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PAPER

Particle chain display – an optofluidic electronic paper†‡

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A particle-based display medium and a driving mechanism insensitive to the charge polarity of those particles, based on the transformation of particle chains, are developed for reflective electronic paper displays. Particle chains are formed by dipole–dipole interactions between polarized particles with an appropriate electric field applied across the tested display medium, *i.e.* the solution that regulates the light in the field of display technology, containing neutral polystyrene (PS) particles dispersed in water. Formation of the particle chains results in a large change in optical transmittance and reflectance of the display medium. The performance of the particle chain displays (PCD) was evaluated according to macroscopic (device), microscopic (particle) and optical (reflectance) points of view. A display medium (thickness 100 μm) containing colored PS particles (3 μm, 2.5% w/v) was polarized to display the fixed images of the directly driven electrodes and programmable images of arrayed (5 × 5) electrodes with electric fields (0.48 MV m^{-1} and 0.09 MV m^{-1}, 500 kHz, respectively). The formation of particle chains under electric fields (0.2 MV m^{-1} and 0.4 MV m^{-1}, 500 kHz) was observed in the microscopic images of a display medium (thickness 100 μm) with fluorescent PS particles (5 μm, 1%). Images recorded with a confocal microscope demonstrated the particle chains. The opacity, a common parameter serving to characterize a display medium, was derived by measuring the reflectance ratio of a black background to a white background of the display medium with varied thickness and particle concentration. The temporal response of a display medium (thickness 50 μm) with black PS particles (3 μm, 5%) was tested. When an electric field (0.6 MV m^{-1}, 500 kHz) was applied, the reflectance increased twice at the first data point in 0.7 s, attaining a contrast ratio of 2. Application of a voltage (20 s) yielded a contrast ratio of 10. The performance of a tested display medium, composed of simple PS particles and water and driven to form particle chains by polarization, is reported.

Introduction

The importance of electronic paper is increasing with urgent demand and keen competition in consumer electronics. Electronic paper is a paper-like display pursuing the goals of being reflective, flexible, bendable, portable and bistable, and with small consumption of electric power. Of several new display technologies reported, some have already been made commercially to fulfill the demands of electronic paper. We classify these approaches into electronic paper that is either particle-based or non-particle-based. In the former case, electrophoretic displays (EPD),[1,2] Gyricon displays,[3] quick-response liquid-powder displays (QRLPD)[4] and other techniques have been demonstrated. Cholesteric liquid-crystal displays,[5] electrowetting displays and [6,7] micro-electro-mechanical system (MEMS) displays[8] have been reported to achieve non-particle-based electronic papers. The actuation mechanisms (*e.g.*, electrophoresis and electrowetting) and materials (*e.g.*, liquids and particles) found in most displays are also commonly investigated in the field of microfluidics. Electronic paper can, hence, be regarded as a promising example of optofluidics that applies microfluidics to achieve optical effects.

In general, a particle-based display provides a large reflectance at a small cost relative to other technologies. The dyed particles strongly reflect the incident light and display the desired saturated colors. Particle suspensions are suitable for developing bendable and flexible displays because a slight change in the

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‡ Electronic supplementary information (ESI) available: calculations of the electrophoresis and dipole–dipole interaction forces under electric field 2 MVm^{-1}; video of operating a display medium (thickness 100 μm) with red PS particles (3 μm, 2.5%) under an electric field (0.25 MV m^{-1}, 500 kHz) (video 1); apparatus for reflectance measurements (Fig. S1); effective transmittance measured with a UV-visible spectrophotometer (Fig. S2); demonstrations of display medium materials (Fig. S3), and proposed color PCD (Fig. S4).

thickness of the suspension does not influence the display performance, unlike liquid-crystal displays (LCD) that typically require a precise and fixed thickness. Among the particle-based techniques, electrophoretic deposition (EDP) is a mechanism well known to drive particles used in commercial products.[1,2] In EPD, particles in a couple holding opposite charges are implemented, generally driven with a DC electric field. Oppositely charged particles are separated; each particle is attracted to the corresponding electrode based on its charge polarity. The main concept of EPD is to present dyed particles of one color by selectively attracting them beneath the upper electrode with an appropriate electric field. Common EPD can, hence, present only two colors or shades, such as black and white. Although various configurations of devices have been demonstrated, including use of a colored solution or particle movement in plane,[9] particles in at most two groups with separate charge polarities can be driven by electrophoresis in a pixel at the same time, which makes color EPD more challenging.

