Single-layer color router for solid state image sensors: To propagate or not?

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Abstract—**We design a color router made of a single layer only and show that it achieves very high optical efficiency (> 0.7) and low cross-talk simultaneously, despite being a significant simplification of an ideal color router. Unlike other single-layer approaches, a single-layer color router separates colors directly at its output without additional external propagation. This allows for better performance compared to single-layer approaches that use a propagation distance to separate colors. We illustrate the importance of the non-propagating, near-field contributions to creating highly-efficient color separation devices.**

I. INTRODUCTION

Absorbing color filters are very inefficient optical components in solid-state image sensors pixels (Fig. 1). Since filters reject any light with out-of-channel content, a color filter approach is intrinsically photon inefficient. In the case of red (R), green (G), and blue (B) color channel filters, most of the light (i.e., 2/3 of the visible spectrum in each filter) is absorbed to provide the color functionality. Hence, possible replacements for color filters have attracted great interest in recent years, [1-8]. While improving photon efficiency is important for any pixel size, it is critically important for CMOS image sensors with sub-micrometer size pixels, since the photodetector area decreases with quadratically with pixel size [5]. Figure 2 shows different color separating approaches for solid state image sensors. They are based either on volumes (a,b) [3-5] or single layers (c,d) [6-8]. Some require a propagation distance to separate colors (b,d) [1-3,6-8], while others do not rely on external propagation (a,c) [4,5]. The approaches that use a propagation distance, which typically measures several wavelengths, have been shown for larger micrometer size pixels [1-3,7].

II. COLOR ROUTER

To address the inefficiency of color filters with an approach that scales to sub-wavelength size pixels, we recently introduced color routers using lossless dielectrics (Fig. 2a) [4,5]. A color router separates colors using internal scattering of light (within the device) without additional external propagation and can, in principle, achieve ideal optical efficiencies with negligible optical crosstalk between color channels [5]. To illustrate photon efficiency as well as scaling performance [5], our ideal color router design used tens of layers, which is challenging for fabrication.

Here, we design a *color router made of a single layer only* (Fig. 2c) and show that it achieves very high optical efficiencies and low cross-talk despite this significant simplification. We also illustrate the importance of non-propagating, near-field contributions to color routing, i.e., color separation directly at the output plane of the color router. This is in contrast to color separating meta-surfaces (and -volumes) that operate using different physics and do require additional propagation after the device to separate light according to color [1-3,6-8]. The latter being similar to a lens, which does not form an image directly after the lens, but at a propagation (image) distance behind the lens.

III. SINGLE-LAYER COLOR ROUTER

A. Geometry

In this work, we assume 0.5 μm CMOS image sensor (CIS) pixels and consider a single-layer color router for a 2-by-2 pixels RGGB Bayer layout. The color router in this case replaces the optical stack, i.e., the micro-lens array and the RGGB color filter array, and consists of a single patterned layer made from two lossless dielectrics (silica and titanium dioxide). The layer is placed directly on a silicon substrate where the CIS pixel photodetectors are located. The pattern has sub-100 nm size design elements which are made of either silica or titanium dioxide in the optimized design. Even with these assumptions, the design space is very large. To take advantage of the large number of degrees of freedom, we use an efficient computational design approach.

B. Design and Optimization

To design a single-layer color router and evaluate its color separation performance, we use three-dimensional (3D) electromagnetic design with an adjoint-variable method and gradient-based optimization [4,5]. The performance of the color router design is quantified by the optical efficiency of each color channel [4,9,10].

This is the fraction of the total optical power incident on the entire device that is routed to the photodetector of the intended color channel. We also calculate the optical crosstalk between the color channels [4,10,11]. This is the fraction of the incident optical power for the intended color channel that is improperly routed to the photodetectors of the adjacent color channels.

We calculate the color router response to incident light using first-principles 3D electromagnetic field simulations [4,5]. The gradients required to optimize the structural design parameters, i.e., the dielectric properties of each design element, which are initially continuous but converge in the optimization process to discrete values [4,5] are calculated with an adjoint variable method [12,13]. A gradient-based optimizer using the method of moving asymptotes maximizes the optical power routed to the photodetector of each color channel based on the color content of incident light [5]. This is performed mathematically by maximizing an objective function that sums the optical efficiencies of the R, G, and B color channels and subtracts the optical crosstalk between these channels [4,5].

