Acoustic levitation in mid-air: Recent advances, challenges and future perspectives

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ABSTRACT

Mid-air acoustic levitation is becoming a powerful tool to suspend and manipulate millimetric objects. Because of its unique characteristics, acoustic levitation is suitable to trap a wide variety of materials such as liquids, solids, soap bubbles and even living creatures. Acoustic levitation can also be combined with noncontact measurement systems, allowing contactless analysis and characterization of levitating samples. In this article, we review some of the advances that have been made over the last decade. We also present the technical challenges that must be overcome in order to extend the capability of current acoustic levitation devices and, finally, we point out future directions for acoustic levitation.

Acoustic levitation[1,2] uses the acoustic radiation force[3] exerted by sound waves to suspend objects in mid-air. Acoustic levitation is not only an interesting physical phenomenon, but it is a promising tool for multiple disciplines such as biology, chemistry or pharmacy. The unique features of acoustic levitation also have great potential for performing some tasks in industry such as the contactless manipulation of fragile objects or processing small volumes of liquids. In this article, we first highlight several breakthroughs that have been achieved over the last decade. Then, we describe some of the technical challenges that must be overcome to untap the full potential of acoustic levitation. Finally, we present emerging applications for acoustic levitation that are becoming more and more established. The physics behind acoustic levitation may also be employed for trapping, sorting, and manipulating microparticles and cells inside a liquid medium[4–6], but in this article we focus our attention to mid-air acoustic levitation.

The first experiments with acoustic levitation date back to 1933, when Bücks and Müller[7] reported the acoustic suspension of ethanol droplets at the pressure nodes of a

1

standing wave generated between a vibrating rod and a reflecting wall. Although acoustic levitation was demonstrated almost a century ago, most significant advances have been made in the recent years. From the early 1930s to the first decade of this century, the usual method for acoustically levitating objects has remained mainly the same. Most of the experiments trapped a small object (relative to the acoustic wavelength) in a pressure node of a standing wave, which was generated either using a single-axis levitator[8–11] composed of an emitter and an opposing reflector [Fig. 1(a)], or inside a closed cavity[12]. Most standing wave levitators operate at the ultrasonic range (with a typical frequency between 20 and 100 kHz) and they are suitable for trapping objects ranging from hundreds of micrometers to few millimeters, although acoustic levitation may also be employed for levitating smaller or larger objects.

Nowadays, acoustic levitation systems are not only able to trap but also to rotate and translate the particles in three dimensions. Furthermore, acoustic levitation is no longer restricted to the Rayleigh regime (i.e. particles much smaller than the acoustic wavelength), and distinct approaches are available to trap in the Mie regime (i.e. particle size comparable to the wavelength).
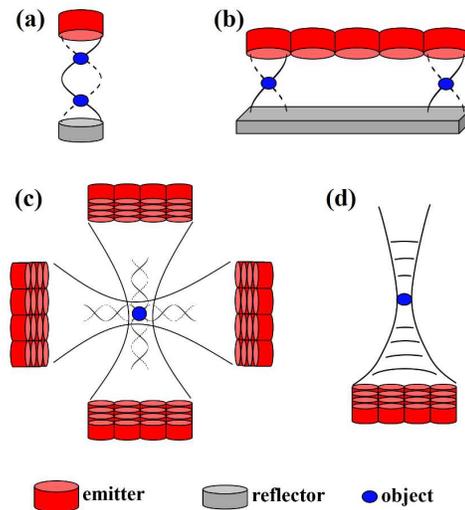

FIG. 1. Schematic of different types of acoustic levitators. (a) Single-axis acoustic levitator. (b) Two-dimensional manipulation of multiple drops using an array of Langevin-type transducers and an opposing reflector. (c) Three-dimensional manipulation of levitated particles using 4 orthogonal arrays of ultrasonic emitters. (d) Single-beam trapping.

Over the last decade, we have seen vast advances in acoustic levitation. Starting in 2010, Koyama and Nakamura showed a system based on linear transporters[14] and contactless rotary junctions[15]. In 2013, Foresti *et al.*[13] demonstrated the contactless transportation and merging of multiple drops in two dimensions using an array of high-power Langevin transducers and an opposing reflector. This levitation concept, illustrated in Fig. 1(b), can be of great interest for performing chemical reactions between drops and in DNA transfection of cells[16]. One of the most popular developments of the last decade was achieved by Ochiai, Hoshi, and Rekimoto[17–19], who developed an acoustic levitation system consisting of four orthogonal arrays made of low-power ultrasonic emitters that was able to control the position of levitated objects in three dimensions [Fig. 1(c)]. This work also marked the transition from the use of high-power Langevin transducers to arrays made of dozens of small low-power ultrasonic emitters (see review article by Morris *et al.*[20]).

