Luciola: A Millimeter-Scale Light-Emitting Particle Moving in Mid-Air Based On Acoustic Levitation and Wireless Powering

YUKI UNO, The University of Tokyo
HAO QIU, The University of Tokyo
TORU SAI, The University of Tokyo
SHUNTA IGUCHI, The University of Tokyo
YOTA MIZUTANI, The University of Tokyo
TAKAYUKI HOSHI, The University of Tokyo
YOSHIHIRO KAWAHARA, The University of Tokyo
YASUAKI KAKEHI, Keio University
MAKOTO TAKAMIYA, The University of Tokyo

In this paper, we present an approach to realize the levitation of a small object with an embedded electronic circuit. Luciola is a light-emitting particle with a diameter of 3.5mm and a weight of 16.2mg moving in mid-air in a 10.4cm × 10.4cm × 5.4cm space through acoustic levitation using two 40-kHz 17 × 17 ultrasonic transducer arrays placed face-to-face at a distance of 20cm and wirelessly powered by 12.3-MHz resonant inductive coupling. The novelty of this paper is the acoustically levitated electronic object by the combined application of ultrasonic levitation and wireless powering to the levitated electronic object. A new shape of the levitated object and a new placement of the receiver coil to simultaneously realize acoustic levitation and wireless powering are proposed, achieving a stable wireless powering to a rotating levitated object at the bottom of an acoustic potential. To enable the levitation of a particle, a custom IC chip is essential in reducing the size and weight of the particle. In the design of the custom IC chip, a new voltage detector circuit enabling an accurate voltage detection and a correct output during the start-up is proposed to achieve an intermittent lighting of the LED to increase the maximum distance between the transmitter and the receiver coil. Luciola is applied to a self-luminous pixel in a mid-air display and drawings of characters in mid-air are demonstrated.

CCS Concepts: • **Human centered computing → Human computer interaction (HCI)**

General Terms: Design, Hardware

Additional Key Words and Phrases: Millimeter-scale; levitation; ultrasound; wireless powering; IC chip

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1 INTRODUCTION

In this paper, we propose a smart millimeter-scale particle levitated in the mid-air, which has internal electronics. In the particle scale, it has been hard to install active levitation mechanisms on the object due to their size, weight, and power consumption. Thus, external fields such as electric, magnetic, air-flow have been adopted to generate levitation force and control particles in mid-air. Among others, acoustic levitation is one of the most promising ways to keep the objects suspended in the air. By using ultrasonic phased array speakers, the system enables two-dimensional or three-dimensional position control of levitated particles. This approach has an advantage with quick and precise movement control of particles. On the other hand, the particles have a strong constraint on their weight, size, and shapes to maintain its balance in mid-air. Thus, previous systems tended to use non-electric materials, which don't have any further functions themselves, just for position controls.

Our ultimate goal is making a swarm of smart levitated particles. Each tiny particle has abilities to change their appearances by sensing the surroundings and talk to each other. As a first step toward this concept, we propose Luciola, a levitating-particle consisting of the LED, the receiver coil for wireless powering, and a custom IC chip for the rectifier, the voltage regulator, and the intermittent lighting of the LED implemented in 180-nm CMOS process. The 3D position, as well as the ON/OFF timing of the LED, can be computationally controlled, making it possible to control the lighting of the LED depending on the position and the context.

This paper includes the following contributions:

(1) An acoustically levitated electronic object is realized for the first time.

(2) A new shape of the levitated object and a new placement of the receiver coil are proposed to simultaneously realize the acoustic levitation and the wireless powering.

(3) In the custom IC chip, a new voltage detector circuit enabling an accurate voltage detection and a correct output during the start-up is proposed to achieve the intermittent lighting of the LED to increase the maximum distance between the transmitter and the receiver coil.

From the following sections, we will show the detail of our concept, design, implementation, technical evaluations and potential application scenarios.

2 RELATED WORKS

The novelty of this paper is the acoustically levitated electronic object, combining an ultrasonic levitation and a wireless powering to the levitated object. Though each technology of the acoustic levitation and the wireless powering is not new, the simultaneous realization of the acoustic levitation and the wireless powering presents a new challenge. To realize it, a new shape of the levitated object and a new placement of the receiver coil are proposed, which will be described in section 4.3. In this section, related past works of the levitated small objects and the wireless powering to small objects are reviewed.

2.1 Levitated Small Objects

To overcome the constraints of gravity and move the smart objects freely in the air, many attempts have been made by researchers. In this section, we introduce past research works that tries to lift the object and suspend in the air. In this paper, drones (multicopters) are not discussed, because self-powered millimeter-scale drones are not available. Conventional approaches to lifting up objects and keep it suspended in the air use invisible external forces in the field. Typical examples of such invisible fields include magnetic, electric, air-flow, and acoustic field. ZeroN [1] is one of the earliest attempt to allow users to take physical components of tabletop tangible interfaces off the surface and place them in the air. An electromagnetic suspension system is used to keep a spherical dipole magnet suspended. Thus the levitating object needs to be made of magnetic material. A floating tangible user interface named floatio [2] takes advantage of the Coandă effect. A polystyrene light ball of 3.5cm diameter is suspended by the airflow generated by a blower fan. The restriction of this approach is that the floating object must be a smooth sphere and lightweight. Fairly lights [3] is a system that draws aerial images in mid-air using a laser-induced plasma. The size of the volumetric image is at millimeter-scale. People can touch and feel the energy of the plasma, but it is impossible to embed computational functionality in the voxel.

In this paper, an ultrasonic field is used to levitate a millimeter-scale particle, because the spatial resolution of the ultrasonic levitation is high (e.g. 0.5mm [4]). Since 1970's, the ultrasonic levitation system using a single transducer and a reflector plate to make a standing wave has been developed for a containerless crystal growth in space experiments [5].

After that, using one or two ultrasonic transducers, a manipulation of two droplets in air [6], the levitation of small living animals in air [7], and a non-contact manipulation in air [8] are demonstrated. The past innovation was a two-dimensional ultrasonic transducer array [9] to generate a focal point by a beamforming. The two-dimensional ultrasonic transducer array is originally developed for a haptic interface [9], and a commercial product is available [10]. The two-dimensional ultrasonic transducer array is applied to the three-dimensional non-contact levitation of small particles [11]. In Lapillus bug [12] a transducer array is used to suspend a physical particle in mid-air as a means to provide a new interaction of objects in the physical 3D environment. In Pixie Dust [4], two sets of two transducer arrays facing each other can produce a 2D grid of focal points and hold multiple particles at 4.2-mm intervals. Using Pixie Dust, a mid-air screen with projection is demonstrated. Thanks to an intelligent phase control algorithm called a holographic method [13], the efficiency and the controllability of the ultrasonic levitation are greatly improved. Based on the holographic method, three-dimensional mid-air displays using levitated particles are demonstrated as Levipath [14], Floating Charts [15], and JOLED [16]. Problem of all the past works in the ultrasonic levitation is that the levitated particle is non-electric and has no electronic functions. In this paper, an electronic particle is introduced into the ultrasonic levitation to realize a self-luminous pixel in the three-dimensional mid-air display.