C. Results

Figure 3 illustrates the color routing response of an optimized single-layer color router for 0.5 μm pixels. Figure 3(a) shows the optical efficiency spectrum over the visible wavelength range. An optical efficiency value of 1 indicates that all light incident on the color router, which covers all (four) color channel pixels, is routed to the correct color channel pixel. The efficiency spectra form well-defined passbands around on the design wavelengths of the R, G, and B channels (450, 550, 650 nm). The results in Fig. 3(a) show peak optical efficiency reaching > 0.7 and simultaneously exhibit low cross-talk. Figure 3(b) shows the power flux at the level of the silicon substrate with the photodetectors, which is located at the output plane of the single-layer color router. The power flux distributions are for the wavelengths with peak optical efficiency in the B, G, and R color channels. The power flux at the photodetectors features focused spots with peak flux values in the areas corresponding to the intended color channel detectors. This is the case, in particular, for the B and R channels. We note that in this example we didn't optimize for symmetry in the G channel, but this can be accomplished [5].

Our results show that a single-layer color router, i.e., a single-layer approach using direct routing to separate colors, can provide better performance than single-layer approaches that require external propagation over several wavelengths behind the device to separate colors. Specifically, single-layer approaches based on external propagation have reported lower optical efficiencies and higher levels of cross-talk [2,7,8].

We now investigate the effect that external propagation has on a color separation device. To do this, we place an oxide layer with thickness d between the single-layer color router and the silicon substrate with the photodetectors. That results in a propagation distance d, where the light has to propagate in the oxide layer behind the color router, which can cause diffraction and impact the performance. Figure 4 shows the optical efficiency spectra (left panels) and the power flux distributions at the photodetectors (right panels) for propagation distances $d = 100, 200, 300, 400,$ and 500 nm. As d becomes larger, the effect of the non-propagating, near-field contributions to the response diminishes and only propagating modes contribute to the response. As a result, we find decreasing peak efficiency values and increasing color crosstalk, most notably in the B and R channels, as the propagation distance d increases. Power flux distributions at the photodetector plane (using same color scale as in Fig. 3b) confirm these results, i.e., they become less focused with lower peak values. We found the same trend when we optimize the design with the propagation distance.

IV. CONCLUSION

We designed a color router made of a single layer only. Our results show that a simplified single-layer color router can route light based on color content to subwavelength size (0.5 μm) pixels with well-defined passband spectra that feature very high optical efficiency (> 0.7) and low crosstalk for the R, G, and B color channels. This shows that a single-layer color router can provide better performance than single-layer approaches that use a propagation distance to separate colors. Our results also show the importance of non-propagating, near-field contributions to create highly efficient color separating devices.

REFERENCES

[1] S. Nishiwaki, T. Nakamura, M. Hiramoto, T. Fujii, and M. Suzuki, Nat. Photonics, vol. 7, pp. 240-246, 2013.

[2] M. Miyata, M. Nakajima, and T. Hashimoto, ACS Photonics, vol. 6, pp. 1442-1459, 2019.

[3] P. Camayd-Munoz, C. Ballew, G. Roberts, and A. Faraon, Optica, vol. 7, pp. 280-283, 2020.

[4] N. Zhao, P. B. Catrysse, and S. Fan, Adv. Photon. Res., vol. 2, 2000048, 2021.

[5] P. B. Catrysse, N. Zhao, W. L. Jin, and S. H. Fan, Nanophotonics, vol. 11, pp. 2381-2387, 2022.

[6] S. Yun, S. Roh, S. Lee, H. Park, M. Lim, and S. Ahn, Proc. IEEE Int. Electron Devices Meeting (IEDM), vol. 67, 30.1, 2021.

[7] X. Zou, Y. Zhang, R. Lin, G. Gong, S. Wang, S. Zhu, and Z. Wang, Nat. Comm., vol. 13, 3288, 2022.

[8] C. Kim, J. Hong, J. Jang, G.-Y. Lee, Y. Kim, Y, Jeong, and B. Lee, Science Advances, vol. 10, eadn9000, 2024.

[9] P. B. Catrysse and B. A. Wandell, J. Opt. Soc. Am. A, vol. 19, pp. 1610–1620, 2002.

[10] C. C. Fesenmaier, Y. Huo, and P. B. Catrysse, Opt. Express, vol. 16, pp. 20457–20470, 2008.

[11] Y. J. Huo, C. C. Fesenmaier, and P. B. Catrysse, Opt. Express, vol. 18, pp. 5861–5872, 2010.

[12] G. Veronis, R. W. Dutton, and S. H. Fan, Opt. Lett., vol. 29, pp. 2288-2290, 2004.

