Accurate Design and Yield Analysis of Tunable Distributed MEMS Bandpass Filter

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***Abstract*—The paper presents the design and yield analysis of a tunable bandpass filter consisting of capacitive coupled distributed MEMS transmission lines. It is used an accurate equivalent circuit based on the electromagnetic MEMS analysis results. The yield analysis takes into account the filter parameter dispersion due to the technological resolution.**

Keywords - tunable filter; MEMS; electromagnetic analysis; yield analysis

I. INTRODUCTION

Due to the very small series resistance, MEMS (Micro-Electro-Mechanical-System) devices are very attractive for the realization of low insertion loss microwave circuits, such as switches, phase shifters and BPSK modulators. [1], [2], [3]. Another recent application for MEMSs is to realize low insertion loss tunable filters. The tunable property is due to the possibility to change the MEMS equivalent capacitance versus the DC voltage applied on the MEMS bridge [4], [5], [6], [7], [8].

A possibility to realize bandpass filter is to use resonators, capacitive coupled [9]. If the resonators are based on artificial transmission lines, by using MEMSs or Schottky-varactor diodes, the filter may have tunable characteristics [7].

In this paper, the bandpass filter consisting of MEMS resonators is firstly designed and optimized. They are presented details regarding an accurate design procedure based on an electromagnetic analysis of the MEMS structure. In the second part of this paper, a yield analysis of the filter is performed in order to estimate the influence of the circuit parameters dispersion on the filter characteristics (insertion loss and return loss) due to the technological resolution.

II. FILTER DESIGN

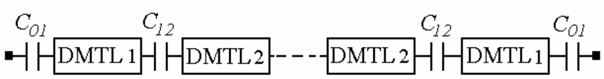
The filter consists of capacitive coupled artificial transmission lines. Each resonator has an equivalent electrical length equals to 180^0, at the central frequency of the bandpass filter. In order to change the central frequency of the filter to another value, the transmission line electrical length must be equal to 180^0 at this new frequency. This aim could be attained if the artificial transmission line is realized by using voltage controlled capacitors, periodically loading a transmission line. If the capacitive MEMSs are used to model the capacitors, the artificial transmission line is a distributed MEMS transmission line (DMTL).

Fig. 1a shows the schematically representation of the bandpass filter having a symmetric structure, consisting of capacitive coupled DMTLs, while in Fig. 1b, the schematically representation of a DMTL is presented. In Fig. 1b, R_{MEMS} and C_{MEMS} are the equivalent MEMS resistance and capacitance, respectively (C_{MEMS} also includes the effect of the MEMS series inductance), $2l_{CPW}$ is the CPW length which connect two consecutive MEMSs and Δl_i is the CPW length which must be added to the both ends of the i^th^ DMTL, to assure that the DMTL electrical length is equal to 180^0 at the central frequency of the bandpass filter.

In this paper, a Butterworth filter having the central frequency of 20GHz, the fractional bandwidth of 4% and the attenuation of at least 20dB for frequencies at 0.5GHz outside the frequency passband edges, has been designed and analyzed. The equivalent electrical lengths of each DMTL, θ_i and the coupling capacitances, $C_{i-1,i}$ may be computed using the formulas given in [9]. For this data, the filter consists of 3 DMTLs and 4 coupling capacitors (θ_1=163^0, θ_2=175^0, C_{01}=42fF and C_{12}=7fF – see Fig. 1a). For the DMTLs, imposing the Bragg frequency, f_B=125GHz, as well as the characteristic impedance of the structure, Z_c=50Ω, it is obtained 31fF for the MEMS equivalent capacitance.

The geometry for the capacitive MEMS used in this paper is given in Fig. 2, where W and w_{CPW} are the width of the CPW central line under the MEMS bridge and between two consecutive MEMSs, respectively, s_{CPW} is the distance between the CPW central line and the CPW grounds and w is the bridge width. Using a simple formula [8], the MEMS capacitance of 31fF may be obtained for w=60μm, W=150μm, g=2.5μm, t_d=0.3μm. The [S] parameters of the structure shown in Fig. 2 have been obtained by using the electromagnetic simulator IE3D–Zeland, for the date given in the previous section and for l_{CPW} =110μm, w_{CPW} =50μm, s_{CPW} =125μm (CPW characteristic impedance Z_{cl} =82Ω), t =1μm (gold), l_p =100μm, Δl = 5–10μm and three values of g (2.5μm, 2μm and 1.5μm). The substrate is silicon (0.4mm thickness and ε_r =11.7) of resistivity equals to 6KΩcm, covered by 1μm SiO_2 layer.