2.2 Wireless Powering to Small Objects

Target applications of the past works regarding the wireless powering to small objects are mainly implanted medical devices or RFIDs, and the wireless powering to levitated objects is not reported. In [17] for the implanted glucose monitoring, the total system including the receiver coil for the wireless powering is integrated on a 1.4mm × 1.4mm IC chip and the power is wirelessly supplied at 900MHz from a transmitter coil with the distance of 1cm. The received power is 6μW, which is too low to light the LED requiring 3.5mW in Luciola. Similarly, in [18] for the RFIDs, the total system including the receiver coil for the wireless powering is integrated on a 3.7mm × 1.2mm IC chip and the power is wirelessly supplied at 24GHz from a transmitter coil with the distance of 50cm. The received power is 1.5μW, which is too low to light the LED. Thus, the conventional wireless powering does not fit the ultrasonic levitation in terms of the size, the distance, and the received power.

3 OVERVIEW OF LUCIOLA SYSTEM

Fig. 1 shows a photograph of Luciola on a fingertip. Fig. 2 shows a photograph of Luciola levitated by the ultrasonic array and emitting light by wireless powering. Fig. 3 shows an overview of the Luciola system. Two 40-kHz 17 × 17 ultrasonic transducer arrays are placed face-to-face at a distance of 20cm and the ultrasound generated from each transducer is focused to a focal point by tuning the phase of each transducer [9]. The focal point is the location where the acoustic levitation force is generated. Luciola floats in mid-air as a result of being trapped at the focal point. By moving the focal point in 3D space using a computer, Luciola moves in mid-air in a 10.4cm × 10.4cm × 5.4cm space. The transmitter coil with a diameter of 31mm for wireless powering is placed near the focal point and transmits the power to the receiver coil in Luciola. The transmitter for the wireless powering includes a switch to control the ON/OFF timing of the LED in Luciola. By synchronously controlling the focal point of the ultrasound and the ON/OFF timing of the switch of the wireless powering using the PC, Luciola displays 3D images in mid-air.

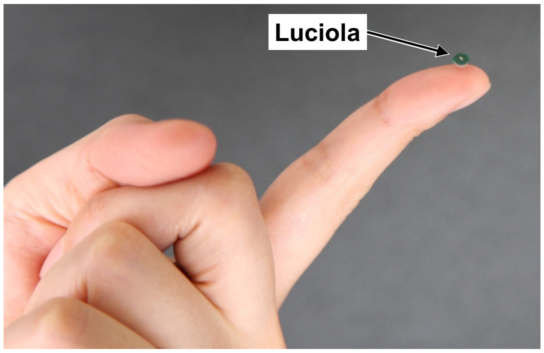


Fig. 1. Luciola particle on fingertip.

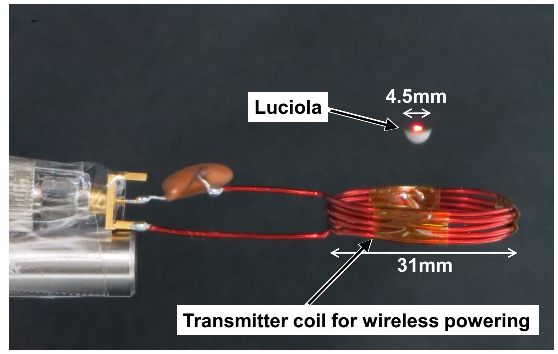


Fig. 2. Luciola levitated by ultrasonic array and emitting light by wireless powering.

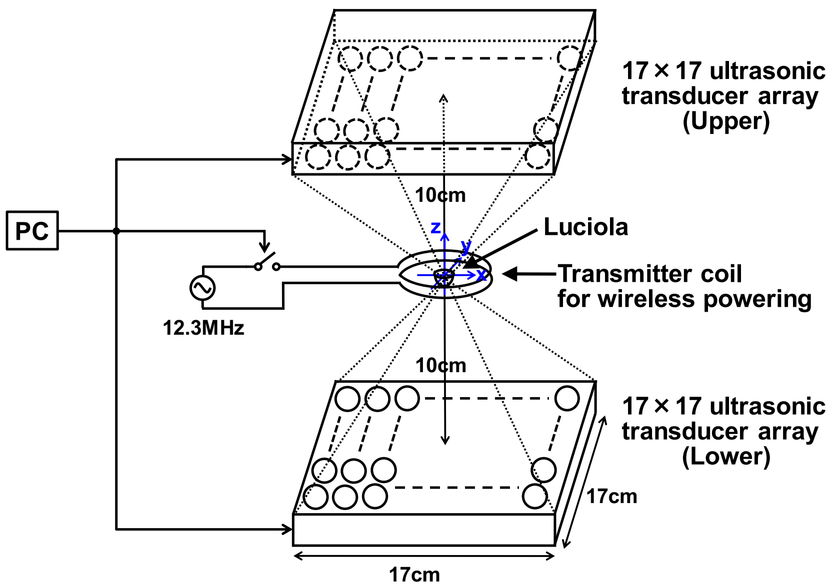
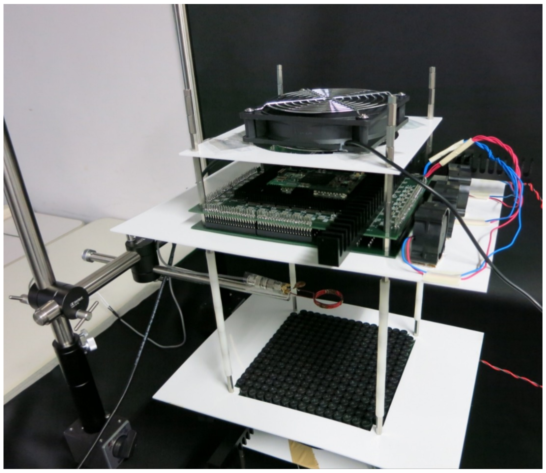
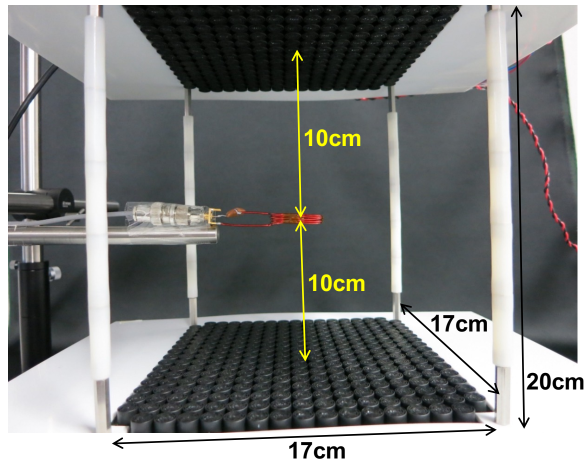


Fig. 3. Overview of Luciola system.

In this paper, two different setups for the Luciola system are used. In the first setup shown in Fig. 4, two 17 × 17 ultrasonic transducer arrays are placed face-to-face [4]. In the second setup shown in Fig. 5, a 17 × 17 ultrasonic transducer array and a reflector plate are placed face-to-face [6, 19]. The transmitter coil is placed below the reflector plate. In the first setup, movement in the x, y, and z directions is possible. In contrast, in the second setup, movement in the x and y directions is possible, and the levitation height is fixed. The first setup is used for 3D movement in mid-air, while the second setup is used for drawing above a piece of paper on the reflector.



(a)



(b)

Fig. 4. (a) Overall view and (b) enlarged view of two 17 × 17 ultrasonic transducer arrays placed face-to-face in Luciola system.

