Directional emission of white light via selective amplification of photon recycling and Bayesian optimization of multi-layer thin films

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Over the last decades, light-emitting diodes (LED) have replaced common light bulbs in almost every application, from flashlights in smartphones to automotive headlights. Illuminating nightly streets requires LEDs to emit a light spectrum that is perceived as pure white by the human eye. The power associated with such a white light spectrum is not only distributed over the contributing wavelengths but also over the angles of vision. For many applications, the usable light rays are required to exit the LED in forward direction, namely under small angles to the perpendicular. In this work, we demonstrate that a specifically designed multi-layer thin film on top of a white LED increases the power of pure white light emitted in forward direction. Therefore, the deduced multi-objective optimization problem is reformulated via a real-valued physics-guided objective function that represents the hierarchical structure of our engineering problem. Variants of Bayesian optimization are employed to maximize this non-deterministic objective function based on ray tracing simulations. Eventually, the investigation of optical properties of suitable multi-layer thin films allowed to identify the mechanism behind the increased directionality of white light: angle and wavelength selective filtering causes the multi-layer thin film to play ping pong with rays of light.

For many recent applications in our everyday lives, light-emitting diodes (LED) are required to emit a light spectrum that features specific optical properties. Such a light spectrum explains how the (relative) power provided by an LED is distributed over its contributing wavelengths and occurring emergent angles. A spectrum that is perceived as white light consists of several wavelengths. Thus, the generation of pure white light using (monochromatic) LEDs has a long scientific history: Beginning with additive to luminescence concepts and including organic approaches, the journey of white LEDs did not end yet. In this work, we elaborate on how to shift the light distribution of white LEDs towards forward directions using a multi-layer thin film (MLTF). As illustrated in Fig. 1a, the term white LED (package) refers to a horizontal stack of a semiconductor chip, the conversion system and an optional multi-layer thin film. Further on, the common LED structure without an MLTF is referred to as the reference design. By multiplication with a color matching function, each light spectrum can be characterized by the so-called color point, a two-dimensional vector in the color space of Fig. 1b, which describes the color of a spectrum. In the common case of a white LED without a MLTF, the chip emits blue light that passes through the ensuing conversion system. Here, two conversion materials, compounded with weight percentages, convert a portion of the blue light to green and red light resulting in white light. The amount of conversion materials determines the degree of conversion and is adapted such that the resulting light spectrum corresponds to the application-specific white target color point C. Another important characteristic of an LED is the power of its radiated spectrum. In radiometry, this power is commonly referred to as radiant flux. Hence, both the color point C(\(\mathbf{w}\)) and the forward power \(P(\mathbf{w})\) featured by an LED in a ±\(\alpha\)-angle cone are computed based on the anisotropic radiated light spectrum. Unfortunately, such emitted spectra of LED packages are unknown a priori for varying conversion materials and/or MLTFs. Thus, the deduction of spectrum-related measures of a
An LED (a) consists of a chip, a conversion system and a multi-layer thin film that features ten layers. The latter focuses the emitted light spectrum into a ± 25°-angle cone. The spectrum is composed of light rays (arrows) of different wavelengths. Such a spectrum is analytically associated with a point \( \mathbf{c} = (C_x, C_y) \) in the color space (b). The color point, roughly speaking, encodes the perceived color of a spectrum. The Euclidean distance between two color points (crosses) is denoted as the color point deviation \( d \). In this work, one of these points is the so-called white (target) color point \( \left( \frac{1}{3}, \frac{1}{3} \right) \).

