ALD Stripline Resonator and Bandpass Filters for VHF and UHF Bands

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***Abstract*— It is shown that for an optimal substrate thickness ALD technology will be promising for IF bandpass filter designing. A two-conductor stripline ALD resonator with central frequency 200 MHz will have Q-factor 53 with total length 3.7 mm (0.0025λ_g) and the frequency separation of the first and the second oscillation modes up to 59. Two bandpass filters for VHF and UHF designed and fabricated for commercial application display good agreement between the simulation and the experiment. A 3-pole bandpass filter with central frequency 255 MHz and lateral size 15.8×3.2 mm^2 has stopband width 13.5f_0, and a 6-pole bandpass filter with central frequency 1250 MHz and lateral size 4.4×5.1 mm^2 has stopband width 9.4f_0.**

Keywords*— *stripline resonator, quality factor, bandpass filter, atomic-layer deposition

I. Introduction

Recently, a number of microelectronics technologies are being actively developing, which make it possible to design multilayer bandpass filters having unique characteristics for commercial or scientific applications. Among them are LTCC [1-4], PCB[5] and LCP[6,7] filters, which are interesting in terms of discreet multilayer devices having unique physical and electrical characteristics; IPD [8], semiconductor (CMOS) [9,10] and ALD technologies are interested because they allow one to integrate passive frequency-selective devices with active components. For a multilayer stripline resonator, which conception was proposed in 2007 [1], it was shown that increase in the number of metallic layers and decrease in the thickness of the dielectric interlayers will bring to significant reduction of resonator length and separation of the resonant frequencies [11]. And it is obvious that the multilayer technologies mentioned above can make filters based on the resonator competitive with SAW and LC-filters in VHF and UHF bands, at least in terms of a filter size and stopband width. Several promising filters have been already presented designed using LTCC [3] and LCP technologies, which confirm the assumption.

Much attention is currently being devoted to the analysis of losses in semiconductor substrates for integrated circuits due to eddy currents; new inductors designs [12], new models [13] and losses calculation methods [14] have been proposed. However, it should

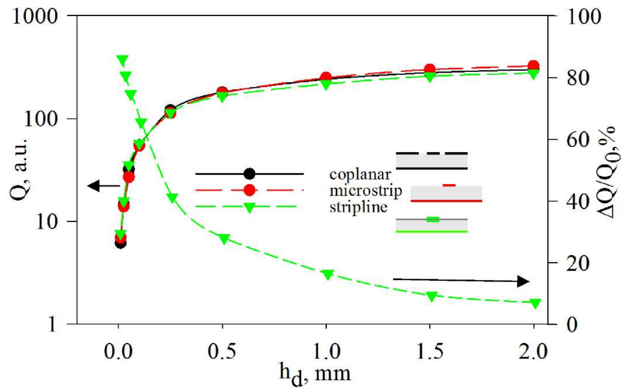

Fig. 1. Dependence of unloaded Q-factor versus substrate thickness h_d for 3 electrodynamic resonators (left axis) and relative change of Q-factor with 10 times change of conductivity of the ground layer for different h_d (right axis, only for stripline resonator).

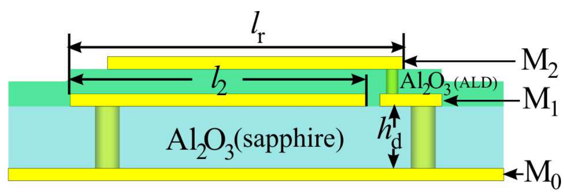

Fig. 2. Structure of the ALD stripline resonator

be marked that among the recently presented filter designs, external grounded layers are situated close to top or bottom topology layers. This situation is more common for LTCC filters [2,3], when the top and the bottom screens are separated from topology layers by dielectric layers with thickness equal 0.1-0.2 mm; and semiconductor filters [9,10], where a ground layer is deposited on the top of a semiconductor substrate. Small separation of topology layers in multilayer structures from screens, of course, reduces the size of devices, but also greatly reduces the unloaded Q_0-factor of resonators.