Here, our objective is to develop a particle-based reflective display medium, signifying a solution that regulates light in the field of display technology and a driving mechanism that is insensitive to the charge polarity of the particles, based on our previous work on particle manipulation in a moving droplet.[10,11] The display medium is a simple suspension of uncharged neutral particles in water; we induce charges on the particles to polarize them instead of using their inherent charges. The polarized particles form particle chains out of plane and parallel to the lines of the electric field. These particle chains decrease the planar density of particles and greatly alter the transmittance and reflectance of the display medium. Hence, particle chain displays (PCD) enable the achievement of a display pixel having bright and dark states using the particle suspension as a simple display medium.

Principles

As described above, EPD has been demonstrated for large black and white electronic paper displays and revealed the opportunities to create palm-top readers with DC electric fields, but with the ability to drive at most two particle groups with opposite charge polarities. Color EPD are achieved mainly with color filters that increase the cost of fabrication and decrease the brightness of the display. To overcome the particle limitations, we attempted to apply varied electric signals to drive the particles. When an electric field (DC or AC) is applied to a particle suspension, the field causes the particle to execute motion and redistributes charges or ions around the particle surface. Two major phenomena – electrophoresis and polarization – are generally observed and applied to manipulate the particles. An appropriate AC electric field causes a charge redistribution at interfaces between the particles and the liquid, at which a discontinuity in conductivity or permittivity exists. An originally random particle (Fig. 1(a)), thus, becomes polarized in the electric field and attracted to neighbor polarized particles to form particle chains out of plane and parallel to the electric field, as shown in Fig. 1(b). Before application of a voltage, the particles are randomly dispersed and reflect the incident light. A display pixel that contains random particles, hence, shows the color of the particles. When a uniform AC field is applied between the upper and lower parallel electrodes, the pixel displays the color of the background because the polarized particles form particle chains and allow incident light to penetrate through the display medium. As a result, we can define two states of a display pixel of PCD – a non-transparent or dark state, as shown in Fig. 1(a) and a transparent or bright state, as shown in Fig. 1(b).

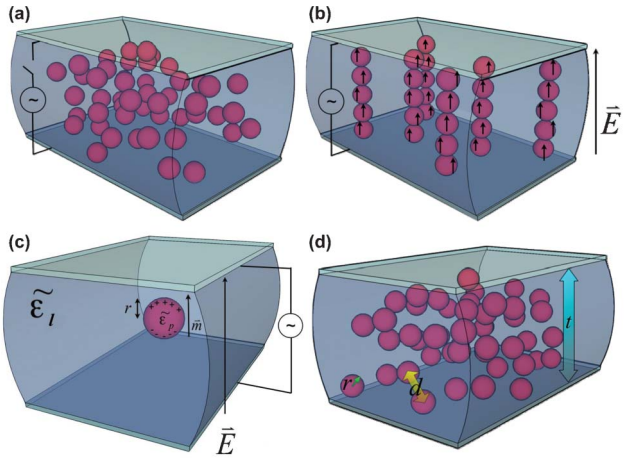

Fig. 1 Principle of the PCD. (a) Dark state for particles in the display medium randomly dispersed. (b) Bright state when an applied voltage polarized the particles to form chains. (c) Dipole moment induced in a uniform electric field. (d) Dimensions required to calculate the dipole–dipole interaction force.

