Color Transparent Monitor using Si/SiO₂ Core-Shell Nanoparticles: Optimum Color Selection

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Abstract
In this paper, core–shell nanoparticles are used to provide a transparent high-quality display. To realize this idea, Si-SiO₂ core–shell nanoparticles have been used to achieve the most suitable nanoparticle composition for a transparent color display with high transparency and contrast. For color transparent monitor the superimposed QDs are used. For transparent color monitors, stacked QDs are used. In this work, we determine the ratio of nanoparticles (three QD ratios) for the three colors in the proposed monitor. Because the red, green, and blue scattering peaks are different because of the scattering physics, which is wavelength-dependent. Therefore, obtaining the optimal ratio for each color is studied. The numerical method of Finite-Difference Time-Domain is used to simulate and calculate the optical properties of the proposed transparent monitor. The effect of different combinations of nanoparticles to have the maximum dispersion at blue, green, and red wavelengths and the minimum absorption at other wavelengths has been investigated. Finally, the optimum ratio and arrangement of nanoparticles for all colors are reported and numerically evaluated.

Keywords Color Transparent Monitor · Nanoparticles · Optimum color tuning · Si/SiO₂ core–shell nanoparticles

1 Introduction
With the development in lifestyle due to advances in electronics in different aspects, the transparent displays used more and more, recently. Depending on how the light is emitted and is supplied, transparent displays are divided into two categories: See-through transparent displays and projector-based transparent displays (Roehrig 2000). Depending on the type of usage, any of the components of the introduced categories can be used to achieve the best technology for a transparent display. The Head-Up displays are the simplest type of monitor which fall into the projector-based transparent display category (Wang et al. 2016;
Qin et al. 2017; Okumura and Shinohara 2016; Mahajan et al. 2015). The holographic optical lens array display is also in the projector-based transparent display category. In this type of display, a volumetric hologram that can scatter light has been used to create a transparent display. Two light beams are needed to create an image on this kind of display (Bang et al. 2019; Hong et al. 2014). In another work, unstructured and homogeneous fluorescent plates were used to create a transparent color display. For this purpose, they used an ultraviolet projector and stimulated the fluorescent screen with the blue wavelength beam (Sun et al. 2013; Cheng et al. 2017). In addition to the previously introduced work, using nanoparticles to have a transparent display is one of the easiest, cheapest, and newest methods.

In (Hsu et al. 2014), a transparent display for the blue wavelength was created using SiO₂-Ag coated spherical nanoparticles. In addition, in Dolatyari et al. (2019), by Si-SiO₂ nanoparticles, a transparent display was made for blue wavelengths with more scattering and less absorption, and consequently more transparency. In (Seyyedi et al. 2020a), the different arrays of Si-SiO₂ nanoparticles with varying radii are compared to find an array of nanoparticles by appropriate radius for RGB wavelength for having higher scattering and lower absorption cross-section. In (Seyyedi et al. 2020b), different morphologies of Si-SiO₂ nanoparticles are studied to find the best morphology for high resolution and brightness transparent display. In (Seyyedi et al. 2021a, b), different arrays such as the Fibonacci, the Thue-Morse, periodic, the P-Bz by 12-fold QC, and Gaussian structure at the different pixels of Si-SiO₂ nanoparticles are investigated to find the best combination of nanoparticles to improve the amount of contrast and transparency in transparent color screens. In (Seyyedi et al. 2020a, b, 2021a, b; Balakirev et al. 2022), by changing the size, morphology, and array of the nanoparticles, we were able to find a relatively optimal combination of nanoparticles to create a transparent color display. In this work, the final structure had a sharper scattering cross-section in the green wavelength than the blue and red wavelengths.

In this paper, finding an optimal structure with equal scattering cross-section for all three wavelengths blue, green, and red is studied. Therefore, by changing the density of nanoparticles used in the optimal structure, we are looking for a structure with a sharper scattering cross-section at all three wavelengths and with more amplitude of scattering and less amplitude of absorption cross-sections. The brightness and resolution of the transparent display are determined by the width and intensity of the scattering spectrum, respectively. Therefore, in this paper, we are looking for the optimal combination of nanoparticles by changing their density.

