

Article

Interplay of Aspect Ratio and Emission Dipole Orientation for Light Extraction in Corrugated Red, Green and Blue OLEDs

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Abstract

Using advanced optical modelling, we quantify how sinusoidal corrugation and emitter dipole orientation jointly govern light extraction from OLED thin-film stacks into a glass substrate for red, green, and blue emission. Irrespective of emission colour, the corrugation aspect ratio ($AR = \text{height}/\text{period}$) is the dominant geometric parameter controlling extraction, with absolute period and height playing secondary roles, as periods of 600–1000 nm deliver similar gains across all colours. Extraction peaks at $AR \approx 0.2$ for predominantly horizontal dipoles, $AR \approx 0.5$ for vertical dipoles, and $AR \approx 0.3$ for isotropic orientations. For the isotropic case, extraction improves by up to 40%, 34%, and 20% relative to flat red, green, and blue devices, respectively. Absorption analysis attributes the principal gains to suppression of surface-plasmon-polariton losses of vertical dipoles, supported by local dipole reorientation, waveguide disruption, and scattering. Because practical texturing can alter dipole orientation, optimum conditions must be re-evaluated; if orientations follow the sinusoidal profile, an AR of approximately 0.2–0.3 is favoured for isotropic to moderately horizontal orientations, whereas higher AR s benefit strongly vertical orientations. The results provide guidelines for co-optimising corrugation geometry and dipole orientation for high-efficiency OLEDs.

Keywords: OLED; light extraction; optical modelling; finite element method; corrugations; anisotropy

1. Introduction

Organic light-emitting diodes (OLEDs) have become a key technology for modern displays and lighting applications, offering unique advantages such as high contrast, vibrant colours, and wide viewing angles. Their low fabrication cost and high energy efficiency, combined with the possibility of use with ultra-thin, lightweight, flexible, and transparent substrates, make OLEDs particularly attractive for advanced lighting and architectural design [1–6]. Their efficiency originates from high internal efficiencies, which, for phosphorescent emitters [7] and thermally activated delayed fluorescence (TADF) materials [8,9], can theoretically reach up to 100%. Nevertheless, external quantum efficiencies (EQEs) for conventional flat-plane devices, without outcoupling solutions, typically remain limited to 20–30%, primarily due to significant optical losses that restrict light extraction [10,11]. These optical losses can be broadly categorised into three main types. First, substrate losses occur due to total internal reflection (TIR) at the substrate–air interface, trapping light within the substrate. Second, waveguide losses arise from TIR at the organic layer (or transparent electrode)–substrate interface, where light becomes guided in the thin-film structure



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and ultimately absorbed. Third, losses occur due to coupling of light to surface plasmon polaritons (SPPs) at organic–metal interfaces. Additional minor losses are attributed to parasitic absorption within the device layers.

Numerous strategies have been proposed to enhance light outcoupling, as summarised in recent reviews [12–14]. Approaches to reduce substrate losses include micro-lenses [15], micro-texturing [16–20], scattering particles [21], and others. Solutions to waveguide and SPP losses, although less studied and under-optimised, mainly due to the complexity of implementation without compromising electrical performance [22], include micro-lens arrays [23], nanoparticles [22], low-index grids [24], surface corrugations [25,26], and others [27,28].

Two of the viable strategies that can enhance light outcoupling from otherwise planar OLED stacks are (i) surface corrugations that can be implemented by texturing the substrate and subsequently depositing the functional layers, resulting in a corrugated device. Corrugations disrupt the planar geometry, primarily redirecting and scattering guided light, thereby improving light extraction [26,29–34]. (ii) Preferential orientation of the emitting molecules (dipoles), anisotropy, shows high efficiency in flat devices, where a predominantly horizontal dipole distribution produces a more favourable angular emission profile, increasing the fraction of power radiated below the critical angle and thus coupled into the far field [20,35–40].

While each aforementioned approach independently improves outcoupling efficiency, their combined effect on light extraction has been scarcely explored. In addition, the interdependence of texture geometry (period, height, and aspect ratio) and emission wavelength (red, green, blue, and white) in governing scattering and thus extraction has received limited attention.

In this contribution, we thus investigate light extraction under the combined influence of corrugation shape and size (with periods from 450 to 1500 nm and varied heights) and emitter dipole orientation across device emission colours from blue to red. In addition to the individual contributions, we quantify their coupled effects and examine possible texture-induced reorientation of emission dipoles and its impact on light extraction.

We adopt a regular two-dimensional sinusoidal texture arranged in a rectangular lattice and fabricated on a glass substrate, with period and height systematically varied. Combining this with the use of a realistic layer growth model [41], which incorporates both isotropic and conformal growth, brings our model closer to an actual non-conformal fabrication process, enabling accurate representation of texture shape and local thickness variations—see example in Supplementary Information (SI), Figure S1. Such textures—and complete OLED devices incorporating them—have already been realised via glass etching, laser processing of glass [17,34], and nanoimprint techniques [33,42,43]. The latter, nanoimprint processes are compatible with roll-to-roll manufacturing, enabling rapid and low-cost production.

We quantify the combined effects of sinusoidal corrugation geometry and emitter dipole orientation on light extraction and optical losses in OLED thin-film stacks by systematically varying the period and height and evaluating their interplay across red, green, and blue wavelengths. We also incorporate possible, texture-induced dipole reorientation by separating horizontal and vertical components and averaging over orientation distributions, thereby capturing its impact under different conditions. By distinguishing between horizontally and vertically oriented dipoles, we show that corrugations primarily affect vertically oriented emitters by suppressing SPP losses, whereas their impact on horizontally oriented dipoles is marginal and can even reduce light extraction relative to flat devices. Contrary to the expected strong coupling between corrugation period and emission wavelength, our results indicate that the aspect ratio ($AR = \text{height/period}$) is

the dominant geometric parameter governing extraction; consequently, a wide range of periods performs similarly well for red, green, and blue OLEDs.