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Since the aforementioned so-called color point optimization problem based on \( \mathbf{w} \) is empirically unambiguous and convex, it is not possible to further increase the power \( P^w(\mathbf{w}) \) if

\[
\mathbf{w} = \arg \min_{\mathbf{w}} \{ d(\mathbf{c}, \mathbf{c}'(\mathbf{w})) \},
\]

holds based on the Euclidean distance \( d = \| \cdot \|_2 \). The proposed idea of this manuscript is to modify the anisotropic light spectrum so as to focus more power \( P^w(\mathbf{w}, \mathbf{t}) \) into the forward angle cone compared to the reference design by using an MLTF—parameterized by \( \mathbf{t} \)—on top of the conversion system; thus, increasing the directionality of white light. In this work, directional emission or directionality of white light refers to the power that is emitted in a particular (solid) angle of interest induced by emitted rays of light accumulated in these directions. The corresponding inverse design problem features \( T + 2 \) parameters that describe the modified LED: In addition to the weight percentages of the conversion materials, the layer thicknesses \( \mathbf{t} = (t_1, \ldots, t_T) \) of \( T \) alternating layers of titanium dioxide (TiO₂) and silicon dioxide (SiO₂) can be adapted. The material system is not investigated in this paper and was chosen based on industrial producibility and reliability constraints only. However, the reported increase of directional white light emission may motivate further research covering the impact of the material system as well, including e.g. optically akin niobium oxide instead of titanium dioxide. Notably, increasing the usable power may compete with achieving the application-specific white target color point. For instance, due to the Stokes shift, designing an MLTF that raises the ratio of blue light in forward direction, obviously increases the usable power but will no longer retain the desired color point. Namely, it will render the LED’s light to appear bluish and no longer convenient for a white light application. In other words, the MLTF is required to not only increase the number of rays that emerge in forward direction but also achieve a particular ratio between blue, green and red rays. This constraint arises from the broad variety of wavelengths contributing to a white LED and is aggravated by the dispersive properties. In contrary, considering a monochromatic LED without a
conversion system only a narrow distribution of wavelengths exists. Here, an optimization could focus on the emitted forward power only. For white LEDs however, the aforementioned challenges result in a multi-objective optimization problem: improving the directionality of white light while preserving the color point associated with the spectrum that exits the LED. More precisely, we aim to increase $P^d(w,t)$ while keeping the Euclidean distance $d^S(w,t) \equiv d(c^a(w,t), C)$ low. To summarize, the contribution of this work is threefold:

- Bayesian optimization is used to adapt the layer thicknesses of an MLTF based on ray tracing simulations of white LEDs.
- MLTFs are investigated with regard to their general ability to increase directionality of white light emission of LEDs.
- The effect that explains the directionality increase of white LEDs in physical terms is identified.

**State of the art**

Although the directional emission of white light is crucial for many applications like head lamps of cars, to the best of our knowledge, none of the aforementioned points were investigated in previous work. Traditionally, the directionality of incoherent light sources like LEDs is increased via optical devices such as reflectors or lenses\(^{15,16}\), which shape the beam profile of a light source\(^{17}\). Notably, such optics are often bulky and therefore cause optical loss or limit the design. On the nanoscale, meta\(^{18–20}\) and microlenses\(^{21,22}\) have been introduced to manipulate light by microscopic structures. In addition, scientific work has been conducted towards the development of incoherent and direction light sources based on periodic or random gratings that dielectric\(^{23,24}\) or plasmonic\(^{25}\) structures. Moreover, extensive studies regarding metasurfaces\(^{26,27}\) have been conducted to increase the directional outcoupling of emitters. However, all of these systems are challenging to fabricate in mass-production or apply to coherent light sources only. Notably, they do not affect the light source itself but rather shape the light distribution over angle that exits a light source like an LED package. In contrast, the proposed epiphenal deposition of an additional MLTF on top of the conversion system of an LED is straightforward from an engineering viewpoint, allows compact integration in existing LED packages, implies only low additional expenditure and is directly applicable for mass-production of optical semiconductors. The closest investigation to ours may be the study conducted by Zheng and Stough\(^{28}\). They proposed to use an MLTF as a wavelength selective filter between the LED chip and the conversion system to increase the global efficacy of white LEDs. This filter allows the blue light coming from the chip to pass while simultaneously reflecting the green and red light emitted by the conversion system. Thereby, reabsorption effects of non-blue photons in the chip are suppressed. In other words, the MLTF enforces the green and red light to exit the package rather than irradiating the chip and thus increases the overall extraction efficiency. Such an MLTF is included into the optical LED model used in this work and further considered as integral component of the LED chip. In contrast, the contribution of our work is to improve the directional emission into an angle cone rather than increasing the overall outcoupling efficiency. Therefore, we demonstrate that an MLTF, acting as an angle and wavelength selective filter between the conversion system and the ambient air, can increase the directional emission of white light. Thereby, the MLTF helps to shape the angular and spectral light distribution directly through ray ping pong during its generation process rather than to collimate the outcoupled light.