2 Computational method and mathematical modeling

Achieving an optimal structure to have a display with high transparency and contrast are one of the most important goals in fabricating a transparent screen. Therefore, to have an optimal structure for a transparent display, it seems necessary to use powerful simulation software. For this purpose, in this article, the Lumerical FDTD solution has been used for simulation. The FDTD solution is used to simulate optical structures. The boundary of this method is to calculate absorption and scattering cross-section is perfectly matched layer (PML). The optical range is set to simulate a transparent display between 400 and 700 nm because we need to study the visible range. The source used in these simulations is a Total-field scattered field (TSFT) source. This kind of source is often used to study nanoparticles scattering and absorption cross-section. This source divides the computational area into two areas. In the first area, it studies the sum of the
incident field and the scattered field. In the latter area, it examines only the scattered field. According to Eq. 1, the scattering cross-section can be calculated by the total scattered power and the intensity of the incident source. In addition, according to Eq. 2, the cross-section of the absorption can be obtained from the total power absorbed by the nanoparticles. By numerical calculations and by Eq. 3, the scattering and absorption cross-section is obtained.

\[ \sigma_{\text{sca}}(\omega) = \frac{P_{\text{sca}}(\omega)}{I_{\text{int}}(\omega)} \]  

\[ \sigma_{\text{abs}}(\omega) = \frac{P_{\text{abs}}(\omega)}{I_{\text{int}}(\omega)} \]  

\[ \sigma_{\text{ext}}(\omega) = \sigma_{\text{sca}}(\omega) + \sigma_{\text{abs}}(\omega) \]

We used a computer with 128 GB RAM 24C and CPU E5-2650 to simulate and obtain optimal structure. There are two important parameters for finding the optimal structure. The first parameter is called a figure of merit (FOM) (Hsu et al. 2014). To calculate a figure of merit, the maximum scattering value at the desired wavelength \( \sigma_{\text{sca}}(\lambda_0) \), the average scattering value along the studied spectrum \( \bar{\sigma}_{\text{sca}}(\lambda) \) and the maximum absorption value in the studied spectrum \( \text{max}\{\sigma_{\text{abs}}(\lambda)\} \) are required. Equation 4 shows the formula of the figure of merit.

\[ FOM = \frac{\sigma_{\text{sca}}(\lambda_0)}{2\bar{\sigma}_{\text{sca}} + \text{max}\{\sigma_{\text{abs}}(\lambda)\}} \]

The second parameter is called scattering to absorption ratio (SAR), which determines the ratio spectrum of scattering cross-section to absorption cross-section (Seyyedi et al. 2020a, b, 2021a, b). Equation 5 shows the formula of SAR.

\[ SAR = \frac{\sigma_{\text{sca}}}{\sigma_{\text{abs}}} \]
nanoparticles leads to a redshift and a sharper scattering peak, respectively. The schematic of the nanoparticle density in the optimal structure is shown in Fig. 1.

3 Simulation results and discussion

As mentioned in Seyyedi et al. 2021a, it was found that by combining three nanoparticles with a suitable radius for blue, green, and red wavelengths horizontally, a more appropriate structure in terms of scattering and absorption cross-section can be achieved. It is clear that by placing this combination in different arrays, a better response can be achieved to have higher and narrower scattering cross-sections and lower absorption cross-sections. Hence, as shown in Fig. 2, an almost suitable composition of three horizontal nanoparticles has been identified for maximum scattering cross-section at the blue, green, and red wavelengths. To perform the simulation, we used 9 combinations of nanoparticles that are placed periodically and 3 by 3. In each nanoparticle combination, there are three nanoparticles with a specific core radius and shell thickness suitable for the three wavelengths blue,
green, and red. For better evaluation, Table 1 shows the values of scattering cross-section, FOM, and SAR at the desired wavelength.

