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Post-Fabrication Laser Trimming of Micromechanical Filters

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Abstract

Semi-automatic post-fabrication laser trimming of a second order vibrating micromechanical clamped-clamped beam (CCB) filter has been demonstrated via a pole-correcting algorithm that identifies the individual resonators associated with each peak in a distorted filter response, then uses this information to compute correction factors needed to trim each resonator towards the desired filter passband. Both increases or decreases in resonator frequency are possible via the laser trimming due a geometrically-derived location-dependence, where the direction of the frequency change depends strongly on the location at which the laser removes material. By compensating for dimensional errors due to finite absolute and matching tolerances in planar processes, this trim procedure might eventually be instrumental in making available the banks of very small percent bandwidth micromechanical filters presently targeted for RF-channel selection in future multi-band wireless handsets.

Introduction

Having recently been demonstrated at frequencies past 1.5 GHz with Q's >10,000 at atmospheric pressure [1], vibrating micromechanical resonators stand as one of the few (if not the only) room temperature on-chip, transistor-compatible technologies capable of realizing the tiny percent bandwidth filters required for RF channel-selection. If actually achievable, RF channel-selection could revolutionize the design and performance of future wireless transceivers by literally removing all interferers (including adjacent channel ones) in the received signal before they reach any transistor electronics, thereby making practical the use of a variety of alternative, low power, low dynamic range receiver circuits that otherwise would be unusable [2].

To achieve RF channel-selection, however, filters with percent bandwidths as small as 0.03% are needed. Although the Q >10,000 achievable by micromechanical resonators makes this possible without excessive insertion loss, Q is only one of several considerations. In particular, practical considerations, such as the ability to set frequencies exactly, will be equally important.

Pursuant to raising the accuracy to which frequencies can be set, this work utilizes a bidirectional, location-dependent laser trimming methodology [3] to demonstrate passband correction for small percent bandwidth clamped-clamped beam

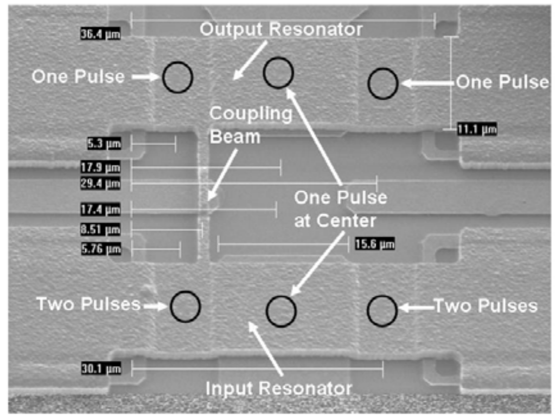

Fig. 1: SEM of a second order CCB filter showing the locations of trimming laser pulses.

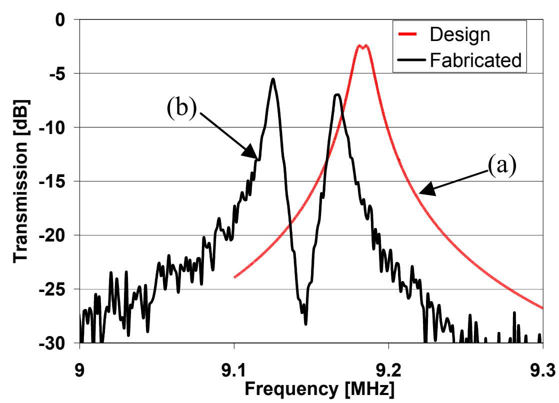

Fig. 2: (a) Measured untrimmed frequency response of the filter in Fig. 1 compared to (b) the design response.

("CC-beam"), multiple-resonator filters [4]. In this endeavor, an algorithm that first identifies the constituent resonators responsible for each filter pole, then trims them individually to achieve the needed pole frequencies, has been used to correct the passband of a 0.2% bandwidth, 2-resonator CC-beam filter centered at 9.183 MHz.

Micromechanical Filters

Fig. 1 presents the SEM of the second order, 0.2% bandwidth, CC-beam micromechanical filter [4] trimmed in this work. As shown, and as detailed previously in [4], this device comprises a beam network, where two (identical) flexural-

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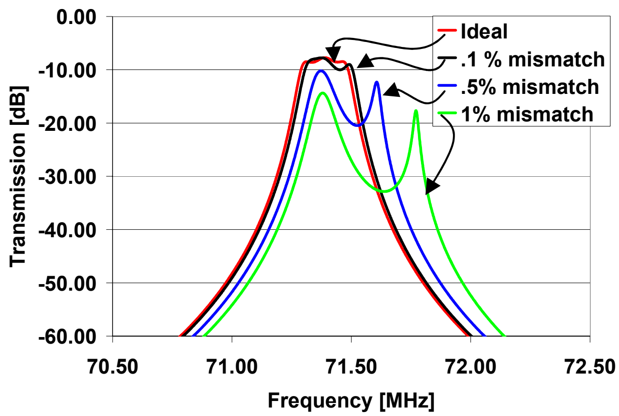