Designing MLTFs that feature a particular target reflectivity or transmission over angle of incidence and wavelength is a common engineering challenge and therefore many optimization methods have been developed: Some of them are based on gradients\(^{29}\) or biological inspirations\(^{30,31}\). Recently, even some approaches including neural networks\(^{32–34}\) or reinforcement learning\(^{35–36}\) have been implemented to efficiently scan the search space for suitable MLTF designs. These techniques rely on fast-to-evaluate computations regarding the transfer matrix method (TMM) that allow to compute the optical characteristics of an MLTF, e.g. reflectivity or transmission over wavelength and angle of incidence. Based on e.g. a notion of reconstruction error, it takes not even a second to measure how close a particular MLTF’s optical characteristic is to an optimal one. However, in contrast with applications like anti-reflection coatings\(^{31}\), a specific optical characteristic that causes an MLTF to increase the directionality of white light is not known a priori. To circumvent this lack of information, we conduct noisy ray tracing simulations in order to optimize the power and color point of the LED spectrum in forward direction regarding the layer thicknesses of an MLTF. Thereby, the optical characteristic of MLTFs is implicitly optimized towards the a priori unknown optimal one and can be investigated further a posteriori, e.g. via TMM. Due to the strict assumption of propagating plane waves between parallel material interfaces\(^{38}\), the influence of an MLTF on the spectrum of an LED can not be directly inferred via TMM. Namely, the presence of significant material interactions like scattering or photon recycling renders ray tracing simulations mandatory. Notably, the noisy simulations take about 4 min for a given MLTF, which is 420 times longer compared to computing the optical characteristics of the MLTF itself based on TMM. Thus, ray tracing simulations are relatively expensive-to-evaluate and render most of the aforementioned data-hungry (TMM-based) optimization methods of MLTFs impractical. Therefore, we propose to adapt the individual MLTF layer thicknesses in order to maximize $P^d(w,t)$ while minimizing $d^c(w,t)$ via a variant of Bayesian optimization\(^{39}\). Although Bayesian optimization has shown satisfying results on many mathematical test functions as well as expensive-to-evaluate real-world problems regarding engineering, physical and chemical sciences\(^{40–46}\), to the best of our knowledge no application towards ray tracing simulations is reported in scientific literature. After optimizing an MLTF, its optical characteristics, like transmission, allow to physically deduce target behaviors that an MLTF needs to fulfill in order to further increase the directionality of white light. Hereby, an effect called **ray ping pong** is identified to be responsible for the improved directional emission of white light. Related effects like photon recycling\(^{47}\) were studied in previous work for solar GaAs cells\(^{48–50}\), perovskite LEDs\(^{51}\) or thin films themselves\(^{52–54}\). In our work, depending on their wavelength and incident angle, the rays are considered to be partially trapped in the LED package by an MLTF: enforcing interactions between rays and LED package materials like scattering, (re-)absorption, (re-)emission or non-radiative effects. The MLTF can
Here, a high forward power \( P^f \) may be bounded from below with regard to the weight percentages \( w \). This means that the target color point is not reachable for a given MLTF. In such cases, the comparison of power values for different MLTFs at different color points becomes invalid due to the Stokes shift. Here, \( W(\cdot) \) allows to guide the course of optimization towards suitable MLTFs: The weighting punishes excessive deviations from the target color point by decreasing the objective, although the power of an MLTF may be high. In practice, more weighting functions may be introduced to account for various conflicting or competing effects during LED development.