As shown in Fig. 1(c), under an electric field E, the induced dipole moment, m, of the suspended spherical particle is expressible as[12,13]

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

in which 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 term within parentheses, called the Clausius–Mossotti factor, depends on frequency because the complex permittivity $\tilde{\varepsilon}$ is expressed as

$$\tilde{\varepsilon} = \varepsilon - i\frac{\sigma}{2\pi f} \quad (2)$$

in which ε denotes the permittivity, σ the conductivity and f is the frequency of the applied electric field. According to eqn (1), the dipole moment is proportional to the amplitude of the electric field, the cube of the radius and the Clausius–Mossotti factor. 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 (shown in Fig. 1(d)) results from a dipole–dipole interaction and is described as[14]

$$F = \frac{6m^2}{4\pi\varepsilon_l d^4} = \frac{24\pi r^6 \varepsilon_l \left(\frac{\tilde{\varepsilon}_p - \tilde{\varepsilon}_l}{\tilde{\varepsilon}_p + 2\tilde{\varepsilon}_l} \right)^2 E^2}{d^4} = \frac{24\pi r^6 \varepsilon_l \left(\frac{\tilde{\varepsilon}_p - \tilde{\varepsilon}_l}{\tilde{\varepsilon}_p + 2\tilde{\varepsilon}_l} \right)^2 V^2}{d^4 t^2} \quad (3)$$

in which m is the dipole moment, expressed by eqn (1), V is the voltage drop across the display medium and t is its thickness. As

eqn (3) shows, when we use a particle suspension with an increased concentration of particles, for a particular E, decreased d increases F and consequently a more rapid response of the PCD occurs. To provide a particular value of E with a smaller applied voltage, decreasing t is appropriate, but the concentration (correlated with d) and thickness of the display medium also influence the tint and contrast ratio of the display pixel. We therefore designed varied experiments to demonstrate the performance of the PCD from the macroscopic (device), microscopic (particle) and optical (reflectance) points of view.

Experimental results

Device preparation

Aqueous suspensions of polystyrene (PS) microspheres containing fluorescent (3 μm, Polysciences Inc., and 5 μm, Duke Scientific Corp.) or colored (3 μm, Polysciences Inc.) particles were tested as the display medium of PCD because of their desirable properties, including precise size, variable colors and well documented electric properties.[15–17] Water was similarly used in this work because of its well known properties. In theory, the formation of particle chains applies to various particles with varied size and electric properties in various liquids. Three examples of the use of other particles and liquids are shown in the ESI.‡ The tested device contained two parallel glass plates (thickness 0.7 mm) coated with indium tin oxide (ITO), as shown in Fig. 2(a). The ITO layer on the lower plate was patterned with photolithography and wet chemical etching. The patterned ITO was then covered with a negative photoresist SU-8 (thickness 1 μm, SU-8 2002, MicroChem) as a dielectric layer. A fluorocarbon (thickness 55 nm, Teflon, AF 1600, DuPont) layer was then spun to make the surface hydrophobic to prevent adhesion of the particles. The ITO on the upper plate was not patterned, but coated with a fluorocarbon film (Teflon, thickness 55 nm). The two plates were separated with appropriate spacers, such as double-sided tapes, stainless steel spacers (MiSUMi) and microfabricated polydimethylsiloxane (PDMS, Dow Corning) structures to ensure the height of the display medium. The employed ITO, SU-8 and Teflon are highly transparent. The dielectric layer, SU-8, is unnecessary when driving particles that are dispersed in a non-conductive liquid. An adequate particle suspension was dispensed between the plates for assembly. The upper unpatterned ITO electrode was connected to the electric ground. For devices with multiple patterned ITO electrodes, their contact pads on the lower glass plates were electrically connected to the common terminals of single-pole double-throw (SPDT) relays (LU-5, Rayex Electronics). The electric potential of the electrodes was switched with the relays between the electric ground and high potentials. An AC electric potential was generated from a function generator (33210A, Agilent Technologies) and amplified with an amplifier (A-303, A. A. Lab Systems). The relays were switched by the digital output signals of a data acquisition device (USB-6251, National Instruments) programmed with software (LabVIEW).

