Light Recycling Using Perovskite Solar Cells in a Half Cylinder Photonic Plate for an Energy Efficient Broadband Polarized Light Emission

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Abstract

Energetic efficiency in many illumination devices is far from optimal. For instance, in liquid crystal displays a large fraction of the emitted light is lost provided absorbing polarizers are used for the image formation. In here, a light guiding structure to achieve diffuse polarized light emission from the top of the guide, combined with light harvesting and conversion back into electricity of the light with the unwanted polarization is proposed. Key in achieving such double goal is the use of a half-cylinder photonic plate for an ergodic light guided propagation incorporating a non-absorbing reflective multilayer light polarizer and perovskite solar cells. In the complex combination of micro- and nanometric dimensions of the proposed structure, light propagation was resolved using ray optics tracing interlaced with a full wave vector inverse integration approach. A broadband polarization extinction ratio of 0.1 for the light diffused from the top surface is demonstrated, while close to 90% of the s-polarized light remains trapped and can be recycled back to electricity by the perovskite solar cells placed on the front and back ends of the guide. Perovskite cells are shown to be optimal in such conversion with an overall efficiency ranging from 38% to 52%.

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1. Introduction

A significant fraction of the world current energy consumption goes into illumination sources or devices that incorporate an illumination source in them.[1,2] To enable a reduction in the use of fossil fuels, an optimization of the efficiency in such illumination devices may become as relevant as the use of renewable energies to power them up. Note that in some of the electronic devices incorporating a liquid crystal display (LCD) more than 90% of the light emitted by the illumination source may end up being lost.[3] The need for a linearly polarized illumination in the LCD implies that light emitted with the unwanted polarization is discarded.[4] A reduction of such light waste is partially solved by the incorporation in the LCD of a dual brightness enhancement film,[5–7] made of hundreds of layers alternating isotropic and birefringent polymers aiming at transmitting one polarization component while the other one is reflected and later converted into the desired polarization by means of a conversion element, such as a prism film or a diffuser plate.[7] However, the need for a large number of optical sheets in the illumination structure hinders current efforts undertaken to reduce the LCD thickness.[8–10] Therefore, the integration of different functionalities such as, for instance, diffuse and polarized light emission, as well as light recycling, into a single hybrid structure appears as a promising alternative for simpler and thinner LCD designs.[11] In that later approach, some proposed illumination configurations incorporate the option to recycle the discarded light by converting it back to electricity. Typically, photovoltaic cells have been proposed as the element for such light to electricity conversion.[12] Of special interest for that purpose are perovskite (PVK) solar cells, given their broad band gap tunability[13,14] and low $V_{oc}$ losses,[15,16] added to an efficient photon to collected electron-hole pair conversion.[17]

Herein, we propose a novel light guiding structure to achieve diffuse emission of polarized light combined with a potential harvesting and conversion back into electricity of the light with the
unwanted polarization. The key to achieve such double goal is to combine a half-cylinder photonic plate (h-CPP) for an ergodic light propagation in the guide\textsuperscript{[18–20]} with a non-absorbing multilayer reflective polarizer (MRP). To reach a broadband polarization selectivity, such polarizer will be shown to be composed of a random sequence of dielectric layers. Without any loss of generality, it will be numerically optimized for light at 466 nm, 560 nm, and 630 nm, corresponding to the emission wavelength of blue, green and red light emitting diodes (LEDs), respectively, which are commonly used in LCDs.

2. Results and Discussion

The specific light guiding structure we consider to polarize and recycle light is schematically shown in Figure 1. As can be seen in such figure, in addition to the MRP on top of the periodic array of half-cylinders, the guide incorporates a highly reflective element on the bottom and two perovskite photovoltaic cells for light conversion to electricity on the front and back ends of such guide. Detailed information about the geometry of the guiding structure herein proposed can be found in section 1 of the Supporting Information.
Figure 1. Schematic representation of the guide proposed in this study, whose core is a half-cylinder photonic plate for an ergodic propagation of the light, covered by a MRP. It also includes a highly reflective element with very low losses on the bottom and two perovskite solar cells on the front and back ends. The light from the LEDs can be introduced with a certain deviation angle, $\theta_d$, relative to the guide axis, by means of an optical prism or any other suitable light coupling element. The drawing is only a schematic representation of the guide. The dimensions are not at scale and the number of layers or half cylinders do not correspond to any of the studied configurations.