According to Fig. 2 and Table 1, the scattering cross-section for green is slightly higher than the other two wavelengths. Therefore, by adding other nanoparticles to the nanoparticle composition, we try to equalize the scattering cross-section and FOM. The changes obtained for scattering and absorption cross-section, the figure of merit, and SAR by adding different percentages of nanoparticles are shown in Fig. 3 and Table 2.

As shown in Fig. 3 (a) to (d), the scattering cross-section changes with the addition of different percentages of nanoparticles to the structure. As shown in Fig. 3(a), we add a blue nanoparticle to the combination of nanoparticles, the scattering cross-section for the blue wavelength improved but the scattering cross-section for the red wavelength decreased. In Fig. 3(b), by adding other nanoparticles for the red wavelength, we try to improve the scattering cross-section for the red wavelength but, it decreases the scattering cross-section for the blue wavelength. In the next step, we change the order of nanoparticles (blue, green, and red). Therefore, we noticed small changes, by changing the position of the nanoparticles in Fig. 3(c). We realized that to achieve the optimal structure, we need more blue nanoparticles per two nanoparticles with the suitable radius for the red wavelength and one nanoparticle with the appropriate radius for the green wavelength. Therefore, we increased the number of nanoparticles for the blue wavelength to 4 nanoparticles. The scattering profile for these changes is shown in Fig. 3(d). As shown in Fig. 3 and Table 2, we have the three equal peaks in blue, green, and red wavelengths and a relatively equal amount of scattering cross-section and FOM for the BBRGRBB combination of nanoparticles.

It seems that by considering a ratio of quadruple suitable nanoparticles for blue wavelengths and double appropriate nanoparticles for red wavelengths compared to one proper nanoparticle for green wavelengths, a structure with a sharper scattering cross-section can be achieved. In the next step, by maintaining the percentage of nanoparticles in each structure, we randomly changed their permutation to observe the effect of nanoparticle position on the scattering cross-section and figure of merit. The purpose of this work is to obtain a relatively equal scattering cross-section and FOM in each permutation of the nanoparticle combination. A random combination of four blue nanoparticles, two red nanoparticles, and one green nanoparticle with different permutations of nanoparticles is shown in Fig. 4.

By maintaining the order of the three red-green-red nanoparticles in each combination, we changed the ratio of blue nanoparticles on both sides. As shown in Fig. 4 and Table 3, the FOM and scattering cross-section were relatively equal. FOM and scattering cross-section are about 0.64 and 4.5, respectively. We have given the figure of three random

| B-R-G | Blue   | Green | Red    |
|-------|--------|-------|--------|
| Wavelength | 460.6 | 522.8 | 628.9  |
| Scattering cross-section | 2.262 | 2.555 | 2.299  |
| SAR    | 3.96   | 2.904 | 14.69  |
| FOM    | 0.57   | 0.64  | 0.58   |
Fig. 3 Scattering and Absorption cross-section for the horizontal composition of suitable nanoparticles for RGB wavelengths with (a) blue-blue-red-green, (b) blue-blue-green-red, (c) blue-red-green-red-blue, (d) blue-blue-red-green-red-blue nanoparticles. (Colour figure online)

combinations as an example in the article. In the next step, we change all seven nanoparticles’ permutations in each combination. As mentioned, we have nine combinations of nanoparticles in each structure. The random permutation for the four compounds of seven nanoparticles is shown in Fig. 5 and Table 4.
By changing the order of red-green–red nanoparticles in a row, the amount of FOM decreases. But the scattering cross-section remains the same at all three selected wavelengths. The SAR value in this mode increases compared to the previous case, especially in the red wavelength. As shown in Fig. 5, by shifting the nanoparticles in a row in each combination, the scattering cross-section is relatively uniform.

