

Novel Parametric-Effect MEMS Amplifiers/Transducers

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I. INTRODUCTION

A parametric effect amplifier has been built at 200 kHz (input) and 1.84 MHz (output) using a MEMS time-varying capacitor. The capacitor is composed of a thin low stress metallized silicon-nitride diaphragm and is pumped by a large signal voltage at 1.64 MHz. This results in a large change in the capacitance, and parametric amplification of an input signal at 200 kHz. To our knowledge, this device is the first-ever mechanical up-converter parametric-effect amplifier, with an up-conversion ratio of 9:1. Its main advantages are the absence of any resistive and $1/f$ noise, and most importantly, it provides gain at the transducer level. Some advantages over CMOS based electronic amplifiers are the possibility to operate at very high temperatures (200-600 °C), under high particle bombardment (nuclear applications), and very low noise operation due to the absence of thermal and shot noise in parametric amplifiers.

II. PARAMETRIC AMPLIFICATION THEORY

In 1956, Manley and Rowe derived a pair of equations governing the power balance of passive and lossless one-port devices with an arbitrary nonlinear characteristics [1]. This device can be part of a parametric circuit, and is simultaneously fed by a signal source at frequency f_s and a pump source at frequency f_p . Due to its non-linear characteristics, time varying currents and voltages are generated, in principle, at all combination frequencies: $f_{n,m} = nf_s + mf_p$ with $n, m = -\infty \dots \infty$. In practice, only a single combination frequency is kept besides the signal frequency f_s and the pump frequency f_p , the other combination frequencies are filtered. Manley and Rowe have demonstrated that for the non-inverting up-converter case (input frequency: f_s , and output frequency: $f_u = f_p + f_s$; f_p is the pump frequency, Fig. 1) the power gain is equal to the ratio of output to input frequencies: $G_p = f_u/f_s = (f_p + f_s)/f_s > 1$. Therefore, one can build a mechanical amplifier with a large gain if $f_u \gg f_s$.

III. MEMS PARAMETRIC UP-CONVERTER

The parametric effect results from a time-varying capacitor which consists of a metallized membrane (top electrode) suspended above a heavily doped silicon bulk (bottom electrode). By pumping the movable top electrode with a large signal voltage at the pump frequency (ω_p), one generates a time-varying capacitance $C(t) = C_0(1 + 2\gamma_1 \cos(\omega_p t) + 2\gamma_2 \cos(2\omega_p t) + \dots)$. The fabrication process is summarized in Fig. 2 and more details can be found in [2]. Fig. 3 shows the capacitance variation of the MEMS capacitor versus dc bias conditions. The suspended nitride membrane is 0.6 μm thick, 50 μm radius and with a residual stress of 170 MPa. The total device area is 1 cm^2 . In the electrical domain, assuming an appropriate electromechanical transducer, a mechanical resonator can be modeled as a series LCR network (Fig. 4). From the measurement of its electrical transfer function, the mechanical properties of the resonant MEMS capacitor such as the quality factor Q and the resonant frequency are extracted. Under a dc bias of 80 V, the capacitor membrane has a resonant frequency of 1.64 MHz and a Q of 18. From the plot of the real (Fig. 5) and imaginary (Fig. 6) parts of the parameter Y_{12} , the series parasitic resistance R_c , the parallel capacitance C_0 and the equivalent electrical lumped elements of the resonator (L_x , C_x and R_x) are extracted (see Figs. 5 and 6). The design and the gain characteristics of the parametric up-converter depend strongly on the MEMS capacitor nonlinear characteristics. By applying a large electrical pump signal at a frequency (ω_p) corresponding to the main mechanical resonance of the MEMS capacitor and by analyzing the spectrum of the current flowing through it (Fig. 7), the Fourier series coefficients of the MEMS time varying-capacitance $C(t)$ versus the power of the electrical pump signal can be extracted. Under the bias conditions of $V_{dc}=60$ V and $V_P=15 \cos(2\pi f_p t)$, the Fourier series coefficients γ_1 , γ_2 and γ_3 are, respectively, 0.22, 0.05 and 0.01. Fig. 8 shows the measured and simulated transducer gain of the parametric up-converter versus the load resistance. The measured optimum load of 140 Ω is in accordance with the value (133 Ω) calculated by using the analytical relationships given in [3]. Fig. 9 presents the measured transducer gain versus the coefficient γ_1 which depends on the pump signal power. For these measurements, the matching networks and input/output filters has been optimized for $\gamma_1=0.22$. As predicted by the simulations, the transducer gain of the MEMS parametric up-converter increases with γ_1 .

