M. Koskenvuori and I. Tittonen, Improvement of the conversion performance of a resonating multimode microelectromechanical mixer-filter through parametric amplification, IEEE Electron Device Letters, 28, pp. 970-972 (2007).

Improvement of the Conversion Performance of a Resonating Multimode Microelectromechanical Mixer-Filter Through Parametric Amplification

M. Koskenvuori and I. Tittonen

Abstract—**The down-conversion performance of a multimodal microelectromechanical mixer-filter is improved over 30 dB by parametric amplification. The input signal is an amplitude-modulated signal with a carrier frequency of 0.5 GHz. The obtained amplification is shown to depend on the particular eigenmode in a predetermined way. Finally, a qualitative explanation for the behavior is given.**

Index Terms—**Communication systems, filter, microelectromechanical devices, mixer, parametric amplification.**

I. INTRODUCTION

MICROELECTROMECHANICAL system mixer-filters ("mixlers") have been presented for mixing applications, and even their use in RF reception has been suggested. However, all presented devices exhibit a rather large conversion loss [1]–[4] or require significant local oscillator (LO) [5] power for effective conversion, making them inappropriate for low-power wireless applications, although some studies have shown that the performance is likely to improve with improved impedance matching [3].

In this letter, we study the possibility of using parametric amplification to improve the conversion efficiency even further. Previously, the performance of mechanical oscillators [6]–[9], various sensors [10]–[13], and even filters [14] have been enhanced or tuned with parametric resonance or amplification. In parametric amplification, one well-defined physical property is modulated at a frequency of $2\omega_0/n$, where ω_0 is the fundamental resonance frequency of vibration and n is an integer. We perform the parametric amplification with $n = 1$ through the modulation of spring constant k_0 by the gradient of the electric field. We use a resonator consisting of two double-ended tuning fork (DETF) periods that are coupled by a mechanical beam for increased isolation as a mixler [Fig. 1(a)] [3].

The differential equation describing parametrically amplified mechanical system can be written in the form of

$$m\ddot{x} + \frac{m\omega_0}{Q}\dot{x} + \left[k_0 + \Delta k \sin(2\omega_0 t)\right] x = F_0 \cos(\omega_0 + \varphi) \tag{1}$$

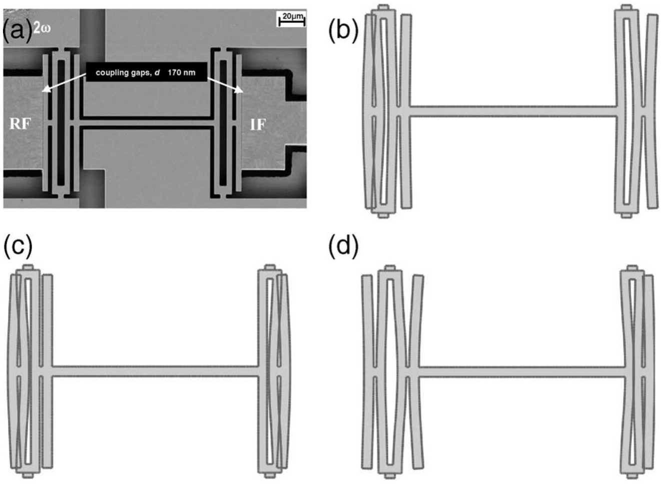

Fig. 1. (a) Scanning electron microscopic image of the resonator. The labels RF, IF, and 2ω mark the corresponding electrodes that were used throughout the text. (b)–(d) First three eigenmodes of the resonator calculated with Comsol Multiphysics.

where m and Q are the effective mass and quality factor of the resonator, respectively. Δk is the modulation amplitude of the spring constant, and φ is the phase difference between the exciting and the pumping signal. The displacement x and gain G are [6]

$$x(t) = \frac{F_0 Q}{k_0}\left(\frac{\cos\varphi}{1+\frac{Q\Delta k}{2k_0}}\sin(\omega_0 t) + j\frac{\sin\varphi}{1-\frac{Q\Delta k}{2k_0}}\cos(\omega_0 t)\right) \tag{2}$$

$$G = \left[\left(\frac{\cos\varphi}{1+\frac{Q\Delta k}{2k_0}}\right)^2 + \left(\frac{\sin\varphi}{1-\frac{Q\Delta k}{2k_0}}\right)^2\right]^{1/2}. \tag{3}$$

In this letter, the feasibility of parametric amplification for the improvement of the device performance is analyzed, and the results not only indicate the validity of the method but also bring important design aspects into the consideration of the reader.