2. Modelling and Simulations

Optical modelling of advanced optoelectronic devices has been mastered with a coupled modelling approach, both for light incoupling in photovoltaics [44,45] and for light outcoupling in OLEDs and perovskite LEDs [17,19,46]. Optical simulations of OLEDs on flat and corrugated substrates are performed with a focus on extracting generated light from the thin-film structure into the glass substrate and on light outcoupling into the far-field medium (air). These are defined as the ratio between the light generated inside the emission layer and the light reaching either air (η_{out} —light outcoupling) or the substrate (η_{ext} —light extraction).

For light extraction, in simulations, we assume the substrate to be semi-infinite, so all light reaching the substrate is considered useful, without further optical losses. In real devices, this can be achieved by attaching a hemispherical lens, which almost ideally eliminates substrate/air reflections. This approach focuses only on losses due to the thin-film structure, without additional effects from a thick substrate. Since OLED devices with near-ideal internal efficiencies (e.g., electron-to-photon conversion ratios approaching 100%) have already been demonstrated [7–9], we exclude electrical properties from our simulations and focus solely on optical characteristics, ensuring that potential non-ideal electrical effects do not obscure the optical behaviour.

2.1. Model Details

Our devices employ nano-scale corrugations with feature sizes comparable to the optical wavelength; thus, full-wave electromagnetic simulations are required. FEM was selected in preference to RCWA and FDTD [47–49] as it enables higher-order discretisation of the electromagnetic field within each element and provides a direct, intuitive treatment of material properties and boundary conditions (e.g., absorbing layers and symmetries). It also accommodates complex three-dimensional geometries and yields steady-state, frequency-domain solutions, in contrast to the time-domain nature of FDTD.

We use a previously in-house-developed optical model [11], which, by applying special periodic conditions, enables us to model nanotextured OLEDs and other thin-film devices (e.g., perovskite LEDs) with incoherent sources (e.g., a single source in a periodic structure). The simulation model and methodology are only briefly summarised here; full details and further verifications are provided in [11], with additional theoretical details on the method itself in [50,51]. Optical simulations were performed using COMSOL software (ver. 6.3) [52] employing standard three-dimensional finite element method (FEM) electromagnetic simulations; however, the approach is transferable to other platforms under the same modelling assumptions.

The model consists of a single unit cell, one period in each lateral direction, with two corresponding pairs of Floquet periodic boundary conditions. To eliminate emission source dipole coherence effects, we employ multiple Bloch terms for the periodic dimensions. Increasing the number of Bloch terms improves accuracy but increases computational cost. We selected the number by calibrating against exact transfer matrix method (TMM) results for planar devices and retained the same value for the corrugated cases, for which we observed even faster convergence (i.e., fewer terms would suffice).

Semi-infinite domains (e.g., glass and air) were truncated with open boundaries implemented as absorbing (scattering) boundary conditions of negligible reflectivity. These boundaries were placed at least $1\text{--}1.5\lambda$ from the thin-film stack. The mesh used 5–6 elements per effective (in-material) wavelength with quadratic (second-order) vector

elements for the electric field. Special care was required for periodic faces, where identical (node-to-node) meshes were enforced to satisfy Floquet periodicity.

2.2. Computational Details

For each combination of period (P), height (h), and wavelength (λ), we simulate light extraction into the glass substrate. Emission sources are modelled as point dipoles placed at discrete locations that uniformly sample one texture period. Previous work has shown that three distinct positions are sufficient to represent the full period, substantially reducing simulation time with minimal loss of accuracy [11]; see our device-specific example in the SI—Figure S2. The same three positions are used consistently across all simulations.

At each selected position, we consider three orthogonal dipole orientations according to the general coordinate system (x, y, z): two in the horizontal plane, (1,0,0) and (0,1,0), and one in the vertical plane (0,0,1). This basis permits reconstruction of any arbitrary general orientation distribution.

Emission dipoles generally exhibit an isotropic in-plane distribution [35,36], while they may show a preferential orientation relative to the layer-stack normal. This later preferential orientation is commonly described by the anisotropy factor a , which is defined as the ratio of vertically oriented dipoles towards all dipoles. The anisotropy factor thus reduces the otherwise complex task of specifying detailed dipole-orientation distributions to the much simpler problem of defining the relative fractions of parallel and perpendicular dipole moments. For example, $a = 0$ results in only horizontal dipoles, and $a = 1/3$ results in isotropic orientation with an equal ratio of vertical and horizontal dipoles (1 vertical + 2 horizontal).

It is important to note that this method only accounts for general dipole distributions (flat-plane structures) but does not capture outcoupling from a single, specifically oriented dipole on a textured surface; such cases would require separate simulations.

We thus assume that the emission dipoles are randomly oriented within the horizontal plane. This follows the conventional treatment of flat-plane OLED architectures, where random in-plane dipole orientation is taken to represent an effectively isotropic in-plane distribution. We extend the same assumption to corrugated devices, as the emitter layer spans multiple texture periods, with the dipole orientations effectively averaging out to a random in-plane distribution. Under this assumption, the full in-plane average can be represented by two orthogonal horizontal dipole orientations, consistent with the flat-device approach (see SI—Figures S3 and S4). We adopt this assumption for all calculations and analyses presented in this paper.

Moreover, due to the symmetry of both the sine-textured surface and the dipole emission pattern, in combination with the assumption of isotropic general orientation of horizontal dipoles, the two orthogonal horizontal dipole orientations can be treated equivalently. A horizontal dipole placed at any point on the sine texture will, when rotated by 90° , produce an emission pattern identical to that of the original dipole at its initial position. This symmetry allows us to combine the results of both horizontal dipole orientations into a single representative case, simplifying the analysis without loss of generality.