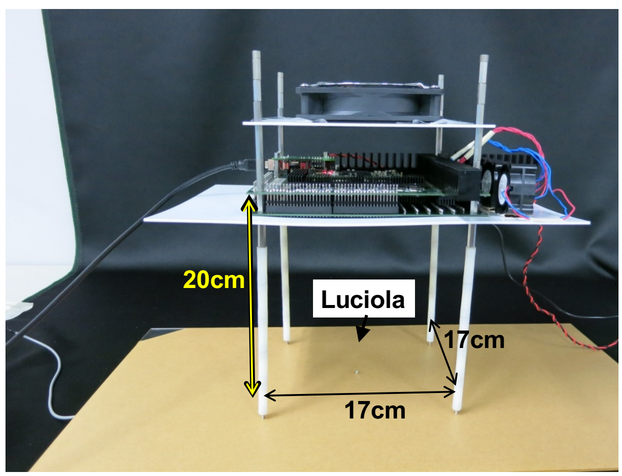


Fig. 5. Overall view of 17 × 17 ultrasonic transducer array and reflector plate placed face-to-face in Luciola system.

4 IMPLEMENTATION

Fig. 6 shows a block diagram of the Luciola system. In this section, detailed implementations of the Luciola system are explained.

4.1 Ultrasonic Transducer Arrays For Levitation and Movement in Mid-Air

The 40-kHz 17 × 17 ultrasonic transducer arrays shown in Fig. 4 and 5 are the same as those in [4]. In each ultrasonic transducer array, 285 ultrasonic transducers (Nippon Ceramic Co., Ltd., T4010B4) with a diameter of 1cm and the sound pressure above 117dB, and 72 drivers (STMicroelectronics, L293DD) with an output voltage of $24V_{\text{peak-to-peak}}$ are used. The measured power consumption of the ultrasonic transducer array is 134W.

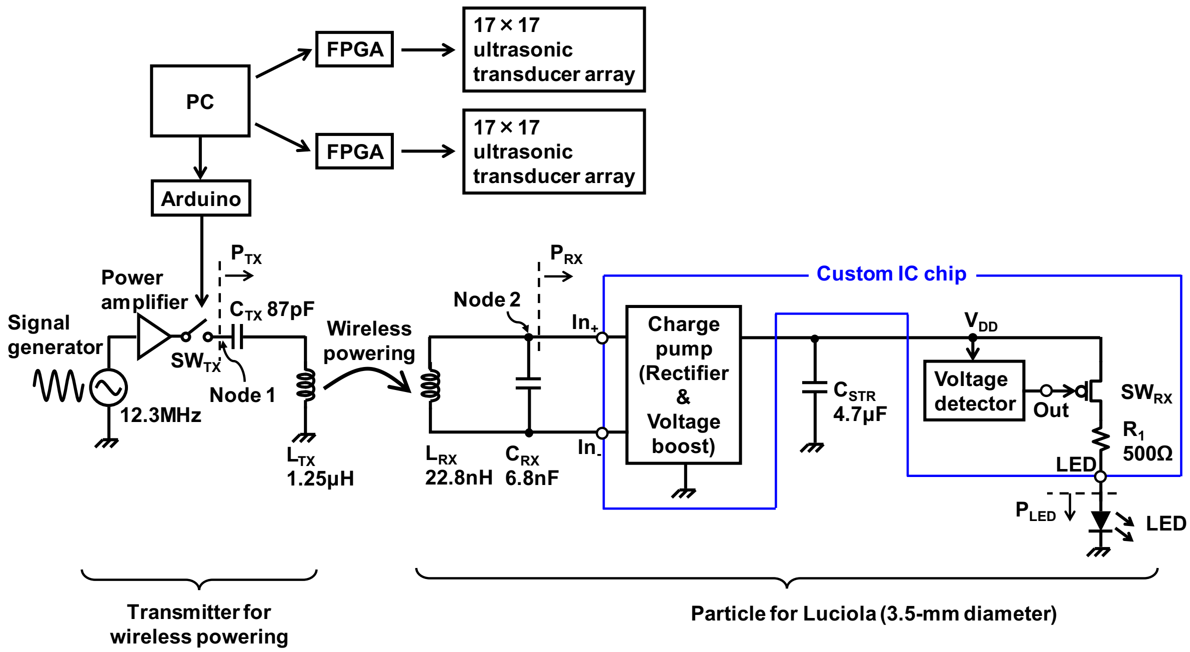


Fig. 6. Block diagram of Luciola system.

4.2 Transmitter For Wireless Powering

Fig. 6 includes a circuit schematic of the transmitter used for wireless powering. A 12.3-MHz sine wave voltage from a signal generator (Agilent Technologies, DSO5054A) is amplified by a power amplifier (NF Corporation, HSA4101). The output power (P_{TX}) of the power amplifier is 3.2W. L_{TX} and C_{TX} are the LC resonator used for resonant inductive coupling. The transmitter coil is made of a copper wire with a diameter of 1mm and has five turns with a diameter of 31mm. The height of the transmitter coil is 5.5mm. The measured inductance of L_{TX} is 1.25μH, and the quality factor of L_{TX} at 12.3MHz is 161. The quality factor of the whole transmitter including the power amplifier is 46. In wireless powering using a resonant inductive coupling, a high quality factor is very important to increase the power transmission efficiency. A resonant capacitor (C_{TX}) of 87pF is selected to achieve the LC resonance at 12.3MHz. For C_{TX}, a capacitor with a rated voltage of 3kV is used, because a very high voltage is generated in the LC resonance.

To control the ON/OFF switching of the LED in Luciola, a switch (SW_{TX}) is inserted between the power amplifier and the LC resonator. A relay (Panasonic Electric Works, TQ2-L2-4.5V) with an ON resistance of less than 50mΩ is used for SW_{TX}. SW_{TX} and the ultrasonic array are synchronously controlled by a PC through Arduino Uno.

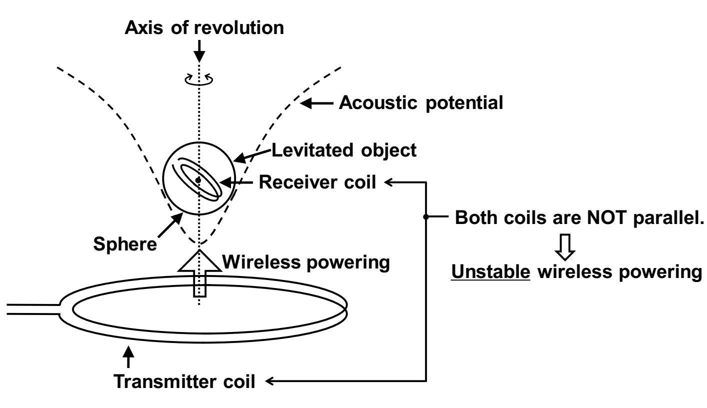
4.3 Proposed Shape of Levitated Object and Placement of Receiver Coil to Simultaneously Realize Acoustic Levitation and Wireless Powering

