Coupling Spring Design and Insertion Loss Minimization of Second Order MicroElectroMechanical Filters

M. Naseer, Th. Bechteler, M. Parlak and Y. Gurbuz

Sabancı University, Orhanlı-Tuzla, TR-34956 İstanbul, Turkey,
Phone: ++90-216-483-9533, Fax: ++90-216-483-9550, yasar@sabanciuniv.edu

ABSTRACT

For a microelectromechanical (MEM) filter a new approach for the coupling spring design is presented. A designed MEM bandpass filter consists hereby of two laterally driven resonance structures which are coupled by a mechanical spring. For this structure an electrical equivalent circuit is presented and analyzed analytically. The transfer function and the correlation between the bandwidth and the coupling spring for this filter are derived. A complete design procedure for micromechanical bandpass filters is presented with simulation results. With changing design parameters the filter response has been demonstrated to be maximally flat as in the case of Butterworth-Filters, or to have a response allowing a wider bandwidth than in the former case. Both of these cases are studied theoretically and simulated for the same frequency range. In respect of the insertion loss value, a modified source and load resistance is applied which keeps it under 1 dB.

Keywords: MEMS, resonator, bandpass filter, coupling

1 INTRODUCTION

Laterally driven MicroElectroMechanical (MEM) resonator based filters are considered as potential replacements of prevalent tank circuits due to their very high quality factor and the chip integration compatibility. Presently, these MEM filters are incompatible for the industry as compared to their off-chip counterparts which have obtained industrial standard due to proper insertion loss and bandwidth. However, MEM filters have been demonstrated to have a very high quality factor (as high as 80 000 under vacuum [1]) which allows greater selectivity. Micromachined bandpass filters have been demonstrated both in high frequency (e.g. 14.5 MHz [2]) and intermediate frequency regions (e.g. 455 kHz [3]) with achieved bandwidths in the order of 0.2% and 0.09% respectively. The insertion losses were as small as 1 dB. For these designs both the coupling spring and the insertion loss should be taken into account. The design of MEM filters follow a cook book approach in which the coupling spring coefficient k_{spring} and the quality factor Q are taken from ready tables [4].

A bandpass structure based on two coupled resonators is investigated. Hereby both resonators are identical. This requirement complies with preferable practical implementations of planar IC processes [3]. In this paper a new approach for the coupling spring design will be presented. The circuit theory approach utilizes an electrical equivalent model of the resonators linked with mechanical parameters as formulated previously in [5].

2 COUPLING SPRING DESIGN

2.1 The Electrical Equivalent Circuit

Mechanical bandpass filters are obtained by coupling e.g. two resonators through a spring. Figure 1 shows a 3-dimensional view of the designed MEM bandpass filter. An AC signal is applied at the drive electrode and the resulting response is detected at the sense electrode. Two identical resonators are coupled with one tether spring C_{spring}.
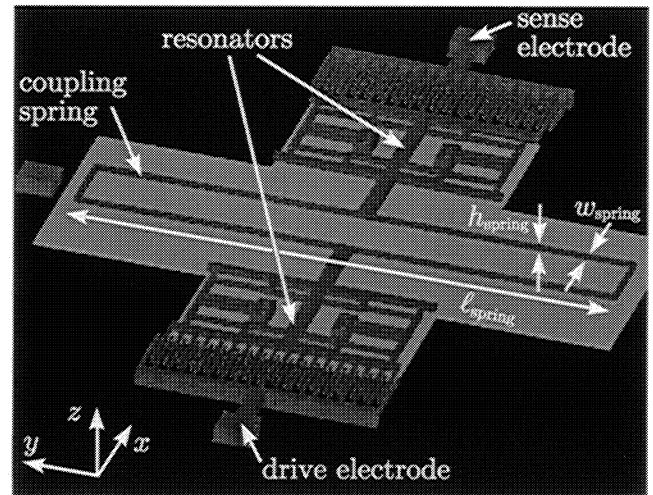

Figure 1: The 3-dimensional view of a mechanically coupled bandpass filter

An electrical equivalent representation has been evaluated in [5] to model the mechanical components. Figure 2 depicts the electrical equivalent circuit. Each series LC tank circuit corresponds to an identical resonator. The coupling spring corresponds to the capacity C_{spring}.
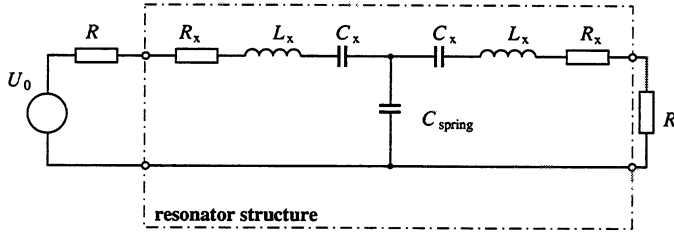
Figure 2: The electrical equivalent circuit

The resistance R_x depends strongly on the atmospheric pressure. With decreasing pressure R_x decreases as well as the quality factor increases.