Device operation

Several devices with varied designs of electrodes, including directly driven and arrayed electrodes, as shown in Fig. 2(a),

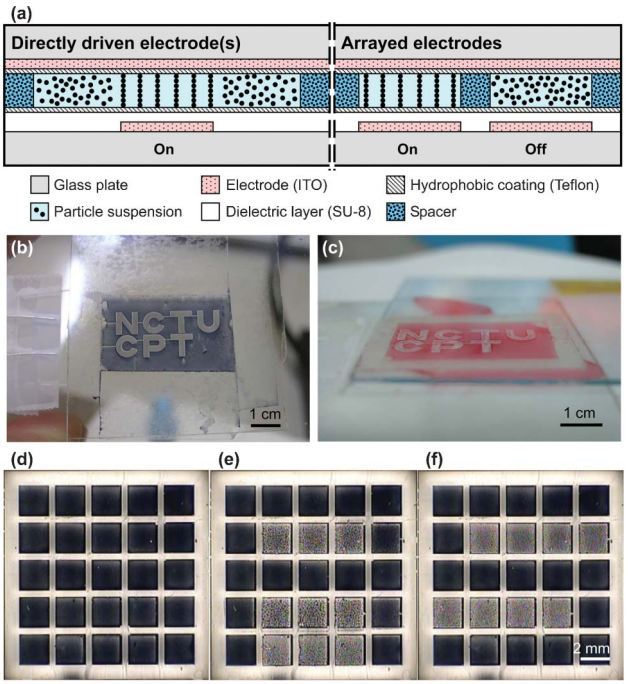

Fig. 2 The device designs and macroscopic observations. (a) The device cross section showing directly driven and arrayed electrodes. (b and c) The display medium (thickness 100 μm) with blue and red PS particles (3 μm, 2.5%) driven on by applying an electric field (0.48 MV m^{-1}, 500 kHz) on the directly driven electrode 'NCTU CPT'. (d–f) A display medium (thickness 100 μm) with black PS particles (3 μm, 2.5%) driven on applying an electric field (0.09 MVm^{-1}, 500 kHz) on particular electrodes of the electrode array (5 × 5).

were tested. As shown in Fig. 2(b) and (c), suspensions of blue and red PS particles (3 μm, 2.5% w/v, *i.e.*, 1.68 × 10^9 particles/mL) were packaged in a gap (100 μm) between parallel plates. When 48 V_{RMS} (*i.e.*, electric field strength 0.48 MV m^{-1}) at 500 kHz was applied between the upper unpatterned and lower patterned electrodes, the particles in the electric field region became polarized to form particle chains. These chains altered the transmittance and reflectance of the particle suspension to display the image of the directly driven electrode pattern 'NCTU CPT' of line width 2 mm. As shown in Fig. 2(b), the device was held in the observer's hand. The suspension of blue particles within the electric field became transparent to the observer, as shown in the regular digital camera image. The distant white background was visible through the 'NCTU CPT' electrode region; the region of random particles showed their color on reflecting the incident light. We have driven particles of varied colors using similar experimental conditions, showing that the color apparently did not alter their electric properties. As is discernible in Fig. 2(c), when observing a device containing red particles from an angle of 70° from the normal of the device (*i.e.*, viewing angle 70°), the white background is clearly visible through the regions of particle chains.

Another device design with arrayed electrodes was fabricated and tested. Fig. 2(d) shows an electrode array (5 × 5) containing segmented suspensions of black PS particles (3 μm, 2.5%) before the application of a voltage. Each compartment of the suspension represented a display pixel of dimensions 2 mm ×

2 mm × 100 μm (stature). The display medium was confined within the molded PDMS microstructures treated with an oxygen plasma for injection of a particle suspension and device bonding. When we applied a voltage (9 V_{RMS}, 500 kHz) on particular electrodes of the array, we demonstrated varied images, as letters shown in Fig. 2(e) and (f). In this experiment, the particle chains were formed even with a weak electric field, 0.09 MV m^{-1}.

Particle observation

Fig. 3 shows the transformation of particle chains observed with a microscope. For observational purposes, we dispensed a suspension of fluorescent PS particles (5 μm, 1%, *i.e.*, 1.4 × 10^8 particles/mL) between parallel ITO glass plates separated by 100 μm. The assembled devices were placed on an inverted fluorescent microscope (Olympus IX71, with cooled CCD camera DP30BW). Fig. 3(a) shows the randomly dispersed particles before the application of a voltage. About 700 particles were counted with the software (Image-Pro, Media Cybernetics) within the microscopic image (150 μm × 117 μm) under observation (Fig. 3(a)). When we applied a uniform electric field (0.2 MV m^{-1}, 500 kHz) to chain the suspended particles, the number of visible particles decreased to about 600, as shown in Fig. 3(b). Fig. 3(c) shows that the number of visible particles further decreased to about 400 when we increased the electric field (0.4 MV m^{-1}, 500 kHz). Variation of the number of particles or the planar density of particles was caused by the formation of particle chains through dipole–dipole interactions. On analyzing the microscopic image, focused on the inner surface of the lower plate, we found that the open area increased from 21.7% in Fig. 3(a) to 32.9% in Fig. 3(b) and 55.2% in Fig. 3(c). The open area, dependent on voltage, demonstrated a particle suspension with a tunable transmittance that can serve as a grey-scale display pixel.

