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Low-power focused-laser-assisted remote ignition of nanoenergetic materials and application to a disposable membrane actuator

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ABSTRACT

Ignition of nanoenergetic materials (nEMs) has great potential for various portable and disposable actuator applications due to the unique ability to release pressure in a controllable manner. The development of highly efficient low-power igniters is very important in this context. Here we present a focused-laser-assisted nEMs igniter that can be remotely operated at low power with a portable laser pointer. The proposed optical igniter is monolithically integrated with a polymeric lens and prepared by a very simple, fast, and reproducible single-step soft-lithographic replication process using polydimethylsiloxane (PDMS). The polymeric lens plays a crucial role in greatly enhancing the laser power density on a target area by efficiently concentrating the incident laser beam, generating thermal energy enough to ignite nEMs. A pressure-driven membrane actuator is fabricated by integrating a thin PDMS membrane to the nEMs-coated optical igniter, and the actuation behavior is characterized in response to pressure released by nEMs ignition with different numbers of nEMs coats. Finally, the pressure-driven membrane actuator is demonstrated in an alarm switch to trigger stable operation of an electric buzzer with a blinking light-emitting diode as a potential application.

1. Introduction

Composite energetic materials (EMs) consisting of fuel metals and oxidizers can rapidly release heat and pressure by converting the stored chemical energy into thermal energy upon ignition. The unique energy release characteristics of EMs make them feasible to be used as heat and pressure sources for operating disposable devices. In particular, nanoenergetic materials (nEMs) have recently gained much attention due to their high exothermic reactivity and high energy density based on significantly high surface-area-to-volume ratio compared to micro-scale EMs [1]. Based on this, so far, many attempts have been made to find various potential uses for nEMs in military and civilian applications, such as micro thrusters [2–5], pressure-driven membrane actuators [6–8], safe initiators [9,10], antimicrobial energetic systems [11], molecular delivery systems [12], and gas generators [13–16].

A proper method of providing sufficient input energy to decompose nEMs is very important for such applications. Among a variety of decomposition methods of nEMs, pyrotechnic approaches have been most widely employed because of the straightforwardness of igniting nEMs based on direct heat transfer [2–20]. In particular, recent advances in microfabrication technologies have enabled the integration of micro-heaters with nEMs on a small chip for nEMs-on-a-chip applications [2–10,12,17,18]. Nevertheless, micro-heater-assisted nEMs igniters suffer from several issues, including complex and expensive fabrication, high power consumption, and high voltage operation, which may critically hinder their practical use in portable and disposable device applications.

Laser beams have recently been considered as one of the most efficient ignition routes for nEMs [21–23]. Unlike pyrotechnic methods, heat from a laser beam can remotely ignite nEMs without micro-heaters, which can make the overall ignition system simpler and more compact. However, most laser igniters are inadequate for integration in portable and disposable compact devices because they generally require complicated and bulky equipment with high-power source to irradiate laser beam onto nEMs.

In this work, we present a low-power focused-laser-assisted remote nEMs ignition system. The simple all-elastomeric architecture of the proposed optical igniter was fabricated by a facile soft-lithographic replication process using polydimethylsiloxane (PDMS) in a very simple, cost-effective, and reproducible manner. The polymeric lens support was designed while considering the focal

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length of the polymer lens and then precisely fabricated by controlling the weight of the PDMS prepolymer. The polymeric focusing lens efficiently concentrated the incident laser beam generated by a portable laser source onto a nEMs layer that was coated on the back of the lens part, resulting in low-power remote ignition of nEMs with a compact platform. Several advantages of the proposed optical igniter including the structural compactness, simple and low-cost fabrication, and low-power and remote operation with a portable laser source offer the possibility for developing various new class of actuator systems. As an application example, the optical igniter was integrated with a thin polymeric membrane to fabricate a pressure-driven membrane actuator, which is capable of achieving controllable vertical displacement in response to pressure released upon the remote ignition of nEMs. A disposable polymeric switch based on the pressure-driven membrane actuator is also demonstrated to remotely operate a simple alarm system with a low-power laser pointer.