The novelty of this paper is the acoustically levitated electronic object. To realize an electronic object, a power supply is required. In this work, a battery-free power supply using wireless powering is used, because batteries are too heavy to induce acoustic levitation. When the ultrasonic levitation and the wireless powering are combined, we encountered a new problem. As shown in Fig. 7 (a), in ultrasonic levitation, the levitated object rotates [20] similarly to a spinning top at the bottom of the acoustic potential [4] generated by the transducer array. In previously published ultrasonic levitations [4, 8, 11-16], spherical objects are levitated. As shown in Fig. 7 (a), however, when the receiver coil for wireless powering is embedded in a spherical object, wireless powering is unstable, because the receiver coil randomly rotates above the transmitter coil and the power transmission efficiency randomly fluctuates. To achieve a stable wireless powering, the receiver coil in the levitated object should be parallel to the transmitter coil. To solve the problem, a new shape of the levitated object and a new placement of the receiver coil to simultaneously realize acoustic levitation and stable wireless powering are proposed. As shown in Fig. 7 (b), the proposed shape is a solid of revolution excluding a sphere. The solid of revolution is a solid figure obtained by rotating a plane figure around a straight line (= the axis of revolution) that lies on the same plane. In the proposed shape, the sphere is omitted, because the sphere has infinite axes of revolution and the axis of revolution is not fixed at the bottom of the acoustic potential, as shown in Fig. 7 (a). As shown in Fig. 7 (b), the receiver coil is proposed to be placed on a plane perpendicular to the axis of revolution. By using the proposed shape and placement, the axis of revolution of the acoustically levitated object is fixed to the z-axis direction and the receiver coil rotates on the x-y plane. As a result, a stable wireless powering is achieved, because the receiver coil is always kept parallel to the transmitter coil. Is this paper, a hemisphere is selected as the shape of the levitated object. The other solids of revolution, however, including a circular cone and a cylinder shown in Fig. 7 (c) can be used.

4.4 Particle Used in Luciola

Fig. 6 includes a circuit schematic of the particle for Luciola. The particle includes a receiver coil (L_{RX}), a resonant capacitor (C_{RX}), a storage capacitor (C_{STR}), a LED, and a custom IC chip. L_{RX} and C_{RX} are the LC resonator used for resonant inductive coupling. L_{RX} and C_{RX} are connected in parallel to increase the voltage at node 2. The functions of the particle are (1) to receive the 12.3-MHz wireless power using the receiver coil (L_{RX}), (2) to rectify the AC voltage into the DC voltage using the charge pump circuits, (3) voltage boosting using the charge pump circuits, (4) storage of the charge in C_{STR}, (4) voltage regulation of V_{DD} using the voltage detector and SW_{RX}, and (5) the intermittent lighting of the LED (described in section 4.5) using the voltage detector and SW_{RX}. To achieve the functions, the custom IC chip includes charge pump circuits to rectify the AC voltage into DC voltage and to boost the DC voltage, a voltage detector to regulate the DC voltage (V_{DD}) for the LED, a switch (SW_{RX}) for the charge storage in C_{STR}, and a resistor (R_1) to limit the current for the LED to avoid its breakdown. In the Luciola, the rectifier circuit to convert AC voltage of the wireless powering to DC voltage is very important, because the power required to drive the LED with the 12.3-MHz AC voltage is 54 times larger than that with the DC voltage according to our preliminary experiment. An AC-drive LED consumes larger power than a DC-drive LED, because the LED impedance decreases with increasing frequency due the parasitic capacitance of the LED and the voltage applied to the LED is reduced.

It is difficult to design the particle for Luciola, because the requirements for the acoustic levitation and the wireless powering are opposite. The acoustic levitation requires a small and lightweight particle, while the wireless powering requires a large receiver coil and heavy electronic circuits. To enable the levitation of the particle, the custom IC chip is essential in reducing the size and weight of the particle. The size of the particle is preferably less than 4.2mm (= half the wavelength of the 40-kHz ultrasound). To investigate the trade-off between the acoustic levitation and wireless powering, two types of the particles, 3.5- and 4.5-mm-diameter hemispherical particles, are fabricated.



(a) Conventional

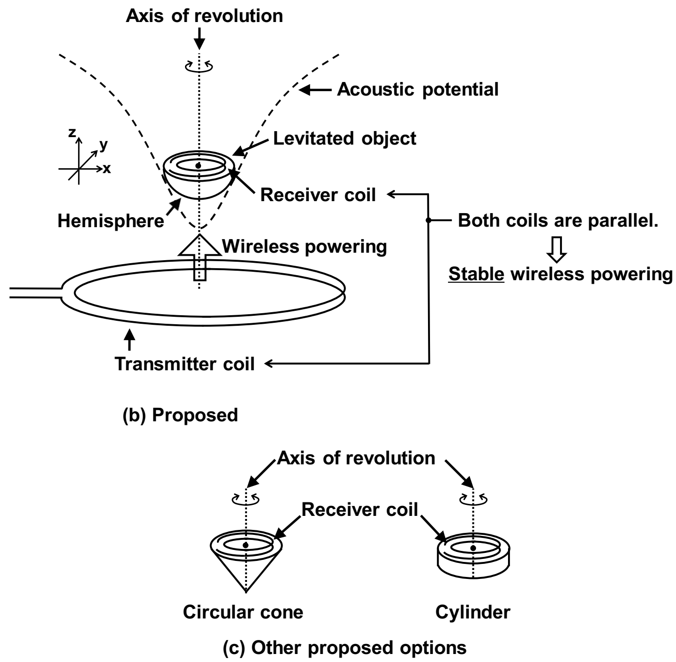


Fig. 7. (a) Conventional spherical object in ultrasonic levitation. (b) Proposed shape of levitated object and placement of receiver coil to simultaneously realize acoustic levitation and wireless powering. (c) Other proposed options.

Fig. 8 shows a teardown photograph of the particle used in Luciola. The diameter of the flexible PCB is 3.5mm. The LED is mounted on the front of the flexible PCB. On the back of the flexible PCB, the custom IC chip, C_{RX}, and C_{STR} are mounted. L_{RX} of 22.8nH is implemented with a 2.5-turn spiral inductor on the flexible PCB with 50-μm copper thickness. The four components (the LED, the custom IC chip, C_{RX}, and C_{STR}) are carefully arranged so that the center of gravity of the circular flexible PCB is on the axis of revolution to achieve a stable wireless powering to a rotating levitated object as discussed in section 4.3 The quality factor of L_{RX} at 12.3MHz is 16. C_{RX} of 6.8nF is selected to achieve LC resonance at 12.3MHz.

To minimize the size and weight of the particle, minimum-size off-the-shelf components are used. Specifically, a multilayer ceramic capacitor (Murata Manufacturing, GRM033R71A682KA01D) with a size of 0.6mm × 0.3mm × 0.3mm is used for C_{RX} of 6.8nF, a multilayer ceramic capacitor (Murata Manufacturing, GRM035R60J475ME15D) with a size of 0.6mm × 0.3mm × 0.5mm is used for C_{STR} of 4.7μF, and an SMD chip LED (Kingbright, KPG-0603SEC-E-TT) with a size of 0.65mm × 0.35mm × 0.2mm is used. The chip size of the custom IC chip is 1mm × 1mm and its thickness is reduced from the initial value of 0.70mm to 0.15mm to minimize the size and weight of the particle. A hemispherical case with a diameter 3.5mm fabricated with a 3D printer (Stratasys, Objet260 Connex3) using MED610 photopolymer is attached to the flexible PCB. Fig. 9 shows the layout and micrograph of the custom IC chip. The chip is fabricated using a 180nm CMOS process and the chip size is 1mm × 1mm. Instead of 1.8V core transistors, 3.3V I/O transistors are used in this design.