For optimisation and verification of devices with flat interfaces, a fast and experimentally verified model based on TMM was used [17,53,54]. Using these optical models we gain wavelength-dependent outcoupling efficiency, $\eta_{\text{out}}(\lambda)$, or light extraction, $\eta_{\text{ext}}(\lambda)$, and Purcell factor, $F(\lambda)$. Purcell factor is defined as a ratio between total emitted light at the source location and total emitted light in infinitive homogeneous medium. Additionally, light absorption by individual layers is being simulated, enabling us to further perform a detailed optical analysis of the entire OLED structure.

2.3. Device Structure

For our analysis, we selected three distinct OLED devices with emission in the red, green, and blue ranges to cover the entire visible spectrum from long to short wavelengths. All three devices share a similar structure, with an optically thin-film structure comprising an emission layer (EML) sandwiched between a hole transport layer (HTL) and an electron transport layer (ETL). For all three devices, electrical contacts are provided by a 90 nm thick, transparent front anode (indium tin oxide—ITO) and a 100 nm thick, opaque back silver cathode. The entire thin-film structure is deposited on a flat or textured glass substrate—see Figure 1.

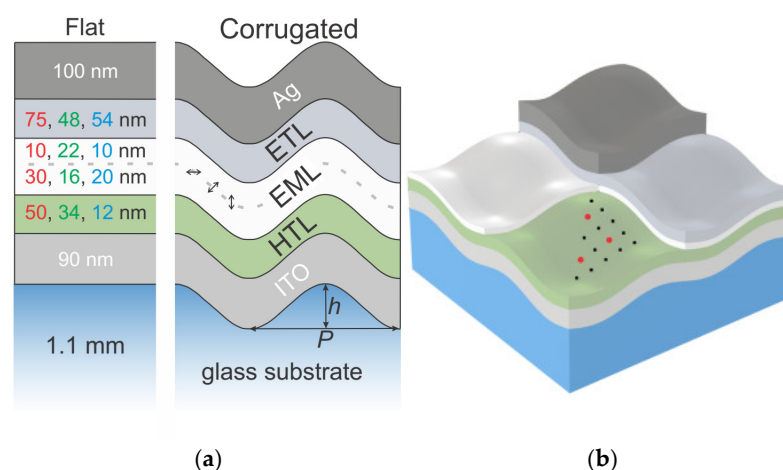


Figure 1. (a) OLED device schematics on flat and corrugated glass substrate in 2D view. Marked are functional layer names with corresponding thicknesses for each colour device (red, green, and blue). (b) 2D sinusoidal texture ($P = 800$ nm, $h = 240$ nm) with the deposited layer stack indicating the resulting profile modifications. Black dots mark all candidate dipole positions across one period; red dots indicate the three positions selected for simulations (3D perspective view).

To maintain generality, we use the same typical materials for the ETL and HTL in all three devices, with colour-specific EML layers for red, green, and blue emission—see emission spectra in SI, Figure S5. For the optical properties of the materials used, see SI, Figure S6. The structures and materials are loosely based on mature devices from [55], while, from an optical perspective, there is only a small difference compared to the newest OLEDs. Thus, all results can correspond to the latest OLEDs and other novel thin-film technologies, such as perovskite LEDs.

An essential aspect of OLED optical design, for both flat and corrugated devices, is the configuration of the thin-film structure—an optical microcavity formed between the substrate and the back reflector [29,56]. To maintain generality, we select a microcavity optimised for maximum light outcoupling to air, assuming isotropic dipole orientation ($a = 1/3$) for each colour device. This provides a neutral baseline for analysing the impact of preferential dipole orientations, whether more horizontal or vertical. Although optimising the optical cavity for a specific anisotropy value would change the absolute efficiencies, the overall trends would remain the same. We optimised the microcavity by adjusting the thicknesses of both transport layers, HTL and ETL, as changing these thicknesses has only minimal impact on electrical properties but a substantial effect on optical properties. The layer thicknesses of the ETL and HTL were optimised using a fast TMM method and are as follows: HTL—50, 34, and 12 nm; ETL—75, 48, and 54 nm for red, green, and blue devices, respectively. A schematic of the device, with optimised thicknesses and functional layer names, is shown in Figure 1a, while in Figure 1b we show an example of blue device on sine corrugations with actual layer growth considered; change in the layer shape through

increasing deposition can be observed. These optimised devices were used in all subsequent simulations. Emission sources, modelled as point dipoles, are positioned at a specific single vertical location within the EML, as determined from [55]—see dashed line in Figure 1a. For corrugated devices, multiple emission point dipoles are positioned on the texture at selected lateral (x - y plane) positions within one quarter of a texture period (Figure 1b). By exploiting the symmetry of the sinusoidal texture, these representative dipole positions effectively account for emission sources across the entire textured surface [11].

Sinusoidal textures, due to their symmetry and periodicity, reduce the number of numerical simulations required, while still capturing extraction trends that can also be generalised to non-sinusoidal and stochastic textures. To explore a broad range of corrugation structural effects, we selected textures with periods of 450, 600, 800, 1000, and 1500 nm and varied their heights to achieve aspect ratios ($AR = h/P$) from 0 to 0.5. At higher ARs, textures become very steep, which can cause difficulties in subsequent material deposition and increase the risk of electrical and structural defects. Additionally, as will be shown later, textures with high ARs (0.5) already reach the limit in reducing thin-film losses.