Fig. 3: Simulated third-order filter response spectra illustrating the effect on the passband of various deviations in the mass of the center resonator.

mode clamped-clamped beam resonators are coupled by a flexural-mode coupling beam to make a coupled two-resonator mechanical system with two modes of vibration that define the passband of a frequency filter. The filter structure is driven electrostatically by an underlying electrode at one resonator, and its output sensed capacitively at the other resonator, yielding an overall transfer function as shown ideally in Fig. 2(b), with a relatively flat passband, and sharp roll-offs to the stopbands.

As described in [4] and [5], the two modes of vibration described above correspond to the pole frequencies of this filter. If these poles are not in the right locations (due to mass or stiffness imbalances, perhaps caused by finite fabrication tolerances), the passband of the filter will be distorted. This is illustrated in Fig. 3, which presents simulations depicting the effect of small deviations in the mass of the center resonator in a 3-resonator micromechanical filter. As shown, just a 0.1% change in the mass of the input resonator causes a *** ppm shift in the frequency of the 71.388 MHz pole, which leads to significant passband distortion.

The degree to which deviations in mass or stiffness can cause passband distortion is dependent on the percent bandwidth of the filter in question. If designed for a percent bandwidth much greater than the absolute and matching frequency tolerances of typical planar processes (on the order of 0.2% matching in a university fab [6]), no trimming is required. But when the filter percent bandwidth approaches these tolerance limits—which is certainly the case for 0.03% bandwidth RF channel-select filters—post-fabrication trimming is often required to fix a distorted passband.

Fig. 2(a) presents the measured frequency response for the 0.2% bandwidth filter of Fig. 1 immediately after fabrication, illustrating the degree of passband distortion possible. For this particular case, not only is the passband distorted, but the frequencies of both poles are also quite distant from the desired center frequency. Evidently, trimming is a must for this 0.2% bandwidth filter.

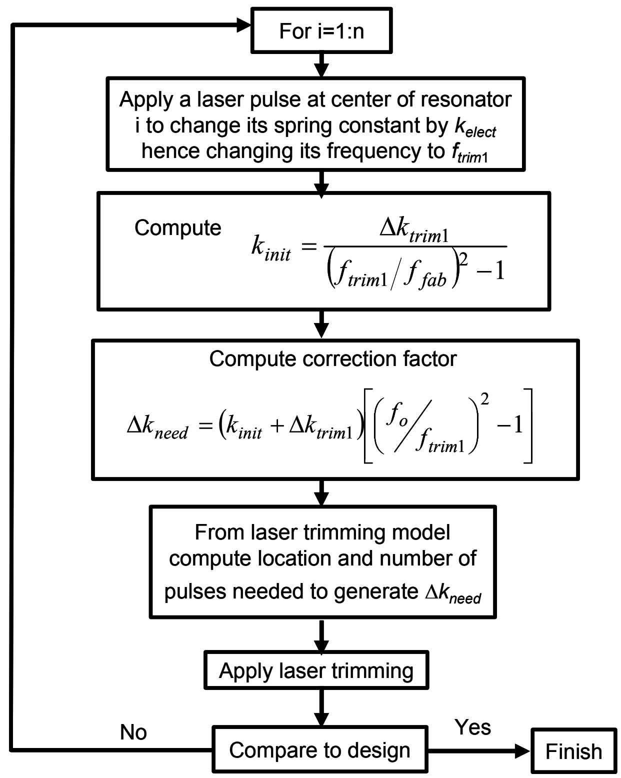

Fig. 4: Flow chart outlining the steps in the algorithm used to trim the 2-resonator filter of this work.

The Pole-Correcting Trimming Algorithm

The pole correcting trimming algorithm, summarized in the flow diagram of Fig. 4, corrects a distorted filter passband by first determining which constituent resonator corresponds to which peak, then adjusting the frequency of each resonator as needed to attain the desired filter passband. Resonator-to-peak associations are identified by firing the laser at the mid-point of each constituent resonator to change its stiffness, one at a time, and each time determining which peak moved the most. For each trial, the peak experiencing the maximum change in frequency corresponds to the resonator under test, as seen in Fig. 5, and as illustrated in Fig. 6 and Fig. 7.