Using these [S] parameters, the values for the lumped components of the MEMS equivalent circuit given in Fig. 3a have been developed, obtaining: L_{sb} =16pH, R_{sb} =0.055–0.07Ω, R_{MEMS} =0.1–0.3Ω and C_{MEMS} =38,4–46fF for the bridge displacement between 0 and 1μm (practically C_{MEMS} does not depend on the frequency, for frequencies between 15GHz and 25GHz [10]). Also, it may be shown that the bridge displacement of 0.5μm and 1μm may be obtained for DC voltages of 27V and 32V, respectively (see again [10]).



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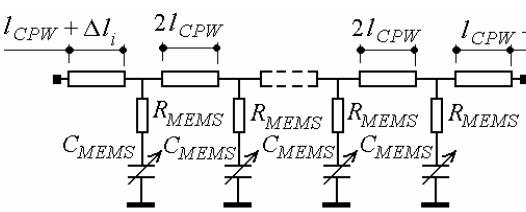

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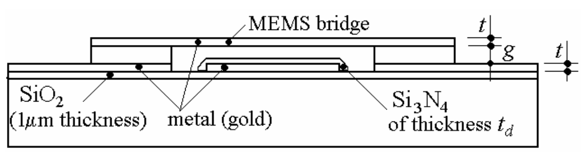
Figure 1. Schematically representation for the capacitive coupled DMTLs bandpass filter (a) and for one DMTL which is part of the filter.



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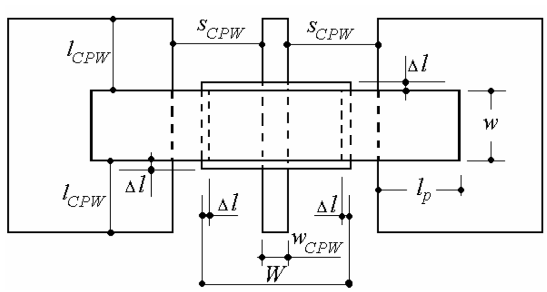
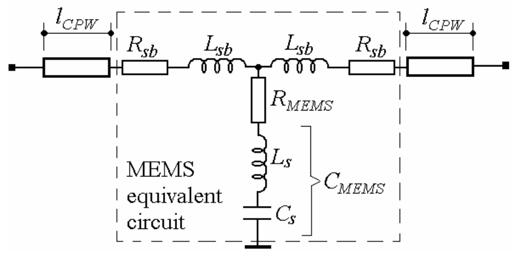
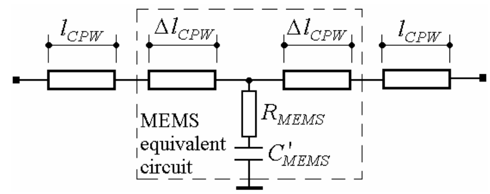


(b)

Figure 2. The cross section (a) and the top view (b) of the MEMS structure used in this paper.



(a)



(b)

Figure 3. The MEMS equivalent circuits obtained from the [S] parameters computed by using IE3D software, for the structure shown in Fig. 2, using lumped elements only (a) and CPW transmission lines (b).

For the DMTL design, in this paper a cell equivalent circuit as in Fig. 3b was used, where the CPW transmission line of length Δl_{CPW} and characteristic impedance Z_{cl} models the inductance L_{sb}, so C_{MEMS} from Fig.3a is replaced with $C'_{MEMS} = C_{MEMS} - C_{sb}$, where $C_{sb} = \dfrac{L_{sb}}{Z_{cl}^2}$. For the analyzed structure, Δl_{CPW} =23μm. The effect of the series resistance, R_{sb}, may be take into consideration, adjusting the metal thickness of the CPW of length Δl_{CPW}. This equivalent circuit for the DMTL cell was used to design the filter.

The filter DMTLs have been designed for a central frequency of 20GHz and C_{MEMS} =41fF (bridge displacement of 0.45μm), computing l_{CPW} and Δl_i, knowing the equivalent electrical length of each resonator, θ_i, given above. They were imposed the characteristic impedance of the filter, $Z_c = \sqrt{\dfrac{2L'_{CPW}}{C_{MEMS} - C_{sb} + 2C'_{CPW}}}$ =50Ω and the CPW characteristic impedance, $Z_{cl} = \sqrt{\dfrac{L'_{CPW}}{C'_{CPW}}}$ =82Ω (chosen to minimize the circuit length as well as the CPW attenuation constant), where L'_{CPW} and C'_{CPW} are the equivalent inductance and capacitance for the CPW of length $l_{CPW} + \Delta l_{CPW}$ (see Fig. 1b). They are obtained L'_{CPW} =77pH, C'_{CPW} =11fF, then l_{CPW} =88μm. Therefore, the equivalent electrical length for one DMTL cell is 22^0, so the three DMTLs of the filter consist of 7 cells.