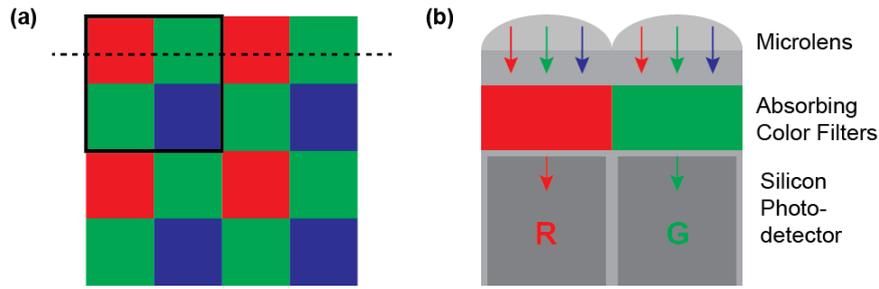[13] W. L. Jin, W. Li, M. Orenstein, and S. H. Fan, ACS Photonics, vol. 7, pp. 2350-2355, 2020.

Fig. 1. Conventional Red-Green-Green-Blue (RGGB) color filter array with inefficient absorbing color filters. (a) Top view of RGGB kernel. (b) Vertical cross-section at R and G color channel pixels.
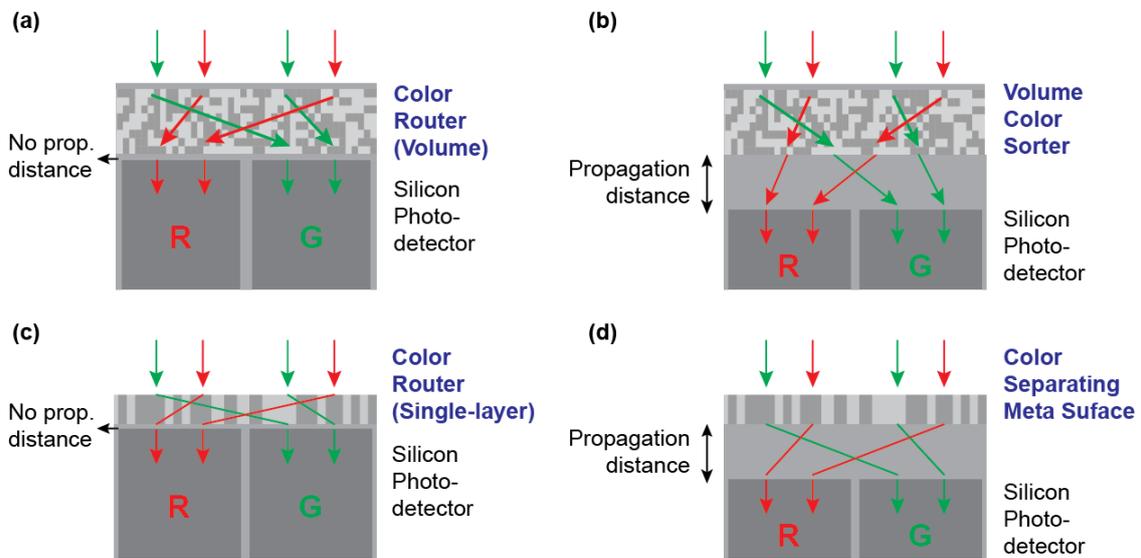

Fig. 2. Color separating devices for solid state image sensors. (a) Volume color router separates colors directly at output, requires no external propagation. (b) Volume color sorter with additional propagation distance. (c) Single-layer color router separates colors directly at output without external propagation. (d) Meta surface requires additional propagation distance to separate colors.
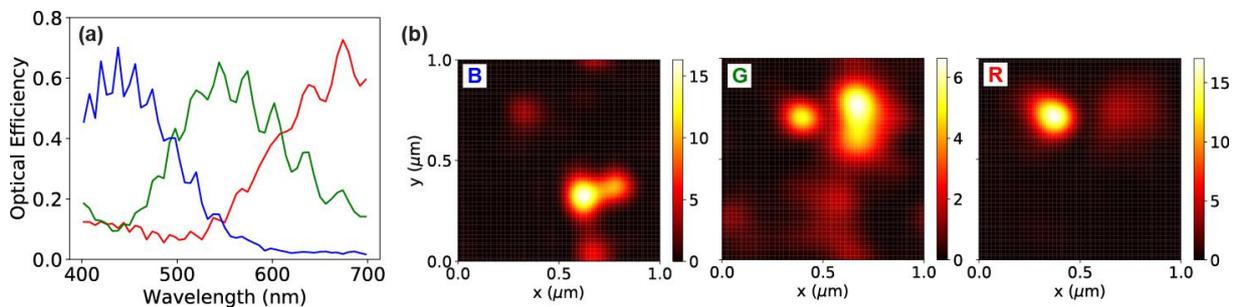