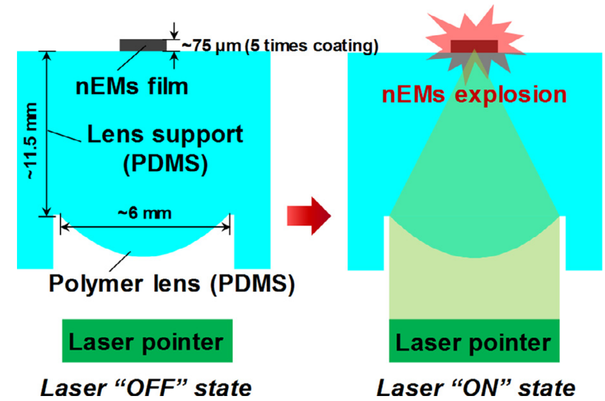

Fig. 1. Schematic illustration of structural design and working principle of the focused-laser-assisted remote igniter for nEMs (not scaled).

2. Experiment details

2.1. Preparation of nanoenergetic materials

Non-toxic and naturally abundant aluminum nanoparticles (Al NPs; NT base) with an average diameter of ~81 nm were used as a metal fuel, and copper oxide nanoparticles (CuO NPs; NT base) with an average diameter of ~98 nm were used as an oxidizer. Al/CuO nEMs were synthesized by the following procedure. The two kinds of the NPs were first put together in an ethanol solution with a fixed Al:CuO weight ratio of 3:7 that was experimentally optimized in our previous work [17]. To completely mix the two NPs, the mixture was then treated ultrasonically for 10 min with 170 W of power and a vibration frequency of 40 kHz. Al/CuO nanocomposite powders were prepared by entirely evaporating the ethanol component from the mixture in a convection oven at 80 °C for 30 min. Finally, the Al/CuO nEMs were diluted in another ethanol solution with a nEMs:ethanol weight ratio of 1:30 for subsequent coating processes.

2.2. Fabrication of focused-laser-assisted igniter and pressure-driven membrane actuator

The proposed optical igniter was prepared by a facile PDMS replication process using a plano-concave glass-based lens mold (Edmund Optics) with a diameter of ~6 mm and a radius of curvature of ~4.71 mm. Liquid PDMS (Sylgard 184, Dow Corning) was mixed with a cross-linker at a weight ratio of 10:1 and poured onto the lens mold placed in a container with a fixed dimension. After thermal curing at 70 °C for 1 h, the solidified elastomeric igniter was prepared by peeling it off from the mold.

Al/CuO nEMs were then patterned at the center of the back of the lens part. First, a polyethylene terephthalate (PET) shadow mask with a rectangular opening hole ($2 \times 2\ mm^2$) was aligned with the prepared lens module. An Al/CuO/ethanol mixture with a fixed concentration of ~26.3 mg/mL was drop-cast onto the hole, followed by evaporation of all the ethanol in ambient conditions. The thickness of the nEMs layer was controlled by varying the number of coatings with a fixed solution volume of 1 µL per coating cycle.

A pressure-driven membrane actuator was prepared by firmly applying a thin polymer membrane fabricated by the PDMS replication process with a cylindrical mold (diameter: ~6 mm; height: ~2.4 mm) to the igniter. Prior to this, both PDMS surfaces of the igniter and membrane were treated for 60 s with oxygen (O_2) plasma under 70 W of power with a gas flow rate of 100 sccm to make them hydrophilic for complete bonding at the interface.

2.3. Fabrication of disposable polymeric switch

A disposable polymeric switch was simply prepared by assembling a pressure-driven membrane actuator with a metallic contact part and a signal transmission line. Two pieces of aluminum foil were attached to a PDMS sheet to construct the signal transmission line with a proper separation gap. The metallic contact part was formed on the top surface of the PDMS membrane by drop-casting silver nanowires (AgNWs), which were synthesized using a previously reported procedure [24]. The average length and diameter of AgNWs used in the present work were ~11.8 µm and ~345.5 nm, respectively. After patterning, the AgNW contact part was thermally annealed in an electric furnace at 200 °C for 1 h to enhance the electrical conductivity by fusing the NW–NW junctions. After O_2 plasma treatment, the two parts were bonded to each other with an intermediate PDMS spacer (~1 mm in height) to provide sufficient space for membrane actuation.

The alarm system was constructed by connecting an electric buzzer with a blinking light-emitting diode (LED) and a flip-flop circuit to the disposable polymeric switch in series.

