Flexible thermochromic displays

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***Abstract*— Large area flexible displays have many applications in information displays, decorative elements, and adaptive camouflage. Reflective displays, which change the actual surface color, have some advantages over emissive displays: they do not need the energy to emit light, they adapt automatically to the ambient lighting, and have a broad spectrum. Thermochromic materials can be used to implement flexible large-area low-resolution displays. We have demonstrated a reflective thermochromic display structure with 5cm x 5cm pixels fabricated on a thin Kapton foil using screen-printed heating elements, spray-coated thermochromic paint layers with controlled layer thicknesses, and copper traces for power delivery. The total thickness of the surface is under 200 µm.**

Keywords — reflective display; large area display; flexible display; thermochromic displays

I. INTRODUCTION

Large area displays have many applications as information displays in public places such as airports, railway stations, roadside advertisements, and traffic signs. Examples are the traditional electromechanical split-flap display, low-resolution light emitting diode (LED) displays, and decorative films. Emissive displays (LED, Organic light-emitting diode (OLED), Electroluminescent (EL), and plasma displays) actively produce light. Transmissive display panels as such (Liquid- crystal display (LCD) and electrowetting), do not emit light but modulate the light from a light source behind the panel. Reflective displays change the actual surface color. Since the display does not actively emit light but reflects incident light, it does not require external energy. On a display, the reflectance spectra of the pixels or symbols are modified to show an image. [1]

Reflective displays have the advantage over emissive displays in adapting to ambient lighting since they reflect a part of the incident light back. To be visible in ambient lighting, the radiosity of the display should be of the same order of magnitude as the irradiance. Outdoors the maximum irradiance of direct sunlight is during the midday and is roughly 1 kW/m^2 corresponding to 100000 lx. Artificial lighting in dimly lit indoors is around 10 lx. The maximum radiosity and the four orders of magnitude dynamic range are difficult to achieve with emissive displays. [2]

Colors of reflective displays have a broad spectrum. On emissive LED displays, the spectrum of the emitted light has three narrow peaks typically around 630nm (Red), 560nm (Green), and 450nm (Blue) [3]. The human eye perceives the color generated by the three separate components as a continuous spectrum. The type of spectra can be measured via a hyperspectral camera, and for example, Fig. 1 shows the wide spectra of four reflective thermochromic pigments.

II. THERMOCHROMIC DISPLAYS

A. *Thermochromic materials*

We have studied the usage and colorimetric properties of thermochromic materials from various sources [4,5]. These materials are readily available from multiple sources, are low-cost and easy to process. The color of thermochromic materials depends on their temperature. For example, thermochromic leuco-pigments change from a colored state in a low temperature to a translucent state in a higher temperature. The transition temperature is typically between 10 °C and 80 °C and the change is gradual within two degrees. Thermochromic pigments are microcapsulated into ~ 5-10 µm particles, with a ~ 1 µm wall [6].

Thermochromic displays can have a large area, a reflective surface, and a thin structure suitable for roll-to-roll manufacturing. On the other hand, the resolution may be low, the color gamut is limited, and controlling the brightness of an element is difficult, restricting the areas of application to e.g. information displays, signage, and adaptive camouflage.

B. *Color mixing on displays*

Our goal is to be able to produce a limited number of different colors, black, green, and brown, with specific hues. For this, color mixing theories and practical approaches to color mixing are widely considered [7,8,9]. There are several ways to arrange the materials on the display to produce different colors (Fig. 2).

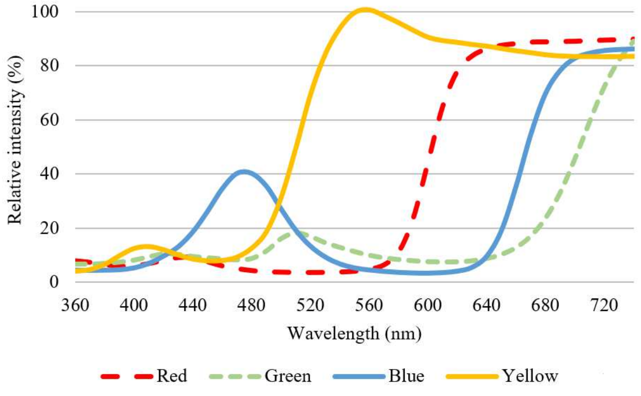

Fig. 1. Reflectance spectra of SFXC pigments at 25 ºC measured with a spectrophotometer CM-2300d (by Konica Minolta).