Holographic techniques, like the ones used in optical trapping[21–23], have also been adapted to acoustic levitation. The phases at each point of the emitter plane can be set to generate intricate acoustic fields that trap particles at the target location, either using phased-arrays[24–26] with dozens of emitters [Fig. 2(a)] or passive modulators[27–30] [Fig. 2(b)]. The phases can be set with previously known patterns or obtained with optimization techniques[24]. With the holographic methods, an object can be trapped using just a single-sided array, as shown in Fig. 1(d), and it is also possible to trap multiple particles and move them individually[26]. When phased-arrays are employed, the levitated objects can be moved in real time; however, the reduced number of emitters leads to limitations in spatial resolution and thus in the ability to produce complex acoustic fields[27,31]. On the other hand, passive structures can create more intricate fields[27–30] but they cannot dynamically change the field to move the particles[27,29].

Objects larger than the acoustic wavelength have been levitated during the past decade. This can be achieved either by generating a standing wave field between the emitter and the object[32–34] or with special vortices of high apperture[25,35]. Fig. 2(c) shows the acoustic levitation of a sphere of 30 mm diameter (3.5 wavelengths at 40 kHz) using an array of 996 low-power transducers.
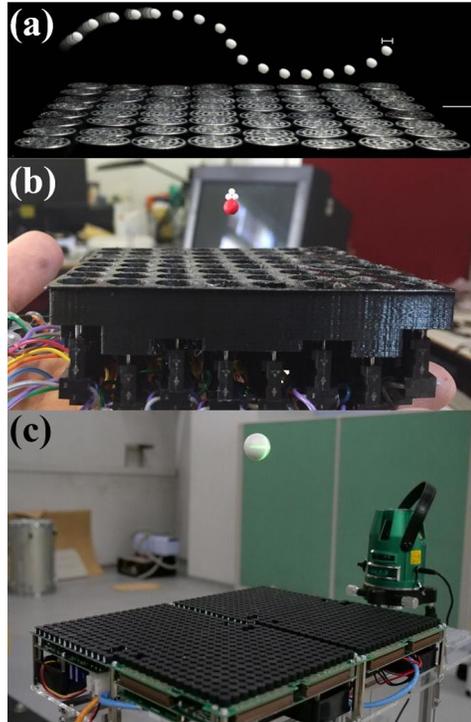
3

FIG. 2. (a) Dynamic manipulation of a 2 mm diameter Styrofoam particle using a single-sided array (Reprinted from ref. 24, licensed under CC BY 4.0). (b) Levitation with a field modulated by a 3d-printed passive structure (Reprinted from ref. 30, with the permission of AIP Publishing). (c) Levitation of a 30-mm diameter sphere (3.5 wavelengths at 40 kHz) using an array of 996 transducers (Reprinted with permission from ref. 25, Copyright 2019, Acoustic Society of America).

Despite the recent advancements in mid-air acoustic levitation, there are multiple technical challenges still to overcome. For example, increasing the manipulation speed of the trapped particles requires more insight about the dynamics of acoustically levitated particles. The trap force is usually modelled as a damped harmonic oscillator with a restoring force based on an ideal spring[36–38], but at high speeds the trapped object may present large displacements in respect to the position of minimum force potential. In this condition, models based on a linear trapping stiffness are no longer valid and the acoustic restoring force must be described by nonlinear stiffness models[39] to capture the softening of stiffness and period-doubling bifurcations that occur in the particle dynamics. Speeds

4

of up to 8.75 m/s have been shown[40] on lightweight particles, however moving heavier particles at high speed is still not possible. Similarly, dampening undesired oscillations of trapped solid objects inside a levitator is not a trivial problem[41], this issue becomes more acute when liquid drops are levitated[42]. To obtain a reliable apparatus usable by the wider scientific community, acoustic levitators would require automatic adjustments of their parameters (e.g. operation frequency or emission phase); for fast movement of the particles, a better understanding of the dynamics is needed.

To date, controlled orientation of an object in three dimensions has not been demonstrated. So far, the orientation has been controlled only in one dimension[13,24] but a full control on the orientation, such as that simulated by Helander *et al.*[43] , would enable applications in spectroscopy, photogrammetry and contactless placement. Additionally, the orientation of spherical objects cannot be adjusted given their symmetries, it is possible to impart angular speed into levitated spheres[35,44,45] but control on static orientation is still to be demonstrated. Dynamic levitation of multiple high-density objects would open up numerous possibilities; however, the trapping strength decreases linearly with the number of traps[26] and the current arrays do not have enough power to levitate multiple high-density objects simultaneously. Further improvement requires the development of arrays with more powerful and frequency-stable emitters. The acoustic levitation and manipulation of multiple objects also requires a better knowledge of the interparticle radiation forces[46,47] (also called secondary force) caused by the scattered wave from other trapped objects.