2.2 Mechanical and Electrical Equivalent Representation of the Coupling Spring

The relation between the coupling spring stiffness k_{spring} in the mechanical design and the capacitance C_{spring} in the electrical equivalent circuit is provided by the following Equations (1) and (2) [6].

$$k_{spring} = \frac{\eta^2}{C_{spring}} = \frac{\left(U_{bias} \cdot \frac{\partial C}{\partial x}\right)^2}{C_{spring}} \quad (1)$$

$$k_{spring} = 2 \cdot E \cdot h_{spring} \cdot \left(\frac{w_{spring}}{\ell_{spring}}\right)^3 \quad (2)$$

whereas k_{spring} is the stiffness constant, U_{bias} is the applied DC voltage, $\partial C/\partial x$ is the differential change in the coupling capacitance per displacement, h_{spring}, w_{spring} and ℓ_{spring} are the height, the width and the length of the mechanical spring, respectively and C_{spring} is the value for the coupling capacitance in the equivalent circuit. E is a constant known as the Young's modulus and taken as 150 GPa in this study.

As seen in Equation (1) k_{spring} is inversely proportional to C_{spring}. The stiffness constant can therefore be taken as a coupling factor as shown in the next section.

For the coupling spring design the circuit analysis yields a design criteria for C_{spring}. Then k_{spring} can be computed by using Equation (1). The found value for k_{spring} is substituted in Equation (2) and the spring length ℓ_{spring} can be calculated. The calculation of ℓ_{spring} is based on pre-defined values for the structural thickness h_{spring} and the spring width w_{spring} which are technology dependent. In this study h_{spring} and w_{spring} are set to 2 μm and 3 μm respectively.

2.3 Filter Bandwidth

In order to find a relation between the coupling spring capacitance C_{spring} and the 3 dB bandwidth BW_{3dB} of

the filter only the $L_x C_x$ tank circuits with C_{spring} are being considered. The value of R_x is firstly neglected to keep the equations simple by assuming $R_x \approx 0$. The equivalent circuit then simplifies as presented in Figure 3.
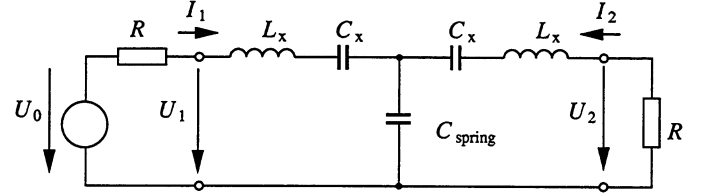

Figure 3: The simplified electrical equivalent circuit

The circuit analysis of this equivalent circuit yields the following set of equations.

$$\omega_{res} = \frac{1}{\sqrt{L_x C_x}} \quad (3)$$

$$X_x = \omega L_x - \frac{1}{\omega C_x} \quad (4)$$

$$B_{spring} = \omega C_{spring} \quad (5)$$

$$Q_e = \frac{1}{\omega_{res} R C_x} = \frac{\omega_{res} L_x}{R} = \frac{1}{R}\sqrt{\frac{L_x}{C_x}} \quad (6)$$

$$BW_e = \frac{f_{res}}{Q_e} \quad (7)$$

$$|H(f)|^2 = \frac{1}{1 + \left[\frac{R B_{spring}}{2} + \frac{X_x}{R} + \frac{X_x^2 B_{spring}}{2R}\right]^2} \quad (8)$$

whereas ω_{res} is the angular resonance frequency for one series resonance circuit, X_x is the reactance of the resonance circuit, B_{spring} is the capacitive susceptance of C_{spring} and Q_e is the loaded quality factor of the resonance circuit due to R. Furthermore, BW_e is the 3 dB bandwidth of one resonance circuit. Here, the transfer function $H(f) = U_2/U_1$ is conveniently presented as the squared magnitude $|H(f)|^2$ and corresponds to the power transfer function.