Observing particles with a confocal microscope[18] provides three-dimensional (3D) images of the particle chains. We utilized a confocal-fluorescence microscope (Nikon A1R) to visualize the 3D distribution of fluorescent particles (3 μm) dispersed in water (concentration 0.6%, *i.e.*, 4.2 × 10^8 particles/mL). The excitation light (argon-ion laser, wavelength 488 nm) was transmitted through an objective lens (plan apochromat VC 20×, NA = 0.75) to illuminate the particles. The entire emitted light was subsequently collected with the same objective lens and then passed through a dichroic mirror (405/488) that excluded light at 488 nm. The emission then passed through a 12.8 μm pinhole to eliminate stray light and further passed through a filter (band pass 500–550 nm) inserted in a filter block; the thus refined light was detected with a photomultiplier tube (PMT). The 3D images were formed on stacking *XY* images in a series, captured individually at various *Z* locations through galvano-scanning. The thickness of an optical slice was set to be 0.5 μm. The scanning resolution in the *XY* plane was 1024 × 1024 and in the *XZ* and *YZ* planes was 1024 × 142. The resolving powers were 0.63 μm for the *XY* plane and 1.80 μm for the *Z* axis. To observe a display medium (thickness 70 μm), the scanning duration of each 3D image, as shown in Fig. 4(a) and (b), was about 9 min. All projection and 3D reconstruction of the images were processed with commercial software (NIS-Elements AR, Nikon, Japan). Before the application of a voltage, the particles were randomly dispersed with some sedimentation, as shown in Fig. 4(a). Particle chains were observed in Fig. 4(b) when a voltage (at 500 kHz) was applied.

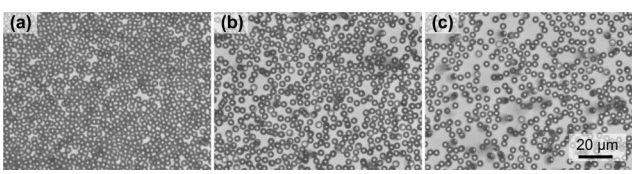

Fig. 3 Microscopic images of a display medium (thickness 100 μm) with fluorescent PS particles (5 μm, 1%) at varied strength of electric field. (a) Open area (21.7%) on the focused plan with no voltage applied. (b) Open area (32.9%) increased on formation of particle chains under an electric field (0.2 MV m^{-1}, 500 kHz). (c) Open area (55.2%) caused by an electric field (0.4 MV m^{-1}, 500 kHz).

Reflectance measurement

To obtain more quantitative information about the PCD, we constructed apparatus comprising basically of an integrating sphere, a halogen lamp, a lens, a CCD and an optical spectrometer (USB4000, Ocean Optics) to measure reflectance, as shown in Fig. S1 of the ESI.‡ The tested device was placed underneath one of three openings of the integrating sphere. Incident light from the halogen lamp (50 W) was transmitted into the integrating sphere from the side opening. The light was first evenly diffused in the integrating sphere and then shone on the device through the lower opening. The diffused light was reflected from the device and passed though the integrating sphere, then focused with lenses positioned above the upper opening of the integrating sphere. A portion of the focused reflected light was collected into an optical waveguide connected to the spectrometer; the rest of the reflected light was acquired by the CCD for observation and positioning of the device. An appropriate background of large or small reflectivity was placed under the device to reflect or to absorb, respectively, the incident light passing through the device. The magnitude of the measured reflectance of the apparatus was calibrated with standard specimens. In this work, the reflectance was analyzed at wavelength 550 nm.