We compared the TS-SOO to the Thompson-sampling efficient multi-objective optimization (TS-EMO) in this work. Here, a high forward power \( P^f \) and a low color point deviation \( d^w \) are considered as (competing) real-valued objectives. Namely, TS-EMO directly searches for joint parameter vectors \( (w, t) \) to entry-wise maximize

\[
\begin{align*}
\mathbb{R}^2 \times \mathbb{R}^T & \to \mathbb{R}^2 \\
(w, t) & \mapsto (P^f(w, t), -d^w(w, t)),
\end{align*}
\]

Hierarchical optimization as a product of weights

Since hitting a suitable color point of an LED is mandatory for production, we reformulate the problem introduced in “Introduction” as a hierarchical optimization task

\[
\max \left\{ P^f(w, t) | w = \arg\min_\omega | d^\omega(w, t) | \right\}.
\]

Figure 2. (a) Illustration of a multi-layer thin film consisting of two dielectric materials (TiO\(_2\) in light grey and SiO\(_2\) in dark grey). (b) The heatmap of the Euclidean color point deviation over weight percentages of two conversion materials for the multi-layer thin film in (a). The green arrow indicates the possible path of a local optimizer initialized near the origin of the search space to the optimal converter weight percentages.
where the aforementioned Stokes shift renders the involved objectives to be competitive in nature. The minus sign of the second entry of Eq. (4) reflects the intention to minimize the color point deviation. Note that the hierarchical structure of the engineering optimization problem is not longer represented in the equation.

**Implementation**

For applications like headights, we set $\alpha = 25^\circ$ and set $d^0(w, t) = 0.005$ as a preliminary upper bound of the objective function (2) or (4) was optimized via TS-SOO or TS-EMO, we set $\alpha = 0.005$ and is based on a ray tracing simulation of $(10 \times 10^3, 50 \times 10^3$ and $100 \times 10^3)$ is started 15 times. The conversion material weight percentages remained unchanged. As expected, the corresponding boxplots indicate that the noise level decreases with an increasing number of rays traced. The horizontal dashed line indicates the reference power obtained with $10^6$ rays. This noise effect holds for the estimated color point $(C_2, C_3)$, too.

**Algorithm 1** Hierarchical optimization approach: Pseudo-code that illustrates the proceeding during optimization. $\mathcal{D}$ denotes the acquired data set of parameters and observations, $\alpha$ denotes the opening angle of the forward cone, and the timeout criterion defines how long the optimization endures. Optionally, the weight percentages are stored in $\mathcal{W}$ for traceability.

1. Initialize $\mathcal{D}, \mathcal{W}, 0 < \alpha < 90$, and set a stopping criterion, e.g. a timeout
2. while stopping criterion not fulfilled do
   3. Suggest (next) $t$ based on $\mathcal{D}$ and TS-SOO
   4. Solve $w = \text{argmin}_w (d^0 (w, t))$ based on Downhill-simplex algorithm
   5. Add acquired data point to data set $\mathcal{D} \leftarrow \mathcal{D} \cup \{(t, f^0(t))\}$ and track $\mathcal{W} \leftarrow \mathcal{W} \cup \{w\}$
3. end while
Results
In this section, we present the results of our investigations. First, we demonstrate that MLTFs can increase the directionality of white LEDs, which may seem counterintuitive beforehand. Second, we give an explanation of the underlying physical effects and discuss how we can make the latter observable in the spectra. The results are summarized in Table 1. Here, we report the MLTFs suggested by TS-SOO and TS-EMO that provided the highest power in $\pm 25^\circ$, while exhibiting a color point deviation lower than 0.002 points—which is an acceptable deviation for the most consumer products in practice. As mentioned, a joint local optimization of both, thicknesses and conversion material weight percentages is conducted after the global Bayesian optimization. Unsurprisingly, the total power of the white LED decreases for all considered MLTFs due to absorption losses. However, more power is available at particular forward angles of interest. This directionality increase is of value for applications like automotive headlamps or projection, where non-forward light does not contribute.