After establishing the needed resonator-to-peak relationships, the algorithm proceeds to compute the optimum number of trim steps and locations required to move each filter pole close to its needed location. To keep things simple, the algorithm uses an effective spring constant concept that lumps all mechanisms for frequency shift, including finite fabrication tolerances and the trim steps (e.g., laser pulses) themselves, into an effective stiffness deviation Δk_{eff}. With this formulation, the required frequency shift can be represented by a single required stiffness shift Δk_{need}, which then allows the use of formulas such as given in [3] to compute the number of trim steps needed to realize the needed effective stiffness shift.

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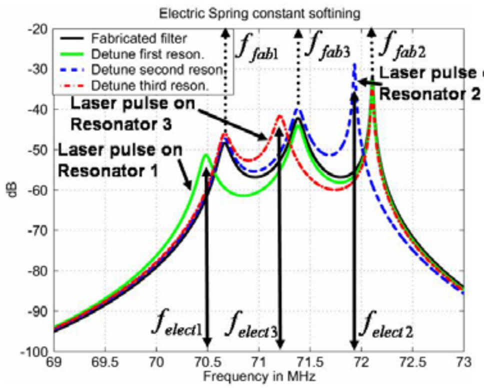

Fig. 5: Simulated response of a third order CCB filter demonstrating how the pole-correcting algorithm identifies resonator-to-peak associations by modifying the spring constant of each resonator, one at a time, then sensing which peak shifts in frequency the most for each trial.

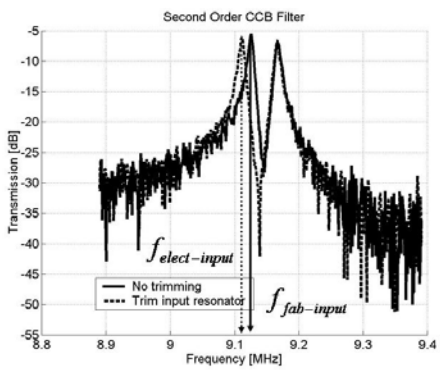

Fig. 6: Measured frequency response for the CC-beam filter before and after the application of one 0.048mJ pulse at the center of its input resonator, which moves the associated filter peak by -14.2 kHz.

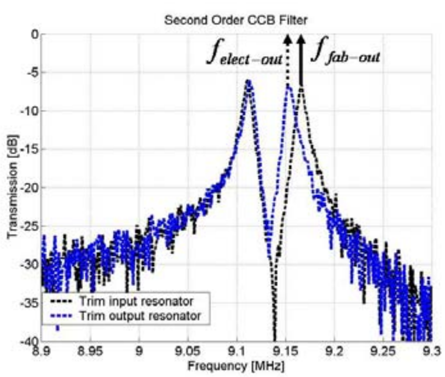

Fig. 7: Measured frequency response for the CCB filter before and after the application of one 0.048mJ pulse at the center of its output resonator, which moves the associated filter peak by -13.5 kHz.

Trims can be applied through any of a number of existing methods [3][7][8] to the individual resonators, tuning them to the design-specified pole locations. As already mentioned, this work utilizes location dependent laser trimming [3], where the laser energy is set at a constant value, and the degree and direction of frequency tuning depends upon the specific location of laser exposure. For the case of the laser trim-

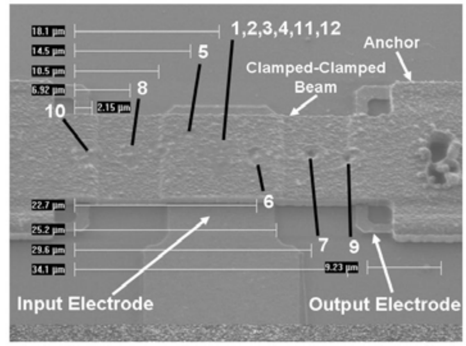

Fig. 8: SEM of a laser trimmed CC-beam, showing the location and sequence of applied laser pulses.

ming in this work, the number of laser pulses of energy E required to attain a needed frequency shift can be obtained by the expression

$$n = \frac{1}{\omega_o}\frac{\Delta k_{need}}{\Delta m(j)} \tag{1}$$

where

$$\Delta m(j) = \zeta E + \alpha k_{top} x_j \tag{2}$$

and where x_j is the trim location; and ζ, α, and k_{top} are constants meant to be obtained empirically [1]. Fig. 8 shows the SEM of a laser trimmed CC-beam resonator upon which 0.12mJ laser pulses have been applied at different locations to tune the resonator frequency by the specific values seen in Fig. 9. Data like this is then used to determine the needed constants in (**) that allow determination of the number of laser pulses needed to affect the effective stiffness shift in the algorithm of Fig. 4.

Since (1) is an empirical formulation, its accuracy is strongly dependent upon how accurately the constants Δm_o, α, and k_{top}, can be determined, and this in turn depends upon the degree to which the “standard” resonator of Fig. 8 is truly representative of all constituent filter resonators.