The filter has been numerically analyzed and optimized, by using Microwave Office software [11], such as to fit the parameters imposed for the filter. Finally they are obtained: C_{01}=43fF, C_{12}=7.5fF, l_{CPW}=94μm, Δl_1=117μm – for DMTL1 and Δl_2=257μm – for DMTL2 (see Fig. 1b).

In Fig. 4a,b,c, the frequency dependence of S_{11} and S_{21} magnitudes are given, for C_{MEMS} equals to 46fF, 41fF and 38fF, respectively, corresponding to 0, 0.45μm and 1μm of bridge displacement. From these figures, it is observed that the central frequency is changed over ~1GHz (from ~19.4GHz to ~20.4GHz). In the filter passband, the insertion loss is ~4dB, while the return loss is higher than 20dB.

The coupling capacitances may be realized as MIM capacitors, using Si_3N_4 as dielectric.

III. YIELD ANALYSIS

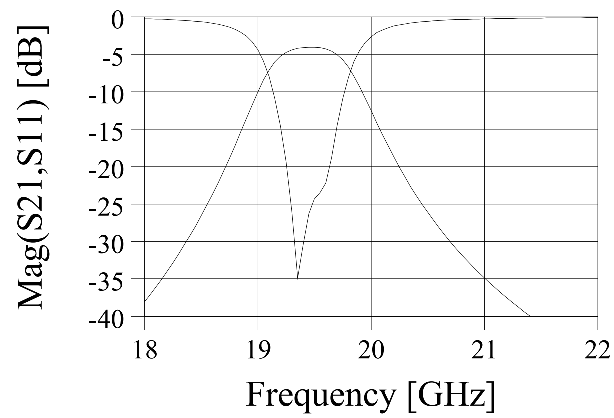
The filter characteristics differ significantly before and after optimization, although the filter parameters change slightly during the optimization procedure. But, the variation of the filter parameters may be caused due to the technological resolution which leads to parameters dispersion of the elements which are part of the circuit.

In order to evaluate these technological effects on the filter characteristics, a yield analysis has been performed by using again Microwave Office software, when the central frequency is 20GHz.

For the clarity of the graphical results shown below, the yield analysis has been performed for 10 iterations only. It is easy to verify that these first iterations are very representative, because for a large number of iterations the conclusions are practically the same.

In Fig. 5a,b, the magnitude of S_{11} and S_{21} are shown, taking into account the effect of the technological resolution on the CPW geometry. In Fig. 5a, it was assumed that w_{CPW}=50μm+/-5μm and s_{CPW}=125μm +/-5μm, while in Fig. 5b, w_{CPW}=50μm+/-3μm and s_{CPW}=125μm +/-3μm. In the both cases, the insertion loss and the return loss are ~4dB and higher than 20dB, respectively, in the filter passband. Only the central frequency is slightly changed, but this may be fixed by changing C_{MEMS}, adjusting the DC voltage applied on the metal bridges. Therefore, for usual technological resolutions the effect of w_{CPW} and s_{CPW} dispersion is small.

The second yield analysis has been performed for C_{01}=43fF+/-10% and C_{12}=7.5fF+/-10% (see Fig. 6a) and also for C_{01}=43fF+/-5% and C_{12}=7.5fF+/-5% (see Fig. 6b). In this analysis, four independent capacitances have been assumed: two independent capacitances C_{01} and two independent capacitances C_{12}. Again the worst results have been obtained for the return loss, while the insertion loss is ~4dB for dispersion of +/-10%, as well as +/-5%. The return loss is greater than 17dB for dispersion of +/-5%, but it is possible to obtain a value smaller than 15dB for a dispersion of +/-10%. The results obtained after this yield analysis show that for dispersion of C_{01} and C_{12} less than +/-10%, the insertion loss is weakly affected and the return loss is good for the most application requirements. Taking into account that C_{01} and C_{12} are MIM capacitors, a maximum dispersion of +/-10% means a technological resolution better than 5μm.



