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A laser-micromachined multi-modal resonating power transducer for wireless sensing systems

Neil N.H. Ching[a], H.Y. Wong[b], Wen J. Li[a,*], Philip H.W. Leong[b], Zhiyu Wen[c]

[a]*Department of ACAE, CUHK, Center for Micro and Nano Systems, The Chinese University of Hong Kong, MMW Building, Room 425, Shatin NT, Hong Kong, PR China*

[b]*Department of Computer Science and Engineering, The Chinese University of Hong Kong, Hong Kong, PR China*

[c]*Laboratory of Optoelectronic Technology and Systems, Chongqing University, Chongqing, China*

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Abstract

This paper presents the development of a vibration-induced power generator with total volume of ~1 cm^3 which uses laser-micromachined springs to convert mechanical energy into useful electrical power by Faraday's law of induction. The goal of this project is to create a minimally sized electric power generator capable of producing enough voltage to drive low-power ICs and/or microsensors for applications where ambient mechanical vibrations are present. Thus far, we have fabricated generators with total volume of 1 cm^3 that are capable of producing up to 4.4 V peak-to-peak, which have a maximum RMS power of ~830 μW with loading resistance of 1000 Ω. The mechanical vibration required to generate this electrical energy has frequencies ranging from 60 to 110 Hz with ~200 μm amplitude. The generator was shown to generate sufficient power at different resonating modes. We have demonstrated that this generator can drive an infrared (IR) transmitter to send 140 ms pulse trains every minute, and also a 914.8 MHz FM wireless temperature sensing system. © 2002 Published by Elsevier Science B.V.

Keywords: Micropower generator; Micropower supply; Micropower transducer; Wireless sensing

1. Introduction

One of the projected goals for MEMS technology is to develop low-cost and high-performance distributed sensor systems for medical, automotive, manufacturing, robotics, and household applications. Ideally, these distributed systems will have their own integrated power supplies to reduce potential problems such as interconnection, electronic noise and control system complexity. Efforts are underway to develop integrated chemically-based power supplies with MEMS devices [1]. However, where shelf life or replacement accessibility is a limiting factor, chemical power supplies may not be the optimal choice. We report here our development of a mechanically-based integrated MEMS power generator that converts vibrational kinetic energy transferred from the immediate environment to electrical energy usable by low-power ICs or integrated microsensors.

Some pioneering work related to vibration-based power generators were done by researchers at the University of Sheffield [2] and Chandrakasan's group at MIT [3]. Nevertheless, to the best of our knowledge, no one has demonstrated a micromachined generator with enough power to drive an off-the-shelf circuit. For this work, micromachining techniques are used to build the vibration-induced power generator because they offer two distinct advantages: (1) precise control of the mechanical resonance which is necessary to produce an efficient generator, and (2) batch fabricability which will allow low-cost mass production of commercially viable generators. The design analysis and experimental results of our first generation microgenerators are presented in this paper.

2. Generator concept and design

Photographs of the microelectromagnetic generator and the measurement setup are shown in Fig. 1. The generator consists of a rare-earth Nd–Fe–B magnet of mass m with magnetic field strength B, springs with total spring constant k, and coil of length l. The spring is attached to the magnet and a solid frame, forming a mass-spring resonator structure. The electrical coil is fixed on the rigid housing of the device. When the rigid housing is vibrated, the magnet will move

* Corresponding author. Tel.: +852-2609-8475; fax: +852-2603-6002.
E-mail address: wen@acae.cuhk.edu.hk (W.J. Li).

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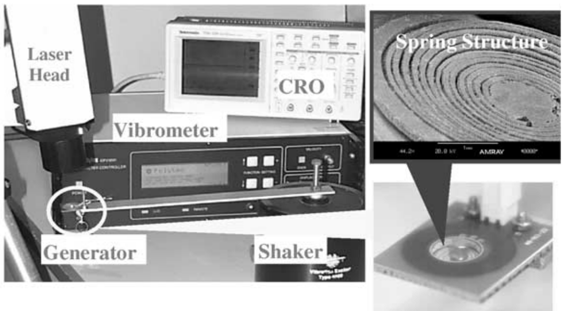


Fig. 1. Experimental setup for generator output and mass displacement measurement, and pictures of a ''spiral'' Cu spring structure and a generator.

relatively to the housing and the coil. This relative movement of the magnet to the coil results in varying amount of magnetic flux passing through the coil. According to Faraday's law of induction, a voltage is induced on the coil. Optimization of the power transducer design based on electro-magneto-mechanical considerations was given in [4].