Increase of directionality. The reference design provides $P^\alpha(w, t = 0) = 0.201$ (W) after adopting the weight percentages $w$, while the deviation between the LED's and the target color point is given by $d^\alpha(w, t = 0) = 0.00151 < 0.002$. After optimizing an MLTF's thickness vector $t$ using Algorithm 1, the forward power of the LED is increased by 25.4% to $P^\alpha(w, t \neq 0) = 0.252$ (W). The Euclidean color point deviation for this design is given by 0.0014 $< 0.002$. Notably, using TS-EMO to solve the corresponding original multi-objective optimization problem (4) achieved only almost 5% more forward power while keeping the color point deviation below the required value of 0.002. This is not surprising, as TS-EMO is not supposed to be used for more than eight parameters. As illustrated in the very right plot in Fig. 4, the local refinement increased the power in forward direction by an additional 3.5% relative to the reference design. Thus, yielding 0.259W or 28.9% more

| $\alpha$ ($^\circ$) | 25  | 45  | 90  |
|-------------------|-----|-----|-----|
| $P^\alpha$ (W)    |     |     |     |
| Reference         | 0.201 | 0.559 | 1.052 |
| TS-SOO            | 0.259 | 0.640 | 0.985 |
| TS-EMO            | 0.210 | 0.569 | 0.978 |
| $d^\alpha$ (1)    |     |     |     |
| Reference         | 0.0015 | 0.0071 | 0.0146 |
| TS-SOO            | 0.0007 | 0.0230 | 0.0275 |
| TS-EMO            | 0.0025 | 0.0262 | 0.0281 |

Table 1. Optimization results regarding color point deviation $d^\alpha$, and power $P^\alpha$ of algorithm 1, and TS-EMO for $\alpha = 25^\circ$, and after local refinement. The designs featuring a multi-layer thin film are compared with the reference design, where only a color point optimization is conducted. In addition to the direct optimization objectives regarding $\pm 25^\circ$, we also report the color point deviations and energies for $\pm 45^\circ$ and $\pm 90^\circ$ observed for the respective optimized MTLFs. For $\pm 25^\circ$, highest power and lowest color point deviations are given in bold.

Figure 4. Color point deviation $d^\alpha$ over power $P^\alpha$ after joint (left, TS-EMO), hierarchical (middle, TS-SOO) and local (right, Downhill simplex) optimization for $\alpha = 25^\circ$. The horizontal black lines denote the color point deviation of 0.005 points, where $W'(0.005) = 0.99$ holds. The vertical black lines denote the power of the reference design without multi-layer thin film. For each sample in these plots, the color map reflects the objective function values obtained by Eq. (2).