Note that the light guiding structure we propose incorporates a unique combination of periodic order in the half-cylinder photonic plate and disorder in the MRP. A proper design for such optical element cannot follow an intuition-based approach to resolve electromagnetic wave propagation, provided it contains a complex combination of micro- and nanometric structures. Instead, the approach we implemented uses ray optics tracing in the core of the guide in addition to a full wave vector propagation in the multilayer structures. The specific configuration for both multilayer structures, the MRP and the bottom high reflective element, is obtained ad hoc using an inverse design approach. As seen in Figure 1, light may be coupled through the top interface using a prism or any other suitable light coupling element. To achieve an even and homogenous diffuse light emission from the top of the guide, we will assume that the incident rays point towards the central part of the guide at an angle ($\theta_d$) deviating from the axis guide by 12 deg. (cf. Figure 1). Note that
the specific angle used results from the total length of the guide considered. Once the configuration for the whole structure is established, light propagation within a ±6 deg. range around such 12 deg. is also considered.

At the incident plane A (cf. Figure 1) we consider 600 equally spaced rays, that may undergo up to 200 reflections within the structure. Each time a given ray is incident at one of the interfaces that separate the core of the guide from the MRP or the bottom reflective element, the corresponding intersection point and angle of incidence are computed and stored. Considering such incidence angle, the transfer matrix formalism, described briefly in section 2 of the Supporting Information, is applied to determine the light transmission, reflection and absorption, for each of the polarization components. The light reflected is used to update the irradiance of the ray propagating inside the guide after such intersection. The light absorbed in the bottom reflector will account for the losses. The light transmitted through the top reflective polarizer is used to calculate the power that would be detected on a plane parallel to the guide (cf. Figure 1), whenever the ray transmitted does not reenter in the guide through one of the neighboring cylinders. For a given ray, the total light transmitted through the polarizer or lost by absorption is obtained by summing the contributions from all the intersections (up to 200) undergone inside the guide. Finally, to simulate the behavior of a realistic beam, with a micrometric diameter, the results obtained for the 600 different initial rays are averaged, for each one of the three different wavelengths considered.

To obtain all layer thicknesses in the MRP with an optimal configuration we used a genetic algorithm based optimization procedure. Since the obvious target is to maximize the transmission of p-pol light, while minimizing the one with s-polarization, the extinction polarization power ratio of the beam \( P(s)/P(p) \) was chosen as the quantity to minimize in the inverse design. To ensure that we obtain what may be generically defined as the optimal configuration, different additional
constraints were incorporated in such inverse design. These constrains are considered in three different scenarios: i) an unconstrained optimization, ii) setting the minimum p-polarized wavelength-averaged power to be detected on a plane parallel to the guide (cf. Figure 1), to 55% of the incident irradiance, and iii) simultaneously limiting the maximum color discrepancy in the power to be detected on a plane parallel to the guide (cf. Figure 1) to less than 5% and the minimum wavelength-averaged p-polarized power to 40% of the initial intensity. A detailed comparison between these three approaches is presented in section 3 of the Supporting Information. For clarity and compactness of the text, in here we provide an analysis and discussion of the results obtained when one follows the inverse design with the restrictions imposed in the second approach. Although all three approaches would yield a final structure that would be useful to accomplish the double goal of diffuse polarized light emission simultaneously to light energy recycling, such second approach ensures a sufficiently high emission of p-polarized light without significantly increasing the polarization extinction ratio or the total losses.

Under such second constraint, the computation yields an optimal reflective polarizer consisting of 29 layers of non-absorbing dielectric materials alternating high and low refractive index. We used the refractive indexes from WO$_3$ and LiF, given in Section 4 of the Supporting Information. We selected such materials provided they exhibit a large index contrast while at the same time they can be effectively deposited on top of the h-CPP to form the curved multilayer polarizer. Changing the materials would result in a different layer sequence but the physics under study would essentially remain the same. The inverse design applied leads to a fully random distribution of thicknesses in the MRP. In other words, no correlation can be established among the thicknesses of the different layers, emphasizing the usefulness of such inverse design approach to find solutions largely differing from the trivial ones.
With the purpose of minimizing light losses by absorption in the bottom reflector, a similar optimization procedure was carried out to determine the layer sequence and thicknesses of the dielectric layers that separate the guide from the metal underneath. Note that the latter optimization was performed once the configuration of the top reflective polarizer was already established, obtaining an almost lossless bottom reflector consisting of an 8-layer structure of non-absorbing dielectrics alternating high and low refractive index, finished with a thick highly reflective metal layer. For clarity, the h-CPP incorporating the top 29-layer MRP and the corresponding optimal bottom reflector will be referred throughout the rest of the text as the h-CPP-P29. The exact configuration of such optimal sample is given in section 5 of the Supporting Information.