The opacity, a commonly-used parameter to evaluate the display media,[1] of the device was first measured because it could provide information about an appropriate concentration and thickness of the particle suspension. As described above, the thickness of the display medium is critical for the performance of the device and directly influences the strength of the electric field and tints of the dyed particle suspension. The effects of concentration and thickness of the display medium were investigated on measuring the opacity, as shown in Fig. 5. The opacity is defined as a ratio of reflectance with a black background and with a white background.[1] When the background is covered completely by the particles, the opacity is unity, signifying that the reflectance is unaffected by the background change. We tested the suspension of black PS particles (3 μm) with three concentrations (2.5, 5 and 10%) and varied thicknesses (50 to 250 μm). As Fig. 5 shows, the particle suspension of a concentration of 10% attained an opaque condition (opacity equal to 1) with thickness 100 μm. For a

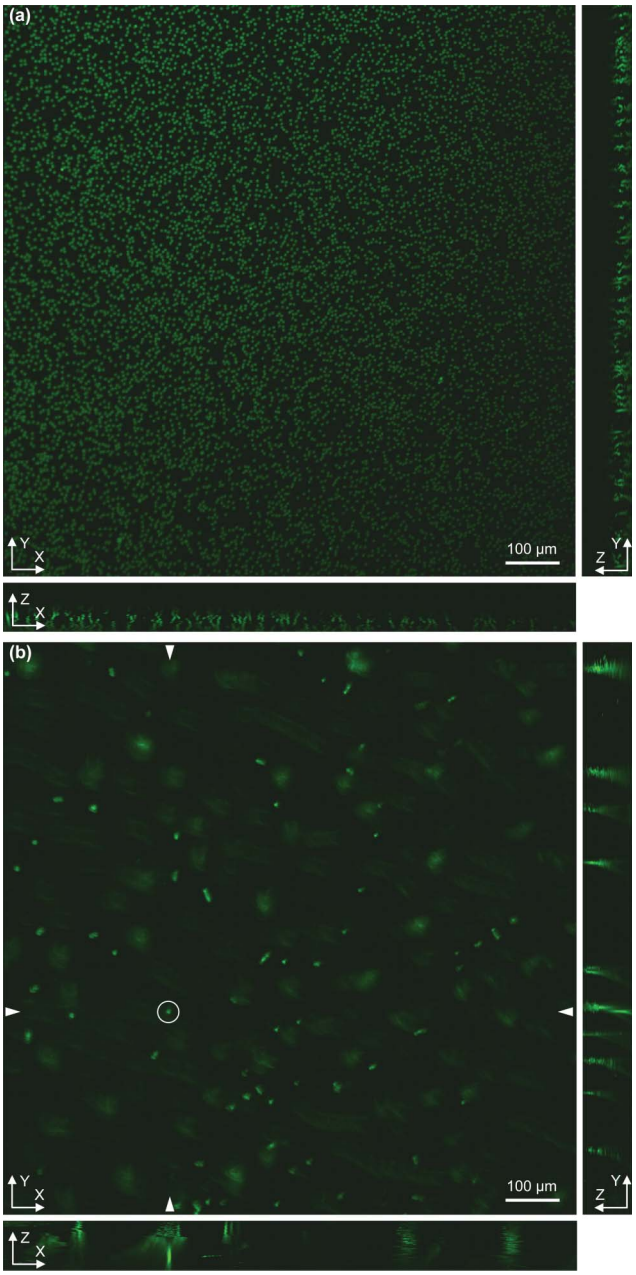

Fig. 4 Confocal microscopic images of a display medium (thickness 70 μm) with fluorescent PS particles (3 μm, 0.6%). (a) Before voltage application, the particles were randomly dispersed, as shown in the *XY* plane image. Some sedimentation of the particles was found as the *XZ* and *YZ* plane images show. (b) When a voltage was applied, particle chains were formed; a particle chain circled in the *XY* plane image is discernible in the *XZ* and *YZ* plane images that show the cross sections indicated with triangle symbols on the *XY* plane image.