II. DEVICE AND OPERATION

The input signal is an $f_C = 0.5$ GHz carrier signal that is amplitude modulated at the resonant frequency f_0 of the resonator. Due to the amplitude-modulated input signal, the conversion is intrinsic, requiring no LO signal [3]. To test the feasibility of the parametric amplification suggested in [2],

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Manuscript received July 3, 2007; revised August 20, 2007. The review of this letter was arranged by Editor Y. Taur.

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Digital Object Identifier 10.1109/LED.2007.907283

TABLE I

RESONANCE FREQUENCY AT A BIAS VOLTAGE OF 7 V AND CHANGE IN RESONANCE FREQUENCY WHEN A DC VOLTAGE OF 30 mV IS APPLIED TO THE 2ω ELECTRODE (EFFECTIVELY A PUMP OF -26.5 dBm). THE CALCULATED SPRING CONSTANT CHANGE GIVES AN INDICATION OF THE FEASIBILITY OF PARAMETRIC AMPLIFICATION

	1st	2nd	3rd
f_0 [MHz]	1.309	1.333	1.470
Q	5400	4500	9000
Δf[Hz]	240	55	4
$\Delta k/k_0$ [$*10^{-4}$]	3.670	0.825	0.058

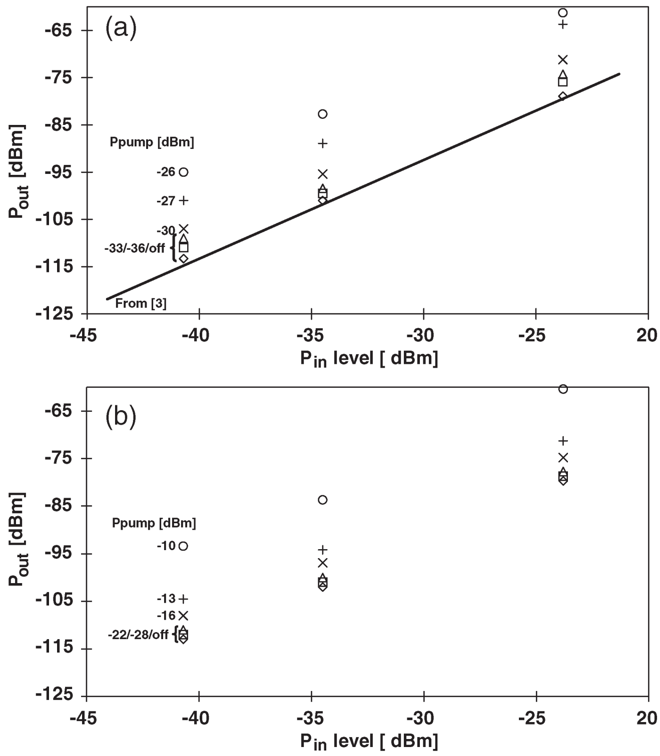

Fig. 2. Output power as a function of input power with variable pump power shows that the measured effect is parametric amplification for (a) the first and (b) the second eigenmode. The line in (a) shows the efficiency of conversion from [3].

the conversion is separately performed using the first three fundamental modes of the resonator [Fig. 1(b)–(d)]. The input signal ($f \approx 0.5$ GHz, P_{in}) is coupled to the RF electrode, and the output ($f \approx 1$ MHz, P_{out}) is read from the intermediate frequency (IF) electrode. Both electrodes are dc biased. The pump signal is coupled to the 2ω electrode. Table I lists some relevant parameters.

From (3), it is clear that, at constant $\varphi = \pi/2$, the modulation of the spring constant amplifies the vibration of the resonator until $Q\Delta k/k_0 = 2$, after which the pumping leads to spontaneous oscillation despite the input signal. For practical realization, maintaining phase relation φ is a key issue.

III. RESULT

The output as a function of input for various pump powers for the first and second eigenmodes is plotted in Fig. 2(a) and (b), respectively. With parametric amplification, gains in the excess of 30 dB can be easily reached, but the amplifier is very close to spontaneous oscillations as the ratio $Q\Delta k/k_0 > 1.998$ at these gains. The behavior is similar for both modes; however, when plotting the amplification as a function of the pump voltage in Fig. 3, the difference is easily visible.

