, "Ku-band stop filter implemented on a high resistivity silicon with inverted microstrip line photonic bandgap (PBG) structure", *IEEE Microwave and Wireless Components Letters*, vol. 15, no. 6, pp. 410-412, Jun. 2005.

[5] L. Martoglio, E. Richalot, G. Lissorgues-Bazin and O. Picon, "Low-cost inverted line in silicon/glass technology for filter in the ka-band", *IEEE Tran. on Microwave Theory and Tech*., vol. 54, no. 7, pp. 3084-3089, Jul. 2006.

[6] S. Lucyszyn, K. Miyaguchi, H. W. Jiang, I. D. Robertson, G. Fisher, A. Lord and J. Y. Choi, "Micromachined RF-coupled cantilever inverted-microstrip millimeter-wave filters", *IEEE/ASME Journal of Microelectromechanical Systems*, vol. 17, no. 3, pp. 767-776, Jun. 2008

Reference [#]	Basic Type	Centre Frequency [GHz]	Fractional Bandwidth [%]	Filter Order	Minimum Insertion Loss [dB]
27	Inverted-microstrip over silicon cavity	25	8	Dual mode ring	<1
30	Inverted-microstrip	29	28	4	2.2
17	Coaxial, EFAB®	29.5	4.7	3	1.5
16	Stacked waveguide cavity	29.7	2.2	3-pole	1
10	SMM	30	4	2-pole	1.8
11	Membrane CPW & lumped element	31	10	2-pole	1.5
14	Horizontal cavity	31.7	2.2	2-pole	1.2
25	Quartz, LIGA	33.2	39	4-resonator	1.7
9	SMM	37	3.5	2-pole	2.3
our work	**RF-Coupled Cantilever**	**59.7**	**9.8**	**3**	**2.95**
9	**SMM**	**60**	**2.7**	**4-pole**	**2.8**
9	**SMM**	**60**	**4.3**	**5-pole**	**3.4**
our work	**RF-Coupled Cantilever**	**76.5**	**9.2**	**3**	**0.54**
8	**SMM**	**94.9**	**17.7**	**3**	**1.4**

Table 1. Survey of Micromachined Millimetre-wave filters

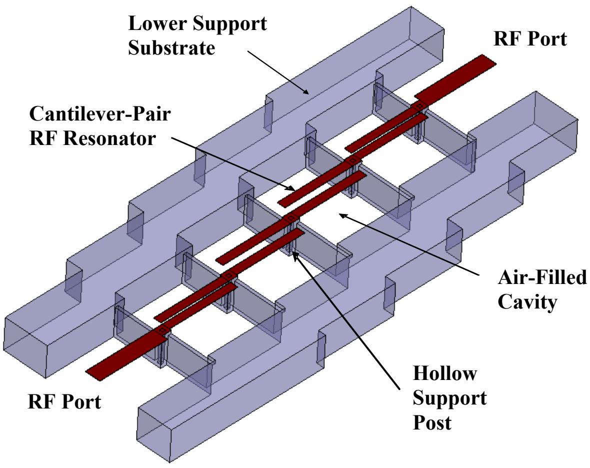


Figure 1. Isometric illustration of the basic inverted-microstrip filter (upper ground plane substrate not shown)