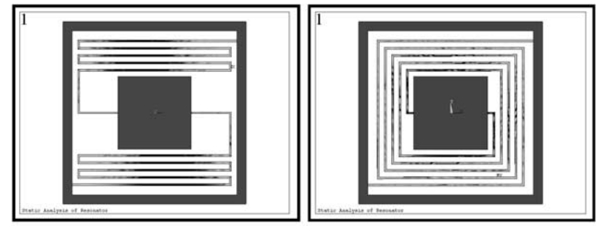
3. Spring fabrication and testing

A comprehensive study concluded that copper is much better than silicon in terms of reliability and power generation for the spring structure [4]. The material properties of some common metals found in micromachining processes are compared in Table 1. It should be noted that although copper is better than Si, it is not the best material in terms of yield stress and fatigue limit. For instance, if extremely large displacement of the spring is needed, titanium should be used, as it is able to withstand a much higher stress. If the generator is required to work at low frequency range, 55-Ni-45-Ti should be used, as its Young's modulus is lower than copper. Our ongoing work is to explore 55-Ni-45-Ti as a low-frequency power generator. We employed copper and brass to fabricate the prototypes only because they are much more economical compared to titanium and 55-Ni-45-Ti. Calculations showed a low resonant frequency of about 10 Hz can be achieved by using copper and brass spiral spring [5].

Different patterns of springs were modeled to optimize the resonating spring design, i.e. ''zig-zag'' and spiral structures (Fig. 2). ANSYS simulation results showed that the spiral

Table 1
Material data for the spring structure [6]

	Young's modulus (GPa)	Yield stress (MPa)	Ultimate stress (MPa)	Fatigue limits (MPa)	Fatigue ratio
Brass	96–110	70–550	200–620	98–147	0.31
Copper	130	55–760	230–830	63	0.29
Titanium	120	760–1000	900–1200	364	0.59
55-Ni-45-Ti	83	195–690	895	–	–



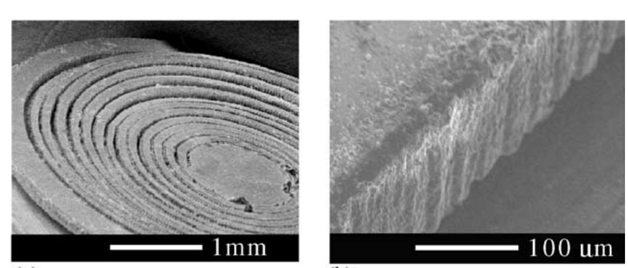
(a) (b)

Fig. 2. ANSYS modeling for different spring patterns: (a) ''zig-zag'' spring; (b) spiral spring.

springs have lower spring constant and lower stress concentration, thus, a larger displacement can be obtained. Moreover, if circular spiral shape is used, the stress can be further reduced [5].

Based on ANSYS modeling results we have used a Q-switch Nd:YAG (1.06 μm wavelength) laser to micromachine copper spiral spring structures as shown in Fig. 3. The Electrox Scriba II D40 laser, which has 40 W of maximum power, was used in our work. The frequency of the laser pulse was set at 2 kHz and the pulse width of the laser was 100–300 ns. The laser beam was focused by a scanning lens ($f\theta$ lens) with a focal length of 100 mm onto the sample surface. The Gaussian spot size of the beam was determined to be around 400 μm^2 at 1064 nm (diameter, d_b: ~22.6 μm at $1/e^2$ intensity). A laser system was used to micromachine the resonating springs because it offers direct and fast fabrication of copper springs with reasonable resolution. Our final system will involve high-aspect-ratio electroplating of copper using lithographic techniques.

Using the setup as shown in Fig. 1, the mechanical input vibration and frequency, the transducer spring-mass motion, and the electrical output of the transducer were measured. Conventional model (as given in [4]) predicts that the power output should be proportional to the square of the vertical mass amplitude. However, we have observed experimentally that if springs were designed to have non-vertical resonance vibrations, voltage generated can be significantly higher. As shown in Fig. 4, for a ''spiral'' spring, the generator gave relatively high voltage at higher frequencies even though the vibration amplitude was almost negligible in the vertical direction.



(a) (b)

Fig. 3. Laser-micromachined copper springs: (a) a planar copper spring with total diameter of 4 mm; (b) close-up of the spring shown in (a).