Experimental Results

Fig. 10(a) presents measured responses for the filter of Fig. 1 at different steps in the trim sequence and the response after the final trimming step. Fig. 10(b) presents a zoom-in on the trimmed response and compares it to the design specs, showing good agreement between the two, and verifying the potential of this algorithm for automating post fabrication trimming. The sequence of laser trims required to attain the response of Fig. 10 are summarized in Table 1. Here, trim subsequences are separated into portions that delineate each phase of the pole-correcting trim process.

The total number of trim pulses required is 9, with a total cumulative laser energy of 0.432mJ. This value of total laser energy is small enough to be amenable to a massively parallel trimming system, capable of trimming numerous filters si-

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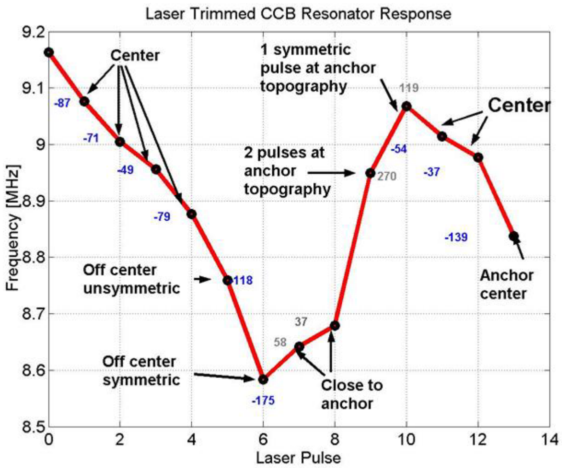

Fig. 9: Change in resonance frequency of the CC-beam of Fig. 8 as a function of 0.12mJ laser pulses shot in sequence in the indicated locations.

Table 1: Filter Passband Correcting Trim Sequence

No. of Laser Pulses	Location x [μm]	Corresponding ESCA Step
1	0 , Input Resonator	peak to resonator association
1	0 , Output Resonator	peak to resonator association
4	13 , Input Resonator.	trim input resonator
2	13 , Output Resonator	trim output resonator

multaneously without excessive power densities. The ability to trim numerous filters simultaneously should lower the cost of future small percent bandwidth micromechanical filters.

Conclusions

Permanent post fabrication trimming of a 0.2% bandwidth micromechanical filter has been demonstrated using location-dependent laser trimming together with a pole-correcting algorithm based on an effective spring constant concept. This effective spring constant approach helps to simplify algorithmic details, and serves to reduce the total number of trim steps required for a given trimming scenario. The complete algorithm was able to trim the 2-CC-beam filter with only 0.432 mJ of total energy, making it amenable to larger scale trimming, where many filters (perhaps hundreds) might be trimmed simultaneously without concern for excessive power densities. Although effective in reducing the number of trim steps, the effective spring constant approach is still limited by resolution limitations of the trimming apparatus, so some amount of iteration at the end of the trim sequence was still required. Modifications to the present algorithm to allow more efficient iterative portions at the tail end of the sequence are the subject of ongoing research.

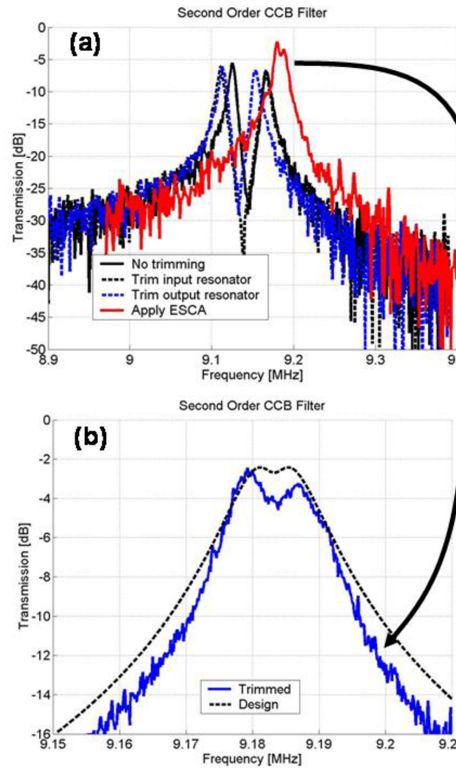

Fig. 10: (a) Filter response spectra measured after the resonator-to-peak association steps, then after the final application of the pole-correcting algorithm, showing actual trimming of a two-resonator CCB filter. (b) Zoom-in on the measured trimmed filter response compared to the design response, showing good agreement. Here, 0.048mJ laser pulses were used for finer trimming resolution.

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