2.4. Characterization

The nEMs film patterned on the laser ignition system was ignited using a portable laser source (OX-V40, OXLaser) with an output power of 500 mW and a wavelength of 405 nm. For all ignition experiments, the laser beam was irradiated onto the optical igniter at a distance of ~3 cm. The thickness of the nEMs film as a function of the coating cycles was measured using a non-contact laser interferometer (NV-1000, Nanosystem). Time-dependent temperature profiles and the corresponding thermal images of the igniters with and without a polymer lens were measured using an infrared (IR) thermal camera (Ti400, FLUKE). The maximum pressure generated by the laser ignition of the nEMs was measured using a commercially available piezoresistive silicon pressure sensor (XGZP 6847, CFSensor) connected with a digital oscilloscope (TDS 2012B, Tektronix). The maximum vertical deflection of the PDMS membrane actuator upon ignition was measured from a cross-sectional digital image taken during the ignition process.

3. Results and discussion

Figure 1 shows a schematic illustration of the structural design and working principle of the proposed focused-laser-assisted remote igniter of nEMs. The optical igniter consists of a polymeric lens, lens support, and nEMs film, which are all integrated monolithically in a single compact platform. The polymeric lens made of a transparent PDMS plays an important role in enhancing the

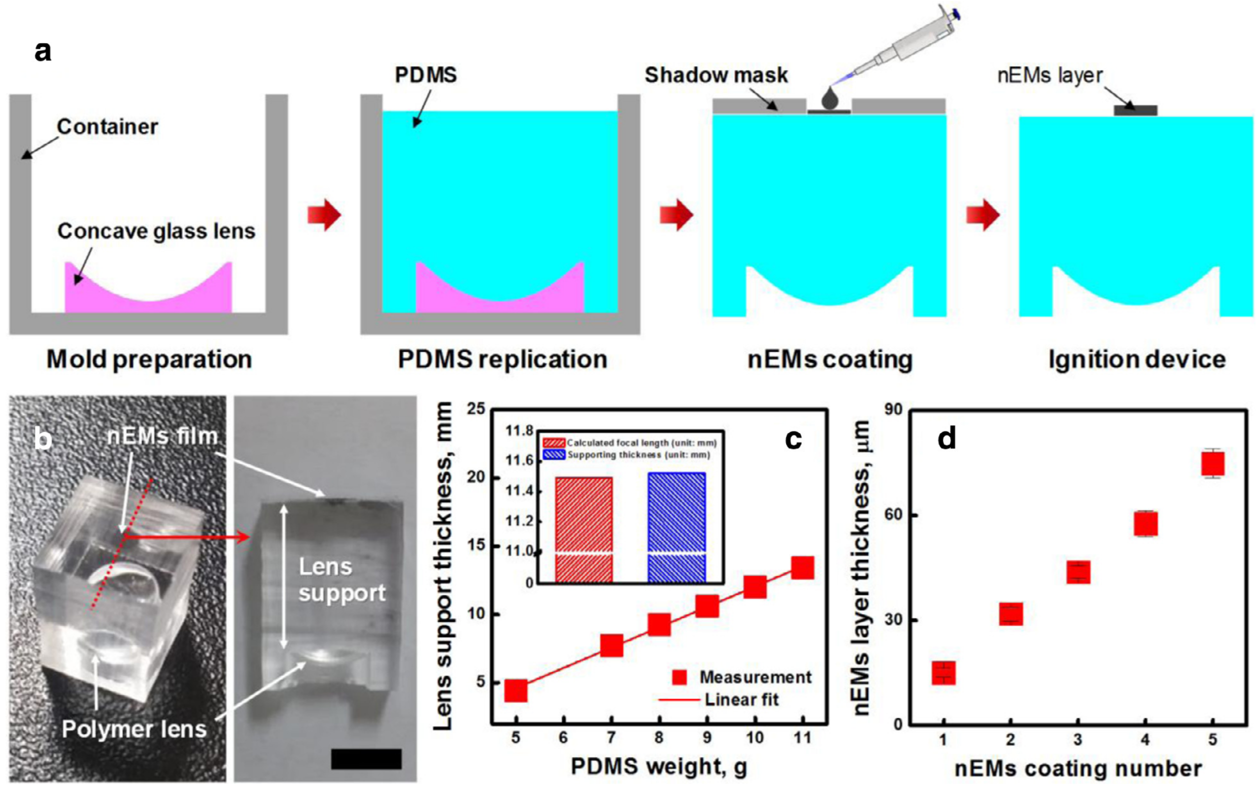

Fig. 2. Fabrication of focused-laser-assisted nEMs igniter. (a) Schematic illustration of fabrication procedure, (b) digital images of the fabricated optical igniter (scale bar: 50 mm), (c) change in thickness of lens support as a function of PDMS weight (inset: calculated focal length and optimized lens support thickness of the polymeric igniter), and (d) change in thickness of nEMs film as a function of the number of coats with a fixed amount of Al/CuO nanocomposite powder (~26.3 μg) per coating.