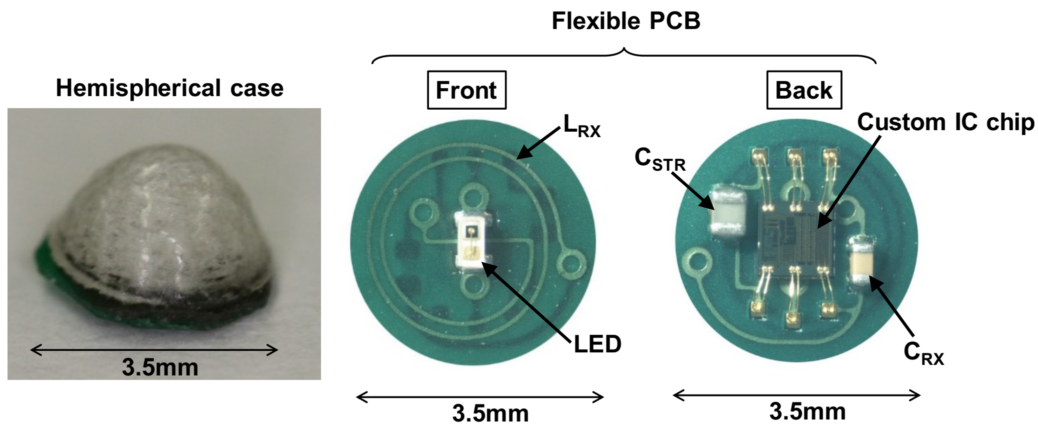


Fig. 8. Teardown photograph of particle used in Luciola.

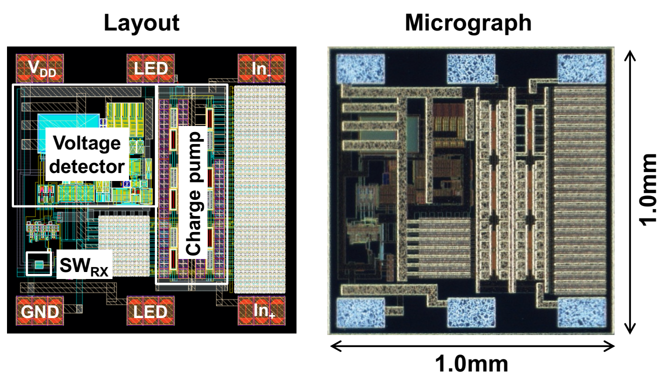


Fig. 9. Layout and micrograph of custom IC chip.

Fig. 10 shows a breakdown of the measured weight of each component in the 3.5-mm-diameter hemispherical particle. The hemispherical case, a potting, the flexible PCB, and solder account for 31%, 25%, 21%, and 12% of the total weight of 16.2mg, respectively. The potting is a gelatinous compound covering the custom IC and the bonding wires to provide resistance to shock and vibration. Owing to the reduced-weight design, the electronic components (C_{STR}, Custom IC, C_{RX}, and LED) account for only 10% of the total weight.

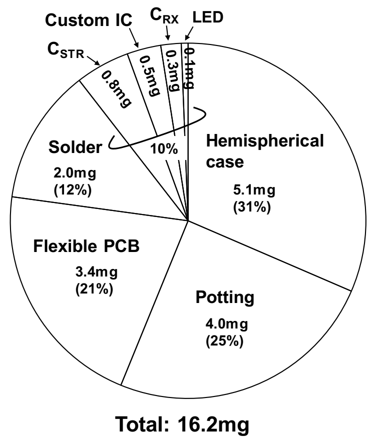


Fig. 10. Breakdown of measured weight of each component in 3.5-mm-diameter hemispherical particle.

4.5 Proposed Voltage Detector With Accurate Voltage Detection and Correct Output During Start-Up For Intermittent Lighting of LED

4.5.1 Intermittent Lighting of LED. To light the LED in Luciola, a power of more than 3.6mW is required. To continuously light the LED, a power of more than 3.6mW must be delivered to the LED in the wireless powering. In this case, however, the maximum distance between the transmitter coil and the receiver coil is limited. In this paper, a charge storage circuit to enable intermittent lighting of the LED is used to increase the maximum distance. Initially, in Fig. 6, C_{STR} is disconnected from LED using SW_{RX} and is charged by the charge pump. When V_{DD} is increased to a predefined voltage, SW_{RX} is turned on to connect C_{STR} and the LED, and the LED is turned on. Using the charge storage circuit, the LED intermittently lights even if the wireless power is less than 3.6mW. For example, if the power delivered to C_{STR} is 0.36mW, the charge storage circuit enables the intermittent lighting of the LED with a duty cycle of 10% (10% ON time and 90% OFF time), thereby increasing the maximum distance between the transmitter and the receiver coil.

4.5.2 Proposed Voltage Detector with Accurate Voltage Detection and Correct Output during Start-up In the circuit design of the custom IC chip in the particle, a new voltage detector circuit with an accurate voltage detection and a correct output during the start-up is proposed to achieve the intermittent lighting of the LED. The voltage detector in Luciola has two requirements: (1) an accurate voltage detection and (2) a correct output during the start-up. In Luciola, V_{DD} should be regulated between 3.3V (= voltage rating of transistors) and 2.1V, and the voltage variations of 3.3V and 2.1V due to process-voltage-temperature (PVT) variations are not allowed, because an operation above 3.3V V_{DD} will damage the transistors and an operation below 2.1V V_{DD} will not light the LED. At the start-up, V_{DD} increases from 0V, because Luciola is a wirelessly powered battery-free system. During the start-up, Out in Fig. 6 should be always high to keep SW_{RX} turned off. If Out incorrectly goes to low during the start-up, SW_{RX} is turned on and the charge stored on C_{STR} is accidentally discharged, which results in the malfunction of the intermittent lighting of the LED. When a conventional low-power bandgap reference circuit [21] to generate a constant reference voltage (= 1.23V) insensitive to PVT variations was used in the voltage detector, we encountered a new problem and proposed a new voltage detector to solve this problem. As shown in Fig. 11 (a), the output voltage (V_{REF1}) of the bandgap reference during the start-up is in the metastable state and is incorrect, resulting in the malfunction of the intermittent lighting. The metastable state originates from feedback circuits included in the bandgap reference. To achieve the correct output during the start-up, a 2-transistor voltage reference [22] is used. As shown in Fig. 11 (b), the output voltage (V_{REF2}) of the 2-transistor voltage reference during the start-up is correct, resulting in the normal operation of the intermittent lighting. The problem of the 2-transistor voltage reference, however, is that V_{REF2} is sensitive to process variations. For example, when the threshold voltage of the transistors has ±0.05V variations, V_{REF2} will have ±0.1V variations [22].