IV. CONCLUSION

Parametric amplifiers can be built for sensors (thermal, acceleration, chemical, etc.) without any CMOS electronics. This means that a pre-amplification stage can be provided for non CMOS sensors before sending the signal to a CMOS wafer for more gain and processing.

[1] J. M. Manley and H. E. Rowe, *Proceedings of the IRE*, pp. 904-914, July 1956.

[2] Xuecheng Jin, *etal.*, *IEEE Journal of Microelectromechanical Systems*, vol. 8, no. 1, pp. 100-114, March 1999.

[3] L. A. Blackwell and K. L. Kotzebue, "Semiconductor-diode parametric amplifiers", *Prentice-Hall, Inc., N.J.*, 1961.

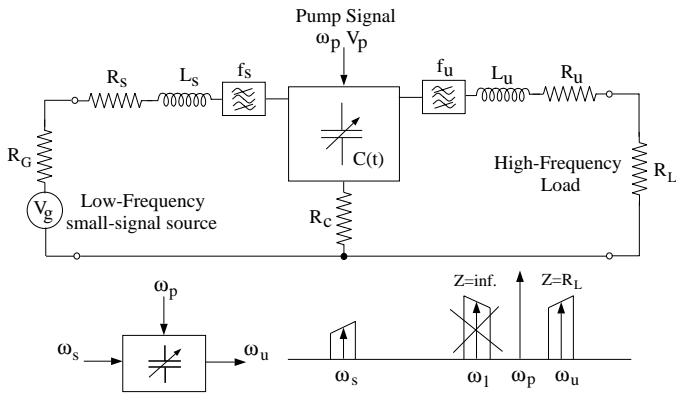


Fig. 1. Scheme and spectra for the MEMS parametric up-converter.

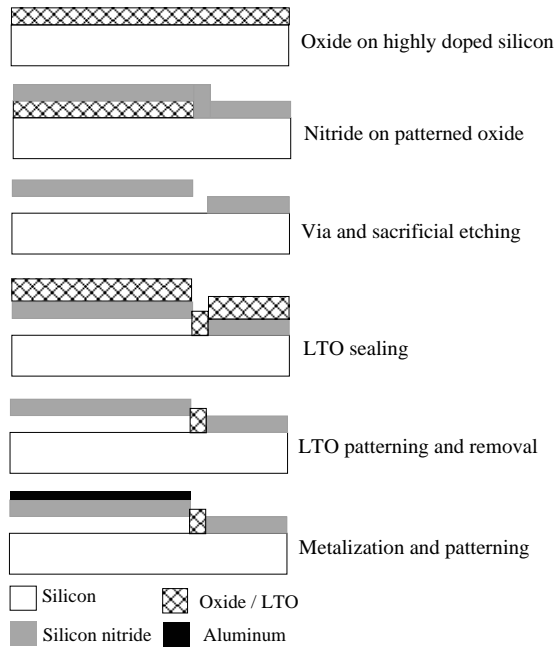


Fig. 2. Fabrication steps of the MEMS capacitor array.