In this letter we present a simulation result for three main currently used resonators, displaying how the distance to the ground influences on the unloaded Q_0-factor. Next, a resonator and two bandpass filters (VHF and UHF bands), having lateral size comparable with the smallest presented filters, are demonstrated, where

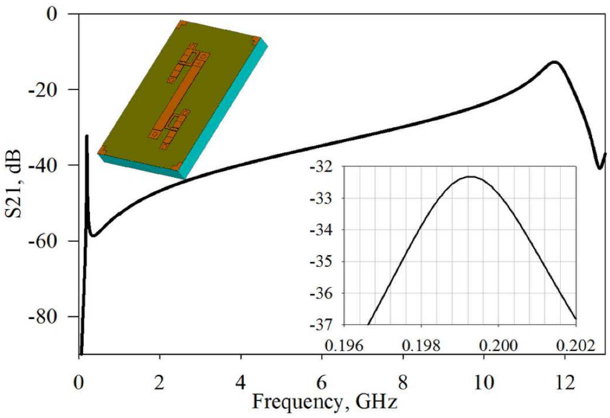

Fig. 3. Topology of the ALD resonator, its frequency response in wide and narrow frequency range.

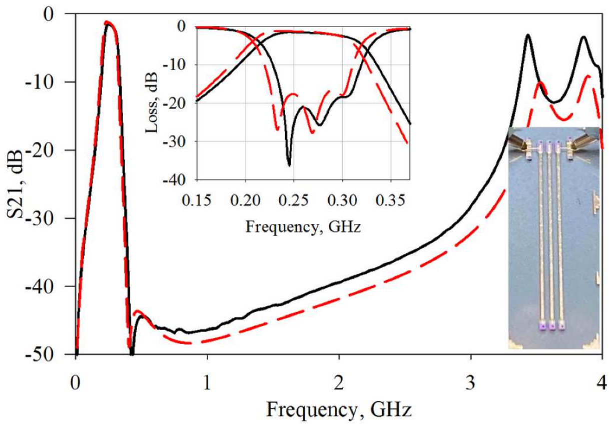

Fig. 4. Topology of the 3-pole VHF bandpass filter, and comparison of its simulated (dashed line) and measured (solid line) frequency response in narrow and wide frequency range.

dielectric substrate were obtained by atomic layer deposition of Al_2O_3.

II. Unloaded Q-Factor

Three main electrodynamic resonators are used in the modern bandpass filters: microstrip resonators; coplanar resonators; and stripline resonators. All the resonators are very sensitive to a dielectric loss in a substrate, however, resonators unloaded Q_0-factor is also sensitive to substrate thickness. Thickness reducing leads to decrease of an inductance per unit length and, correspondingly, Q_0-factor. For example, for microstrip line with low dielectric permittivity of substrate L can be approximately found as [15]:

$$L \approx \mu_0 \ln\left(\frac{8h}{w}\right), \text{ and } Q_0 = \frac{Z_{eqv}}{R} = \frac{1}{R}\sqrt{\frac{L}{C}},$$

where h is substrate thickness, w is resonators width, C is a capacitance per unit length.

A simulation was performed in CST Studio Suite for all 3 resonators under consideration for the fixed width of the stripline conductor (1 mm) and distance to the top ground cover (4 mm), how the distance to bottom ground layer h_d influence on the Q-factor of the resonator the results is presented in Fig.1 (left axis). It should be marked that during simulation alumina was chosen as dielectric material and copper as metal material. For each value h_d the resonators were tuned to 1 GHz. One can see that, when the distance between the strip and the ground layer becomes less than 0.5 mm, a swift decrease of the Q-factor is observed. Moreover, when the ground layer approaches closer, the resonator becomes very sensitive to a change of its conductivity as a current density in the stripe increases for a thinner substrate, which leads to increase of eddy current in the ground layer. To prove this a simulation was performed for each distance, for the stripline resonator, where two simulations were performed with different conductivity of metal case (δ_{Co} and $0.1{*}\delta_{Co}$, where δ_{Co} – copper conductivity). The relative change in the unloaded Q_0-factor ($\Delta Q/Q_0$) for two cases versus distance is presented in Fig. 1(right axis). And again, for the distance closer than 0.5 mm, it is observed a great change in Q-factor meaning that resonator becomes sensitive to a quality of the ground plane.

