PROCORE - FRANCE/HONG KONG JOINT RESEARCH SCHEME COMPLETION REPORT

Project Reference Number

F-HK003/12T

Project Title

Novel Approaches to Thermal Actuation in High Frequency Micromechanical Resonators for Sensing and Timing Applications

傳感及計時應用中高頻機械諧振器的新型熱驅動方式之研究

Particulars

	Hong Kong team	French team
Name of Project Co-ordinator (with title)	English: Lee En-yuan Joshua Chinese: 李恩源	Libor Rufer
Name of Co-Investigator (if any)	English: Chinese:	
Institution or Institutional affiliation	✓ CityU ☐ CUHK ☐ HKBU ☐ HKIEd ☐ HKU ☐ HKUST ☐ LU ☐ PolyU	☐ CEA ✓ CNRS No. 5159 ☐ INFREMER ☐ University of ☐ Others: ☐ INRA ☐ INRIA ☐ INSERM No.
Other project team members (if any)	Haoshen Zhu (PhD student)	Josué Esteves (PhD student)

Funding Period

	1st year	2nd year (if applicable)
Start Date	01/01/2013	01/01/2014
Completion Date	31/12/2013	31/12/2014

Objective(s) as per original application

1. Formulate the first empirically validated electromechanical models that accurately describe the underlying physics behind thermal actuation of mechanical resonators at high frequencies (> 30MHz)

2. Implement a two-port configuration format by separating the input and output ports so as to reduce direct coupling interference (feedthrough) between the input and output ports

3. Identify the limits to the application of thermal actuation in high frequency resonators from the view of technological bottlenecks and fundamental limits imposed by physical laws

[Please attach relevant document(s)]

i) Outline of proposed research and results obtained

Micromechanical resonators are micron-scale vibratory structures that have been employed in both sensing and timing applications. Scaling devices to such limits reduces the signal output, posing a challenge on the detection especially as we push towards higher frequencies. For instance, while thermal excitation can be used to actuate the resonator, thermal actuation has commonly been seen as only suitable for low frequencies due to long thermal time constants. Counter to this notation are recent demonstrations of thermally actuated resonators above 60MHz, though the underlying physics of these counter-intuitive results still lack a robust model prior to this PROCORE joint research project. Given the potential of thermal actual for high frequencies, our research collaboration has sought to identify the limits to this less well-understood approach and formulate a robust model which can accurately describe the underlying physics. At the end of the project, we have achieved all the research objectives we have set out at the time of proposal. These achievements and results are described in the following.

Objective 1: Modeling the underlying electro-thermo-mechanical coupling mechanism behind thermal actuation of mechanical resonators at high frequencies (> 30MHz)

We have successfully demonstrated resonance at 64MHz using thermal actuation combined with piezoresistive sensing in a silicon-based resonator that is only 50μm by 25μm. The device has been fabricated using standing silicon-on-insulator micromachining techniques. We have achieved insertion losses as low as 35dB. This is an exception performance for an SOI resonator realized using standard lithography techniques since the method of thermal actuation does not require fabricating narrow gaps as needed by capacitive actuation and detection. The resonator retains a reasonably high quality factor (Q) over 50,000. This is close to the frequency (f)-Q product of capacitive silicon resonators vibrating in the extensional mode. The fQ product is an indication of fundamental limits on Q determined by phonon-phonon interaction. As such, the thermal actuated resonators implemented in this project do not suffer from loss in Q even while achieving significantly enhanced electromechanical coupling. As a reference, we have not been able to measure any signals from the same devices when using capacitive actuation. We have also managed fit the measured data an analytical model. These results were presented at APCOT 2014 in Daegu held at the end of June 2014.

Objective 2: Feedthrough cancellation techniques

We have successfully demonstrated cancellation of feedthrough by a 47dB. One of the key challenges that were identified at the time of the proposal was the large resistive feedthrough coupling directly from the input port to the output port through the low resistive silicon structure. Based on the techniques described in the proposal, we configured a pair of resonators balance out each other's parasitic feedthrough current. Furthermore, we were able to show that the device pair can be configured to realize a filter with a tunable bandwidth. By leveraging on the benefits of thermal actuation, we were able to achieve low insertion loss that was simply unreachable using capacitive transduction methods. We were able to also fit a model curve to the measured frequency response novel thermally actuated bandpass filter with a center frequency of 64MHz and pass band ripple of less 1dB.

