

# Silicon Color Filters for Light-Recycling Displays

Emma C. Regan<sup>1,2</sup>, Yichen Shen<sup>1</sup>, Aviram Massuda<sup>1</sup>, Owen D. Miller<sup>3</sup>, Marin Soljačić<sup>1</sup>

<sup>1</sup> *Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

<sup>2</sup> *Applied Science and Technology Graduate Group, University of California Berkeley Berkeley, CA 94709, USA*

<sup>3</sup> *Applied Physics and Energy Sciences Institute, Yale University, New Haven, CT 06520, USA*

Corresponding author: [ycshen@mit.edu](mailto:ycshen@mit.edu)

We propose a set of silicon reflective transmission filters for light-recycling displays that are compatible with high-throughput nanofabrication technologies and have excellent angular stability.

The backlight in a liquid crystal display [Fig. 1(a)] uses significant power in commonly-used devices. In most situations, a smartphone backlight consumes more power than any other functional component of the phone [1]. Beyond personal electronics, industrial displays for advertising and entertainment also consume an enormous amount of energy. To increase display efficiency, a reflective diffuser is typically used to recycle light directed to the back of the display panel by a reflective rear polarizer [2]. However, light recycling has not been fully explored. Common filters based on dyes and pigments absorb more than 70% of the backlight power instead of recycling it.

While light-recycling transmission filters could save energy, effective and low-cost filters do not yet exist. Planar, multi-layer dielectric stacks (Bragg filters) can serve as efficient reflective transmission (RT) filters and have been used for resonant enhancement in many optical devices [3]. However, each color requires a different thickness and number of layers, so they are incompatible with high-throughput fabrication methods. Plasmonic filters are an interesting alternative, but they are largely absorptive due to the metal components. [4].

In this work, we take advantage of the low absorption and high refractive index of crystalline silicon (c-Si) [5] to design energy-saving RT filters. We optimized a patterned c-Si slab on a quartz substrate, while restricting the thickness to be the same for all filters [Fig. 1(b-d)] [6], so the filters are compatible with existing high-throughput nanofabrication platforms. The interaction of visible light with the filters provides color selection and light recycling over standard dye and pigmentary filters [7].

We computed the transmission and reflection properties of the silicon-on-quartz filters using rigorous coupled wave analysis (RCWA) for layered periodic structures [8]. The results indicate that using high-quality c-Si, instead of commonly-studied sputtered metals, significantly enhances the filter quality. A common LED backlight emission spectrum [Fig. 2, dashed lines] has discrete peaks in the red, green, and blue wavelength ranges, which allows for a cleanly defined optimization figure of merit  $F$ . For example, for a green filter,  $F = r(R_B + R_R) - (1 - T_G)$ ,

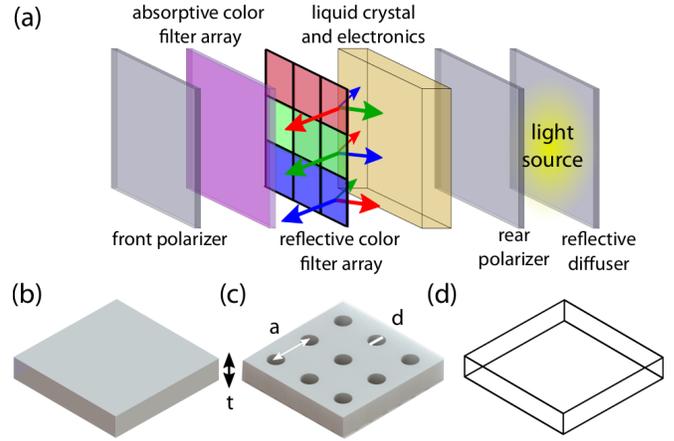


FIG. 1: (a) Schematic of a liquid crystal display with RT filters. If the RT filters are ideal (transmit 100% of one color, reflect 100% of the other two colors), the absorptive filter array is not needed. Each color filter can be (b) a thin layer of c-Si characterized by thickness  $t$ , (c) a photonic crystal slab with holes of diameter  $d$ , periodicity  $a$ , and thickness  $t$ , or (d) a blank space.

where  $R_B$  and  $R_R$  are the average reflected blue ( $425 < \lambda < 480$ ) and red ( $600 < \lambda < 655$ ) light, and  $T_G$  is the average transmitted green ( $505 < \lambda < 575$ ).  $r$  is a measure of the efficiency of the recycling process, and is defined as the fraction of initially reflected light that reaches the color filters a second time.