particle suspension (10%) of a thickness greater than 100 μm, the suspension is considered oversaturated, with an excessive thickness or concentration. The oversaturated particle suspension would display a perfectly dark state, but might not present an ideal bright state. We hence avoided using a suspension with unit opacity. For example, in the following reflectance experiment, we examined the display medium with an opacity of 0.2. Moreover, the transmittance between 400 and 800 nm of the

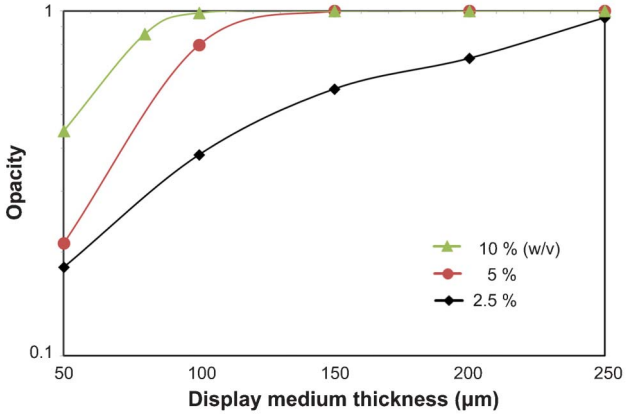

Fig. 5 Opacity measurements of a display medium with black PS particles (3 μm) of varied thicknesses and concentration.

display medium was measured with a UV-visible spectrophotometer, as shown in Fig. S2‡.

Fig. 6 shows the temporal response, recorded as the reflectance, of a display medium (thickness 50 μm) with black PS particles (3 μm, 5%) driven at 100 and 500 kHz. Limited by the speed of the spectrometer, each data point was spaced by 0.7 s. The reflectance change during the first 20 s after application of the signals (100 and 500 kHz) with varied strength

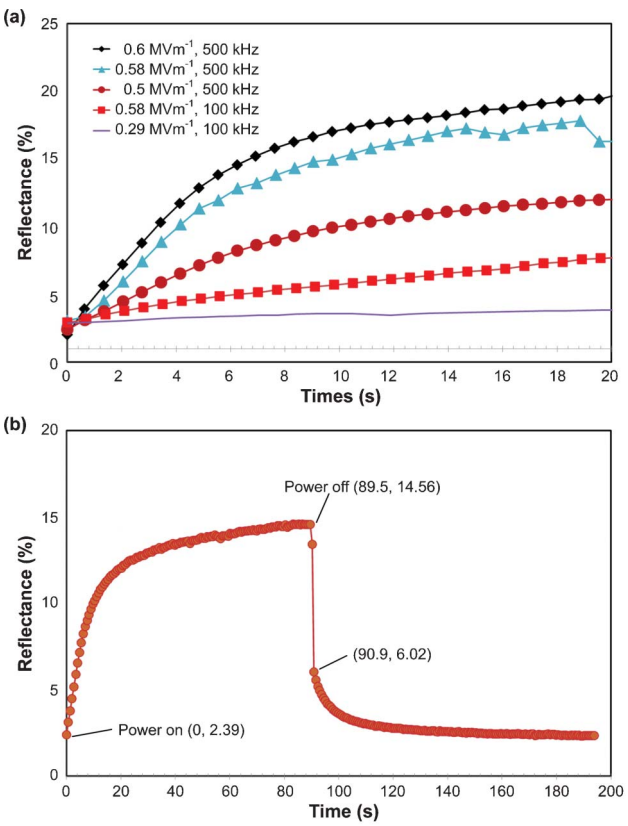

Fig. 6 Temporal response of a display media (thickness 50 μm) with black PS particles (3 μm, 5%). (a) Increase of reflectance on transformation of particle chains with varied applied signal. (b) On/off response on applying and terminating the electric field (0.5 MV m^{-1}, 500 kHz).

of electric field was recorded and is shown in Fig. 6(a). For signals at 100 kHz, the electric field (0.29 MV m^{-1}) scarcely altered the reflectance. With an electric field at a strength of 0.58 MV m^{-1}, we observed variation of reflectance by the 100-kHz signal. With the same field strength (0.58 MV m^{-1}), the signal (500 kHz) formed particle chains more efficiently, because the induced dipole moment depended on frequency, as described in eqn (1). For 500-kHz signals, a stronger electric field increased the reflectance; the applied voltage and frequency can, thus, both serve to tune the grey scale of a display pixel. When an electric field of 0.6 MV m^{-1} at 500 kHz was applied, the first data point (in 0.7 s) gave a contrast ratio of 2. During those 20 s, the contrast ratio increased to about 10. The contrast ratio or response time would be enhanced on increasing the strength of the electric field.