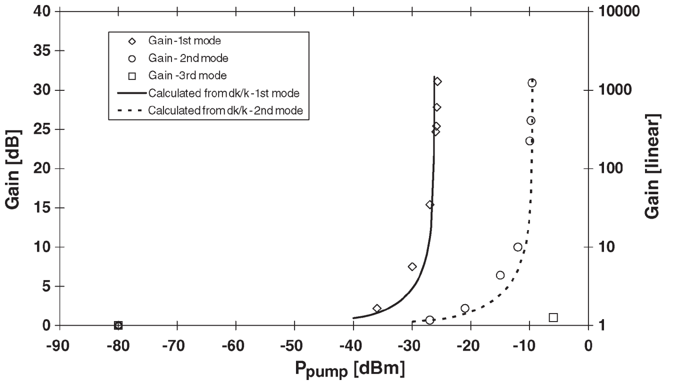

Fig. 3. Gain as a function of pump (2ω) power for the first three eigenmodes shows the different power that is needed for amplification. The measured limits for spontaneous oscillation are -25.6 and -9.3 dBm for the first and second modes, respectively. Solid and dashed lines represent the gains that were calculated (3) from the measured values of $\Delta k/k_0$ shown in Fig. 4.

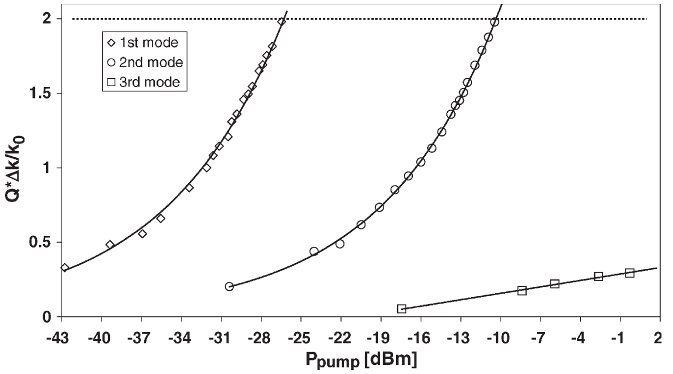

Fig. 4. Change in the spring constant when the pump signal is applied to the 2ω electrode. Dotted line marks the limit of spontaneous oscillation.

From Table I and Fig. 4, it is evident that the first mode is the easiest to parametrically amplify, as the $\Delta k/k_0$ ratio is the highest. As the amplification is related to $\Delta k/k_0$, it is evident from Table I and Fig. 4 that, despite the highest Q-factor, the third eigenmode of the resonator is even harder to amplify by parametrically modulating the spring constant. This is verified by Fig. 3, as the amplification is only on the order of 1 dB with a pump signal of -6 dBm.

Qualitatively, the difference in the amplification of different eigenmodes can be explained as follows: the spring constant modulation through the electric field applies only to the beams next to the electrodes, but the beams in the middle do not experience this spring constant change—this contributes to the amplification being weaker for the second and third modes. The explanation can be backed up by measuring $\Delta k/k_0$ for a single DETF period (inset of Fig. 5) where all the mechanical beams experience the spring constant modulation. This device shows identical behaviors for both eigenmodes (Fig. 5). This is

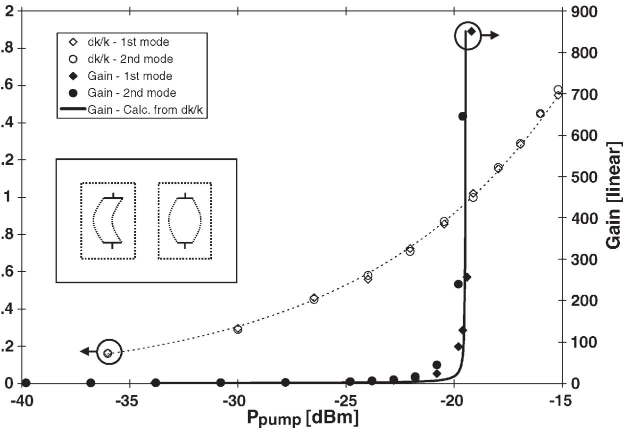

Fig. 5. $\Delta k/k_0$ and gain for a single DETF period shows that the relative spring constant change and, therefore, the amplification is identical for both eigenmodes (shown in inset).

yet another reminder about the importance of mechanical aspects when designing electronic devices with micromechanical components.

IV. CONCLUSION

The feasibility of reducing the conversion loss of a micromechanical multimode resonant mixler by parametric amplification was analyzed. Similar improvements of over 30 dB when converting gigahertz-range signals were measured for the first two fundamental modes, indicating that the conversion efficiency of a mixler can be considerably increased with parametric amplification. However, the maximum amplification was reached with different pumping powers for different modes due to the strength of mechanical spring constant modulation being different for different modes of resonance.

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