output power density by concentrating the power of the incident laser beam onto a target area. In conjunction with this, in particular, optimal design of the lens support thickness makes it possible for the incident laser beam to be focused precisely onto the nEMs film coated on the back of the lens part, minimizing the laser spot size projected on the surface of the nEMs film. When a laser source is turned on, the laser beam exposed to the polymer lens is predominantly concentrated on the nEMs film while providing sufficient thermal energy to ignite the nEMs with the increased power density. This simple process enables the igniter to be operated remotely even with a low-power laser source such as a portable laser pointer. This highlights the great potential for applications in various compact remote system applications in association with the simple architecture.

The proposed nEMs igniter was simply fabricated by a standard PDMS replication process based on a plano-concave glass lens mold and subsequent shadow mask-assisted drop-casting of nEMs solution, as illustrated in Fig. 2(a). A simple combination of the well-established facile fabrication techniques makes the overall process highly reproducible and cost-effective, clearly suggesting that the optical igniter is greatly suitable for being used in disposable device applications. The compact and mechanically robust all-elastomeric architecture of the fabricated optical igniter is shown in Fig. 2(b). The width, length, and height of the fabricated prototype igniter were ~10, ~10, and ~14 mm, respectively. In this case, as a proof-of-concept demonstration, the optical igniter was fabricated using a glass lens mold with fixed dimensions (diameter of ~6 mm and radius of curvature of ~4.71 mm). However, it is important to note that the architecture and performance of the igniter can be optimized further by simply modifying the glass lens mold (i.e., using different sized lens molds). To effectively concentrate the incident laser beam onto the nEMs film through the polymer lens system, the focal length (f) was first calculated as $f = R/(n-1)$, where R is the radius of curvature of the lens, and n is the refractive index of PDMS. The lens support thickness (t_{ls}) corresponding to the calculated focal length was determined by controlling the weight of the PDMS prepolymer using a container with fixed dimensions (Fig. 2(a)). Prior to this, the change in t_{ls} was investigated as a function of the PDMS weight, as shown in Fig. 2(c). As expected, a linear relationship was found between t_{ls} and the PDMS weight.

Using the PDMS weight extracted from the fitting data, the designed value of t_{ls} was achieved with a negligible error of <0.3% compared to the calculated f, as shown in the inset of Fig. 2(c). The thickness of the nEMs film can also be easily controlled by varying the number of nEMs coats with a fixed amount of Al/CuO nanocomposite powder (~26.3 μg) per coating cycle. As shown in Fig. 2(d), it was found that the nEMs film thickness is linearly proportional to the number of nEMs coats, which represents the potential ability to control the resulting explosion reactivity.

The effect of using the polymer lens on the ignition of nEMs was quantitatively examined by calculating the laser power density on a target location where the nEMs film is formed upon laser exposure, as shown in Fig. 3(a). For comparison, another PDMS block was fabricated with the same architecture as the optical igniter but without a polymer lens and characterized under the same conditions. In this case, the laser power density was defined as the ratio of the input laser power to the projected area of the incident laser beam on the target location. In the case of the PDMS block without the polymer lens, the laser power density was calculated to be ~17.7 mW/mm^2, and no explosion of the nEMs was observed. In contrast, the output power density increased dramatically to ~636.6 mW/mm^2 after integrating the polymer lens, even with the same power of the incident laser beam. In this case, the