3. Results

For all three different colour devices, we first simulate a case with flat interfaces without corrugations. The light extraction results show good agreement between FEM-based simulations and the exact transfer-matrix method (TMM) for both horizontally and vertically oriented dipoles across all three-colour devices (see SI—Figure S7). These simulations also enable mode analysis, revealing that waveguide and surface plasmon polariton (SPP) losses account for over 50% of the generated light—and exceed 90% for only vertically oriented dipoles (see SI Figure S8)—highlighting the dominant optical loss channels and the significant potential for enhancing OLED light extraction by mitigating these losses.

3.1. Corrugations

By varying texture P and h for each device emission colour in combination with different anisotropy, we aimed to systematically evaluate how light extraction depends on these parameters. Figure 2a–c shows simulated results for all red, green and blue devices across various P and h (expressed as AR) combinations, separated for horizontal ($a = 0$ Figure 2a), vertical ($a = 1$; Figure 2b) and isotropic ($a = 1/3$; Figure 2c) anisotropy.

From the results, we first observe general similarities in light extraction trends across different emission colours. Regardless of texture P , all colours exhibit comparable behaviour with respect to the texture AR . For horizontally oriented dipoles (Figure 2a), light extraction increases with AR up to 0.2, beyond which extraction efficiency begins to decline. We can see absolute improvement towards flat devices (for flat: $\eta_{\text{ext-red}} = 0.64$, $\eta_{\text{ext-green}} = 0.56$, and $\eta_{\text{ext-blue}} = 0.52$) with maximum improvements of +2% ($\eta_{\text{ext-red}} = 0.66$), +5% ($\eta_{\text{ext-green}} = 0.61$) and +5% ($\eta_{\text{ext-blue}} = 0.57$) for red, green, and blue OLEDs, respectively. For higher AR values above 0.4, extraction falls below that of flat devices, indicating that corrugations can actually reduce extraction efficiency for horizontally oriented dipoles. In contrast, for vertically oriented dipoles (Figure 2b), there is a steep increase in extraction efficiency with rising AR up to 0.3–0.4, followed by a slower increase and eventual saturation at AR around 0.5. The results show a high maximum extraction increase at $AR = 0.5$, with absolute increases of +55% ($\eta_{\text{ext-red}} = 0.56$), 42% ($\eta_{\text{ext-green}} = 0.43$), and 30% ($\eta_{\text{ext-blue}} = 0.33$) compared to flat devices ($\eta_{\text{ext-red}} = 0.01$, $\eta_{\text{ext-green}} = 0.01$, and $\eta_{\text{ext-blue}} = 0.03$) for red, green, and blue devices, respectively. Even devices with low AR textures significantly outperform devices with flat interfaces for vertically oriented dipoles. For both orientations, extraction improves up to $AR \approx 0.2$; beyond this point,

trends diverge—efficiency decreases for horizontal dipoles and further increases for vertical ones—indicating a trade-off depending on the anisotropy value. This suggests that an optimal AR must balance these opposing effects. Moreover, as shown in our previous publication [11], the position of the dipole on the corrugation influences outcoupling; horizontal dipoles near the top of the texture exhibit higher extraction compared to those at the bottom, while vertical dipoles achieve the highest extraction when positioned at the middle of the texture. Possible local clustering of emitters can therefore play an important role. For the case of isotropic dipole orientation ($a = 1/3$) and uniform distribution of emission dipoles, the optimal AR is approximately 0.3, as observed in Figure 2c. Since the ratio of horizontal to vertical dipoles here is 2 to 1, improvements to vertical dipoles have a smaller impact on overall performance in this case. For $a = 1/3$, the overall highest improvement towards flat ($\eta_{\text{ext-red}} = 0.43$, $\eta_{\text{ext-green}} = 0.39$, and $\eta_{\text{ext-blue}} = 0.37$) is +18% ($\eta_{\text{ext-red}} = 0.61$), +13% ($\eta_{\text{ext-green}} = 0.52$), and +7% ($\eta_{\text{ext-blue}} = 0.44$) for red, green, and blue OLED devices.

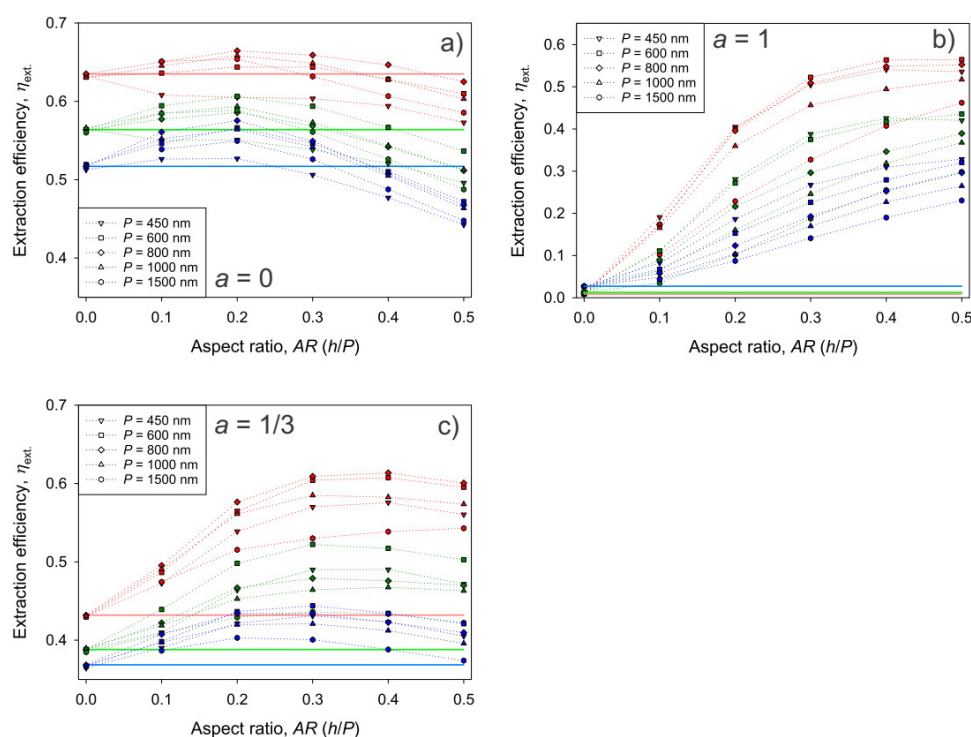


Figure 2. Extraction efficiency (in glass substrate) in dependence of AR for different P and for all three: red, green and blue OLEDs with specific dipole orientations: (a) only horizontal ($a = 0$), (b) only vertical ($a = 1$) and (c) isotropic ($a = 1/3$) orientation.

