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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.

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.

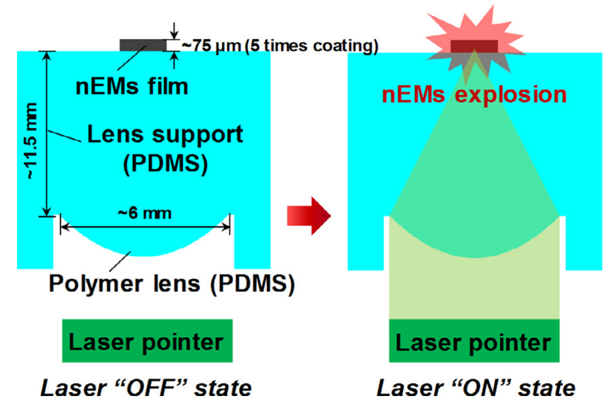

Fig. 1. Schematic illustration of structural design and working principle of the focused-laser-assisted remote igniter for nEMs (not scaled).

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