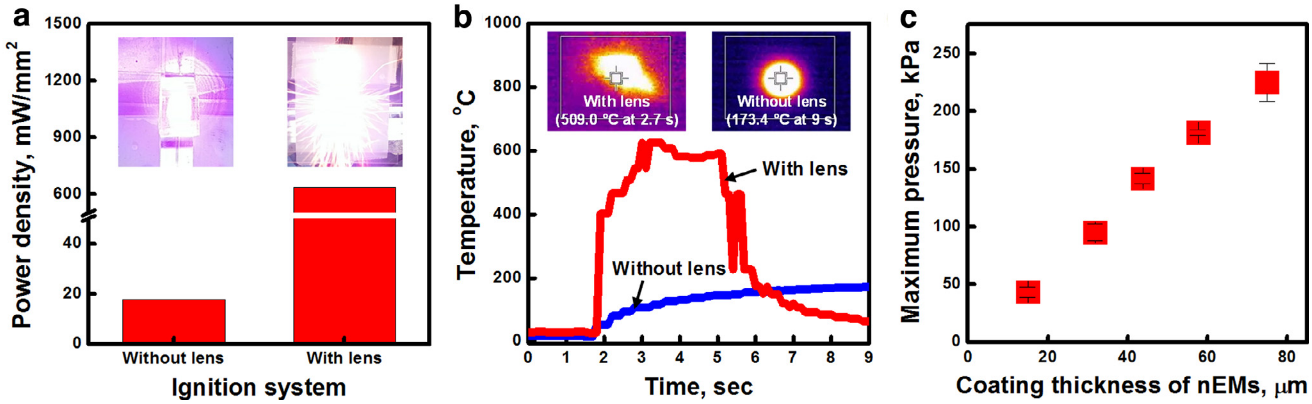

Fig. 3. Ignition characteristics of focused-laser-assisted nEMs igniter. (a) Calculated laser power densities on the igniters with and without polymer lens under laser exposure (inset: corresponding top-view digital images of the igniters under laser exposure), (b) temperature profiles on the igniters with and without a polymer lens upon laser exposure (inset: corresponding IR camera images at 2.7 s (explosion) and 9 s (no explosion) for the igniters with and without a polymer lens), and (c) change in maximum pressure released from the igniter under laser ignition of nEMs as a function of the coating thickness of nEMs.

nEMs coated on the ignition system exploded immediately after aligning the incident laser beam to the nEMs film, implying that the laser power concentrated by the polymer lens is high enough to initiate the ignition of nEMs, as shown in the inset of Fig. 3(a).

Heating by a laser irradiation induces the ignition of nEMs by providing sufficient thermal energy to the nEMs beyond the activation energy for reactions. For better understanding of the underlying mechanisms of the laser ignition, the time-dependent temperature profiles on the nEMs film during laser exposure were recorded in real-time, as shown in Fig. 3(b). The temperature gradually increased at the location coated with nEMs on the system without the polymer lens in response to the incident laser beam, but the maximum temperature was insufficient to thermally ignite the nEMs. This means that a laser source with much higher power is inevitably required to ignite the nEMs in this case. In contrast, the temperature rapidly reached ~509 °C within 1 s on the nEMs film on the polymer lens-integrated system after aligning the focused laser beam to the film. The nEMs exploded immediately, as shown in the left IR camera image in the inset of Fig. 3(b). This clearly proves that the laser beam concentrated by the polymer lens is an efficient provider of sufficient thermal energy that is higher than the explosive reaction energy of nEMs. After explosion, the temperature increased further and was held for several seconds, probably due to the sudden release of heat by the decomposition of nEMs.

In addition to heat, pressure is also suddenly released when igniting the nEMs, and the peak magnitude can be regulated by controlling the explosive reaction of the nEMs. Precise control of the peak magnitude of the released pressure is particularly important in developing pressure-driven actuators that employ the nEMs as a pressure source. As one of the simplest ways of controlling the explosive reactivity, we varied the number of nEMs coats with a fixed coating volume, as shown in Fig. 2(d). Figure 3(c) shows the maximum pressure generated by the fabricated optical igniter under laser exposure as a function of coating thickness of nEMs. The maximum pressure was found to be linearly proportional to the coating thickness of nEMs, as expected from the linear relationship between the nEMs film thickness and the number of coats (Fig. 2(d)). This would be greatly helpful for designing pressure-driven devices in a predictable manner. These experimental observations demonstrate that the proposed polymer lens-integrated compact system can efficiently ignite the nEMs by a low-power laser without any complicated and bulky laser modules, clearly representing the possibility for being used as a miniaturized heat and pressure source in various portable device applications.

As a simple demonstration, we fabricated a pressure-driven membrane actuator by monolithically integrating a thin PDMS membrane with the optical igniter. Furthermore, the fabricated membrane actuator was bonded with a PDMS sheet with a signal transmission line for an alarm switch application, as shown in Fig. 4(a). Prior to bonding the two parts, a metallic contact part was formed on the polymeric membrane by depositing AgNWs using a drop-casting process. In the present work, we chose an AgNW percolation network as a conductive material to form the contact part because it is flexible enough to retain its electrical properties without significant degradation even when the membrane is maximally deformed upon ignition.