Less distinct trends in light extraction can also be observed depending on corrugation P for each emission colour—see Figure 2. For horizontal dipoles at constant AR, all three colours show the lowest efficiency at the smallest P (450 nm), while for vertical dipoles, the lowest efficiency occurs at the largest P (1500 nm). In general, the highest extraction efficiencies for each colour are found at intermediate P between 600 and 1000 nm, regardless of general dipole orientation. More specifically, for vertical dipoles, extraction is improved for all three colours as P decreases from 1500 to 450 nm (at constant AR), whereas, for horizontal dipoles, this trend is less pronounced, with the highest extraction typically observed for periods between 600 and 1500 nm at the same AR.

When combining these results for isotropic orientation ($a = 1/3$) at constant AR = 0.3, the 1500 nm period consistently performs worst across all colours, while periods between 600 and 1000 nm yield the highest extraction. These findings suggest that textures with periods in the 600–1000 nm range (dimension in the range of emission colours wavelengths)

and AR between 0.2 and 0.3 offer high light extraction across all emission colours ($a = 1/3$). This simplifies the selection of effective corrugation geometries, as multiple periods within this range are suitable for a broad spectrum of wavelengths, making them also suitable for white colour devices.

3.2. Orientation Change

OLED emission sources can exhibit a range of general dipole orientations, mainly from isotropic to strongly horizontal. To further analyse how these orientations affect light extraction across different corrugation geometries, we recalculated extraction efficiencies for various dipole anisotropy factors, ranging from $a = 0$ to 1. Selected results are shown in Figure 3 for red (3b), green (3c) and blue (3d) OLEDs, using a texture with P of 800 nm, which corresponds to high extraction for all colours. Additional data for other periods are provided in the SI—Figure S9.

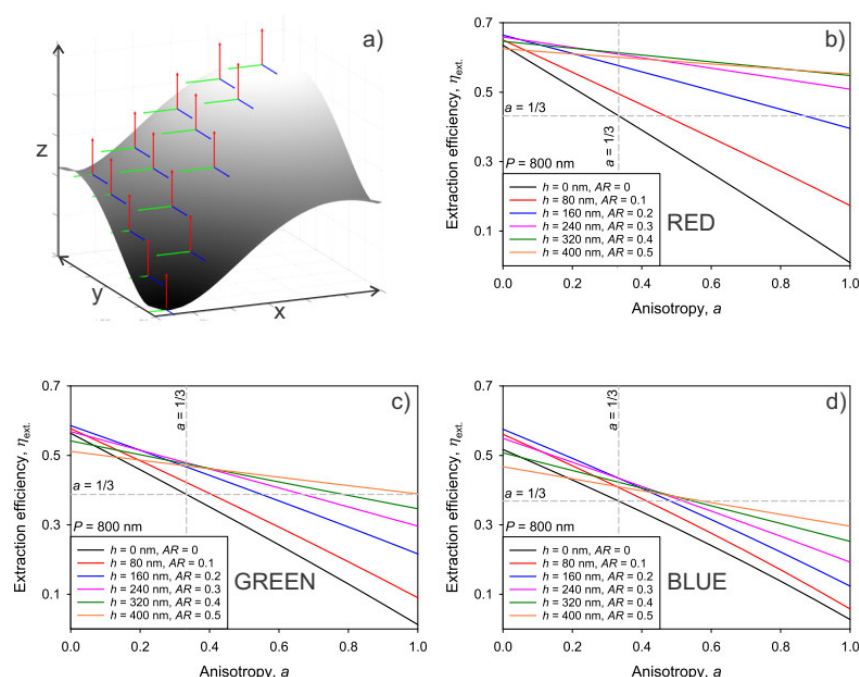


Figure 3. (a) Representation of dipole orientation on corrugation—same as on flat. Light extraction regarding to initial anisotropy for corrugation of $P = 800$ nm and different heights, for (b) red, (c) green, and (d) blue devices.

In this analysis, the general orientation of dipoles on textured surfaces is considered as unchanged, referenced to a fixed global coordinate system—see Figure 3a. Results illustrate how light extraction efficiency depends on general dipole orientation (a), with respect to corrugation parameters such as AR, P , and h . Overall, the results show (Figure 3b–d) that corrugation enhances light extraction across all a values, with some minor exceptions observed for highly horizontal dipole orientations combined with high AR corrugations. A near-linear relationship between anisotropy value and light extraction is evident, with the slope varying across different AR values. It is also observed that textures with AR values between 0.2 and 0.3 consistently yield optimal light extraction for anisotropy below $1/3$, independent of emission colour.

3.3. Changed Orientation

However, in practice, the orientation of emitting dipoles may change during fabrication, when deposited on textured surfaces. Such changes can be inferred from Figure 3b–d or recalculated using data for purely horizontal and vertical dipole contributions. One

possible scenario is that the dipole orientation follows the local slope of the texture—see Figure 4a—meaning that dipoles originally aligned on a flat substrate may become locally reoriented according to the surface inclination. This alters the effective ratio of horizontal to vertical dipoles. Although the ratio between the two horizontal dipoles also changes, due to the symmetry of the system, the overall response remains effectively unchanged. As a result, the only significant variation arises in the ratio between vertical and horizontal dipole contributions.