The response of applying and terminating the signal (0.5 MV m^{-1}, 500 kHz) was recorded for more than 180 s, as shown in Fig. 6(b). The initial reflectance at the dark state was 2.39%. The reflectance increased rapidly on application of the signal. Before terminating the signal, the reflectance attained 14.56% and the contrast ratio was 6.1, at 89.5 s. After terminating the applied signal, the reflectance decreased from 14.56% to 6.02% within 1.4 s and it returned to the initial reflectance, as shown in Fig. 6(b). Video 1 in the ESI‡ shows the response of a display medium (thickness 100 μm) with red PS particles (3 μm, 2.5%) on application of a signal (0.25 MV m^{-1}, 500 kHz) on the directly driven electrode 'NCTU'. The device operated continuously for several hours before the evaporation of the particle suspension hindered the formation of the particle chain. Packaging techniques resistant to water and vapor must be employed in the future to improve the packaging methods using double-sided tapes or PDMS bonding. The use of slightly volatile liquids can alternatively eliminate the evaporation.

Discussion

On comparison of the particle-based PCD and EPD technologies, several theoretical advantages are found in our PCD that are worthy of further development. In EPD, the DC electric field drives the particles traveling through the entire thickness of the display medium, generally several tens or hundreds of micrometers.[2] In PCD, the dipole–dipole interaction force needs only to drive the particles towards neighboring particles at a distance of a few micrometers. For example, the mean distance (d) between PS particles (3 μm) at a concentration of 5% (*i.e.*, 3.36×10^9 particles/mL) is only 6.7 μm. Moreover, the driving force in PCD is larger with the same strength of electric field. For example, the electrophoretic force to drive a slightly charged particle was about 5.2 pN in a DC electric field of 2 MV m^{-1}.[2] With an AC electric field of 2 MV m^{-1}, the dipole–dipole interaction force of the suspension of PS particles (3 μm, 5%) is 296.2 pN, calculated from eqn (3), assuming a Clausius–Mossotti factor of 0.5. Calculation of the electrophoresis and dipole–dipole interaction forces is present in the ESI.‡ Furthermore, because the particle chains alter the reflectance and transmittance of the particle suspension, PCD are suitable for developing not only reflective, but also transmittive and transflective electronic papers.

With a simple suspension of PS particles, we have demonstrated reflective PCD. Because particle movement depends on the properties of the particle and the liquid, the performance can be optimized in the future. For example, on applying a stronger electric field, a more rapid response and greater aspect ratio is achievable. Besides the use of PS particles and water, we have driven PS particles in glycerol to decrease the driving frequency to 10 kHz (Fig. S3‡). Polymers sensitive to temperature have been dissolved in water to provide tunable viscosity and particle stability. Inexpensive materials, charged particles of a laser-printer toner dispersed in silicone oil, have shown polarization at 150 Hz and DC electrophoresis. Core–shell particles, commonly used in electrorheological fluids,[19,20] would be candidates for the development of color PCD containing particles of three kinds in a single display pixel, because core–shell particles have typically two non-polarized frequencies, *i.e.*, cross-over frequencies,[12,13] that can serve to polarize and to drive particles in the other two groups (Fig. S4‡).

Conclusion

A new optofluidic display technology, PCD, suitable for application as reflective electronic paper is demonstrated with a simple display medium – an aqueous suspension of PS particles – addressed with a driving mechanism insensitive to charge that transforms the particle chains. The testing devices and systems were established. Information was displayed on applying electric fields (500 kHz) on the directly driven and arrayed electrodes between parallel glass plates to alter the transmittance and reflectance of the display medium. The performance was evaluated according to the measured reflectance. Optimizing the driving parameters and the employed materials will produce flexible, bistable electronic papers based on color PCD with improved contrast ratio and a more rapid response.

Acknowledgements

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