Objective 3: Limits of the approach

Having been able to fit our analytical models to the measured data has provided insight into the differences between thermal actuation at the high frequencies we have used in our devices and previously reported devices driven by thermal actuation at low frequencies. The thermal characteristic of the device is normally described by its thermal resistance. This is the case at low frequencies where the operating frequency is much lower than the thermal time constant of the structure. At high frequencies that go beyond the thermal time constant, it is the thermal capacitance that determines the thermal characteristic of the device. From theory, the dominance of the thermal capacitance over the thermal resistance would manifest itself in the form of a phase shift according to our model. In our measurements, we see this phase shift, which verifies that underlying basis for being able to drive the device at frequencies higher than the equilibrium range set by the thermal time constant. Hence in principle, our results based on the model suggest that the thermal time constant of the device does not set an upper bound on the frequency at which a resonator can be driven. Although the model shows that the electromechanical coupling scales with the inverse square of the frequency, this reduction could be compensated by increasing the bias current. In addition, both electrical resistance and thermal capacitance are reduced as the physical dimensions are scaled down to push up the frequencies to higher bands. Reducing the thermal resistance and capacitance has the further benefit of enhancing thermodynamic feedback. We have observed a weak presence of thermodynamic feedback in our studies. This effect would be stronger if the devices could made smaller, for which we do not have the capability and infrastructure. Thermodynamic feedback can be used to enhance the quality factor of the resonator by tuning the bias current. This in turn further compensates any additional losses incurred at high frequencies. Hence in principle, the upper limit on the frequency bands to which thermal actuation can be applied effectively is limited by the state of art fabrication technology rather than of the approach itself.

During the collaboration, the nominated PhD student (Haoshen Zhu) from the Hong Kong partner spent about 4 months at the French partner's institution. Travel expenses were covered by the 2nd year of the travel grant including a month supplementary allowance (supplementary allowance for the other 3 months was provided by the Hong Kong partner's institution). His stay at TIMA led to a prize winning work that was awarded Best Paper at the 2014 European Frequency and Time Forum (EFTF 2014). The prize winning showed for the first time the possibility to cancel nonlinearity in silicon bulk-mode resonators electronically by using the bias current applied in the piezoresistive detection setup that forms the output port of the thermally actually resonators.

ii) Significance of research results

With regards to the nonlinear cancellation technique presented at EFTF 2014, this was the first time that the capability to cancel nonlinear bifurcations in silicon bulk mode MEMS resonators was demonstrated. This is highly significant as it paves an approach to extend the power handling capability of the device. The small size of MEMS resonators is an advantage in many consumer electronics applications that have tight space budget. The tradeoff is a reduction in the amount of power the device can take before its deviates from linear behavior. This deviation is known to degrade the performance of an oscillator in which the resonator is embedded. In beam resonators, it is possible balance out the various nonlinear components so as to use one to compensate the other. But beam resonators are mechanically much softer compared to bulk mode resonators. It is for this reason that bulk mode resonators are interest due to their higher stiffness that can be beneficial for reaching higher frequencies and possess higher energy storage capacity. But the high stiffness also means that methods for nonlinear cancellation applied to beams cannot be transferred to bulk mode resonators. Hence our results that demonstrate nonlinear cancellation in a bulk mode resonator, and that this can be done by tuning the electrical signals, opens up a new thread for further inquiry in extending the power handling capability of these small devices. We are now in the process of drafting a journal paper co-authored by both partners to describe the underlying physics behind the observed phenomenon that we envisage will have even deeper implications when extended to oscillation systems eventually.

iii) Research output

The successful cooperation between the Hong Kong and French partner has resulted in the following joint-author conference publications. One of the papers was selected by the conference awards committee of the European Frequency and Time Forum (EFTF) for the best student paper in the topical category of Materials, Resonators, and Resonator Circuits. EFTF is the premier technical conference in Europe for time and frequency products and related technologies, bringing together researchers and technologists from manufacturers, service providers, operators, application developers, national metrology laboratories, defense timing, and standards bodies to share the latest information and promote the development of precise time and frequency systems and components

H. Zhu, C. Tu, L. Rufer, and J. E.-Y. Lee, "Active electronic cancellation of nonlinearity in a high-Q longitudinal-mode silicon resonator by current biasing," in Proc. of the 28th European Frequency and Time Forum (EFTF 2014), Neuchâtel, Switzerland, 23-26 Jun 2014 **(STUDENT AWARD)**

C. Tu, H. Zhu, L. Rufer, and J. E.-Y. Lee, "Low impedance very-high-frequency (VHF) band thermal piezoresistive silicon bulk acoustic resonator," in Proc. of the 7th Asia-Pacific Conf. on Transducers and Micro/Nano Technologies (APCOT 2014), Daegu, Korea, 29 Jun - 2 Jul 2014

We are currently in the process of putting together a joint-author journal paper submission based on the award winning work. The focus of the journal submission will be on the physical basis of the electronic nonlinear cancellation phenomenon reported in the EFTF conference following extensive experiments and finite element modeling since the conference presentation.

iv) Potential for or impact on further research collaboration

An important outcome of the collaboration between the TIMA Laboratory and Universities in Hong Kong has been the joint preparation of an ANR-RGC proposal that involves partners from CityU, HKUST and TIMA. The project, unfortunately, could not be submitted in 2015 for administrative reasons. We are now planning for a new submission in 2016. The new funds will provide resources to sustain the collaboration that has been initiated through the support of this PROCORE travel grant over the period of 2013-2014. In addition, we have initiative a move to place students from the French partner's institution in CityU for at least a summer to carry research jointly supervised by the PIs of this PROCORE grant. Starting from this summer, one student from TIMA will be undertaking her summer internship at CityU to work on a project of mutual interest to both PIs.