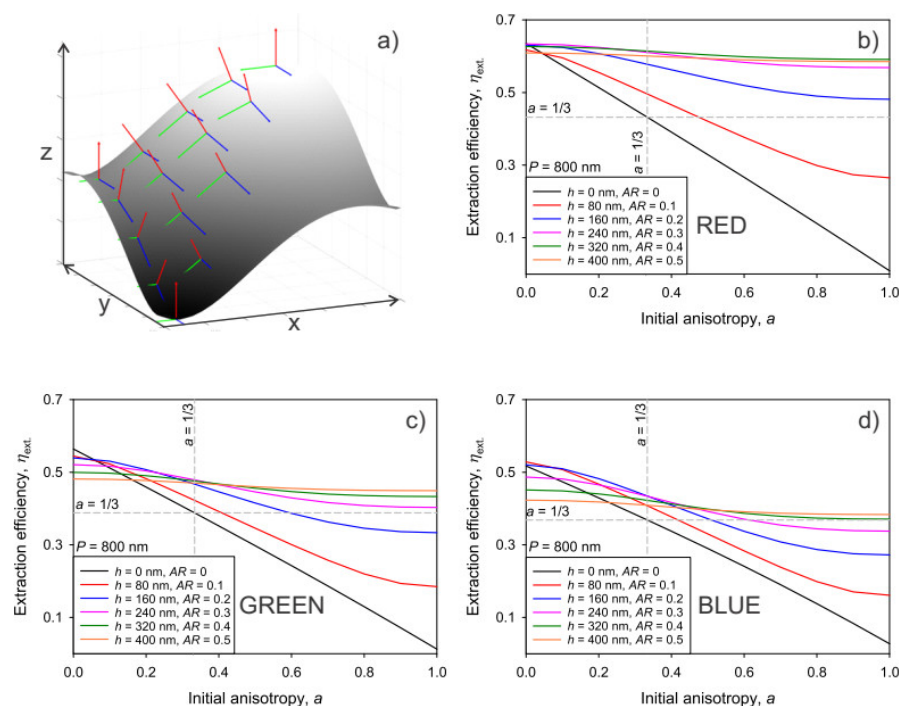


Figure 4. (a) Representation of dipole orientation on corrugation—following the corrugation slope. Light extraction regarding to initial anisotropy for corrugation of $P = 800$ nm and different heights, for (b) red, (c) green, and (d) blue devices.

The results for this case, shown in Figure 4b–d, now reflect light extraction not only due to the texture but also due to a change in general dipole orientation. When examining light extraction, we first observe that there is no longer a linear change corresponding to the general dipole orientation. In this case, the general dipole orientation itself changes and, depending on the slope, horizontal dipoles can locally become more vertical and vice versa.

If we first consider extreme cases—where dipoles are initially ideally horizontally oriented on flat interfaces—and place them on a textured surface, the slope causes a partial reorientation of the general dipole orientation towards vertical. As a result, instead of having only horizontal dipoles, we now observe a mixture of horizontal and vertical dipoles. As shown in Figure 3, vertically oriented dipoles, regardless of the texture, exhibit lower outcoupling compared to horizontally oriented dipoles on the same texture. Therefore, shifting the orientation towards vertical dipoles results in reduced outcoupling, as seen in Figure 4. Conversely, if we start with ideally vertically oriented dipoles and place them on a textured surface, the general orientation shifts towards horizontal, leading to higher outcoupling efficiency. Here, two factors contribute: enhanced extraction due to the corrugated surface and a change in general dipole orientation towards the opposite alignment. A shift from mostly vertical to horizontal dipoles has a positive effect, while the opposite trend has a negative effect.

Nonetheless, it can again be observed that certain textures with specific ARs perform well across all OLED colours, regardless of dipole orientation. For instance, textures with

$AR \approx 0.2$ provide high outcoupling for any $a < 0.35$, while, for devices with $a = 0$, $AR \approx 0.1$ is more effective. For $a > 0.35$, higher ARs yield better performance. Overall, corrugations with $AR \approx 0.2$ offer the best general solution for $a < 0.33$ across all red, green, and blue OLEDs, although further optimisation of AR for specific a values can achieve higher extraction.

Our results also show that highly horizontally oriented dipoles exhibit high outcoupling even without corrugations, with only slight increase, or even decrease, in light extraction when corrugations are applied. This raises doubts about the benefit of introducing corrugations in devices with predominantly horizontal dipole orientation (low a), as additional fabrication steps and potential defects may negate any gain in light extraction, making flat devices more favourable. In contrast, for devices with higher a , outcoupling can be significantly improved.

4. Discussion

4.1. Analysis of Optical Losses

To analyse the effects of corrugation on light extraction, we examine absorption in selected layers and the amount of extracted light for varying ARs of the texture. We analyse light extraction, absorption in the back reflector, and absorption in thin layers. We combine absorption in the ETL, HTL, EML, and ITO into a single value, referred to as absorption in thin layers. Results for a selected case of a red OLED with a corrugation $P = 800$ nm and h ranging from 0 to 400 nm are presented in Figure 5 and numerically in Table 1. The analysis is separated into horizontal ($a = 0$), vertical ($a = 1$), and isotropic ($a = 1/3$) dipole orientations.