To solve the problems, a new voltage detector circuit with an accurate voltage detection and a correct output during the start-up is proposed. Figs. 12 and 13 show the circuit schematic and timing chart of the proposed voltage detector, respectively. In the proposed voltage detector, the 2-transistor voltage reference [22] and bandgap reference [21] are combined. During the initial wake-up, the 2-transistor voltage reference is used to obtain a correct output. After the wake-up, the bandgap reference is used to realize an accurate voltage detection. The mode transition from the 2-transistor voltage reference to the bandgap reference is managed by logic circuits shown in Fig. 12. The details of the operation of the proposed voltage detector are explained. During the start-up mode in Fig. 13, the 2-transistor voltage reference instead of the bandgap reference is used for the correct output. The incorrect outputs (Detect_2.1V and Detect_3.3V) of the bandgap reference during the start-up mode are ignored to prevent the incorrect turn-on of SW_{RX}. When the increasing V_{DD} crosses 1.6V, Detect_1.6V of the 2-transistor voltage reference changes from low to high, which reset the logic circuits. After that, when the increasing V_{DD} crosses 3.6V, Detect_3.6V of the 2-transistor voltage reference changes from high to low and the LED is turned on, which means the end of the start-up mode and a normal operation mode using the bandgap reference starts. When the decreasing V_{DD} crosses 2.1V, Detect_2.1V of the bandgap reference changes from high to low and the LED is turned off. After that, when the increasing V_{DD} crosses 3.3V, Detect_3.3V of the bandgap reference changes from high to low and the LED is turned on. The turn-on time of the LED (t_{ON}) is constant, while the turn-off time of the LED (t_{OFF}) depends on the received wireless power. When the LED current is assumed to be 2mA, t_{ON} is calculated as 4.7μF × (3.3V − 2.1V) / 2mA = 2.8ms, which is close to the cognitive limit of human eyes. By increasing C_{STR}, t_{ON} is increased at the cost of increasing the physical size of the capacitor. In Fig. 13, 3.3V and 2.1V are constant regardless of PVT variations, while 3.6V and 1.6V depend on the process variations. The inaccuracy of 3.6V and 1.6V is acceptable, because 3.6V and 1.6V are used only at the initial start-up. In this way, the proposed voltage detector achieves both the accurate voltage detection and the correct output during the start-up, achieving the intermittent lighting of the LED to increase the maximum distance between the transmitter and the receiver coil. The simulated power supply current of the proposed voltage detector is 546nA at V_{DD} of 3.3V.

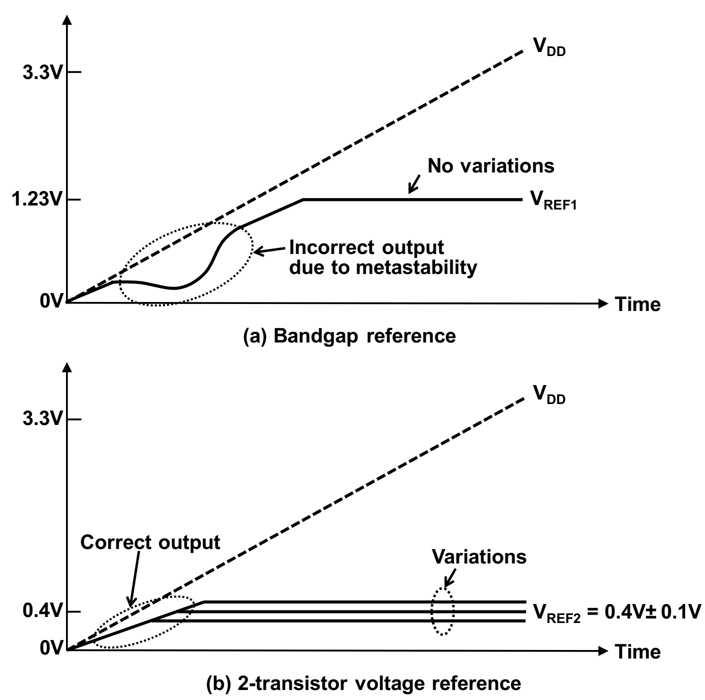


Fig. 11. (a) Output voltage (V_{REF1}) of bandgap reference during start-up. (b) Output voltage (V_{REF2}) of the 2-transistor voltage reference during start-up.

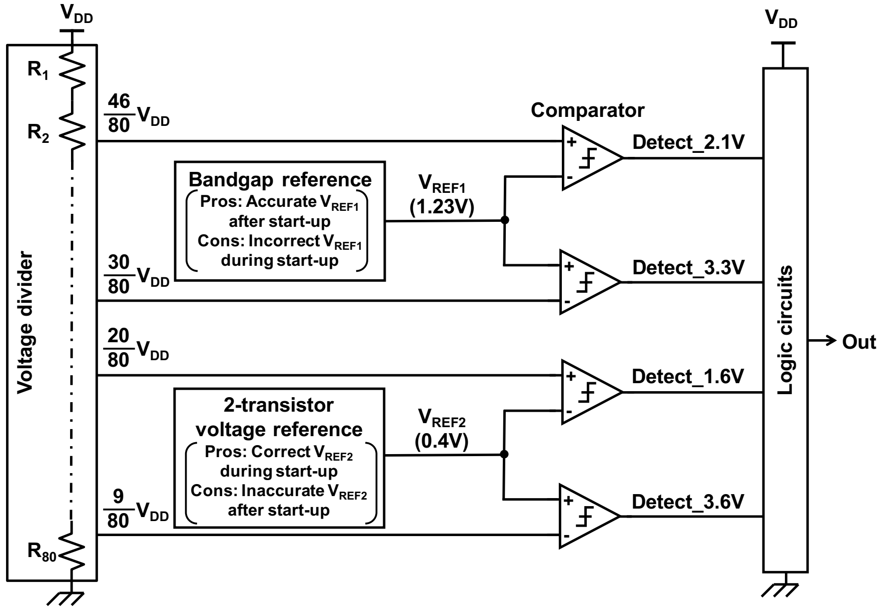


Fig. 12. Circuit schematic of proposed voltage detector.