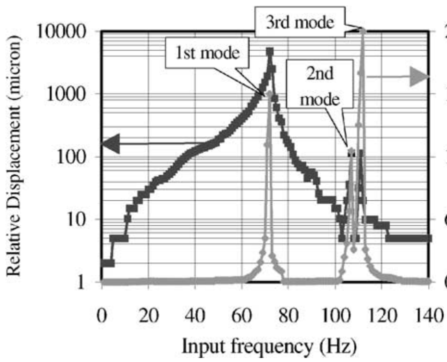


Fig. 4. Vibrational amplitude of the mass and the resulting voltage generated for a 2DOF spring structure.

The motion of the mass-spring with three different modes of resonant vibration were captured digitally and analyzed. Using a strobe light to synchronize, the vibration motion of the mass, the mass was observed to have a second and third mode resonance (Fig. 5b and c). The mass appeared to cyclically rotate about an axis parallel to the plane of the coil. Furthermore, it was observed that the amplitude of the rotation was very small compared to the vertical vibration at the first mode resonance (Fig. 5a). We, therefore, conjecture that if the a spring can be designed to vibrate in a horizontal plane with rotation, rather than a vertical plane relative to a coil, even under a force in the vertical direction, the voltage output can be increased and the stress on the spring can be reduced.

Physically, this can be explained by the fact that Faraday's law predicts the voltage output to be proportional to the rate

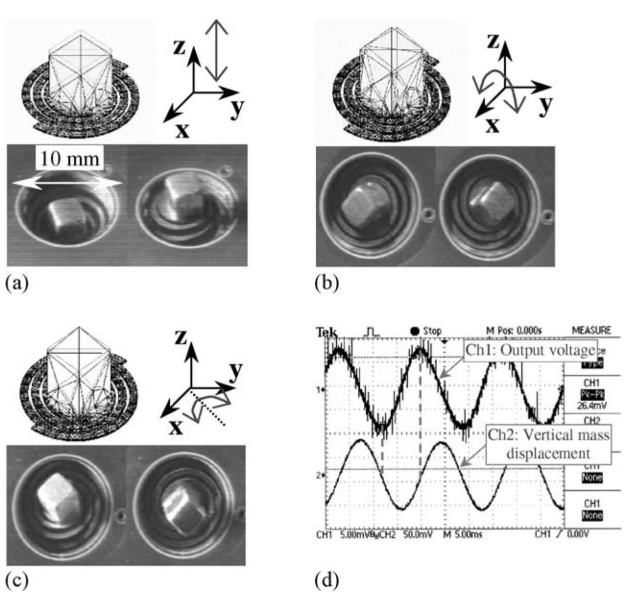


Fig. 5. FEA simulation and experimental results both found three different resonant vibration modes: (a) first mode vibration (vertical); (b) second mode vibration (horizontal); (c) third mode vibration (horizontal); (d) the phase difference between the output voltage of the generator and vertical displacement of the magnet at the third mode vibration.

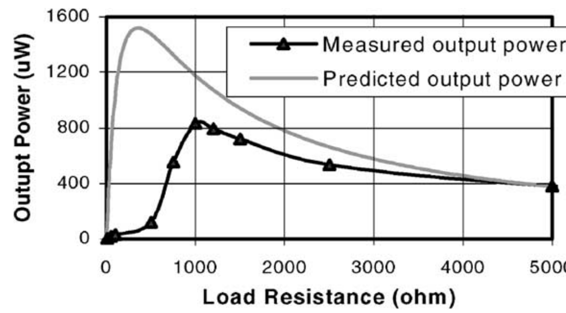


Fig. 6. RMS output power vs. load resistance.

of changing magnetic flux, and hence, faster the translation and rotation of the mass, the greater current induction. As shown in Fig. 5d, at third mode resonant vibration, the faster the rate of change of vertical displacement (i.e. slope of Ch2, it represents the "angular velocity" of the magnet), greater is the voltage induced.

We have also performed ANSYS dynamic modeling for the spring design shown in Fig. 5, which matched the motion observed experimentally. Some discrepancies exist between the experimentally observed and the ANSYS-modeled modal resonant frequencies, which are most likely due to the imprecise packaging technique that we currently use, i.e. the magnetic mass is attached to the spring by epoxy without accurate alignment procedures, which will cause a shift of resonant frequency. We are currently developing a better packaging technique to overcome this problem.