Figure 2. (a) s- and (b) p-polarization components of the reflectance for the optimized 29-layer MRP, as a function of the wavelength and angle of incidence ($\theta_0$) at the interface that separates the h-CPP from the multilayer polarizer. The three different wavelengths considered in this work are identified in the maps, with vertical dashed lines.

As seen in Figure 2, when s-polarized light propagating inside the h-CPP-P29 is incident from 0 to 90 deg. at the interface separating the h-CPP from the polarizer, a broadband reflectivity approaching unity, spanning from 450 to 650 nm, is obtained. This means that, to a large extent, the s-polarized light will remain trapped in the h-CPP until it exits either from the front or back ends of the guide. On the contrary, for the three wavelengths of interest the p-polarized light is transmitted rather effectively when the angle of incidence at the interface separating the h-CPP from the polarizer ranges, approximately, from 30 to 40 deg., in other words, when the p-polarized light is
incident in the neighborhood of the Brewster angle. Note that the chaotic nature of the light propagation combined with the semi-cylindrical shape at the top of the guide allows for many rays to be incident on the polarizer within the 10 deg. range for which the p-polarization reflectance drops, resulting in a rather effective emission of such p-polarized light.

The end result is that for the h-CPP-P29 a broadband polarization selectivity can be achieved while recycling the light with the discarded polarization becomes feasible provided the low light losses in the guide. Indeed, as seen in Figure 3, close to 42% of the light entering the guiding structure is diffused through the top interface with a polarization extinction ratio of ~0.1, while the light losses on the bottom reflector are limited to less than 3%. On the other hand, as also seen in Figure 3, more than 54% of the light trapped in the guide, mostly with the s-polarization, will arrive to the

Figure 3. Distribution of the irradiance alongside the light guide and power detected in a plane parallel to the guide, for the s- (grey) and p-polarization (black) components separately. For the power detected, the light lost by absorption on the bottom reflector and the one that propagates until reaching the edges of the guide, where the PVK cells are incorporated, only the wavelength-averaged value is shown. For the irradiance transmitted through the reflective polarizer, the individual wavelength components are also presented: 466 nm (blue), 560 nm (green) and 630 nm (red).

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front and back ends of the guide. Note that the irradiances reported in Figure 3 sum up only to 98%, as we have neglected light rays which, when emitted from the top of the guide, intersect an adjacent half-cylinder and reenter the guide. Accounting for the contribution from such rays would significantly increase the computation complexity without introducing any relevant change in the h-CPP-P29 structure or the results reported in Figure 3.

