DISPLAY MEDIUM WITH PARTICLE MANIPULATIONS IN AN EMULSION DROPLET ARRAY

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ABSTRACT

A self-assembled and packaged display medium is fabricated using microfluidic emulsion technology to encapsulated droplets of particles solutions in a curable continuous phase, which greatly simplifies the packaging process. After photo crosslinking, we obtain an emulsion droplet array of regularly and densely arranged droplets containing uniformly dispersed particles that are further addressable by the externally applied electric field to alter the reflectivity and perform as a display medium.

INTRODUCTION

Manipulation of particles in liquid droplets has been widely applied to various purposes and research including displays. E-Ink, for example, developed electrophoretic displays (EPD) by moving charged particles in microcapsules [1]. We have previously demonstrated particle chain displays (PCD) with neutral but electrically polarizable particles, which is insensitive to the particle polarity and applicable to a variety of particles [2]. In addition, the in-droplet manipulation can be further applied to cell spheroids formation [3] and controllably merging of droplets with particle movements [4]. In addition, particles were concentrated at the interface of two immiscible fluids with electrical manipulations [5].

Here we investigated neutral polystyrene (PS) particle manipulations in a well-arranged droplet array established by microfluidic emulsion technology to reduce the difficulties of particle droplet assembly and packaging. This technology accomplishes a novel reflective display medium with particles manipulations in emulsion droplets. Such a reflective display medium can be used as an electronic paper consuming less power and providing comfortable reading experience with the high readability even under sunlight. In this research, we demonstrated a display medium constructed with the microfluidic emulsion technology, holding most of the advantages of a reflective display.

PRINCIPLE

Emulsion Droplets

The emulsion droplets are commonly produced by shear force between two immiscible fluids with added surfactant. Surfactant acts as an emulsifier in production of emulsion droplets whose surface tension is effectively reduced with the surfactant. The T-junction microchannel design can stably segment two immiscible fluids by shear force to form two discrete phases (continuous phase and dispersed phase) [6].

In our study, the emulsion droplets consisted of water as the dispersed phase and a photo crosslinkable solution as the continuous phase. Norland Optical Adhesive (NOA) 74 was adopted as the continuous phase because of its high adhesion to the hydrophobic PDMS channel walls and moderate viscosity in our study.

Particle Polarization and Dielectrophoresis

Particle polarization and dielectrophoresis (DEP) are the two forces investigated for manipulation of particles between two parallel plates with electrodes. By UV light irradiation, the continuous phase of a photocrosslinkable solution successfully encapsulated display medium droplets in the microchannel. Therefore, particles were freely dispersed in the emulsion droplets encapsulated by the crosslinked and solid continuous phase. When applying an AC electric signal between two parallel plates, particles are polarized to form vertical chains at first. With an electric field *E*, the induced dipole moment *m* of the suspended spherical particle is expressed as [2]:

$$m = 4\pi r^3 \varepsilon_l \left(\frac{\tilde{\varepsilon}_p - \tilde{\varepsilon}_l}{\tilde{\varepsilon}_p + 2\tilde{\varepsilon}_l}\right) E, \tag{1}$$

where r denotes the radius of a particle, ε_l is the permittivity of the liquid, and $\tilde{\varepsilon}_p$ and $\tilde{\varepsilon}_l$ are the complex permittivities of the particle and liquid, respectively. The particle chain transformation is thus not only determined by the amplitude and frequency of the electric field, but also strongly influenced by the electric properties of the particles and liquid. The attractive force between polarized particles spaced *d* results from a dipole–dipole interaction and is described as [2]:

$$F = \frac{6m^2}{4\pi\varepsilon_l d^4}, \tag{2}$$

where *m* is the dipole moment, expressed by Eq (1). For a particular *E*, we can obtain a more rapid particles movement by increasing the particle concentration to decrease *d*. After particles were chained in vertical lines, they were then aggregated to the sides of the emulsion droplets by the negative DEP force due to the non-uniform electric field within the droplet sphere. the DEP force is expressed as [7]:

$$F_{DEP} = 2\pi r^3 \varepsilon_l Re\left(\frac{\tilde{\varepsilon}_p - \tilde{\varepsilon}_l}{\tilde{\varepsilon}_p + 2\tilde{\varepsilon}_l}\right) \nabla E^2, \tag{3}$$

With shear forces on two immiscible fluids, the emulsion droplets are produced stably in microchannel. The display medium is future encapsulated by the photocrosslinked continuous phase. Moreover, the suspended neutral polystyrene particles are actuated by particles polarization and DEP forces to achieve a display medium in microchannel as shown in Fig. 1.