Further advancements also require better models and theoretical understanding of the forces acting on the levitated objects. With few exceptions, most models employ the Gor'kov[48] equation to simulate the acoustic radiation force acting on the levitated objects, which is only valid for spherical objects much smaller than the acoustic wavelength. Furthermore, relevant physical phenomena, such as acoustic streaming[49–51], acoustic viscous torques[52], and harmonic generation[53,54], are ignored in most models.
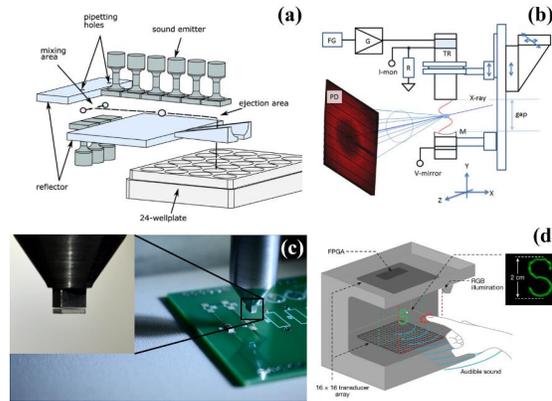
FIG. 3. Potential applications for acoustic levitation: (a) Acoustic levitation method for DNA transfection of cells (Reprinted from ref. 16, licensed under CC BY 4.0). (b) X-ray diffraction of protein crystals in levitated drops (Reprinted from ref. 55, licensed under CC BY 4.0). (c) Pick-and-place of electronic components using inverted near-field acoustic levitation (Adapted from ref. 56, with the permission of AIP Publishing). (d) Volumetric display with a fast-moving particle and persistence of vision (Reprinted with permission from ref. 40, Copyright 2019 Springer Nature).

Over the last years, we have seen the emergence of multiple applications for acoustic levitation, but so far they are restricted to academic research. For instance, acoustic levitation has been used as a contactless platform for manipulating and mixing samples of living cells and DNA plasmids[16], as shown in Fig. 3(a). Acoustic levitation has also been applied to suspend samples of protein crystals while synchrotron X-ray diffraction is employed for characterizing its molecular structure[55] [Fig. 3(b)]. It has also been demonstrated that electronic components can be manipulated without contact using inverted-near field acoustic levitation [Fig. 3(c)]. Another interesting use for acoustic levitation was to create a volumetric display with a fast-moving levitated particle [Fig. 3(d)].

Despite its increasing use in academic research, there is still no industrial application or mass-produced solution based on acoustic levitation, i.e., a "killer application" with the potential to revolutionize industrial processes. Acoustic levitation could be the base technology for a contactless liquid processing platform with the ability to programmatically mix, split and translate droplets without contact. This platform would allow the same operations as current electrowetting systems[57,58], but given the wide range of wavelengths that acoustic systems can employ, it would be capable of operating

6

from the micro to the milliliter scale. However, in contrast with electrowetting systems, splitting liquid or granular media is not possible yet with acoustic levitation; mixing has been achieved[13,59,60] but for a complete contactless fluidic solution, splitting is an essential operation. Mid-air acoustic levitation systems are becoming more widely available either in do-it-yourself (DIY) flavours[61,62] or commercial equipment (e.g. Manipulator Model D, Neurotechnology – Ultrasound Research Group; L800, BOROSA Acoustic Levitation GmbH; Single-Axis Acoustic Levitator (SAL[TM]), Materials Development, Inc.). However, this is not the case for trapping systems that operate with water as the propagation medium, even when many applications are only possible in water-based media.

Promising applications and future research will be derived during the next years. Increasingly more synchrotron experiments use acoustically levitated samples to increase the sensitivity and provide unprecedented results. With the appearance of affordable and simple to use levitators, these experiments will keep raising in popularity. Another promising application is to use acoustic levitation for producing amorphous drugs with enhanced solubility[63,64]. On the other hand, contactless picking and placing of fragile components can be performed with inverted-near-field acoustic levitation[56,65] and replace current methods based on vacuum suckers that can scratch, shock or cross-contaminate sensitive components. Another emergent research topic is displays made up of levitating particles acting as physical voxels or tracers: from uniform groups of particles[19] , charts[66] and props[67] to fast-moving particles with persistence of vision[40,68]. Finally, trapping in non-homogenous media is an open research topic, most simulations and experiments have been conducted in open space. However, the capacity of sound to reflect and diffract could enable interesting possibilities to trap around obstacles or in porous media.