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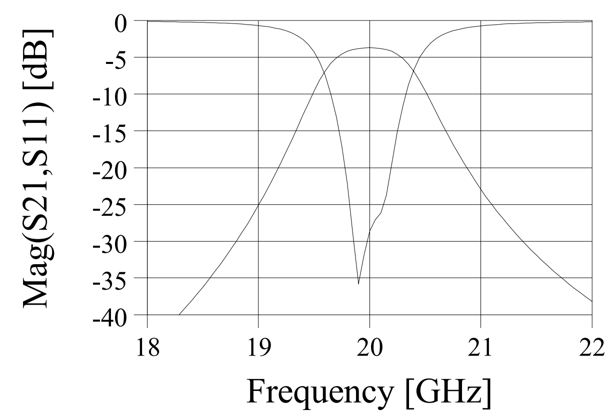

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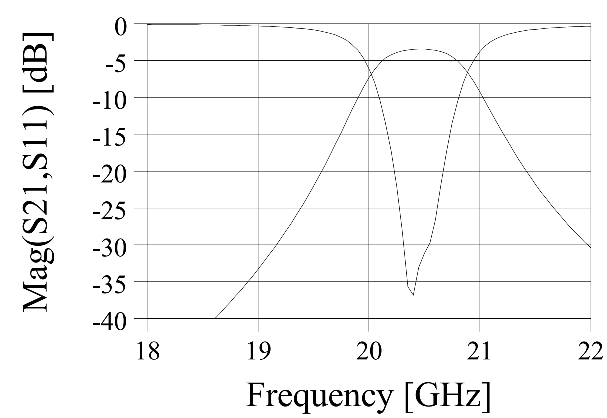


(c)

Figure 4. Magnitude of S_{21} and S_{11} in [dB] for C_{MEMS} equal to 46fF (a) 41fF (b) and 38fF (c).

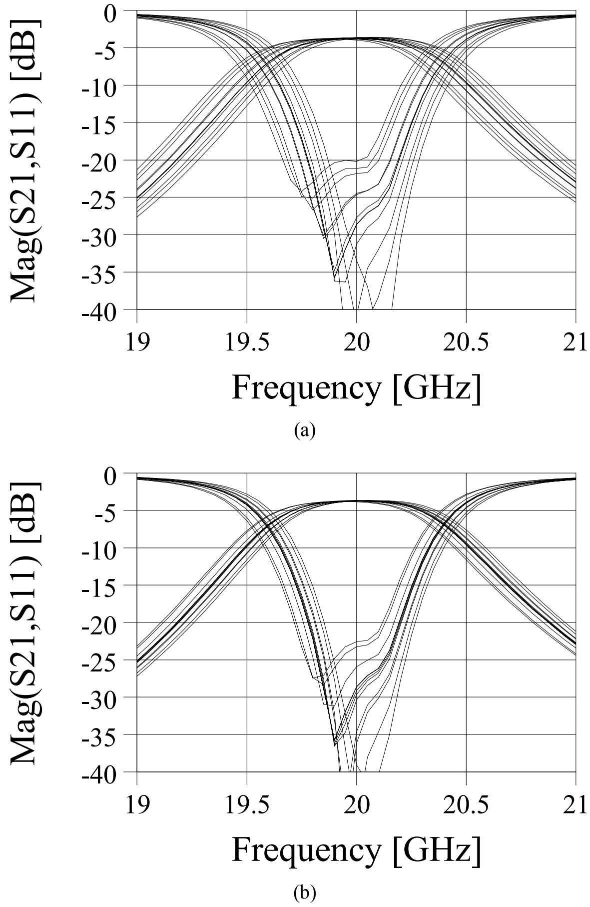


Figure 5. Magnitude of S_{21} and S_{11} in [dB] when w and s have a technological resolution of +/-5μm (a) and +/-3μm (b), around the nominal values of 50μm and 125μm, respectively.