The working principle of the alarm switch is illustrated in Fig. 4(a). In the initial state (laser-OFF state), the signal transmission line is initially separated at the center region while the input and output terminals are electrically isolated (switch-OFF state). When igniting the nEMs with a laser pointer (laser-ON state), the PDMS membrane is accordingly deflected by the released pressure, which leads to intimate contact between the contact part and signal line while allowing the signal to flow from the input to the output thermal (switch-ON state). The polymer membrane was fabricated by replicating PDMS from a cylindrical mold using a standard soft lithography, and the thickness was precisely controlled by controlling the weight of the PDMS prepolymer with respect to the same mold, as shown in Fig. 4(b).

Figure 4(c) shows the maximum vertical deflection of the PDMS membrane upon ignition as a function of the number of nEMs coats. The cross-sectional digital image in the inset of Fig. 4(c) indicates that a ~260-μm-thick PDMS membrane was stably deformed upward in response to the pressure generated by the nEMs ignition, presenting a corresponding maximum deflection of ~3.6 ± 0.16 mm for five nEMs coats. The maximum membrane deflection almost linearly increased with increasing the number of nEMs coats, which is consistent with the linear relationship between the maximum pressure and coating number (Fig. 3(c)).

The fabricated alarm switch was operated by remotely igniting the nEMs with a laser pointer to apply pressure to the PDMS membrane. It should be noted that ignition of the nEMs is generally unable to supply pressure steadily to hold the deformed state of the actuator due to the instantaneous energy release characteristics. This might be a critical challenge for use in practical pressure-driven actuator applications. To address this issue, we connected a flip-flop circuit capable of maintaining the output state indefinitely to the alarm switch that is connected with an electric buzzer with a blinking LED device.

Figure 4(d) shows the electrical current at the output terminal of the flip-flop circuit. This indicates that the current flow enabled by the switch operation is continuously maintained, even

