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Microscale ultrahigh-frequency resonant wireless powering for capacitive and resistive MEMS actuators

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ABSTRACT

This paper presents a versatile chip-level wireless driving method for microelectromechanical system (MEMS) actuators. A MEMS actuator is integrated as an electrical component of a coupled LCR resonant circuit, and it rectifies the energy sent through an ultrahigh-frequency (UHF) radio frequency (RF) wave. Two types of actuators were remotely driven using the proposed method: thermal (bimorph) actuators used as the R component and capacitive (comb-drive) actuators used as the C component of a resonant receiver circuit. We demonstrated the remote actuation of a 13 Ω thermal actuator transferring 7.05 mW power with a power efficiency of 15.8%. This was achieved using coupled 500 μm diameter 5.5-turn planar coil antennas over a distance of 90 μm. When an impedance-matching configuration ($Z_o = 50\,\Omega$) was used, the efficiency over a distance of 65 μm was measured to be 55.6%, which was 8.2 times greater than that of simple inductor coupling. The proposed method can be applied to future deployment scenarios, where fragile MEMS are placed on top of a system and must directly interface with the environment (thus, being prone to break). The authors propose to fabricate MEMS and energy receiver circuits monolithically on a chip, and place them on another energy transmitter chip. Thereby, the MEMS chip can avoid electrical feedthrough so that (a) the MEMS chip is easily replaceable if it breaks, and (b) the MEMS chip can move beyond wiring cable limitations. Four features are underlined in the article: (1) MEMS itself can rectify the RF energy owing to the fact that the governing equation of the MEMS actuator involves the square of the voltage and/or current, thereby, ensuring higher system-level efficiency than any other RF transceiver circuits using additional rectifying components (e.g., diodes). (2) Both the transmitter and receiver use coils of the same design, whose sizes are equivalent to those of the MEMS actuators (hundreds of micrometers). Moreover, they can be operated at UHF, owing to the much higher self-resonant frequency (f_s > GHz) when compared to conventional transmitters ($f_s \approx$ MHz). In addition, by using LCR resonant circuits, it is possible to not only (3) increase the transmission efficiency but also (4) multiply the driving voltage of the capacitive MEMS actuator, because of LC resonance. Voltage multiplication is quite useful for electrostatic MEMS operations because the movement is proportional to the square of the voltage across the MEMS capacitance. Comprehensive designs, implementations, and demonstrations of wireless operation are presented in this paper, for both thermal (resistive) and electrostatic (capacitive) actuators. Remote operation includes on–off-keying for MEMS without mechanical resonance and amplitude modulation of sinusoidal signals to stimulate the mechanical resonant frequency of MEMS.

1. Introduction – methods of wireless MEMS powering

Microactuators that interact with the surrounding environment have always been hot research topics since the 1980s. In 1990, Fujita proposed the concept of an arrayed microactuator that could interact with the environment cooperatively [1]. Microac-

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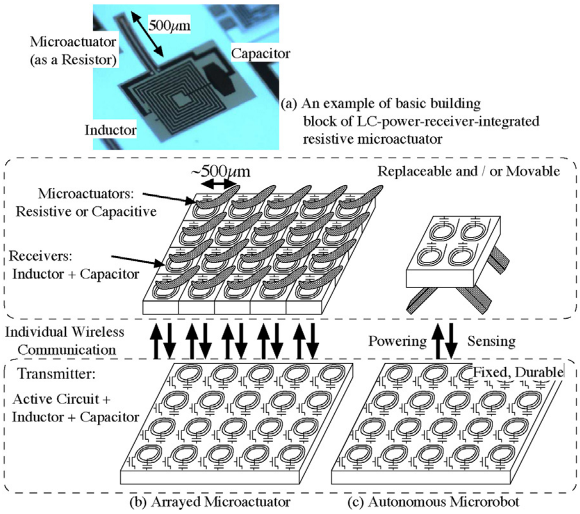

Fig. 1. Conceptual view of the proposed replaceable MEMS actuator.

tuators based on this concept were demonstrated by Ataka et al. in 1993 for use in cooperative microconveyance applications as ciliary motion microactuator arrays [2], which were arrays of thermal bimorph actuators. Then, several variants with different actuation principles were proposed. Konishi et al. in 1994 proposed a surface micromachined electrostatic air-flow actuator array [3], which was further improved using a deep-reactive ion etching (RIE) electrostatic valve [4], by Fukuta et al. in 2006. Another variant was the top-down inverted scratch drive electrostatic actuator [5] developed by Mita et al. in 1999. Micro (sub-centimeter-sized) self-movable machines have also attracted many MEMS researchers. Ebefors et al. demonstrated a walking inchworm MEMS robot in 1999 [6], which was based on a thermal bimorph actuator. Then, Hollar et al. demonstrated electrostatically driven long-range legs [7] for a walking robot in 2004, and Saito et al. demonstrated a sub-centimeter six-legs walking robot in 2013 [8]. Miki et al. demonstrated an alternating-magnetic-field-driven sub-centimeter MEMS helicopter in 1999 [9]. Uno et al., demonstrated in 2017 a wireless powering of ultrasonic-levitated 3.5 mm-ϕ hemispherical tiny object that they call “Luciola” [10]; an integrated LED was turned on and off by power conditioning LSI circuit. A couple of independent research groups presented pond-skating microrobots with electrowetting on dielectrics (EWOD). One of these was based on the swaying principle [11] by Chung et al., and the other was based on the bubble-jet principle by Mita et al. [12].