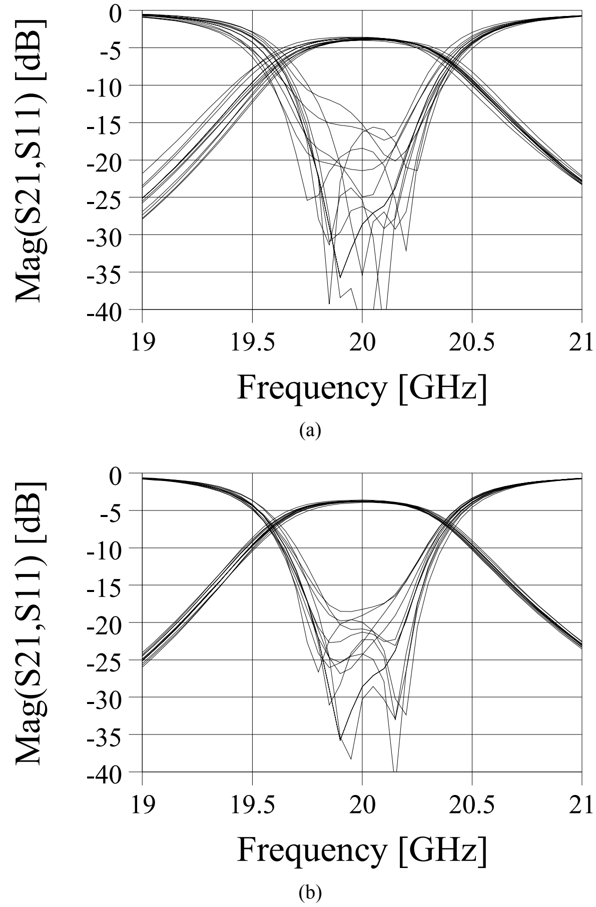


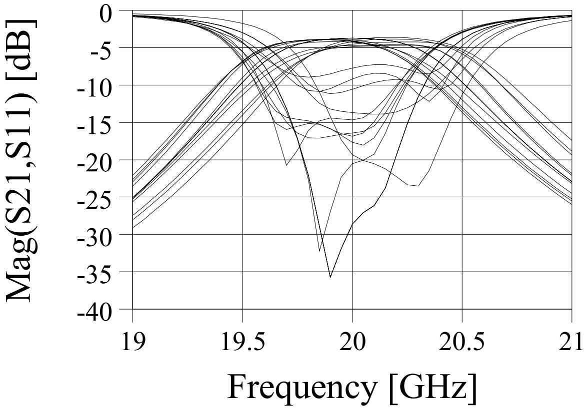
Figure 6. Magnitude of S_{21} and S_{11} in [dB] when C_{01} and C_{12} have a technological dispersion of +/-10% (a) and +/-5% (b), around the nominal values of 43fF and 7.5fF, respectively.

The last yield analysis has been performed assuming that the dispersion of the MEMS capacitances is +/-10% (see Fig. 7a) and +/-5% (see Fig. 7b), considering that the all 21 MEMS have independent values. In this case, again the insertion loss is ~4dB. The return loss has the smallest value compare to the results obtained in the previous analyses. From Fig. 7a,b, it is observed that for a dispersion of the MEMS capacitances of +/-10%, which means a technological resolution of ~5μm, the return loss could be less than 10dB, while for a dispersion of +/-5%, which means a technological resolution of ~3μm, the return loss could be less than 15dB. Therefore, a good return loss for the most practical purposes may be obtained for technological resolution better than 5μm.

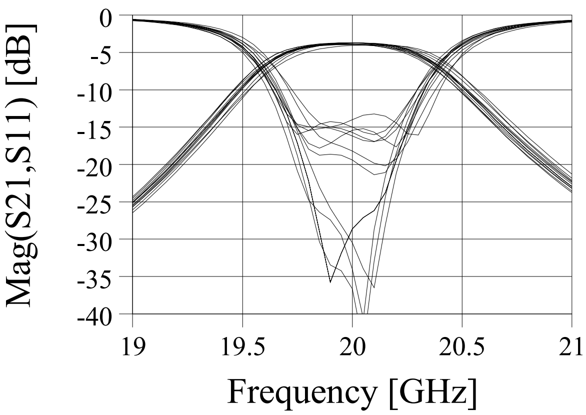
In the all yield analyses performed and presented above, the technological resolution referred to the wrong alignment of the successive process masks. Other important technological factor which may affect the circuit performances is the thickness of the Si_3N4 layer. If this factor is taken into consideration, it may be shown that the technological resolution must be better with the same percentage as the Si_3N4 thickness is changed over the wafer, given also in percentage variation.

IV. Conclusion

In this paper, a filter consisting of a distributed transmission lines capacitive coupled has been designed, optimized and finally yield analyzed. The design procedure is based on an accurate equivalent circuit developed taking into account the electromagnetic analysis results, performed on the MEMS structure, by using the IE3D–Zeland software. The filter has been analyzed and optimized by using the Microwave Office software. The optimization is necessary, but the difference between the values of the filter parameters before and after optimization was small. Therefore, a filter analysis taking into account the technological resolution must be performed before the technological implementation of the filter. For this aim, a yield analysis of the filter has been performed by using again the Microwave Office software. The analysis results show that for usual parameter dispersion, the insertion loss is not changed significantly, but the return loss



(a)



(b)

Fig.ure 7. Magnitude of S_{21} and S_{11} in [dB] when C_{MEMS}'s have a technological dispersion of +/-10% (a) and +/-5% (b), around the nominal values of 41fF.

shows an important changed, especially when the dispersion increases the difference between the MEMS capacitance values.

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