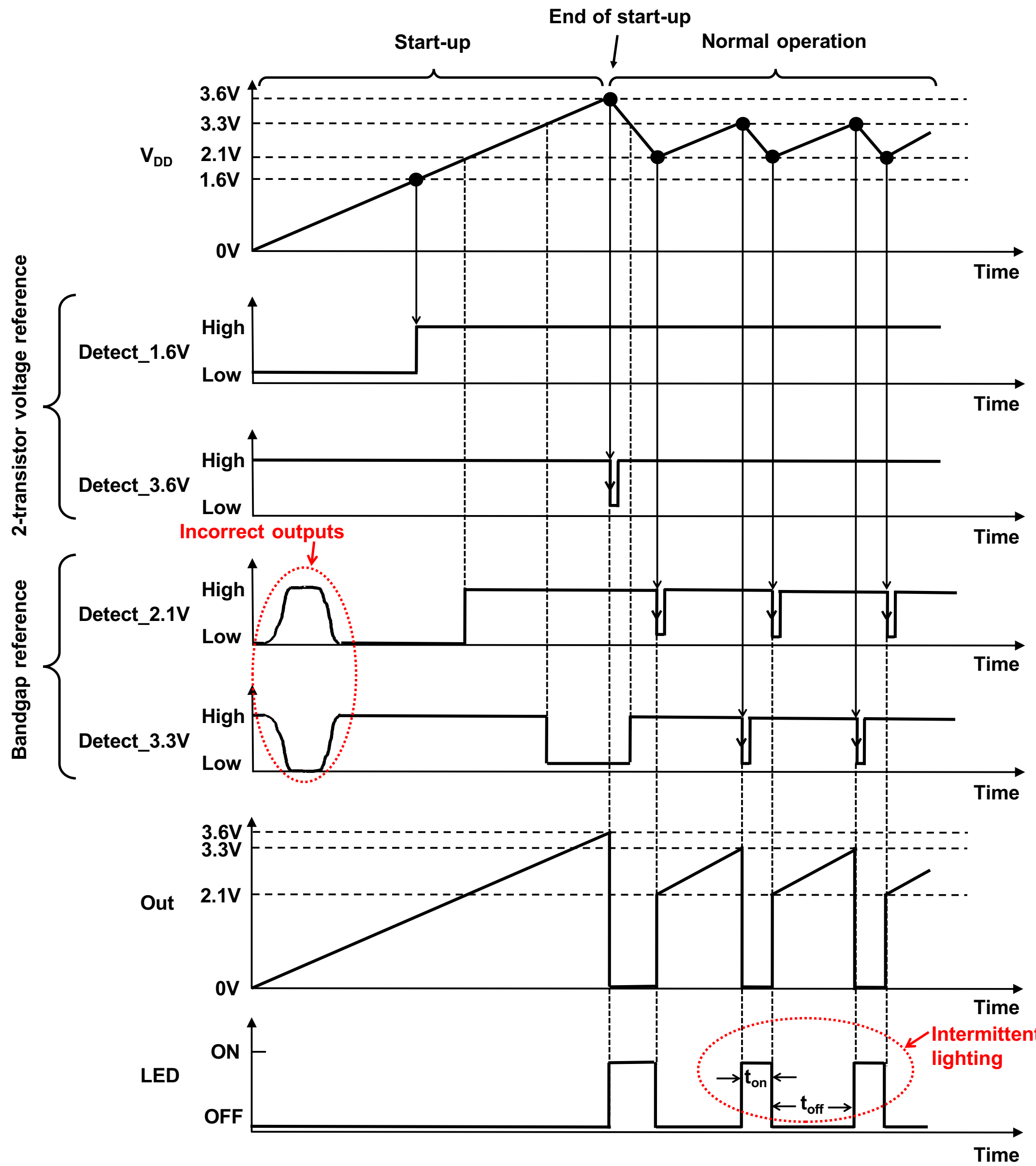


Fig. 13. Timing chart of proposed voltage detector.

5 EVALUATION

5.1 Range of Motion of Luciola

To investigate the 3D range of the levitation, the moving range of motion of Luciola is measured. In the setup with the two 40-kHz 17 × 17 ultrasonic transducer arrays placed face-to-face at a distance of 20cm shown in Fig. 4, the transmitter coil is removed and the 3.5-mm-diameter hemispherical particle is slowly moved from the origin in the x- and z- directions. Because the two ultrasonic transducer arrays have symmetry about X-axis and Y-axis, only the motion in the positive X-direction is measured. Similarly, because the two ultrasonic transducer arrays have symmetry about the Z-axis, only the motion in the positive Z-direction is measured. Fig. 14 shows the measured range of motion of Luciola along the X- and Z-directions. For each condition, ten trials are performed. The average maximum range of motion from the origin along the X- and Z- directions is 52mm and 27mm, respectively.

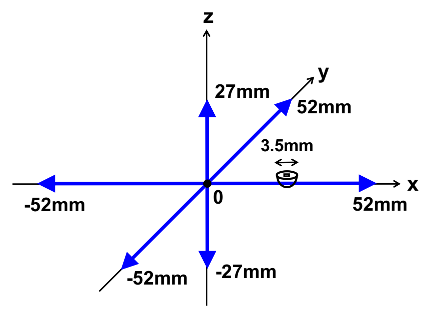


Fig. 14. Measured range of motion of Luciola along X- and Z-directions.

5.2 Range of Lighting of LED Using Wireless Powering

The range of the lighting of the LED using the wireless powering, and the increased range thanks to the intermittent lighting are investigated. Similar to the symmetry discussion in section 5.1, the dependence of the duty cycle of the LED on the position of Luciola in the XZ plane is measured. Fig. 15 shows the dependence of the measured duty cycle of the LED on the position of Luciola in the XZ plane for the 3.5- and 4.5-mm-diameter hemispherical particles. The output power (P_{TX}) of the power amplifier is 3.2W. The position is varied in steps of 1mm. For both hemispherical particles, the maximum range in the X-direction is around 15mm, which corresponds to the radius of the transmitter coil. The maximum z at $x = 0$ with a duty cycle of 0% in the 3.5-mm-diameter particle is 8.3mm, while for the 4.5-mm-diameter particle it is 16.4mm. Next, the increased range owing to the intermittent lighting is investigated. For the 3.5-mm-diameter particle, the maximum z at $x = 0$ with a duty cycle of 100% is 6.0mm, while that at $x = 0$ with a duty cycle of 0% is 8.3mm, indicating that the range of lighting of the LED is extended by 38% owing to the intermittent lighting. Similarly, for the 4.5-mm-diameter particle, the maximum z at $x = 0$ with a duty cycle of 100% is 14.0mm, while that at $x = 0$ with a duty cycle of 0% is 16.4mm, indicating that the range of lighting of the LED is extended by 17% owing to the intermittent lighting.

6 APPLICATIONS

Utilizing the advantages of Luciola of (1) levitating in mid-air and moving in three dimensional directions, (2) self-luminous pixel, and (3) ON/OFF control of the LED depending on the position of Luciola, drawings of characters in mid-air and a levitating and moving micro book light in mid-air are shown. The speed of Luciola of between 0.5cm/s and 1.5cm/s is used.

Fig. 16 shows a setup photograph and a long-exposure photograph of a drawing of an answer of a sum in mid-air using the setup shown in Fig. 5. The exposure time is 20s. The size of the drawn “8” is 20mm × 13mm. Luciola moves from the origin to the starting point of the drawing. At the starting point, LED of Luciola is turned on. Then, Luciola draws “8”. After finishing the drawing of “8”, LED of Luciola is turned off and Luciola returns to the origin. This demonstrates the possibility of interaction with printed materials. The advantage of displaying graphics and characters above the book and the paper is that an electronic display for the book and the paper is not required and conventional books and papers can be used, which greatly increases the opportunities to present and overlay information above the conventional physical objects.

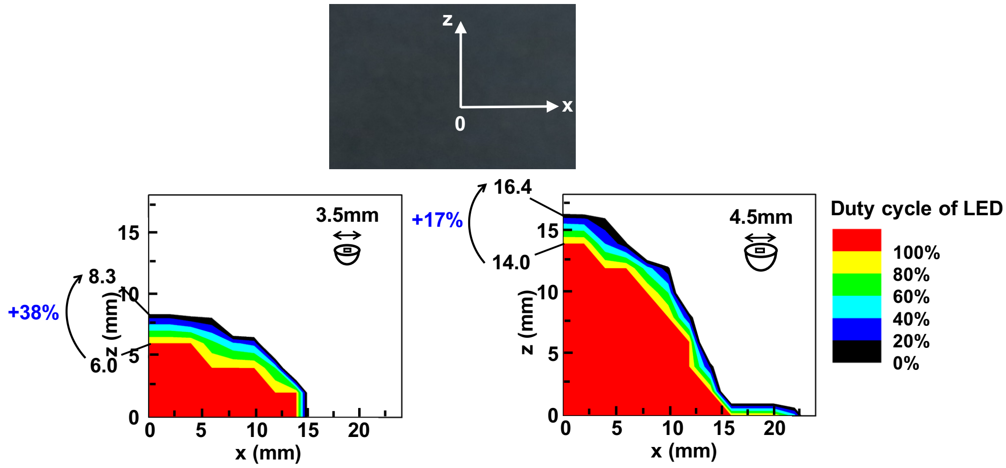


Fig. 15. Dependence of measured duty cycle of LED on position of Luciola in XZ plane for 3.5- and 4.5-mm-diameter hemispherical particles.