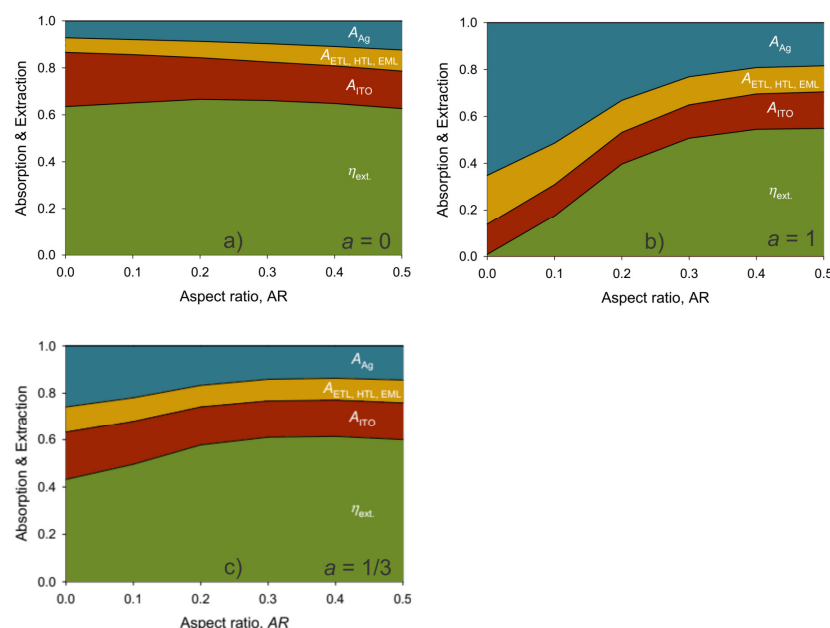


Figure 5. Absorption and extraction by layer groups for red OLED with $P = 800$ nm corrugation and different heights, corresponding to $AR = 0$ – 0.5 . (a) Only horizontal ($a = 0$), (b) only vertical ($a = 1$) and (c) isotropic orientation ($a = 1/3$).

For horizontal orientation in flat devices, most losses occur in the ITO, with smaller amounts in the thin-film layers and the back reflector; thus, over $\eta_{\text{ext.}} = 64\%$ of the generated light is successfully extracted into the glass substrate. In contrast, for vertical dipoles, only minimal light extraction is observed ($\eta_{\text{ext.}} < 1\%$), with relatively low losses in the thin layers but very high absorption in the silver back reflector. These results reflect the favourable emission characteristics of horizontal dipoles, whose angular intensity distribution (AID) supports efficient outcoupling. Vertical dipoles, on the other hand, tend to emit light

into guided modes and suffer from high SPP losses due to strong TM-polarised light coupling to the metal—see the typical AID of horizontally and vertically oriented dipoles in SI, Figure S10.

Table 1. Numerical values for layer absorption and light extraction of presented data in Figure 5.

AR	Horizontal— $a = 0$			Vertical— $a = 1$			Isotropic— $a = 1/3$		
	η_{ext} (%)	A_{Ag} (%)	$A_{\text{thin-film}}$ (%)	η_{ext} (%)	A_{Ag} (%)	$A_{\text{thin-film}}$ (%)	η_{ext} (%)	A_{Ag} (%)	$A_{\text{thin-film}}$ (%)
0	64	7	29	1	65	34	43	26	31
0.1	65	8	27	18	51	31	50	22	28
0.2	67	9	24	40	33	27	58	17	25
0.3	66	10	24	51	23	26	61	14	25
0.4	65	11	24	55	19	26	61	14	25
0.5	63	12	25	55	18	27	60	14	26

As AR increases, absorption loss ratios for horizontal dipoles change only slightly. For $AR = 0.3$, absorption in thin layers is slightly reduced, while absorption in the Ag back reflector is slightly increased, resulting in a minimal improvement in light extraction of approximately 2%, with only small changes observed for all presented ARs. A slight increase in Ag absorption with increasing AR can be attributed to local reorientation of emitters towards the vertical, which strengthens the TM polarised field and enhances coupling to SPPs at the Ag interface. The same reorientation also channels more power into thin-film waveguide modes, which would ordinarily increase absorption in the functional layers and ITO. However, we observe a modest reduction in absorption in these layers. In planar stacks, guided light propagates between the Ag and glass (within the functional layers and ITO) until it is absorbed. With corrugations, perturbations of the waveguide enable partial extraction of waveguided light before it is absorbed. As a result, net absorption in the organics and ITO decreases despite the larger guided mode fraction.

For vertical dipoles, however, increasing AR (up to $AR = 0.5$) leads to a significant reduction in Ag losses, dropping from 65% to 18%, and lower absorption in thin layers, resulting in a substantial increase in light extraction to $\eta_{\text{ext}} = 55\%$ (from less than 1%). In planar devices, absorption in the Ag back contact is dominated by SPP coupling. The pronounced decrease observed here can therefore be attributed primarily to the suppression of SPP losses, which we ascribe to local dipole reorientation away from the vertical and the associated reduction in the TM-polarised field at the Ag interface.

Due to the angular emission characteristics of vertical dipoles, more power couples into the waveguide between Ag and glass, trapping light. The introduction of corrugations disrupts this waveguide and scatters part of the guided power into radiative channels before it is dissipated, further reducing absorption in the functional layers and ITO. Additionally, local reorientation towards more horizontal dipoles reduces coupling into the waveguide in the first place. Together, these two effects—waveguide disruption and orientation-induced suppression of TM content—result in the observed decrease in organics/ITO absorption and the significant gain in light extraction, reflecting the interplay between geometry and dipole orientation.

In the case of isotropic orientation of emitting dipoles ($a = 1/3$)—Figure 5c,—the dominant improvement results from reduced Ag absorption, mainly due to mitigation of SPP-related losses for vertically oriented dipoles. A smaller reduction occurs in the functional layers and ITO due to enhanced extraction of guided modes. Because isotropy implies

a 2 to 1 weighting of horizontal to vertical components, the substantial Ag-loss reduction for vertical dipoles is partially offset by the more modest gains for horizontal dipoles.