To derive the 3 dB bandwidth BW_{3dB} of the bandpass filter the abbreviations κ as the coupling factor and the normalized frequency deviation ν [7] are defined as followed.

$$\kappa := \frac{1}{R B_{spring}} = \frac{1}{R \omega C_{spring}} \quad (9)$$

$$\nu := \frac{\omega_{res}}{\omega} - \frac{\omega}{\omega_{res}} \quad (10)$$

Hence the power transfer function can be written in terms of κ and ν as

$$|H(f)|^2 = \cfrac{1}{1 + \left[\cfrac{1}{2\,\kappa} - Q_e\nu + \cfrac{1}{2\,\kappa}(Q_e\nu)^2\right]^2} \qquad (11)$$

By the inspection of Equation (1) and Equation (9) the coupling factor κ for the electrical circuit and the coupling coefficient k_{spring} for the mechanical structure are directly corresponding. For $\kappa < 1$ it is an under-critically coupled filter, for $\kappa = 1$ or $\kappa > 1$ the filter is critically or overcritically coupled respectively. Considering low insertion losses only the two latter mentioned cases are of interest.

The coupling factor κ can be considered frequency independent within the small filter bandwidth. Also by using the Taylor expansion to simplify the normalized frequency deviation ν, the relationship between the 3 dB bandwidth BW_{3dB} of the bandpass filter and the coupling factor κ is

$$BW_{3dB} = \frac{f_{res}}{Q_e}\sqrt{\kappa^2 + 2\,\kappa - 1} \qquad (12)$$

The 3 dB bandwidth BW_{3dB} is defined at those frequency points when the voltage amplitude is 3 dB lower than the maximum voltage U_{max} as depicted in Figure 4.
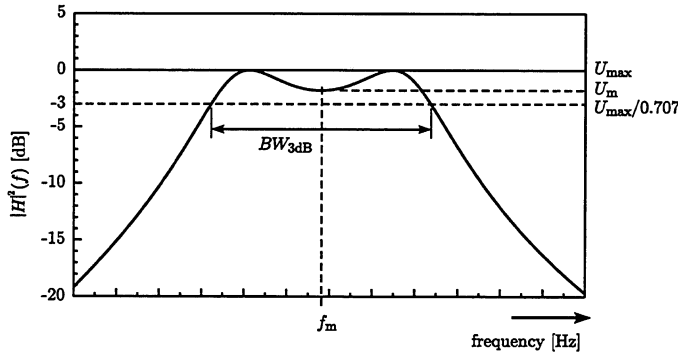
Figure 4: Definition of the 3 dB bandwidth

Figure 4 shows the case for an overcritically coupled bandpass filter ($\kappa > 1$). As the bandwidth increases the saddle point U_m decreases until $U_m = U_{max}/0.707$. This condition entails the maximum allowable bandwidth. Solving Equation (11) in respect to the saddle point yields the range for the coupling factor and for the bandwidth.

$$1 \quad < \quad \kappa \quad < \quad 1 + \sqrt{2} \qquad (13)$$

$$\sqrt{2} \cdot BW_e \quad < \quad BW_{3dB} \quad < \quad 3.108 \cdot BW_e \qquad (14)$$

3 SIMULATION

With a commercial simulation tool several simulations are performed to verify the design of mechanically coupled bandpass structures using the above method. The simulation results for two cases ($\kappa = 1$ and $\kappa = 3.108$) at about $f = 840$ kHz are presented in Figure 5, and Table 1 shows the summarized simulation data.
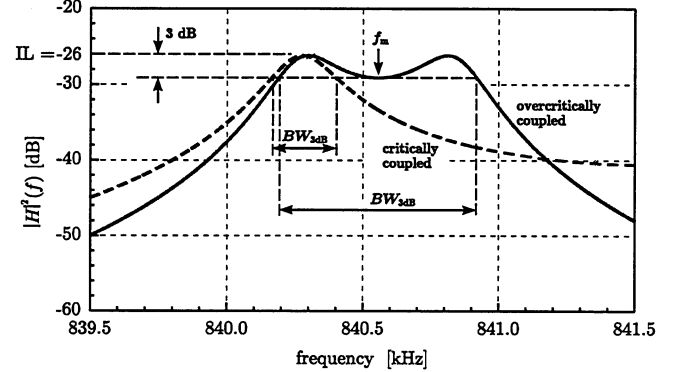

Figure 5: Simulation result for the critically and over-critically coupled filter at $f = 840$ kHz

Table 1: Summary of the simulation data

f_m [kHz]	κ	BW_{3dB} [Hz/%]	C_{spring} [fF]	ℓ_{spring} [μm]
840.30	1	243.5 / 0.0290	1.62	364
840.55	3.108	728.0 / 0.0866	0.673	271

$$\begin{aligned} \text{with} \quad R &= 12.0 \text{ M}\Omega \\ R_x &= 116.54 \text{ M}\Omega \\ L_x &= 78875 \text{ H} \\ C_x &= 4.5485 \cdot 10^{-19} \text{ F} \end{aligned}$$

For these two presented cases reasonable coupling spring lengths ℓ_{spring} are obtained by using the method established in Section 2.3. The percentage bandwidth is defined as $BW_{3dB}/f_m \cdot 100\%$. Further necessary values are the bias voltage $U_{bias} = 35$ V and $\partial C/\partial x = 2.59 \cdot 10^{-9}$ F/m.