According to the results of the simulation, it can be recommended to design bandpass filters with at least 0.5 mm distance between resonator and ground layers, otherwise an enlarged loss will be observed with a decreased selectivity of a filter.

III. ALD Resonator.

As it has been mentioned for the stripline multiconductor resonator a thinning of dielectric interlayer brings to a significant frequency lowering of the first oscillation mode. This means that atomic layer deposition of Al2O3, which gives rather good dielectric (ε = 7.5, tanδ = 0.001) and mechanic properties, will allow designing very small bandpass filters for VHF and UHF bands.

A structure of a 2-layer stripline resonator designed on 0.6 mm sapphire substrate (ε = 9.8, tanδ = 0.0005) having 300 nm Al_2O_3 interlayer deposited by means of atomic layer deposition is presented in Fig. 2. It consists of three metallic layers:

M_0 – ground layer deposited on the opposite side of the sapphire substrate;

M_1 – contains the lower strip of the resonator and patch for the grounding of top strip deposited on top of the substrate;

M_2 – contains top strip of the resonator and coplanar feedlines, deposited on top of ALD Al_2O_3 layer.

M_1 is deposited by means of ion-beam evaporation, M_0 and M_2 by means of magnetron deposition and galvanic growth of copper.

M_2 and M_1 are connected through 50 μm holes in Al_2O_3, obtained by chemical etching, which further were filled by galvanic growth. M_1 and M_0 are connected by 200 μm holes made by laser ablation and metallized with magnetron sputtered copper.

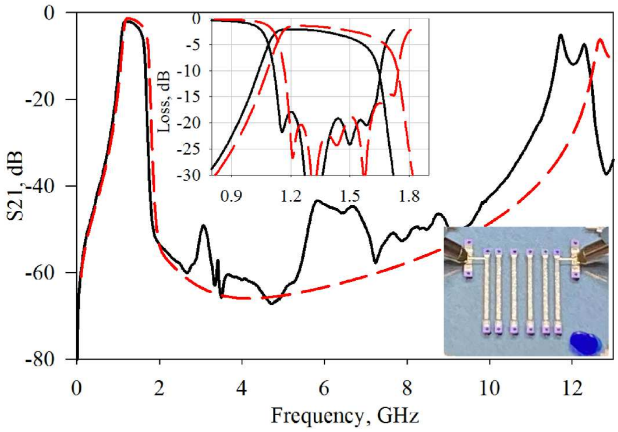

Fig. 5. Topology of the 6-pole UHF bandpass filter, and comparison of its simulated (dashed line) and measured (solid line) frequency response in narrow and wide frequency range.

In Fig. 3 the frequency response of the resonator having strip width 0.5 mm, the total length 3.7 mm and an overall overlap coefficient (l_2/l_r) 85% is presented. For metallization thickness 20 μm the simulated unloaded Q-factor was found to be 53 at 200 MHz of the first oscillation mode. An application of such a thin interlayer allows to obtain separation of the first and the second oscillation mode f_2/f_1 = 59 and resonator length equal 0.0025λ_g, making the resonator be one of the smallest among the electrodynamic one. In comparison 1 mm width λ/4 microstrip resonator designed at 1 mm alumina substrate (ε = 9.8, tanδ = 0.0001) will approximately has unloaded Q-factor around 110, depending on boundary conditions, meaning that 39 times reduction in resonator length decreases Q-factor only twice.