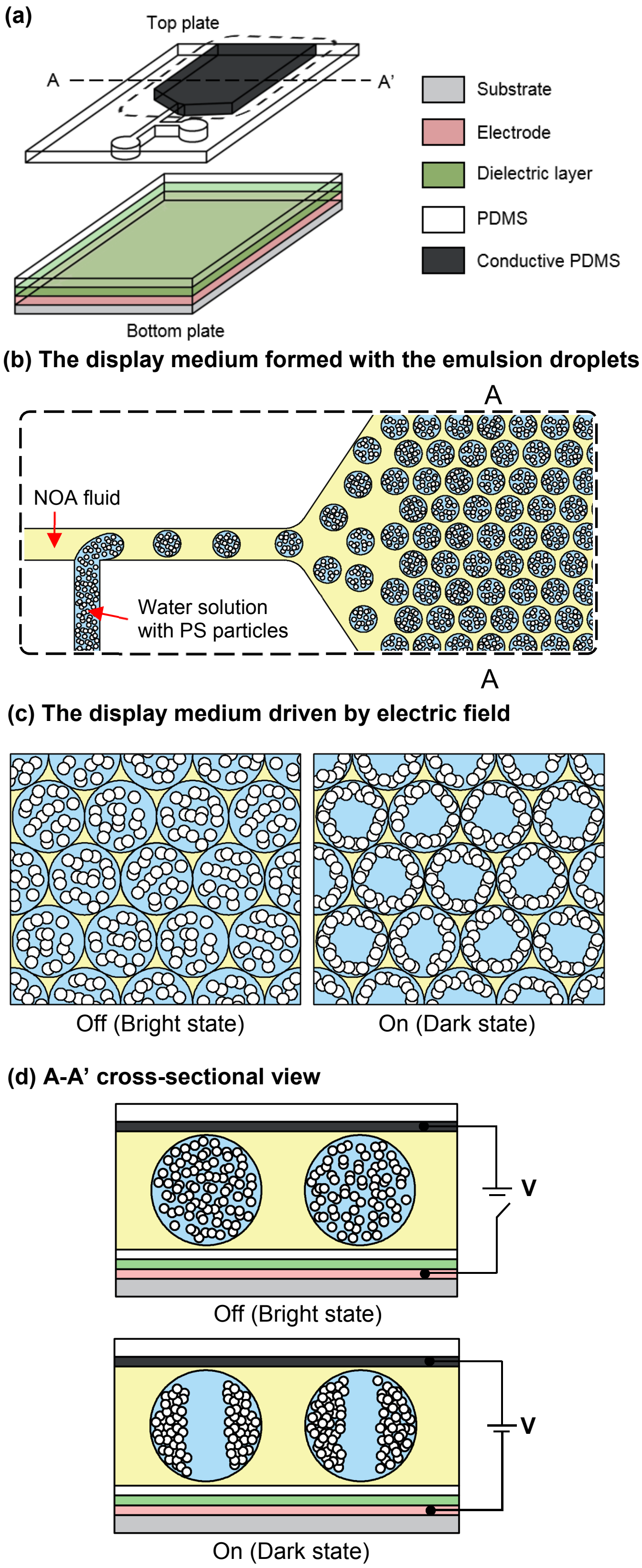

Figure 1: The schematic illustration of a particle-based display medium. (a) Angled view with a structured top plate and a plane bottom plate. (b) The display medium formed by the emulsion droplets accumulated and fixed with the NOA fluid crosslinked by UV light. (c) and (d) The top view and A-A' cross-sectional view of the tank area during operation.

DESIGN

The display medium was prepared and driven between two plates as shown in Fig. 1. The top plate was composed of microchannel structures made of conductive polydimethylsiloxane (PDMS) and a downstream tank area using conductive PDMS mixed with carbon black (4 wt.%) powders for following display medium driving. The bottom plate was a glass substrate coated with indium tin dioxide (ITO), SU-8 (dielectric layer, thickness 1.1 μm), and PDMS (thickness 1 μm) as shown in Fig. 1a. Emulsion was constructed along the microchannel with the dispersed phase of water solution with white PS particles (diameter 3 μm) and the continuous phase of a photo crosslinkable solution. The display medium was obtained by curing the closely accumulated emulsion droplet array in the tank with a UV light source (Fig. 1b). After the emulsion droplets were fixed, the PS particles were actuated by polarization and negative dielectrophoresis forces (Fig. 1c and 1d).

EXPERIMENT

Emulsion Droplet Formation in Microchannel

The emulsion droplet (diameter 110 μm) array was successfully formed in the microchannel and accumulated in the tank with stable pressure applied to the continuous phase (100 mbar) and the dispersed phase (80 mbar) as shown in Fig. 2a and 2b. The display medium was completely encapsulated with NOA fluid cross-linked by UV light (320-500 nm 556 mW/cm^2 for 5 s) as shown in Fig. 2c.