Table 2 Scattering cross-section, FOM, and SAR for the horizontal composition of suitable nanoparticles for RGB wavelengths with different percentages of nanoparticles

| Parameters       | Blue  | Green | Red  |
|------------------|-------|-------|------|
| B-B-R-G          | Scattering cross-section | 2.644 | 2.704 | 2.087 |
|                  | SAR   | 2.736 | 4.35  | 14.39 |
|                  | FOM   | 0.82  | 0.84  | 0.65  |
| B-B-R-G-R        | Scattering cross-section | 2.659 | 4.077 | 4.256 |
|                  | SAR   | 2.294 | 4.32  | 5.646 |
|                  | FOM   | 0.497 | 0.762 | 0.795 |
| B-R-G-R-B        | Scattering cross-section | 2.535 | 4.274 | 4.086 |
|                  | SAR   | 3.384 | 3.92  | 7.36  |
|                  | FOM   | 0.44  | 0.747 | 0.714 |
| B-B-R-G-R-B-B    | Scattering cross-section | 4.695 | 4.609 | 4.636 |
|                  | SAR   | 2.605 | 8.536 | 7.097 |
|                  | FOM   | 0.65  | 0.647 | 0.65  |
Fig. 4  Scattering and Absorption cross-section for the horizontal composition of suitable nanoparticles for RGB wavelengths with a) B-B-B-R-G-R, b) B-R-G-R-B-B-B and c) R-G-R-B-B-B permutation.
As shown in Figs. 4 and 5, by nanoparticle permutation, despite the broadening of the scattering cross-section for some compounds, an equal amplitude response is obtained for the scattering cross-section for all three desired wavelengths. Therefore, in the optimal combination, the obtained density of nanoparticles can be used randomly to achieve a transparent color display with higher transparency and so the solution process nanotechnology can be used to synthesize nanoparticles and randomly mixed and spin-coated on a transparent screen to make a transparent display. Therefore, color selection is possible using the density of nanoparticles for different colors.

### 4 Conclusion

In this paper, we used core–shell nanoparticles with Si as the core and SiO₂ as a shell to provide a high-quality color transparent display. We used the finite-difference-time-difference numerical method to simulate and calculate the optical properties. We examined different compositions of nanoparticles and obtained a composition that has equal peaks for the scattering cross-section at blue, green, and red wavelengths. As a result, we found that for each suitable nanoparticle for green wavelength with a high scattering cross-section, we need four and two nanoparticles for the blue and red wavelength, respectively. In the next step, we changed the permutation of the nanoparticles in the composition to examine the most random states possible. Finally, to have an equal scattering cross-section, the percentage of nanoparticles density in blue, green, and red wavelengths are about 57%, 14%, and 29%, respectively.
Fig. 5 Scattering and Absorption cross-section for the horizontal composition of suitable nanoparticles for RGB wavelengths with a) B-B-R-R-G-B-B, b) B-G-R-B-B-B-R, c) B-R-B-B-R-B and d) G-B-R-B-R-B permutation.
Table 4  Scattering cross-section, FOM, and SAR for the horizontal composition of suitable nanoparticles for RGB wavelengths with different random permutations of nanoparticles

| Parameters       | Blue  | Green | Red  |
|------------------|-------|-------|------|
| **B-B-R-R-G-B-B**| 4.159 | 4.076 | 4.257|
| Scattering cross-section |       |       |      |
| SAR              | 2.19  | 7.10  | 15   |
| FOM              | 0.57  | 0.563 | 0.58 |
| **B-G-R-B-B-R**  | 4.217 | 4.146 | 4.173|
| Scattering cross-section |       |       |      |
| SAR              | 2.256 | 6.848 | 16.63|
| FOM              | 0.572 | 0.56  | 0.56 |
| **B-R-G-B-R-B-R**| 4.027 | 4.223 | 4.306|
| Scattering cross-section |       |       |      |
| SAR              | 2.1   | 6.18  | 18.83|
| FOM              | 0.53  | 0.557 | 0.568|
| **G-B-R-B-B-R-B**| 4.563 | 4.226 | 4.649|
| Scattering cross-section |       |       |      |
| SAR              | 2.186 | 9.47  | 7.10 |
| FOM              | 0.598 | 0.584 | 0.609|

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