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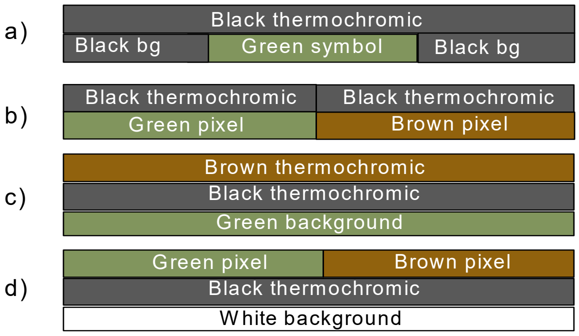

Fig. 2. Approaches for thermochromic displays: a) simple pixels, b) optical color mixing, c) layered color mixing, and d) the reversed structure.

Monochromatic displays with simple pixels or symbols can be directly implemented (Fig. 2a). Multicolor displays can be implemented with optical color mixing or with stacked structures of pigments with different activation temperatures. In optical color mixing subpixels of different primary colors are used (Fig. 2b). This works well with emissive displays, but because thermochromic pigments have a broad spectrum and only two states, colored and translucent, optical color mixing is not an optimal approach.

Layered color mixing is based on the use of several thermochromic pigments with different transition temperatures (Fig. 2c). In low temperatures the surface has the color of the top layer. At a higher temperature, the top layer becomes translucent, and the color of the underlying layer becomes visible. The approach can be used also with several layers of pigments. The problem is that in a colorless state, the layer is not completely transparent but translucent and reflects some of the incident light back, thus decreasing the color saturation of the underlying layers.

The structure can also be turned upside down (Fig. 2d). A black thermochromic layer is on top of a bright white base layer. In a low temperature, the surface is black and in a high temperature, the surface is white. The diffuse reflectance from the colorless thermochromic layer does not matter. The desired color is printed on top of the structure as it would be printed on white paper. In this approach, the hue of the color can be freely chosen since it is not limited to the hues of the available thermochromic pigments.

The Kubelka-Munk (KM) theory is a widely used model for describing the optical properties of pigments and paints [10]. The KM theory relates the reflectance R and transmittance of a material to its absorption K and scattering S coefficients, which describe how light interacts with the material. With KM theory, it is possible to calculate the absorption and scattering coefficients from the reflectance and transmittance data, and vice versa. Unfortunately, the coefficients are not available for thermochromic pigments.

A simplified one-parameter KM theory gives adequate results if S is the same for all components [11]. The thermochromic pigments are microcapsules of the same type of material and of the same size, thus it is feasible to assume that the light scatters equally in their colorless state. Is it enough to know the K/S-ratio of all components:

$$(K/S) = (1-R)^2/2R \tag{1}$$

$$(K/S)_{mix} = C_1(K/S)_1 + C_2(K/S)_2 + \ldots \tag{2}$$

$$R = 1+(K/S) - sqrt((K/S)^2 + 2(K/S)) \tag{3}$$

where (1) the spectrophotometer is used to measure R of thick layers of all components. K/S-ratio for a mixture of components with known concentrations C can then be calculated (2), and further R for the mixture can be solved (3). Moreover, with thermochromic pigments, the measurements must be done in both a colored and colorless state. KM theory was used to calculate the surface colors of a structure with two and three layers of paint to produce the desired colors.

C. *Proof of concept implementations*

Display structure can be thought of as two separate parts: color layers on top of the heating elements. We have designed several proof-of-concept (PoC) implementations of different display structures with both optical and layered color generation. Here we describe two implementations.

1) Optical color mixing on carbon fiber heating elements

The temperature difference between the low and high temperatures must be roughly 10 °C to produce a clear color change. The time for heating the display surface elements depends on their heat capacity and heating power. Cooling the elements is due to the passive dissipation of heat through radiation and transfer to air. Thus, the thinner the structure, the faster the color change.

To create the thermochromic layers, color pigments are mixed with a binder into a paint, which is applied to the surface by e.g. screen printing or spray coating. Screen printing can be used to create the desired pixel or symbol pattern on the surface and the layers are of controlled thickness. Spray coating needs a mask if patterning is required, and the layer thickness is more difficult to control. On the other hand, if the whole surface is to be painted, spray coating is a good choice.

The first PoC consists of lightweight and robust heating elements, which are adhered to pixel control boards. Based on stretchable electronics materials [12], the heating elements are made from two laminated thermoplastic polyurethane films (230 g/m^2), which have a laser-cut conductive carbon fiber cloth (17 g/m^2), between them. One heating element has three pixels in a row, and each pixel has three colors, and each color is divided into two 12 mm * 80 mm size pixel stripes. A primer, passive color pixels, and UV-protecting layer are applied on the top side of the heating elements. The active thermochromic pixels are brown, green, and black. Altogether, there are 18x12 three colored pixels organized in six-pixel groups, each controlled with an electronics module (Fig.3). The size of the display structure is 55 cm x 85 cm, and it weighs 600 g.

Fig. 3. Assembly of the display with three-colored pixels and carbon fiber heating elements.