The insertion loss (IL) is -26 dB which corresponds to a power loss by the factor of 400. It is of notable significance and is treated in the forth coming section.

4 INSERTION LOSS

The insertion loss is very high due to the high value of the ratio R_x/R. Normally the MEM structures are

operated in vacuum which means that the value of R_x decreases drastically. Typical values are then $R_x \approx$ 500 kΩ [5]. Reasonable low insertion losses of less than 1 dB can be obtained when $R \geq 20 \cdot R_x$. Hence it must be guaranteed that the source and load resistance values are higher than R_x of the filter. For instance, the required high source and load resistances can be realized by a current source and an electrometer amplifier respectively. Figure 6 shows the reduced insertion loss for $R = 20$ MΩ when the structure is operated under vacuum.
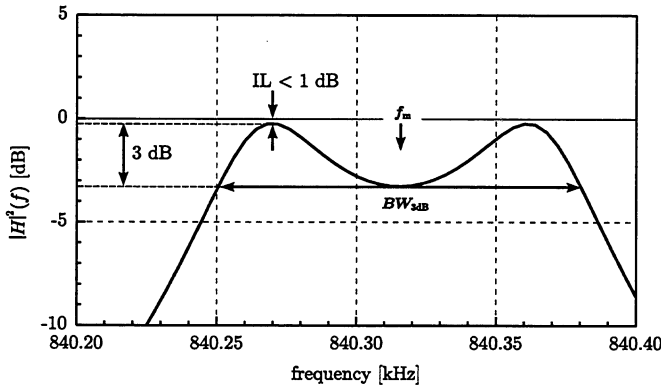

Figure 6: Simulation result for the overcritically coupled filter at $f = 840$ kHz with $R = 20$ MΩ

It is seen that the insertion loss is now less than 0.5 dB. Since the source and load resistances are changed also the coupling spring value C_{spring} has to change in order to keep the filter coupling constant. The new value for C_{spring} is 3.9 fF whereas the values for L_x and C_x are the same. Summarized are the data in Table 2.

Table 2: Summary of the data for low insertion loss

f_m [kHz]	κ	BW_{3dB} [Hz/%]	C_{spring} [fF]	IL [dB]
840.32	3.108	84.0 / 0.010	3.90	< 0.5 dB

$$\text{with} \quad \begin{aligned} R &= 20.0 \text{ M}\Omega \\ R_x &= 500 \text{ k}\Omega \\ L_x &= 78875 \text{ H} \\ C_x &= 4.5485 \cdot 10^{-19} \text{ F} \end{aligned}$$

Due to the lower value of $R + R_x$ in respect to the previous case the bandwidth is smaller. The center frequency is slightly lower.

5 CONCLUSION

A new method of mechanical coupling spring design through its electrical equivalent circuit model is established and linked with important filter parameters, e.g. the bandwidth and insertion loss. The advantage of this technique can be fully employed for the cases whenever flexible bandwidth control is part of design criteria. The design is carried out in the electrical domain which assists the fine-tuning of C_{spring} to meet the bandwidth requirement after which the circuit is optimized for reduced insertion loss. An example filter operating at 840 kHz is designed and simulation results are presented which show agreement with established theory. Future considerations include treatment of shape factor in bandpass filters and more comprehensive coverage of coupling factor κ and its boundary conditions.

REFERENCES

[1] C.T.-C. Nguyen, R.T. Howe, "Quality Factor Control for Micromechanical Resonators," IEDM, 1992.

[2] C.T.-C. Nguyen, "Frequency-Selective MEMS for Miniaturized Communication Devices," IEEE, 1998.

[3] Kun Wang, C.T.-C. Nguyen, High-Order Frequency Micromechanical Electronic Filters," MEMS, Vol. 8, No.4, Dec. 1999.

[4] A.B. Williams, F.J. Taylor, "Electronic Filter Design Handbook," 3rd. Edition, McGraw-Hill, 1995.

[5] C.T.-C. Nguyen, "Micromechanical Signal Processors," Ph.D. Thesis, University of California, Berkeley, 1994.

[6] Liwei Lin, Roger T. Howe, Albert P. Pisano, "Microelectromechanical Filters for Signal Processing", JMEMS, Vol 7, No.3, 1998.

[7] R. Ludwig, P. Bretchko, "RF Circuit Design – Theory and Applications," Prentice Hall, NJ, 2000.