**Figure 4.** (a) Fraction of the input irradiance, for the s- and p-polarized light, that reaches the front and back interfaces of the h-CPP-P29 as a function of the wavelength. LED peak wavelength (466 nm, 560 nm and 630 nm) averaged (b) s-polarized and (c) p-polarized light absorption in the active layer of the perovskite cells and reflection back to the fiber plate, together with the total amount of light that can be reused after reaching the ends of the photonic plate (sum of the previous two contributions), as function of the PVK layer thickness. The three magnitudes are normalized to the irradiance reaching the front and back interfaces at such wavelengths.
The wavelength distribution of the light that reaches the front and back interfaces shown in Figure 4 (a) clearly indicates that the guide can very effectively trap the s-polarized light at the wavelengths of interest. Indeed, close to 90% of the s-polarized and 20% of the p-polarized light tuned at such wavelengths may reach the front and back ends of the guide and can be effectively recycled back to electricity by the incorporation of high $V_{oc}$ solar cells, with the bandgap edge adjusted to the wavelength emission of the red LED. In this work, we consider high band gap PVK cells with a Cs$_x$FA$_{1-x}$Pb(I$_x$Cl$_{1-x}$)$_3$ composition and CsCl to PbI$_2$ ratio of 0.17 (refractive indexes, taken from ref. [21], are presented in section 4 of the Supporting Information) adjacent to the front and back ends of the guide. As seen in Figure 4 (b) and (c), when a perovskite layer thickness of at least 500 nm is used, close to 90% of the light reaching such ends would be absorbed in the active layer. Note that most of the light which is not absorbed in the PVK active layer will be reflected back to the guiding plate, where it will continue to propagate ergodically. As illustrated in Figure 4 (b) and (c), very low light losses (up to 3% of the initial irradiance) are to be expected when such PVK cells would be used in the light to electricity recycling process. In section 6 of the Supporting Information, we estimated the conversion efficiency of such process under the assumption that the cells, with an active layer thickness of 500 nm, are operating at the radiative limit. In that case, such efficiency would range from 38% for the blue and 52% for the red LED light. Thermalization losses in the PVK layer account for the largest loss fraction in such conversion, but note that in all cases the conversion efficiency would be well above the Shockley-Queisser limit of the cells under sunlight illumination.[22]
For the same h-CPP-P29, when we consider light propagating at angles larger or smaller than 12 deg., we obtain a partially polarized light emission spatial distribution along the horizontal position of the guide as the one shown in Figure 5(a) for the p-polarization at 466 nm. For the discrete set of five angles we considered, polarized light emission from the top surface of the guide is seen to be fairly homogeneous in an ample spatial range. A similar homogeneous distribution is obtained when light at 560 nm and 630 nm is considered, as reported in Figure S6 of the Supporting Information. This means that for a standard LED source, emitting light in an angular cone, one would obtain a very homogenous emission of diffuse light along the entire top surface of the guide, practically without changing the light distribution alongside the guide, as shown in Figure S8 of the
SI file. When we consider the emission angle for such transmitted light (cf. Figure 5 (b)), one observes that such emission is maximum in a broad angular range that spans from -40 to +10 deg.

Figure 6. Variation of the main parameters of the guiding structure with the number of layers in the MRP (from 9 to 33), for the average of the three LED peak wavelengths (466nm, 560nm and 630nm). (a) Polarization extinction ratio. (b) Total power detected, in a plane parallel to the guide, (c) light lost by absorption in the bottom reflector and (d) total irradiance reaching the ends of the guide where the PVK cells are incorporated, for both s- (blue circles) and p-polarized (orange circles) light.

A study of the performance of the guide as a function of the number of layers in the MRP shows that neither the polarization extinction ratio nor the light recyclability capacity can be improved by increasing the number of layers in the polarizer beyond 29. As seen in Figure 6 (a), the continuous
decrease in the s-polarized light transmitted through the top surface saturates beyond 29 layers in the MRP. Provided the p-polarized light is to a large extent independent from the number of layers in the MRP, the polarization extinction ratio as a function of the number of layers follows a similar pattern as the s-polarization light transmission, as illustrated in Figure 6 (b), stabilizing at ~0.1. On the other hand, since the losses in the bottom reflector are quite small and do not vary much with the polarizer used (cf. Figure 6 (c)), simultaneous to the decrease in s-polarization transmission through the top polarizer, one observes an increase in the s-polarization light recyclability capacity, which also saturates beyond 29 layers, as can be seen in Figure 6 (d).

3. Conclusions

We have introduced a novel light guiding structure to emit diffuse polarized light while at the same time offering a high potential for light recyclability by converting the discarded light with the unwanted polarization into electrical power, which has the potential be incorporated in the backlight unit of LCD’s. To obtain a system configuration that can achieve such multipurpose functionality, we have implemented an inverse design approach based on a genetic optimization algorithm simultaneously combining ray and wave optics propagation. The system we propose relies, on the one hand, on a n h-CPP to reach a chaotic light propagation, ideal to subsequently obtain a homogeneous light diffusion and, on the other hand, on a random multilayer polarizer to achieve a broadband light polarization. Indeed, the system proposed uniquely combines order and randomness to achieve ergodicity and broadband light polarization, respectively. Such randomness in the multilayer structure is key to achieve a polarization extinction ratio of ~0.1 for a broadband wavelength range spanning from 400 to 650 nm. This relatively low polarization extinction ratio for a broad wavelength range is obtained using mostly non-absorbing elements, to enable light recycling back to electricity. Note that such extinction ratio would not change the polarization state or the light-to-dark ratio of a potential display device, which in a standard configuration would also
incorporate an absorbing polarizer, but it would rather reduce the light losses originated in such polarizer. Alternative approaches to limit the light losses in an LCD consider the use of dual brightness enhancement films, where a reflective polarizer is combined with a polarization rotation element.[5,6] The use of wire-grid polarizers has also been considered.[23-25] However, such alternatives may either require hundreds of layers or complex lithography techniques, increasing either the total device thickness or cost. Note also that in the configuration proposed additional gains are possible by lost light in the LCD that may re-enter the guiding plate after being reflected by any of the LCD elements.