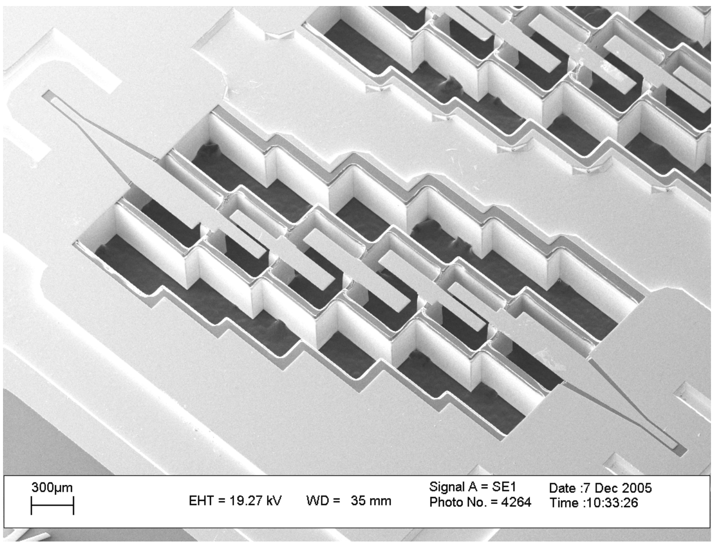


Figure 2. SEM view of complete lower support substrate for the 110 GHz filter

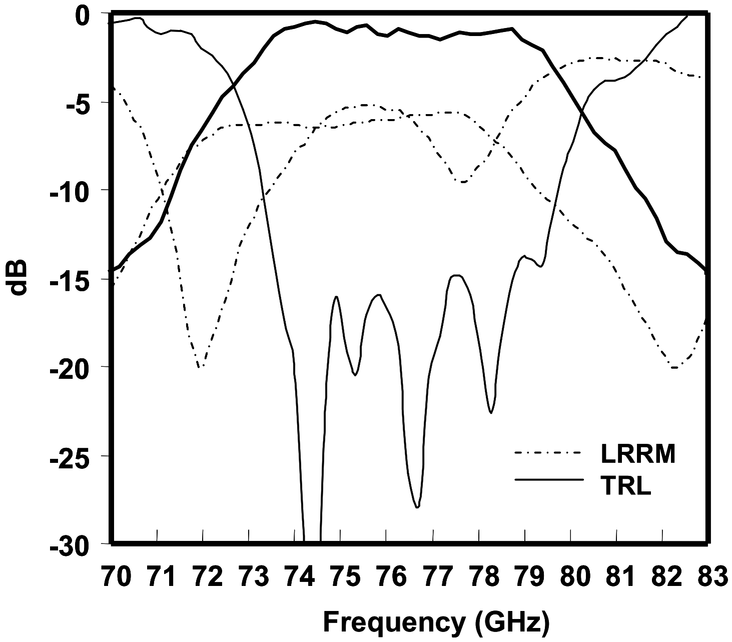
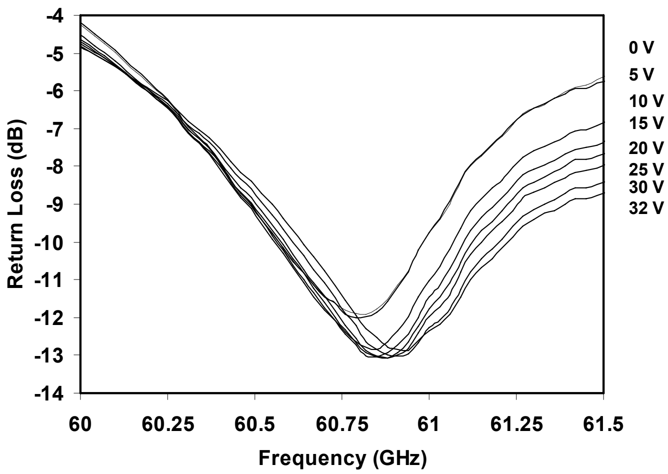
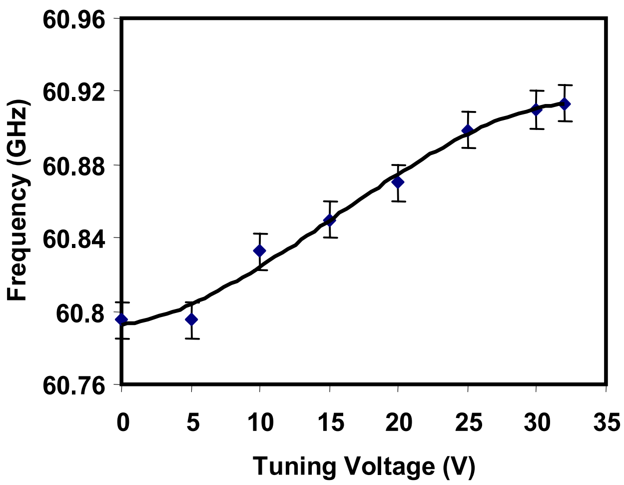


Figure 3. Measured passband insertion and return loss responses without the millimeter-wave absorbing holder for the 76.5 GHz filter



(a)



(b)

Figure 4. (a) Measured 60 GHz resonator return loss frequency responses with tuning voltage without the millimeter-wave absorbing holder; (b) Resonant frequency vs. tuning voltage for the 60 GHz loaded resonator