The experimental generator output was also compared to the theoretical output. Ideally, the generator output with a loading resistance R can be predicted by Eq. (1) if the maximum output voltage $V_{\max}$ and internal resistance r are given. However, an experimental measurement shows a discrepancy (Fig. 6). The reason is mainly attributed to the existence of back emf when current passes through the coils. The effect is significant when the load resistance is small because smaller the resistance, larger the current will pass through the coils.

$$\text{Output power} = I^2 R = \frac{V_{\max}^2 R}{(r+R)^2} \quad (1)$$

4. Applications for wireless transmission

4.1. Infrared transmission

A standard quadrupler circuit (Fig. 7a) was used to step up the ac output from the generator to dc voltage (Fig. 7b). A prototype of this circuit was built using 10 μF, 25 V electrolytic capacitors and Motorola Inc. 1N5817RL Schottky diodes which have a forward voltage of 0.32 V. The output of the generator dropped to 1.3 V when loaded and to 0.448 V when the quadrupler was incorporated. However, the multiplied output dc voltage of 2.3 V is sufficient to drive

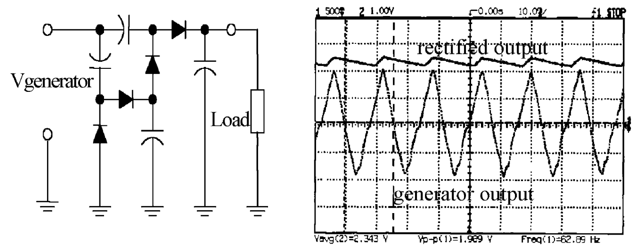


Fig. 7. (a) The quadrupler rectifying circuit. (b) Rectified output and generator output without load.

most low voltage circuits. The measured average current was 40 μA, and hence, the power output for this system is ~100 μW.

An IR transmitter was built using a commercial SM5021 encoder chip. We have experimentally determined that this circuit could operate properly with a power supply as low as 1.8 V. Since the output current from the microgenerator system (generator plus the rectifier) was too small (40 mA) to directly power the chip, the system was first used to charge up a large capacitor, which in turn was used to power the IR transmitter. An IR signal could be sent to a receiver every time a key was pressed. The signal was a 140.8 ms long IR pulse train. For a 2.0 V power supply, the current drawn during a key press was measured to be 1.5 mA and, in standby mode, 2.4 μA.

A capacitor of 1.16 mF was used as the power reservoir in the experiment. It was first charged up to 2.0 V and used to power the transmitter. It took 58 s to charge the capacitor from 0 to 2.0 V and the charge stored is enough for two key presses whereupon the output voltage drops to 1.56 V. It would take another 30 s to charge it back to 2.0 V.

4.2. RF transmission

Again, since the generator could not produce enough instantaneous power and voltage to for this system, its output voltage was rectified and multiplied with a standard tripler circuit and stored in capacitor C_1, which acts as a power reservoir (Fig. 8). The output of the tripler is 3.5 V dc at 70 uA. When the generator starts operating, it will charge up another capacitor C_2 at the same time with a slower rate than C_1 due to presence of the 250 kΩ resistor. The resistance and capacitances were chosen such that the logic gate MC14001, will only switch on after C_1 has been charged to 3.5 V. By doing so, the system will not consume any power before enough energy has been stored in C_1. This will ensure that there is enough energy for the first operation.

There are three main power-consuming components in the system: microcontroller (SX-28), temperature sensor (DS1620) and UHF-FM data transmitter (TX3). The controller is used to control the operations of the whole system, and process data. It instructs the temperature sensor to convert the ambient temperature to digital format and read the converted temperature through three-wire communication protocol. The controller then sends the data serially to the TXD pin of the transmitter (Fig. 9c), which will modulate the digital temperature data into FM signal at 914.5 MHz to be received by the receiver module at a distance of 25 m. The microcontroller then disables all components and enter sleep mode. This allows the reservoir capacitors to be charged up again. After 30 s, the system will