Fragileness and electrical energy feeding are the two common issues faced by microactuators that directly interact with the environment. Most of the above-mentioned actuators [2–8,11] were connected to power supplies through electrical wiring (also called as tethers). Wirings not only impeded the movement of autonomous robots but also inhibited the replacement of these MEMS actuators in case of breakage and/or malfunction. To solve these issues, in this article, the authors propose a micro wireless-powering scheme [13] as shown in Fig. 1. In the proposed scheme, each MEMS actuator is integrated with passive electrical components to form an LCR series resonant circuit (Fig. 1(a)). Another circuit with an LCR resonator is placed underneath, as a transmitter. The inductors of the transmitter and receiver are coupled through magnetic fields, and thus, power is transferred. The idea is to separate the system into a fragile (and/or moving) MEMS part and a fixed electrical powering (and/or sensing through powering) circuit part, and make the MEMS part replaceable (Fig. 1(b)) and/or self-movable (Fig. 1(c)). If the MEMS is broken, the engineer has to physically replace the broken part only, without being bothered by the electrical wiring.

The third important feature of the proposed scheme is the size of the inductor and the operating frequency. The typical size of an LC tank circuit for both the transmitter and receiver proposed in this article is 500 μm × 500 μm, which is in the same order as that of the already-mentioned typical MEMS actuators. In fact, a smaller inductor can obtain a self-resonant frequency f_s[1] that can reach GHz values. In contrast, as summarized and compared in Table 1, most of previous MEMS researchers used relatively “big (centimeter-sized)” inductors in the transmitters and “medium (millimeter-sized)-to-big” ones in the receivers. These devices were driven by relatively low frequencies (in the 10 MHz range[2]) RF wave. In 2001, Takeuchi et al., demonstrated the teleoperation of two electrostatic microactuators [14,15] with a 8.5 mm × 7.2 mm 20-turn planar receiver coil of 4.8 μH operated at 4.1 and 4.8 MHz. Mita’s EWOD microactuator [12] was driven with surface mount devices (SMDs) integrated on a 5 mm × 8 mm MEMS chip at 6.8 MHz. In 2015, Byun et al. demonstrated an EWOD driven by a planar printed circuit board (PCB) coil of 2.3 mm at 1.75 MHz [16]. Basset et al. developed a complete energy rectifier and control application-specific integrated circuit (ASIC) [17] and demonstrated 23 mW remote powering at 13.56 MHz with a 20 mm × 20 mm receiver coil of 1.6 μH. Sekitani et al. demonstrated 1.6–40 W power transfer using 25 mm × 25 mm planar transmitter and receiver coils at 13.56 MHz [18]. Takamiya developed a position-insensitive powering system by using a double-sized (50 mm × 50 mm) receiver on 3 × 3 tiled matrices (yielding 75 mm × 75 mm) of transmitter coils [19]. Laskovski and Yuce proposed a discrete transistor class-E oscillation circuit for wireless power to implants [21]. In the circuit, a 100 × 100 mm 8-turn planar inductor was integrated for the purpose of both oscillating feedback circuit and energy transfer. The circuit oscillated at 27 MHz, and RF power was transferred through 2 cm-thick lean beef to four-stacked 15 × 15 mm 7-turn coil having 30 MHz self resonant frequency [22], with 0.05% (−33 dB) of power efficiency. Another category is so-to-call “medium-sized coils” from Takahata’s group. Their coil size is sub-centimeter and working frequency is from 81.5 to 270 MHz. For example, Mohamed and Takahata integrated [23] shape-memory-alloy (SMA) microgripper with a 4 × 5 mm 9-turn coil made on polyimide film with resonant frequency of 140 MHz (with L = 184 nH and C = 7 pF). By sending 0.2 W RF wave varying from 128 MHz to 150 MHz through 4 mm-diameter coil, temperature of the LC circuit increased due to residual resistance in the coil, and introduced phase change of the SMA.

Fig. 2 shows a thought comparison of RF powering to a “small” (MEMS-sized) 500 μm-diameter receiver (Rx) coil. Case (a) is an extension of the traditional method, in which the size of the transmitter (Tx) coil is in centimeters, and case (b) is the proposed method, in which the size of the Tx coil is the same as that of the Rx coil. Six steps of consideration (I)–(VI) can conclude that case (b) can produce a higher induction in the Rx coil.

(I) **Tx self inductance L_1**: In case (a), the Tx coil can be wound many times to obtain a higher Ampere-turn (nI), whereas the number of turns is limited in case (b) owing to the planar nature and geometrical limitations. The typical values are 100 μH for (a) and 10 nH for (b).

(II) **Total flux Φ_1 induced by L_1**: A magnetic field B is generated by applying a current I to the Tx coil. The total flux is $\Phi_1 = L_1 I$, by

[1] The inductor is no more operational as L at frequencies above f_s, because of the parasitic parallel capacitance C_p.

[2] Frequency of 3–30 MHz, named “HF” (high frequency) band by the International Telecommunication Union Recommendation (ITU-R V.431-7).