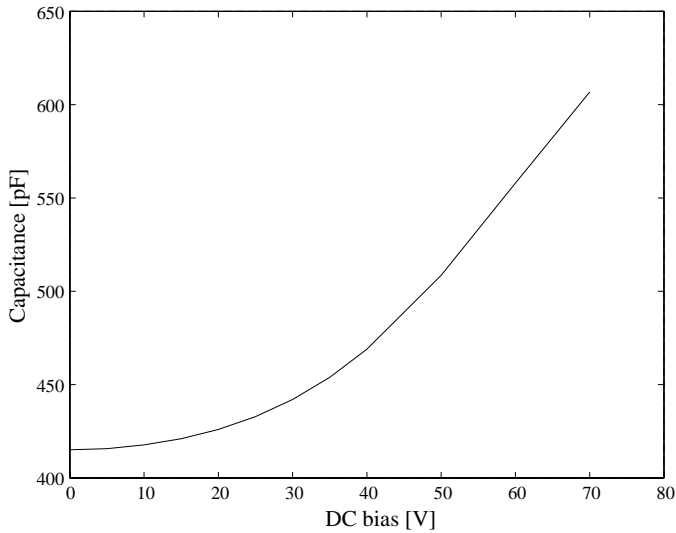


Fig. 3. Measured capacitance variation vs dc voltage.

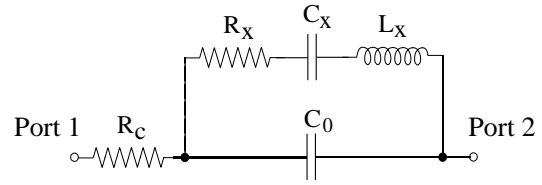


Fig. 4. Small-signal electrical model of the MEMS capacitor.

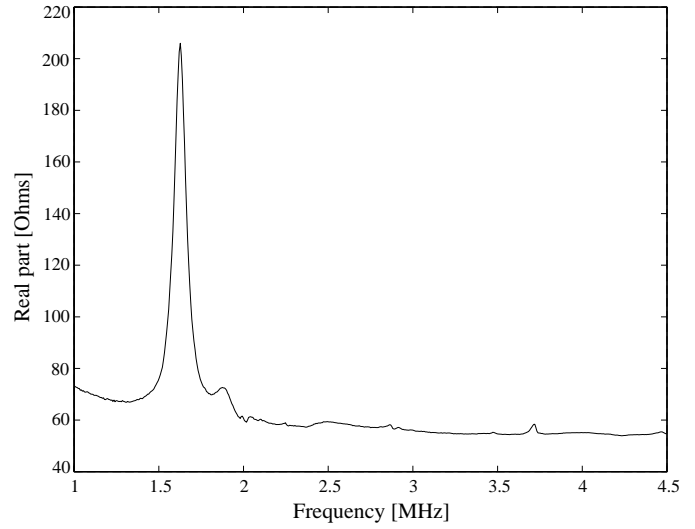


Fig. 5. Measured real part of $1/Y_{12}$ vs frequency. Extracted value of R_c is 52Ω .

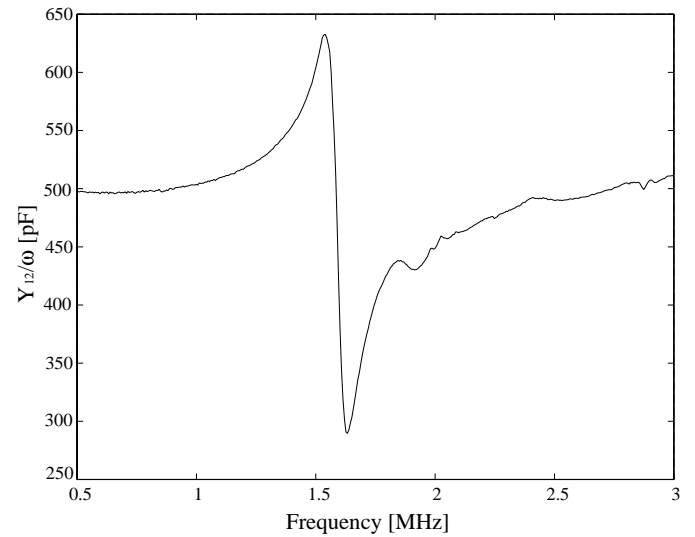


Fig. 6. Measured extracted equivalent capacitance (Y_{12}/ω) around the resonance frequency from the measurements. Extracted values of C_0 , C_x , L_x and R_x are, respectively, 500 pF, 32.5 pF, 0.29 mH and 166 Ω .