In summary, we have presented some of the recent advances in acoustic levitation. We also point out some technical challenges that must be overcome in order to extend the manipulation capability of current levitation devices. So far acoustic levitation has been restricted to applications in academic research, but we expect that industrial applications will emerge and be applied in the following years. In the near future, the current levitation devices may evolve to the point that they would be able to manipulate millimetric objects with the same dexterity as industrial robots, but without any contact between the robot and the object to be manipulated.

7

Data sharing is not applicable to this article as no new data were created or analyzed in this sudy.

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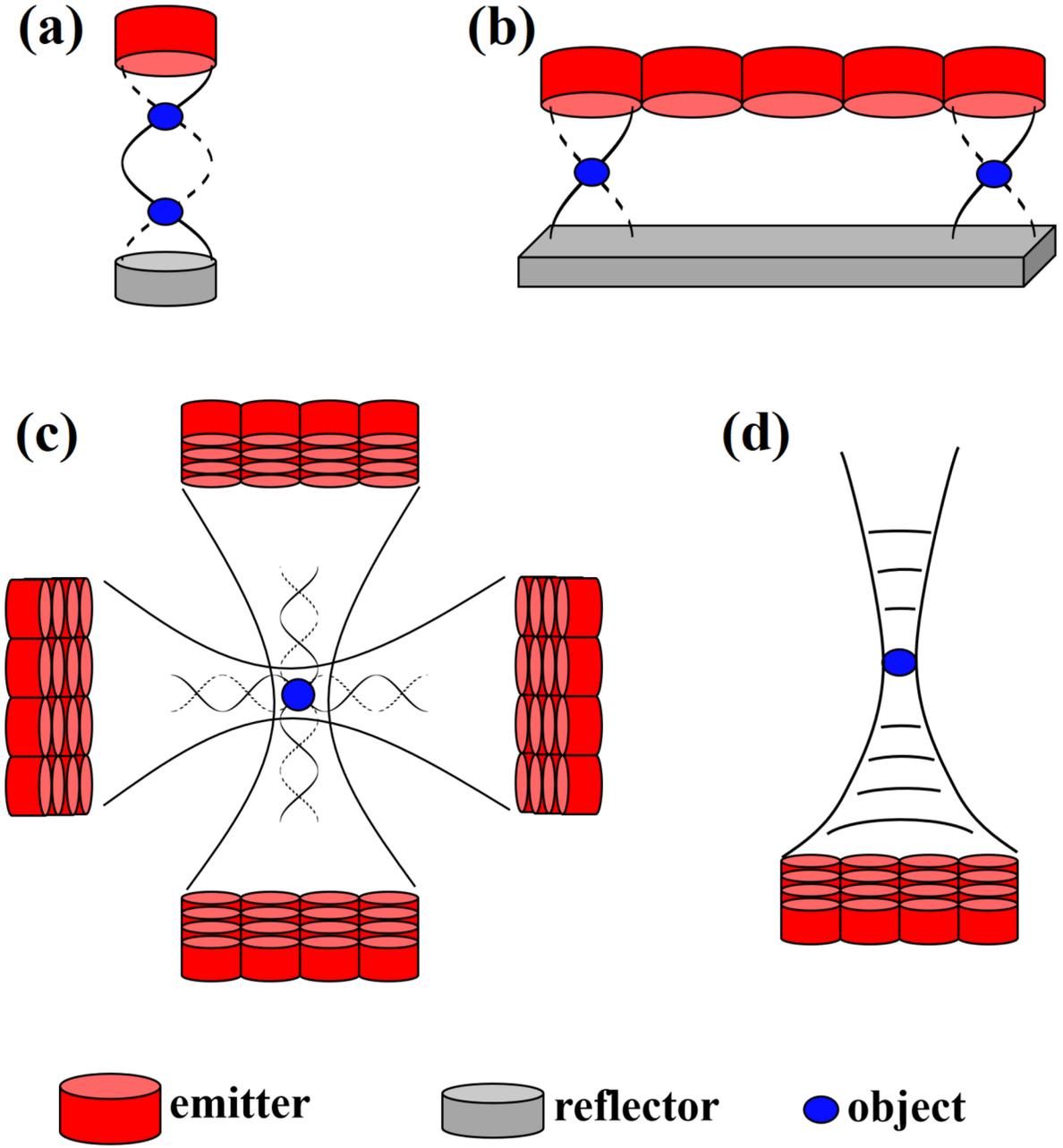
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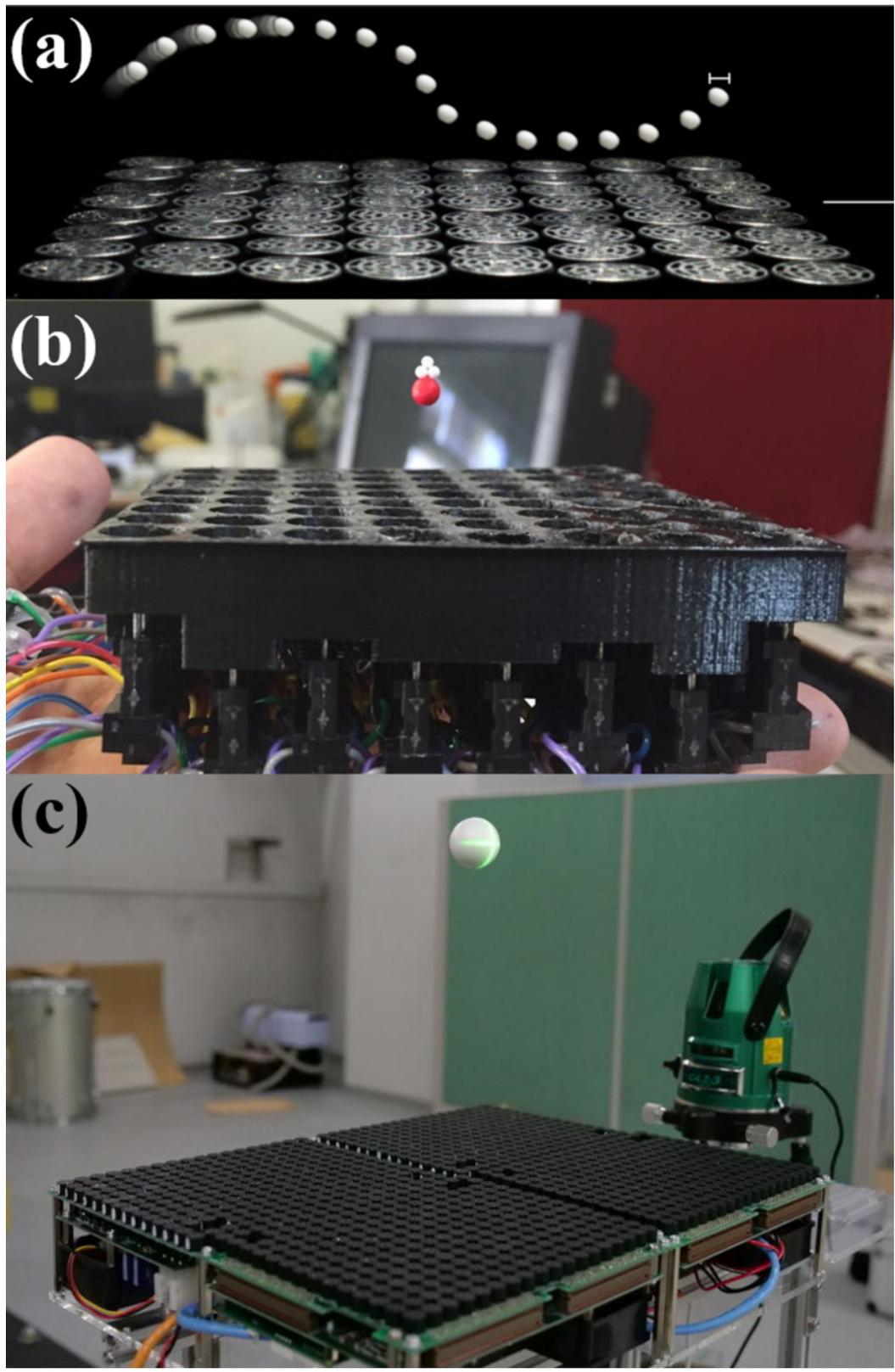[68] T. Fushimi, A. Marzo, B.W. Drinkwater, and T.L. Hill, Appl. Phys. Lett. **115**, 064101 (2019).

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11

(a)

(b)

(c)

(d)

emitter   reflector   ● object

(a)

pipetting holes

sound emitter

mixing area

ejection area

reflector

24-wellplate

(b)

FG — G — TR

I-mon

R

PD

X-ray

gap

M

V-mirror

Y

Z — X

(c)

(d)

FPGA

RGB illumination

2 cm

16 × 16 transducer array

Audible sound