2) *Layered color mixing with printed heating elements*

The second PoC implementation has 5 cm x 5 cm square pixels in a 6x6 matrix with a green and brown colored bottom layer and a black thermochromic top layer. The color change temperature is 27 °C. The thickness of the structure with the heating element and two pigment layers is 160 µm. Heating elements are screen printed with silver ink on 50 µm Kapton, and the resistance of each pixel is 10 Ω. Power distribution is with etched 35 µm copper lines (Fig. 4a).

3) *Heating electronics*

Power for heating resistive (carbon fiber or screen printed) elements is provided by a set of control modules. The main features are a robust RS485 data bus interconnection between a personal computer and the modules, temperature sensors for each pixel, an on-board microcontroller, and the capacity to drive currents up to 2.4 A to each pixel. The maximum practical voltage is 24 V, giving 57.6 W per pixel. Pulse width modulation (PWM) is used for closed-loop control of the power to have stable pixel temperatures in changing ambient weather conditions. Modules can drive 18 separate channels. The module is designed so that it can be implemented as a four-layer flexible PCB of 270 mm x 21 mm (Fig. 4b).

III. RESULTS

On the first PoC with carbon fiber elements, heating a pixel stripe with 6 W changes the temperature from 25 °C to 35 °C in 1.2 seconds. Pixel cools down back to 25 °C in 2.8 seconds at an ambient temperature of 20 °C. The maximum frequency for cyclic color chance is 0.25Hz. The transition temperature of the thermochromic pigments used is 31 °C. Initial field tests have also been performed at ~ 10 °C temperature and the available power is enough for producing the color change. The result of optical color mixing was evaluated only visually.

With the second PoC with screen printed heating elements, in an indoor laboratory environment with 21 °C ambient temperature, heating to 40 °C with 1,2W power per pixel takes 1.3 s. Moreover, passive cooling down below the activation temperature of 27 °C takes 2.7 s. Keeping the temperature at 40 °C requires 200 W/m^2 (Fig. 5).

The pixel colors were measured with a spectrophotometer (Table I), which results are presented in CIE L*a*b*coordinates. The black color of the display is very close to masstone black (dL*a*b*=0.18, on brown).

Fig. 4. a) A screen-printed flexible heating element (on the top) with the etched current distribution lines (on the bottom), b) heating electronics for the heating elements, where the microcontroller, nine load switches and retangular contact pads are visible.

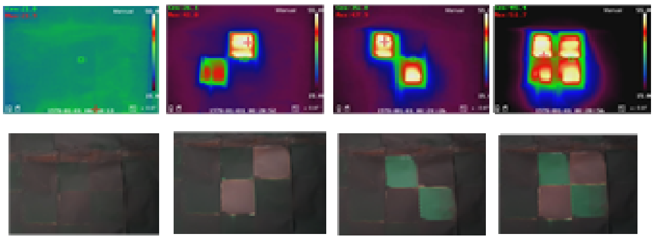

Fig. 5. Thermal images on the top row and corresponding visual images on the bottom row.

TABLE I. CIE L*A*B VALUES FOR COLORS ON DISPLAYS

	L*	a*	b*
Black on brown	25.5	0.73	-0.19
Black on green	25.8	-2.49	0.69
Display brown	35.1	4.23	0.83
Display green	38.6	-15.6	5.62
Brown base layer	31.1	4.64	2.80
Green base layer	34.6	-18.2	8.55
Black masstone	25.5	0.77	-0.01

The green color on display compared to the green base color is slightly brighter (dL*=4.0) and less vivid (da*b*=3.9). The brown color on display compared to the brown base color is also brighter (dL*=4.0) and less vivid (da*b*=2.0).

IV. DISCUSSION

The first PoC implementation was based on optical color mixing and carbon fiber heating elements. The overall colors produced by optical mixing were studied visually and it was found that the quality was not satisfactory. It was mainly a result of the poor quality of color layers and the suboptimal choice of the three primary colors. The small pixel size allowed to have a rather short minimum watching distance of ~10m. The heating element structure was complex to assemble and probably not easy to manufacture on a roll-to-roll production line. Still, the modular electronics units proved to be well-designed and flexible, and the design has been used also in other prototype implementations.

The second PoC design was based on a layered color scheme and screen-printed heating elements. The colors on the display were rather close to what was desired. The slight bleaching of the color when seen through the thermochromic layer can be compensated by decreasing the luminosity of the base layer. The structure is very thin, only 160um, and its heat capacity is low. Thus, heating and cooling is fast. The structure is suitable for roll-to-roll manufacturing.

V. CONCLUSIONS

We have demonstrated that thermochromic materials can be used to implement very thin, light, and flexible large-area displays. On the downside the resolution is low and the color gamut is limited. The structures are simple, and the materials are readily available at low cost. Further development is still needed to be ready for roll-to-roll manufacturing.

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