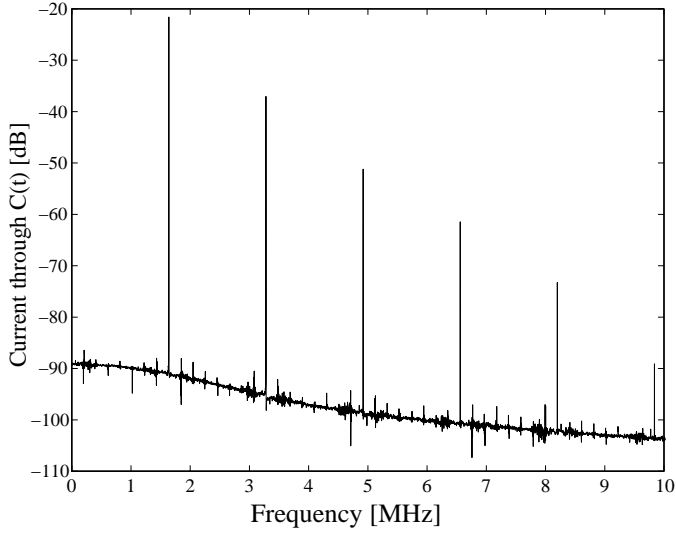


Fig. 7. Measured spectrum of the current flowing through the MEMS time-varying capacitor for $V_{dc}=60$ V and $V_P = 15 \cdot \cos(2\pi f_p t)$ with $f_p = 1.64$ MHz.

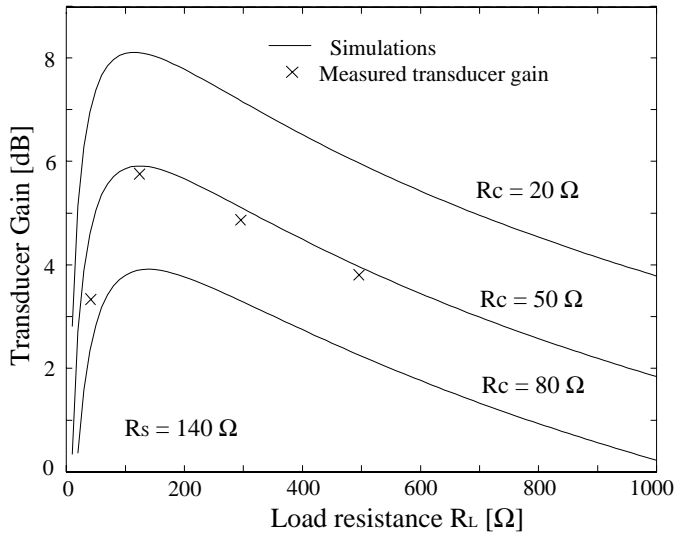


Fig. 8. Measured parametric up-converter transducer gain vs the load resistance value ($f_s = 200$ kHz and $f_p = 1.64$ MHz).

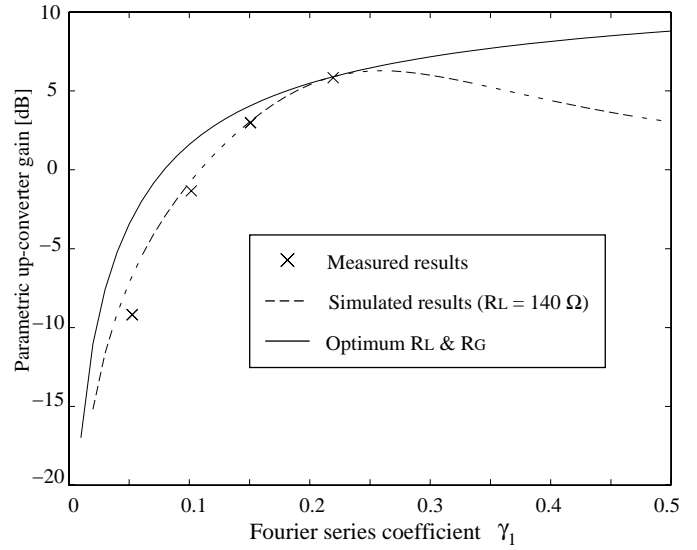


Fig. 9. Measured parametric up-converter transducer gain vs γ_1 ($f_s = 200$ kHz and $f_p = 1.64$ MHz) .