IV. Bandpass Filters.

Two bandpass filters were designed and fabricated. M_0 and M_2 layers were initially deposited by magnetron sputtering with a subsequent galvanic growth of 20 μm copper. M_1 (20 μm) were deposited by means of ion beam evaporation. The thicknesses of dielectric substrate and dielectric interlayer are the same as in Section II.

The first one, 3-pole filter for VHF band, having central frequency 270 MHz and 20% relative bandwidth has in-band loss less than 2.5 dB and return loss better than 15 dB. The second one, 6-pole filter for UHF band, having central frequency 1250 MHz and 20% fractional bandwidth has in-band loss less than 2.5 dB and return loss better than 15 dB. To obtain the required bandwidth and the matching degree, the width of top strip and overlap coefficient were reduced to 0.2 mm and 10%, correspondingly. A tapping microstrip lines having width 0.1 mm and length 0.9 mm attached to the free ends of the external resonators were used.

For VHF filter l_r = 15.4 mm, l_2 = 1.5 mm, S = 0.22 mm. For UHF filter l_r = 4.1 mm, l_2 = 0.4 mm, S_e = 0.22 mm, S_i = 0.38 mm, S_c = 0.41 mm (S_e – gap between resonator 1 and 2 or 5 and 6, S_i – 2 and 3 or 4 and 5, S_c – 3 and 4).

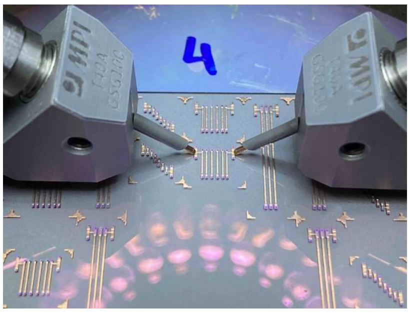

Fig. 6. Photography of the fabricated filters during the measurement.

Frequency responses of the fabricated filters in comparison with responses of their simulated models are presented in Fig. 4 and 5. One can see a very good agreement between simulated and measured results, which allow to suppose that ALD filters can be simulated.

For VHF filter the minimum measured in-band loss was found to be 1.54 dB, the selectivity $\Delta f_{30dB}/\Delta f_{3dB}$ = 3.0, stopband width 13.5f_0 (f_0 is central frequency of the passband). The lateral size of the filter is 15.8×3.2 mm^2 (with grounding patch on layer M_1), which correspond to 0.013 $\lambda_g \times$ 0.002λ_g.

For UHF filter the minimum measured in-band loss was found to be 2.0 dB, the selectivity $\Delta f_{30dB}/\Delta f_{3dB}$ = 2.0, stopband width 9.4f_0. The lateral size of the filter is 4.4×5.1 mm^2 (with grounding patch on layer M_1), which correspond to 0.018$\lambda_g \times$ 0.021λ_g.

There were fabricated 16 VHF and 24 UHF filters, measured on probe station, displaying 100% reproducibility for VHF and 75% for UHF bands. Decrease in the reproducibility of UHF filter can be explained by a small overlapping between layers in the design, meaning that a small misalignment in the layers significantly shifts a resonant frequency in the structure.

V. Conclusion.

It is shown that resonators Q-factor is sensitive to the thickness of dielectric layers between the resonator conductors and the screens. Small interlayer thickness increases a filter loss and decreases its selectivity. Considering this fact, it was demonstrated that ALD technology will allow one to design and fabricate very small bandpass filters, comparable with SAW-filters, that have very wide stopband. Two bandpass filters in VHF and UHV were designed and further fabricated, depicting a good agreement between theory and experiment that suppose the ALD technology will be promising for IF filters for VHF band, as they have classical behavior of group delay response, and unloaded Q-factor is high enough to design either narrow band or wide band filters. Also, ALD technology is suitable with multilayer technology and compatible with some of active device deposited during a single technological cycle.

REFERENCES

[1] Y. Zhang and K. A. Zaki, "LTCC Multi-layer Coupled Strip-Resonator Filters," 2007 IEEE/MTT-S International Microwave Symposium, Honolulu, HI, 2007, pp. 1039-1042.