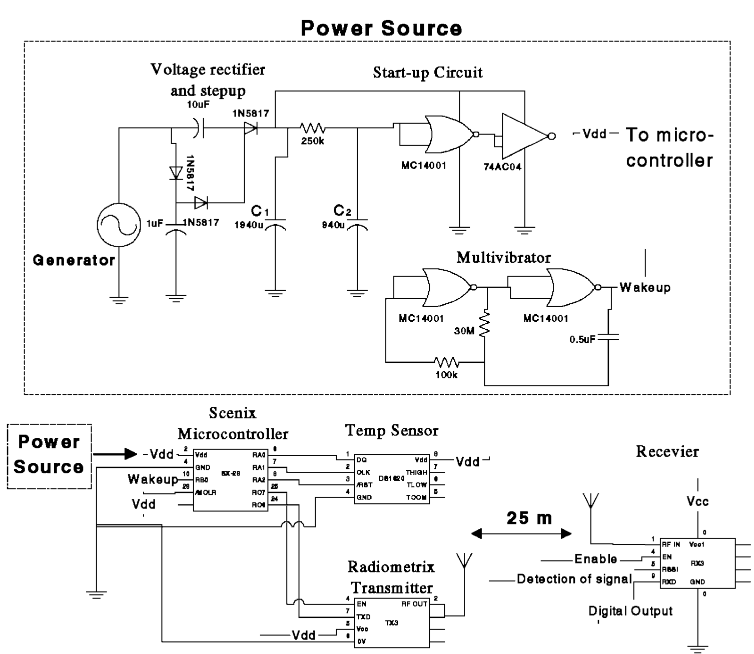


Fig. 8. Schematic diagram of the wireless temperature sensing system.

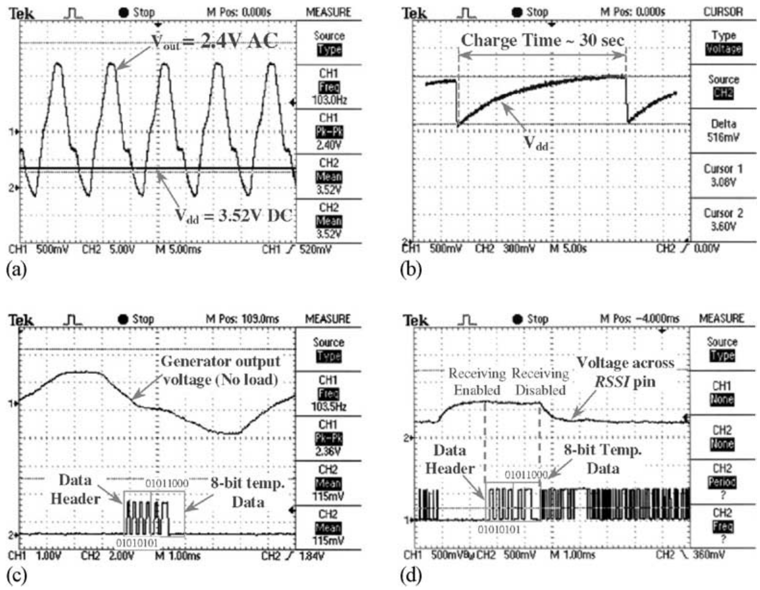


Fig. 9. Readings from CRO: (a) the output voltage of the generator; (b) V_{dd} vs. time (charge time is about 30 s); (c) data read at TXD pin of the transmitter represents the room temperature is 26 °C (01011000, counted from right to left); (d) data read at RXD pin of the receiver is also 26 °C.

be waken up by the wakeup signal from the multivibrator (Fig. 9b) and starts another conversion cycle.

The transmitted data is readily available in digital form from RXD pin of the receiver (Fig. 9d). The RSSI pin will indicate the receiving of new data when voltage goes high and the temperature data can be read after the indication of the RSSI pin.

5. Conclusion

We have demonstrated a magnet-based micropower generator that converts ambient vibration energy into electrical power using Faraday's law of induction. The generator is capable of powering a commercial IR remote control system and a custom built wireless temperature sensing circuit. We have found that, by innovative spring designs, the mass can be made to vibrate horizontally while the input vibration is applied vertically, and that this horizontal vibration gives significantly higher output voltage for the generator. Currently, for a generator with total volume of 1 cm^3 or less, ac peak-to-peak output of 2–4.4 V with maximum RMS output power of 200–830 μW is possible between input frequencies of 60–110 Hz with no more than 200 μm input vibration amplitude. Future work for this project include: (1) design and development of low frequency resonating springs with the aid of ANSYS modeling; (2) fabrication of the spring-mass and coil with an integrated process using optimized coil length; and (3) integration of the generator with low-power ICs and MEMS sensors. We believe that with the current trend in VLSI circuit design to minimize power consumption to extend battery life in portable systems, our microgenerator can be incorporated in many applications, especially in distributed sensing systems.

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References

[1] J.B. Bates, G.R. Gruzalski, C.F. Luck, Rechargeable solid state lithium microbatteries, in: Proceedings of the 6th IEEE Workshop on MEMS, February 1993, pp. 82–86.