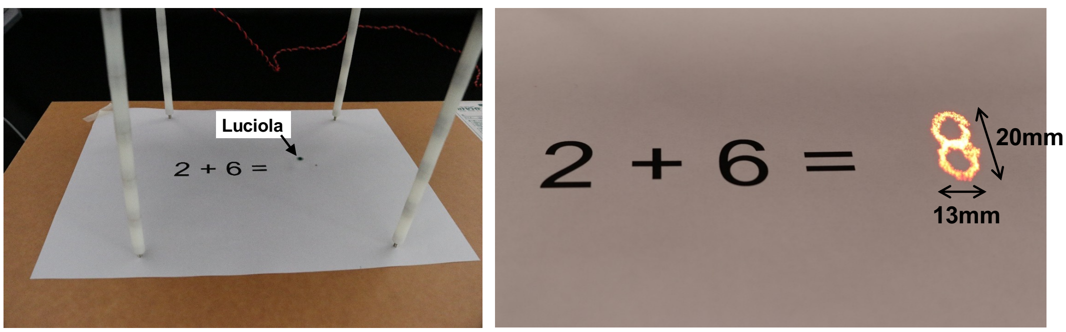


Fig. 16. Setup photograph and long-exposure photograph of drawing of answer of sum in mid-air.

Fig. 17 shows a long-exposure photograph of a drawing of characters of "LUCIOLA" one by one in mid-air using the setup shown in Fig. 4. By synchronously controlling the position of the focal point of the ultrasound and the ON/OFF timing of the switch of the wireless powering using PC, any alphabetical letters can be drawn in mid-air. The exposure time is 15s to 25s meaning that people can hardly recognize these characters unless consciously watching the movement of the Luciola particle at this moment. But the moving speed of the particle could be improved. In the demonstrations in Figs. 16 and 17, the motion pattern is on an XY plane. However, three-dimensional movement is supported as shown in Figs. 14 and 15, and thus drawing of three-dimensional graphics is also possible.

Fig. 18 shows a levitating and moving micro book light in mid-air. In the setup of Fig. 5, a book is placed on the reflector plate and the book works as the reflector plate. The particle for Luciola is levitated approximately 12mm above the book with the LED-side down, moves from left to right along the line of the book, and shines a light on the characters on the book. The transmitter coil for the wireless powering is placed below the book. In the demonstration of Fig. 18, the X-Y coordinate of the moving is set manually. In the future implementations, however, the X-Y coordinate of the moving could be automatically set using an eye-gaze tracking system.

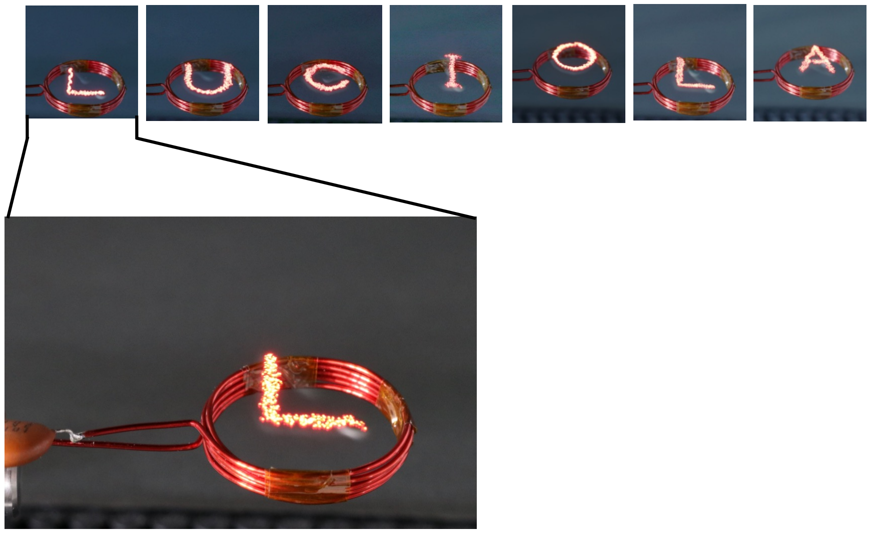


Fig. 17. Long-exposure photograph of drawing of characters of "LUCIOLA" in mid-air.

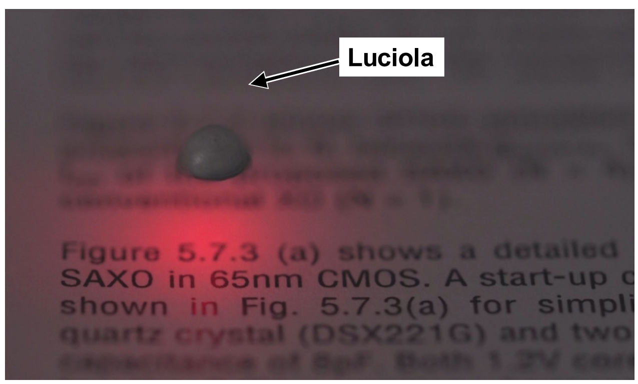


Fig. 18. Levitating and moving micro book light in mid-air.

7 LIMITATIONS AND FUTURE WORKS

In this paper, only one Luciola particle was in operation for demonstration on the stage. In the next step, however, it would be nicer if multiple Luciola particles can be independently operated on the stage. A margin for the levitation, however, is small, and it is difficult to levitate more than two Luciolas independently. There are two ways to control multiple particles simultaneously; (1) increasing the number of the ultrasonic transducer array and (2) reducing the size and weight of the particle.

Increasing the number of the ultrasonic transducer array cause another problem, because it will negatively affect the human auditory system. The upper limit of the sound pressure level at 40kHz is 110dB [9], while the sound pressure level of a single ultrasonic transducer used in this study is 117dB. Therefore, the sound pressure level of the 17 × 17 ultrasonic transducer array is much larger than 110dB, and ear protection is required.

In [12], two particles are independently levitated by switching two focal points at 500Hz using the setup in Fig. 5 and a same ultrasonic transducer array as this work. The particles used in [12], however, are 2.5-mm-diameter polystyrene particles with the weight of 0.5mg and the density of 0.06g/cm^3, which are smaller and lighter than the particles in this work

(3.5-mm-diameter, 16.2mg and 1.4g/cm^3). Therefore, the next step of Luciola will be to downscale the particle smaller and lighter to 2-mm in diameter. A limiting factor for the miniaturization is the receiver coil because the receiver coil is the largest in the particle as shown in Fig. 8 and the heaviest in the electric components as shown in Fig. 10. Therefore, designing a smaller and lighter receiver coil is important. Reducing the diameter of the receiver coil, however, will reduce the range of wireless powering as shown in Fig. 15. In conclusion, as discussed in section 4.4, the trade-off between the acoustic levitation and wireless powering is a fundamental problem in Luciola.

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