We have also demonstrated that the tunability and low $V_{oc}$ losses intrinsic to many perovskite solar cells is ideal to reach a maximum conversion of that light into electricity. Indeed, the guiding structure we propose would be capable of recycling more than 50% of the light emitted by the LEDs in a standard LCD, which may lead to a rather significant reduction in losses when compared with the currently used backlight units. In addition, the partially directional emission predicted may be optimal to further increase the efficiency in devices, such as smartphones or tablets, which are typically viewed from an angular range as the one shown in Figure 5 (b).

**Supporting Information**
Supporting Information is available from the Wiley Online Library or from the author.

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References

[1] G.-W. Yoon, S.-W. Bae, Y.-B. Lee, J.-B. Yoon, Opt. Express 2018, 26, 20802.
[2] J. Kimmel, J. Soc. Inf. Disp. 2012, 20, 245.
[3] T. C. Teng, C. H. Sun, IEEE Photonics J. 2020, 12, 1.
[4] Z. Luo, Y. W. Cheng, S. T. Wu, IEEE/OSA J. Disp. Technol. 2014, 10, 208.
[5] M. F. Weber, C. A. Stover, L. R. Gilbert, T. J. Nevitt, A. J. Ouderkirk, Science (80-. ). 2000, 287, 2451.
[6] Y. Li, S. T. Wu, T. X. Wu, IEEE/OSA J. Disp. Technol. 2009, 5, 335.
[7] M. Y. Yu, B. W. Lee, J. H. Lee, J. H. Ko, J. Opt. Soc. Korea 2009, 13, 256.
[8] T. Ishida, R. Yuki, J. Soc. Inf. Disp. 2011, 19, 923.
[9] S. Xu, T. Yang, H. Miao, Y. Xu, Q. Shen, T. Guo, Z. Cui, E. Chen, Y. Ye, Appl. Opt. 2019, 58, 2567.
[10] S. E. Kim, J. Y. Lee, M. H. Shin, H. J. Kim, Y. J. Kim, IEEE Trans. Electron Devices 2017, 64, 1153.
[11] J.-W. Pan, C.-W. Fan, Opt. Express 2011, 19, 20079.
[12] A. Menéndez-Velázquez, C. L. Mulder, N. J. Thompson, T. L. Andrew, P. D. Reusswig, C. Rotschild, M. A. Baldo, Energy Environ. Sci. 2013, 6, 72.
[13] T. Jesper Jacobsson, J. P. Correa-Baena, M. Pazoki, M. Saliba, K. Schenk, M. Grätzel, A. Hagfeldt, Energy Environ. Sci. 2016, 9, 1706.
[14] S. Gharibzadeh, I. M. Hossain, P. Fassl, B. A. Nejand, T. Abzieher, M. Schultes, E. Ahlswede, P. Jackson, M. Powalla, S. Schäfer, M. Rienäcker, T. Wietler, R. Peibst, U. Lemmer, B. S. Richards, U. W. Paetzold, Adv. Funct. Mater. 2020, 30.
[15] H. Zhang, M. Kramarenko, G. Martínez-Denegri, J. Osmond, J. Toudert, J. Martorell, ACS Appl. Mater. Interfaces 2019, 11, 9083.
[16] M. Kramarenko, C. G. Ferreira, G. Martínez-Denegri, C. Sansierra, J. Toudert, J. Martorell,
An optical guide system for homogeneous emission of broadband polarized diffuse light and capable of light recycling back into electricity by the use of perovskite solar cells. The light guide is
based on a unique combination of periodic order in a half-cylinder photonic plate and randomness in a non-absorbing multilayer reflective polarizer.

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