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light compared to the reference design, while maintaining an acceptable color point deviation of \(0.0007 < 0.002\). Notably, starting a local refinement with the joint parameters provided by the TS-EMO implementation, either the color point deviation could not be reduced under 0.002 or the forward power increase remained below 10.0%. Due to the high computational effort associated with ray tracing simulations, we restarted each optimization procedure—based on TS-SOO and TS-EMO—only three times for 48 h each. The reported data corresponds to the best run regarding the objective function for TS-SOO and TS-EMO, respectively. Because the relative and absolute trends of the results of these experiments appeared to be consistent and showed no unexpected anomalies, they were not evaluated in detail. The Pareto fronts illustrated in Fig. 4 plot the (forward) power against the color point deviation for both, joint optimization using TS-EMO and hierarchical optimization using TS-SOO. As the time horizon was fixed, the different numbers of samples are explained by the implementation of the joint (719 samples) and hierarchical (143 samples) optimization approach: For each thickness vector \(t\) suggested by TS-SOO, the solving of the nested color point optimization (2) based on ray tracing simulations takes about 20 min. Contrariwise, the evaluation of a joint parameter vector \((t, w)\) requires only one ray tracing simulation and thus takes about 4 min. The comparison between the left and middle Pareto fronts in Fig. 4 indicate that TS-SOO circumvents MLTFs that lead to high color point deviations, as those are punished via multiplicative weights (3). In contrast, TS-EMO is not implicitly informed about the engineering structure of the problem via the objective function (4). Namely, an increase in forward power at the cost of color point deviation is of no value for specific LED applications. Therefore, most MLTFs suggested by TS-EMO indeed achieve the same or even higher forward power values compared to TS-SOO, but bring along an unacceptable color point deviation significantly above 0.005.

**Ping pong with light rays.** The results of the previous section allow to deduce an explanation of the mechanism of white light directionality using an MLTF. We can deduce a hypothetical effective spectrum which irradiates the MLTF. Therefore, we conduct pixel-wise division of the observed spectrum in Fig. 5b through the spectral and directional transmission of the optimized MLTF in Fig. 6a. This hypothetical spectrum is illustrated in Fig. 6b and indicates how much relative power is required to impinge on the MLTF from the conversion system for each angle and wavelength, in order to explain the physically detected spectrum that irradiates the ambient air after traversing the MLTF. The transmission describes the probability of a light ray to pass the MLTF, depending on its wavelength and angle of incidence. It was computed by a parallelized version of the TMM package\(^6\) provided by Luce et al.\(^7\). Here, the light-injecting substrate (conversion system) is represented as silicone (\(SiO_2\)) of infinite thickness. Air of infinite thickness defines the ambient environment. Aside from the relative power peak around the chip wavelength of 440 nm, another two contributions of relative power at 555 nm and 600 nm appear as a single broad peak in the spectra of Fig. 5. These green and red wavelength contributions correspond to the conversion material emissions, respectively. As expected, the transmission of the MLTF for all of these wavelengths is low for inconvenient, large beam angles. Thus, non-forward light rays are trapped in the LED package until physical interactions change their directional properties such that they are likely to escape or the light rays vanish optically due to non-radiative thermal effects. We suppose that this phenomenon...
causes the directionality enhancement and refer to it as ray ping pong. Here, the MLTF on top of the conversion system directly influences the emitted spectrum over angle and wavelength of the LED. The MLTF does not only function as an angle selective filter that reflects non-forward light rays back into the LED package, but also balances the statistics of emitted blue, green and red rays in order to appear as white light of a specific color. In other words, the MLTF exploits the process of ray ping pong to reach a statistical equilibrium of emitted rays that is advantageous regarding directionality and color point of the outcoupled light. Notably, the characteristic transmission pattern of an MLTF over wavelength and angle of incidence (see Fig. 6) not only depends on the layer thicknesses, but also the constituent materials. Due to in-house manufacturing limitations and preferences, the default and well-known material system of TiO₂ and SiO₂ remains unchanged in this work. However, a mentionable characteristic of the used material system is their relatively high difference in the complex, dispersive refractive indices for wavelengths of the visible spectrum. Studying Table 1 implies that the MLTF decreases the total efficacy of a white LED corresponding to α = 90°: Rays are trapped in the LED package and are thus more likely to further interact with the LED materials instead of escaping into the ambient air. Such interactions may include photon recycling or scattering, but also non-radiative effects like thermal losses of rays absorbed by the conversion materials. As mentioned, for applications like head lamps only power emitted in forward direction (α ≪ 90°) is usable. In this case, any increase in directionality obviously outweighs a (moderate) drop of global efficacy.