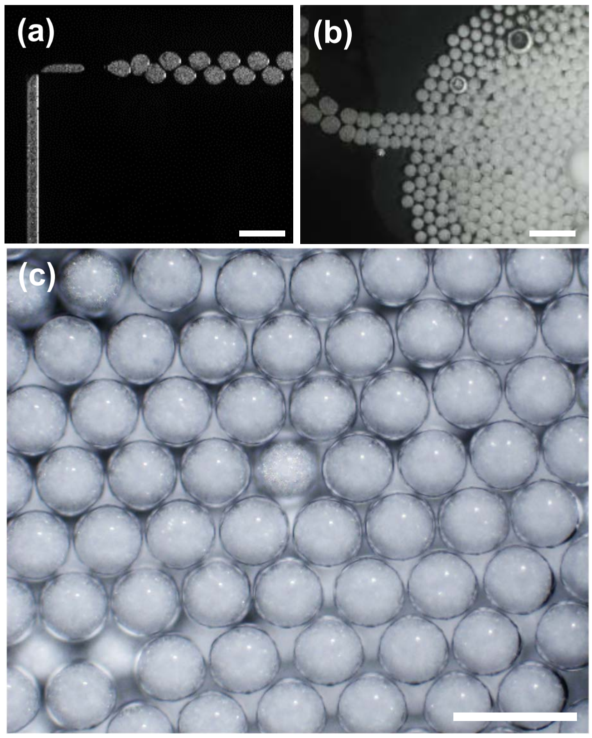

Figure 2: (a) and (b) The emulsion droplets produced stably by shear force in T-junction microchannel with continuous NOA fluid and dispersed white PS particles water solution. (c) The emulsion droplet array encapsulated by NOA fluid crosslinked with UV light. Scale bar: (a-b) 400 μm (c) 200 μm.

Particles Behavior Observation

Inside the droplets, PS particles were manipulated by applying a square wave AC signal with 500 kHz and 40 Vpp to generate an appropriate electric field inside the droplets. The PS particles were actuated by two mechanisms at the same time: (1) particle polarization to form vertical chains with the applied electric field (0.33 MV/m^{-1}), and (2) PS particles chain aggregated to the sides of the emulsion droplets by nDEP force due to non-uniform electric field in the sphere as shown in Fig. 3a and 3b.

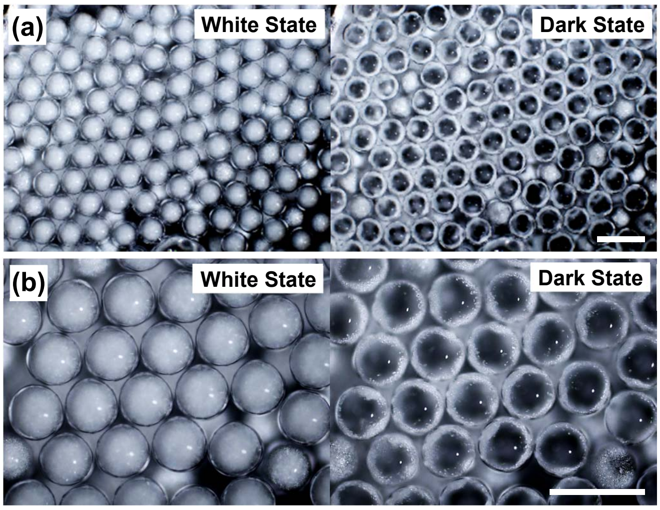

Figure 3: The electronic paper device switched between bright and dark states with voltage application (0.33 MV/m^{-1}). (a) and (b) The observation of the emulsion droplets with varied magnifications with power off (left) and power on (right.) Scale bar: 200 µm.

Display Reflectivity Measurement

For each emulsion droplet, bright and dark states can be switched showing distinct reflectivity with voltage application. The normalized reflectivity of the on and off states were measured and plotted in Fig. 4. Currently, the turn-on time is faster than the passive turn-off time. The responses would be further improved with optimized material and driving signal as well as active turning off scheme.

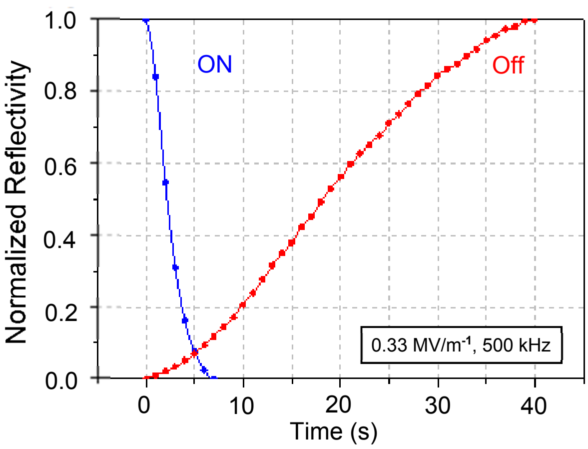

Figure 4: On/off response time with the normalized reflectivity of one emulsion droplet.

CONCLUSIONS

With the emulsion microfluidic technology, we demonstrated a self-assembled and packaged display medium. The droplet formation, droplet encapsulation, and particle manipulations were performed in the microchannel, which greatly simplifies the fabrication, packaging, and driving procedures. The response of the display medium was evaluated with the reflectivity.

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