We chose the thickness, lattice symmetry, and hole parameters as our degrees of freedom and maximized  $F$  using a nonlinear-optimization package NLOpt [9]. We first performed a global optimization [10] to avoid poor-quality local optima, and then we refined the parameters with a subsequent local optimization algorithm [11] to achieve a final design. Throughout, we constrained the hole diameter to be larger than 100 nm to achieve realistic and fabricatable photonic crystal slabs.

The optimization produced a set of red and green c-Si color filters with a thickness of  $t = 134$  nm [Fig. 2]. The green filter is a simple slab [Fig. 1(b)]. The red filter is a slab with holes of diameter  $d = 112$  nm and periodicity

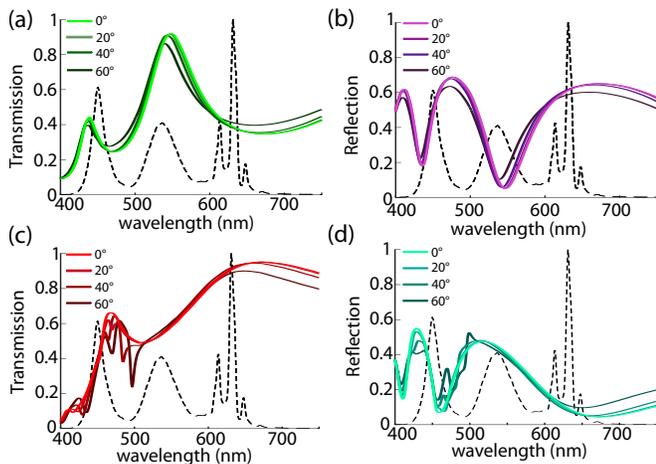


FIG. 2: Rigorous coupled wave analysis (RCWA) simulations of the transmission and reflection of green filter (a,b) and red filter (c,d) for light of various incident angles showing good angular stability. Incident light is randomly polarized. The black, dashed line in each shows the spectrum of a backlight LED, which can be measured from an iPhone 6s display.

$a = 137$  nm in a square lattice. The air holes reduce the effective index of the slab, which shifts the Fabry-Perot resonance to a shorter wavelength. In addition, the hole array supports optical resonances that alter the reflection and transmission spectra via Fano effects [7, 12]. The filters have excellent angular stability due to the high index of silicon, and the Fano resonances in the red filter further improve the filter quality for large angles [Fig. 2]. Regardless of thickness, there was no optimum blue filter due to a spike in the absorption of c-Si near  $\lambda = 350$  nm, so the blue pixel is left blank.

Including RT filters before the absorptive color filter array increases the brightness of the screen for a given backlight power and therefore reduce the required energy. To quantify this improvement, we consider an LCD panel displaying a white image, so all filters are in the on state. At each wavelength, the enhancement  $E$  for an RT color filter can be expressed as a geometric series,  $E = (1 - R_0)/(1 - R_0 r)$ , where  $R_0$  is the angle-integrated amount of light reflected back for recycling. Considering viewing angles of up to 60 degrees, the relative brightness enhancement is shown in Figure 3. Using a single layer of c-Si filters before the standard absorption filters can enhance the brightness by up to 15%, depending on the efficiency of the recycling process, which is characterized by the recycling factor,  $r$ . The recycling factors of current state-of-the-art devices are around 0.5, but this work suggests that improving  $r$  is crucial for reducing display energy consumption.

Furthermore, our design is potentially scalable and compatible with standard high-throughput silicon nanofabrication techniques. We propose the use of commercially available silicon-on-quartz (SOQ) wafers. For

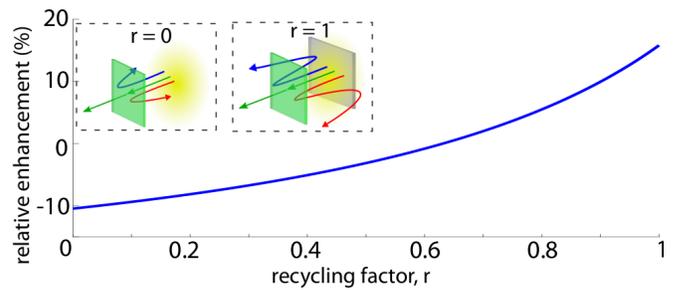


FIG. 3: The brightness enhancement as a function of the recycling factor  $r$  for an RT filter array relative to a standard filter array in a light-recycling display: relative enhancement =  $100(E_{RT}/E_{\text{standard}} - 1)$ . In this model, a standard color filter transmits 100% of one color and absorbs 100% of the other two colors. For  $r > 0.6$ , the RT filter increases the brightness.

each filter set, the green filter can be left unpatterned, the blue filter area can be etched away completely, and the red filter can be patterned with interference [13] or immersion lithography [14].

In this letter, we suggest that light recycling via RT color filters can have substantial consequences for energy savings, even with simple silicon designs.

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