Fig. 3. Single-layer color router: (a) Optical efficiency spectrum, where optical efficiency = 1 indicates all incident light reaches the pixel photodetectors. (b) Power flux distributions at the photodetectors in the silicon substrate placed directly behind the color router (Fig. 2c) for the peak optical efficiency in the B, G, and R color channels, respectively.
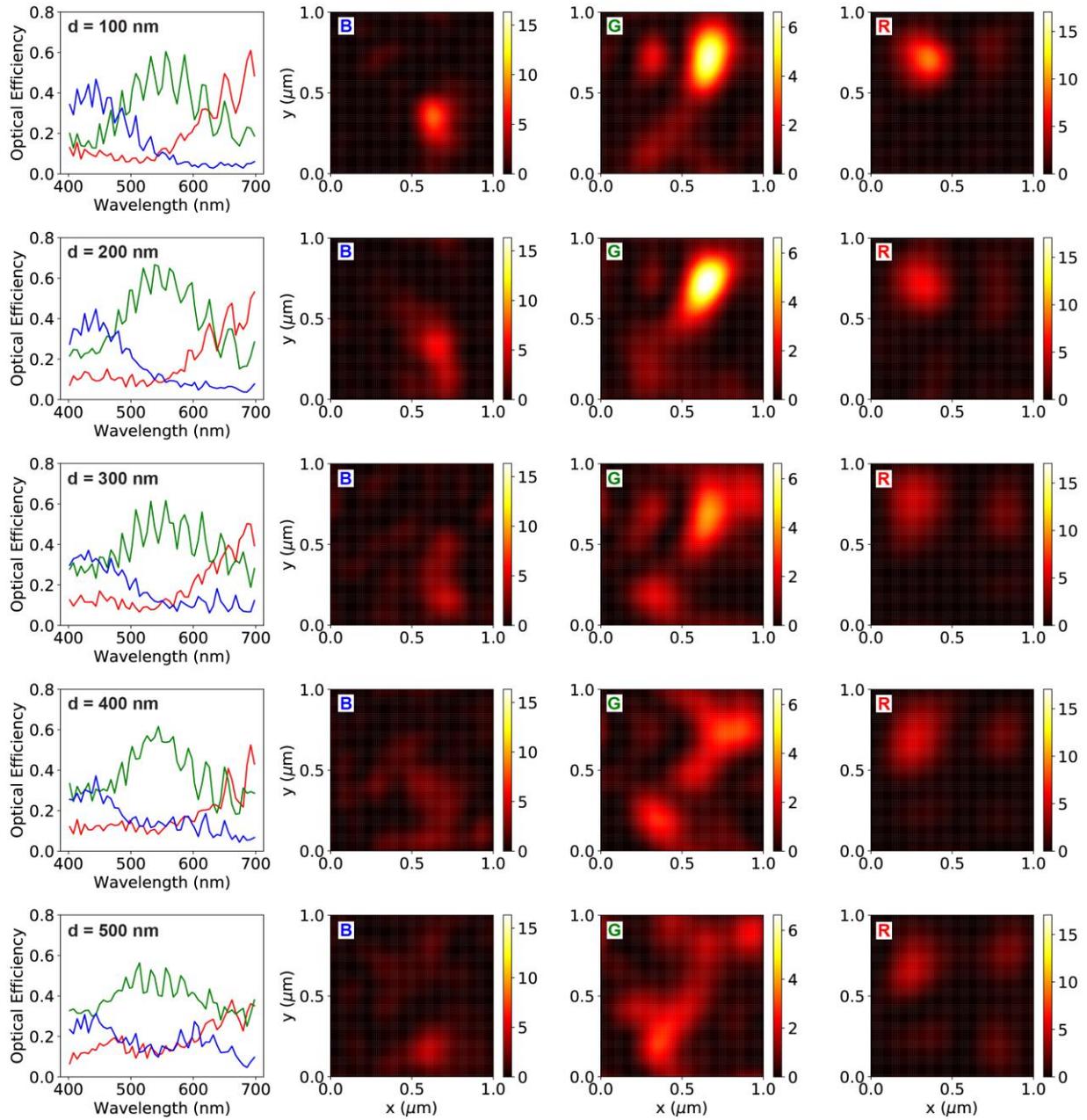
Fig. 4. Single-layer color router with photodetectors placed at propagation distances d = 100, 200, 300, 400, and 500 nm behind the color router: Optical efficiency spectrum and power flux distributions at the pixel photodetectors for the peak optical efficiency in the B, G, and R color channel, respectively.