[2] A. Périgaud, S. Bila, S. Verdeyme, D. Baillargeat and D. Kaminsky, "Multilayer Interdigital Structures for Compact Bandpass Filters Providing High Selectivity and Wideband Rejections," in IEEE Microwave and Wireless Components Letters, vol. 24, no. 2, pp. 93-95, Feb. 2014.

[3] B. Li and Y. Dai, "High performance five-order band-pass filter based on LTCC technology research," 2016 IEEE International Workshop on Electromagnetics: Applications and Student Innovation Competition (iWEM), Nanjing, 2016, pp. 1-3.

[4] A. Périgaud, S. Bila, S. Verdeyme, D. Baillargeat and D. Kaminsky, "Multilayered Coupled Interdigital Resonator Filters for General Chebyshev Filtering Functions," in IEEE Transactions on Microwave Theory and Techniques, vol. 64, no. 5, pp. 1465-1475, May 2016.

[5] S. C. Aksoy, A. İ. Çubukçu and İ. Yıldız, "A multilayered combline filter with high harmonic suppression," 2016 IEEE MTT-S International Microwave Symposium (IMS), San Francisco, CA, 2016, pp. 1-3.

[6] L. Hepburn and J. Hong, "Compact Integrated Lumped Element LCP Filter," in IEEE Microwave and Wireless Components Letters, vol. 26, no. 1, pp. 19-21, Jan. 2016.

[7] K. Aliqab and J. Hong, "UWB Balanced BPF Using a Low-Cost LCP Bonded Multilayer PCB Technology," in IEEE Transactions on Microwave Theory and Techniques, vol. 67, no. 3, pp. 1023-1029, March 2019.

[8] C. Hsiao, S. S. H. Hsu and D. Chang, "A Compact V-Band Bandpass Filter in IPD Technology," in IEEE Microwave and Wireless Components Letters, vol. 21, no. 10, pp. 531-533, Oct. 2011.

[9] Sang-No Lee, Joon-Ik Lee, Yong-Jun Kim and Jong-Gwan Yook, "Miniaturized CBCPW bandpass filter basedon thin film polyimide on lossy silicon," in IEEE Microwave and Wireless Components Letters, vol. 16, no. 10, pp. 546-548, Oct. 2006.

[10] V. N. R. Vanukuru and V. K. Velidi, "Millimeter-wave ultra-wideband bandpass filter with quarter-wavelength short-stubs and port extensions using 0.18-μm CMOS process," 2015 IEEE International Conference on Electron Devices and Solid-State Circuits (EDSSC), Singapore, 2015, pp. 353-355.

[11] B.A. Belyaev, A.M. Serzhantov, A.A. Leksikov, Y.F. Bal'va, A.A. Leksikov, “Multilayered multiconductor stripline resonator and its application to bandpass filter with wide stopband,” in Microw Opt Technol Lett. vol. 59, pp. 2212–2216, 2017.

[12] J. N. Burghartz and B. Rejaei, "On the design of RF spiral inductors on silicon," in IEEE Transactions on Electron Devices, vol. 50, no. 3, pp. 718-729, March 2003.

[13] L. N. Tran, D. Pasquet, E. Bourdel and S. Quintanel, "CAD-Oriented Model of a Coplanar Line on a Silicon Substrate Including Eddy-Current Effects and Skin Effect," in IEEE Transactions on Microwave Theory and Techniques, vol. 56, no. 3, pp. 663-670, March 2008.

[14] A. M. Niknejad and R. G. Meyer, "Analysis of eddy-current losses over conductive substrates with applications to monolithic inductors and transformers," in IEEE Transactions on Microwave Theory and Techniques, vol. 49, no. 1, pp. 166-176, Jan. 2001.

[15] F.B.J. Leferink. “Inductance calculations; methods and equations.” IEEE International Symposium on Electromagnetic Compatibility, 1995, Pp. 16–22.