[2] C.B. Wiiliams, R.B. Yates, Analysis of a microelectric generator for microsystems, Sens. Actuators A 52 (1996) 8–11.

[3] R. Amirtharajah, A.P. Chandrakasan, Self-powered signal processing using vibration-based power generator, IEEE J. Solid State Circuits 33 (1998) 687–695.

[4] W.J. Li, P.H.W. Leong, T.C.H. Hong, H.Y. Wong, G.M.H. Chan, Infrared signal transmission by a laser-micromachined vibration-induced power generator, in: Proceedings of the 43rd IEEE Midwest Symposium on Circuits and Systems, Michigan, USA, August 2000.

[5] W.J. Li, G.M.H. Chan, N.N.H. Ching, P.H.W. Leong, H.Y. Wong, Dynamical modeling and simulation of a laser-micromachined vibration-based micropower generator, Int. J. Non-linear Sci. Simul. 1 (2000) 345–353.

[6] F. Cardarelli, Materials Handbook: A Concise Desktop Reference, Springer, London, 2000.

Biographies

Neil N.H. Ching received his BS and MPhil degrees in mechanical engineering from the Department of Automation and Computer-Aided Engineering of the Chinese University of Hong Kong (CUHK) in 1999 and 2001, respectively. His main technical interests are in laser microfabrication and MEMS system-level integration. He is currently working as a research assistant at the Center for Micro and Nano Systems of CUHK.

Hiu-Yung Wong received his BEng and MPhil degrees in computer science and engineering from the Chinese University of Hong Kong in 1999 and 2001, respectively. He is currently working toward the PhD degree at the University of California at Berkeley. His research interests include novel Si-based devices and analog integrated circuits.

Wen J. Li received the BS and MS degrees in aerospace engineering from USC in 1987 and 1989, respectively. His industrial experience includes The Aerospace Corporation (1987–1995), Silicon Microstructures Inc. (summer 1994), and the Jet Propulsion Laboratory (1995–1997). He began his PhD studies at UCLA in 1992, and received his PhD degree in 1997 specializing in MEMS. Professor Li joined the faculty of the Department of Automation and Computer-Aided Engineering of the Chinese University of Hong Kong in September 1997. He has since then published more than 70 conference and journal papers related to MEMS research. He gave a workshop on Microsensors and Microactuators for Robotics Applications at the IEEE/RJS IROS 2000 (Takamatsu, Japan, November 2000) and has been invited to give a workshop on Microdevices for Micro and Nano Manipulation at the IEEE ICRA 2002 (Washington, DC, USA, May 2002). He has also helped organized several international conferences related to MEMS and robotics research and was the Chair of Organization Committee of the International Symposium on Smart Structures and Microsystems (IS3M) 2000 in October 2000; Dr. Li is currently serving as the Co-Chair of Organizing Committee for the International Conference on Micro and Nano Systems (ICMNS 2002). Dr. Li is also a Visiting Professor of Fuzhou University and a Visiting Scholar of Chongqing University, China. He is currently serving as the Director of the Center for Micro and Nano Systems at CUHK. His research interest is to develop microsystems for wireless communications, and micro/nano automation applications.

Philip H.W. Leong received the BSc, BE and PhD degrees from the University of Sydney in 1986, 1988 and 1993, respectively. In 1989, he was a research engineer at AWA Research Laboratory, Sydney, Australia. From 1990 to 1993, he was a post-graduate student and research assistant at the University of Sydney, where he worked on low-power analogue VLSI circuits for arrhythmia classification. In 1993, he was a consultant to SGS Thomson microelectronics in Milan, Italy. He was a lecturer at the Department of Electrical Engineering, University of Sydney from 1994 to 1996. He is currently an Associate Professor in the Department of Computer Science and Engineering at the Chinese University of Hong Kong and the Director of the Custom Computing Laboratory. He is the author of more than 20 technical papers and three patents. His research interests include analog integrated circuits, biologically inspired systems, reconfigurable computing, digital systems, cryptography and signal processing.

Zhiyu Wen received his BS degree from Sichuan University, Chengdu, China, in 1982. He is currently a Professor at Chongqing University, Chongqing, China, where he is also working towards a PhD degree in engineering specializing in MEMS. His current fields of interest are microsensors and microelectromechanical systems. He has published more than 80 technical papers and owns three patents in field of MEMS.