Limits of directionality increase. The previous section allows us to understand the constraints of our approach. Although no explicit optimizations for angles different from the application-specific 25° were conducted for this work, our investigations regarding the cumulated intensity difference of Fig. 7 indicate that an increase in forward power is possible up to almost 60°. Namely, for angles α > 58.4°, the MLTF would need to re-direct light rays of unsuitable angles between α and 90°. Due to the Lambertian radiation characteristics of LEDs, the quantity of such rays may be too low to outweigh non-radiative effects like thermal losses, which are statistically enforced by the MLTF for each ray. Thus, the deposition of an MLTF may not be suitable for applications that leverage light with a broad range of incidence angles, here larger than 58.4°.

Conclusions

Increasing the (forward) power of a white LED while still maintaining its color point is a hierarchical multi-objective optimization problem: The Stokes shift renders these objectives to be competitive by nature, because a naive increase in power may turn the emitted light bluish instead of pure white. Since the color point is a strict requirement for many applications, a higher forward power of an LED at the cost of color changes is utterly undesired. In this work, we enter into the competition between color point and power with a Bayesian optimization approach that optimizes a physics-guided, weighted objective function. Hereby, weights continuously implement hard constraints and thus preserve approximability via Gaussian processes. The reported results indicate that multi-layer thin films on top of white LEDs can increase the light directionality. The epitaxial deposition of such multi-layer thin films is only implying low additional expenditure and directly applicable for mass-production of many optical semiconductors. Our analyses reveal that a carefully designed multi-layer thin film functions as
Figure 7. The normalized intensity of an LED with and without a multi-layer thin film (MLTF) is denoted on the left axis. The sinus-weighted integral over the intensity difference (grey area)—the so-called cumulated intensity difference—on the right axis indicates that a directionality increase can be achieved up to 58.4°. However, the peak of directionality increase is observed between 35° and 40°.

an angle and wavelength sensitive filter: The filter statistically balances emitted rays of different wavelengths to meet the color point. In addition, it traps rays that would exit the LED at large angles in order to implicitly enforce their forward (re-)emission. To summarize, the proposed objective function guides the optimization towards a multi-layer thin film that leverages statistical ray ping pong to enforce favorable properties of the spectrum radiated by the LED. Thus, we shine a light on the previously enigmatic effect causing the counterintuitive increase of white light directionality using a multi-layer thin film.

Data availability

The optical models and related (commercial) software that support the findings of this study are available from OSRAM Opto Semiconductors GmbH but restrictions apply to the availability of these items, which were used under license for the current study, and so are not publicly available. The generated and analysed data as well as any code-related information is included in this manuscript or already published by third parties.

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The authors declare no competing interests.

### Author contributions

R.W. developed the physics-guided objective function, wrote and ran the code, devised the experiments and edited the manuscript. C.W. and L.K. interpreted the acquired data in terms of the white light. R.B. analysed the results and advised how to avoid the Stokes shift. A.L. provided code to evaluate and discuss multi-layer thin films. S.S. provided the calibrated optical model of a white LED to conduct ray tracing simulations. M.L.S. and E.W.L. made substantial conceptual and editorial contributions to this manuscript. All authors reviewed the manuscript and played a round of ray ping pong.

### Competing interests

The authors declare no competing interests.

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### Author contributions

H.W. developed the physics-guided objective function, wrote and ran the code, devised the experiments and edited the manuscript. C.W. and L.K. interpreted the acquired data in terms of the ray ping pong and contributed application-specific knowledge about white light. R.B. analysed the results and advised how to avoid the Stokes shift. A.L. provided code to evaluate and discuss multi-layer thin films. S.S. provided the calibrated optical model of a white LED to conduct ray tracing simulations. M.L.S. and E.W.L. made substantial conceptual and editorial contributions to this manuscript. All authors reviewed the manuscript and played a round of ray ping pong.