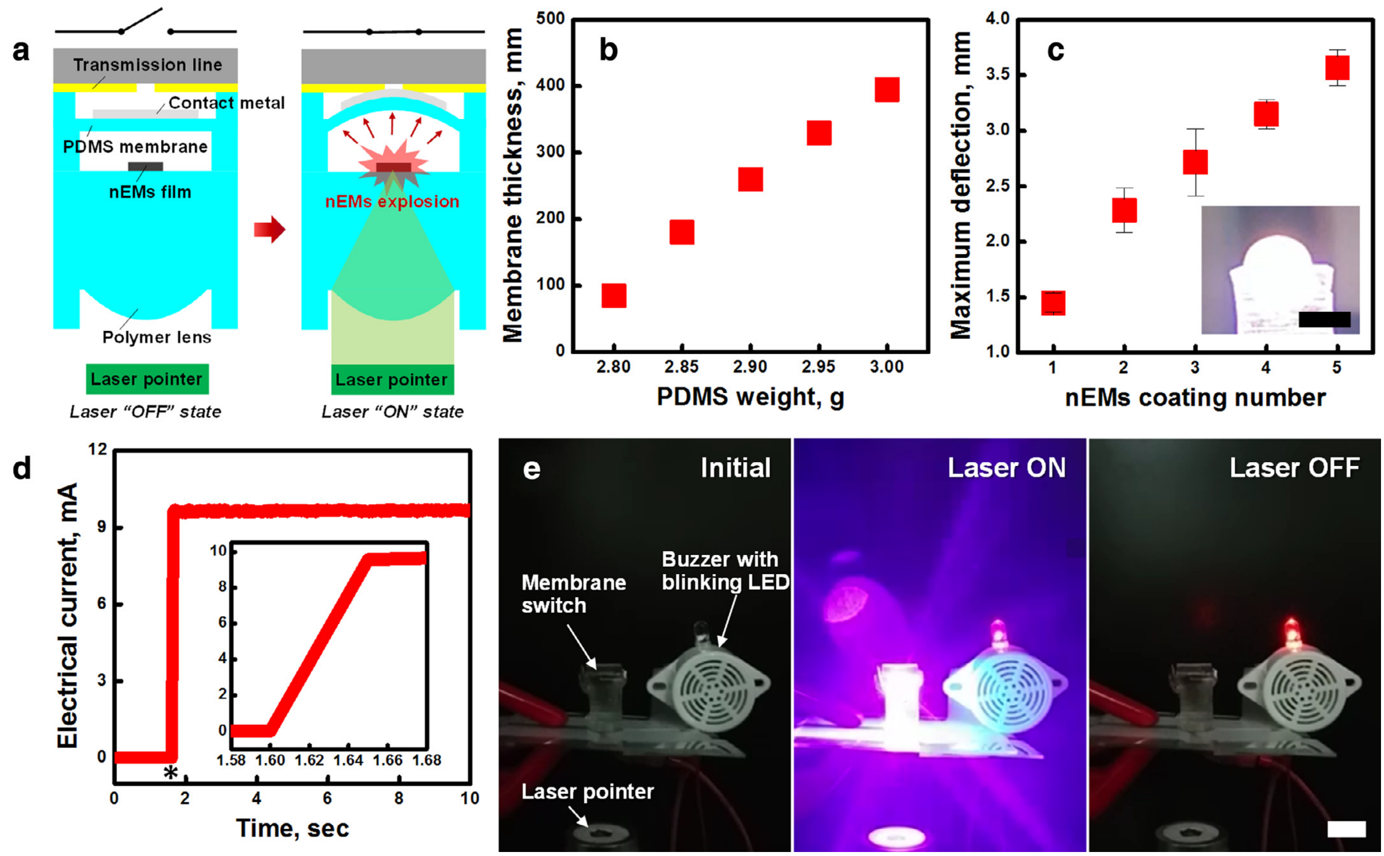

Fig. 4. Alarm switch application. (a) Schematic illustration of structural design and working principle of alarm switch operated remotely using a focused-laser-assisted igniter, (b) change in thickness of PDMS membrane as a function of PDMS weight, (c) change in maximum vertical deflection of PDMS membrane upon laser ignition of nEMs as a function of the number of coats (inset: cross-sectional digital image of pressure-driven membrane actuator under laser ignition (5 coats), scale bar: 50 mm), (d) time-dependent electrical current of flip-flop circuit at the output terminal when ignited using a laser pointer (asterisk (*) indicates a moment when the focused laser beam is aligned to the nEMs film; inset: magnified current profile representing a fast switching time of ~50 ms), and (e) sequential digital images of the alarm system in the initial, laser-ON, and laser-OFF states (scale bar: 100 mm).

though the PDMS membrane recovered to the initial state immediately after the nEMs explosion. In addition, the switch operation was found to be relatively fast with a response time of ~50 ms, as shown in the inset of Fig. 4(d).

Figure 4(e) shows sequential digital images of the alarm system in the initial, laser-ON, and laser-OFF states (for more information, see Movie S1 in the Supplementary Material). When the incident laser was precisely focused onto the nEMs film, the electric buzzer immediately sounded while the LED blinked at the same time (Fig. 4(e), center). With the aid of the flip-flop circuit, the buzzer and LED were able to operate continuously, even after turning off the laser pointer (Fig. 4(e), right). This simple demonstration suggests that the proposed focused-laser-assisted nEMs igniter has great potential as an efficient pressure source in various portable and disposable actuator applications due to its simple, low-cost, and fast fabrication, remote laser ignition ability, and low-power operation.

4. Conclusions

In conclusion, we have developed a very simple yet highly efficient strategy to demonstrate a remotely operated, low-power optical igniter for nEMs with a built-in polymer lens that can focus an incident laser beam onto the nEMs. The lens support thickness was designed to correspond to the actual focal length of the polymer lens, which enabled the incident laser beam to be precisely focused onto the nEMs film on the opposite side of the lens part. The laser beam concentrated by the polymer lens was accordingly able to provide sufficient thermal energy to the nEMs film by greatly enhancing the power density, resulting in explosion of the nEMs, even at a low input power of 500 mW.

The optical igniter was simply fabricated by replicating PDMS from a glass-based lens mold after precisely controlling the weight of the PDMS prepolymer to achieve the designed structure. A pressure-driven membrane actuator was fabricated by monolithically attaching a thin PDMS membrane to the igniter. The maximum vertical deflection of the pressure-driven membrane actuator was easily regulated by varying the coating number of nEMs and was consistent with the linear relationship between the maximum pressure generated upon ignition and the number of coats. As a simple demonstration, continuous operation of an electric buzzer with a blinking LED was successfully triggered by an alarm switch based on the pressure-driven membrane actuator after connecting a flip-flop circuit.

Acknowledgments

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.combustflame.2017.04.021.

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