Overall, corrugation primarily suppresses Ag/SPP losses of vertical dipoles, with secondary benefits from waveguide disruption. A smaller amount of absorbed light could also result in a lower thermal load, contributing to longer device lifetimes.

4.2. Extraction Trends

Interestingly, as observed from the results, the trends in extraction efficiency remain consistent regardless of the actual corrugation P or emission colour, indicating that performance is primarily governed by the texture's AR, with only minor influence from the absolute values of P and h . To explore this further, we must consider the various optical effects at play. Corrugated devices introduce additional mechanisms that can contribute to enhanced extraction: light scattering caused by surface modulation, bending of the waveguide layers, which can redirect light towards the substrate, and local changes in dipole orientation induced by the corrugation geometry. All of these can either enhance or suppress light extraction.

To visualise these effects, we performed one-dimensional simulations showing the normalised electric field ($|E|$) distribution for horizontally and vertically oriented dipoles, located at the centre of the corrugation for different AR values. Figure 6 presents $|E|$ fields for a red OLED ($\lambda = 610$ nm) with a corrugation $P = 800$ nm and $h = 0, 160$, and 400 nm, corresponding to AR values of 0, 0.2, and 0.5. These values represent a flat device, a configuration with optimal extraction for horizontal dipoles (AR = 0.2), and one with the highest extraction for vertical dipoles (AR = 0.5), respectively.

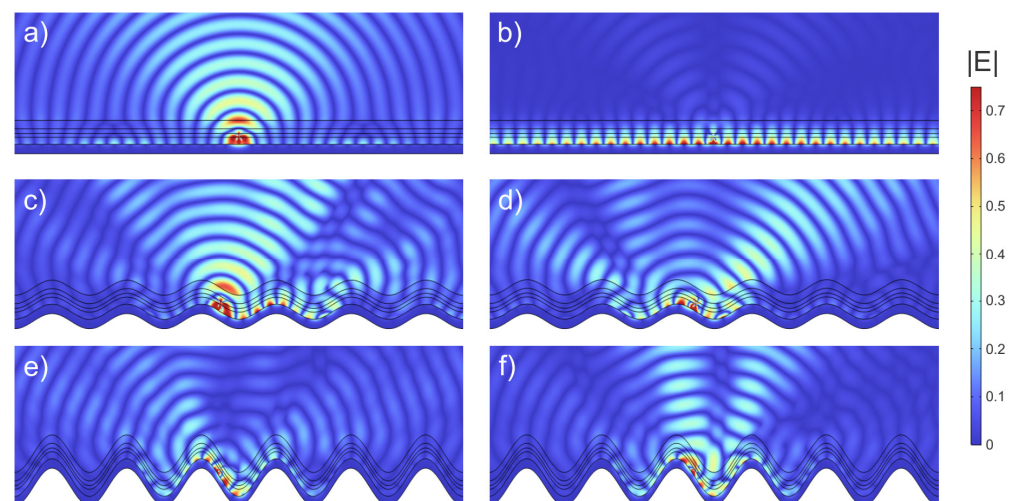


Figure 6. 1D simulated $|E|$ field for red OLED at $\lambda = 610$ nm and dipole positioned at the middle of corrugation. $|E|$ fields simulations are separated for $a = 0$ —horizontal (a,c,e) and $a = 1$ —vertical (b,d,f) orientation of dipoles and for different ARs of texture: AR = 0 (a,b)—flat, AR = 0.2 (c,d)—optimal horizontal extraction and AR = 0.5 (e,f)—optimal vertical extraction.

For the flat device (AR = 0), horizontally oriented dipoles exhibit high light extraction into the glass substrate, with a smaller portion of light guided within the thin-film stack where it is eventually lost, as shown in Figure 6a. In contrast, vertically oriented dipoles emit light that is largely confined within the waveguide structure, where it either couples to surface plasmon polaritons (SPPs) near the dipole or is lost due to parasitic absorption, as shown in Figure 6b. These observations are consistent with the presented results and with the mode analysis shown in SI—Figure S8.

When corrugations are introduced, several additional effects begin to influence light extraction. First, the local orientation of emission dipoles towards the interfaces changes due to the inclination of the textured surface. This leads to two effects: increased or decreased SPP losses, as shown in Figure 5, and a changed angular intensity distribution, resulting in reduced waveguiding and enhanced extraction for vertical dipoles (Figure 6d,f), and, conversely, increased waveguiding for horizontal dipoles (see Figure 6c,e). As these effects mainly depend on inclination, which is governed by the height to period ratio ($AR = h/P$) rather than their absolute values, this reorientation is largely independent of the actual P and h . Consequently, light extraction is governed primarily by AR , not by the specific values of P or h . Additionally, deposition over textured substrates introduces local thickness variations, shifting microcavity resonances and modifying outcoupling.

Moreover, light that enters the so-called waveguide (thin-film layers) in flat devices is typically lost. In textured devices, however, the corrugation introduces bends in the waveguide structure, disrupting its straight geometry. When the waveguide is bent, as in corrugated devices, the geometry changes locally. This disrupts the propagation of guided modes, causing some of the light to scatter out of the waveguide. The bends act as scattering centres, converting guided energy into radiative modes that can escape into the substrate. The efficiency of light extraction from these waveguide bends depends on two key factors. First, for the bend radius, smaller radii (higher AR) cause stronger disruption and allow more light to escape the waveguide. Second, for the position of the emitting dipole, since thin-film waveguides are lossy for dipoles positioned farther from the extraction centres (bends), the guided light must travel longer distances and may be absorbed before reaching a bend, thereby reducing the amount available for extraction. The same effect arises in devices with larger P , where increasing P extends the distance the guided light must propagate before encountering a bend, which in turn enhances parasitic absorption within the waveguide.

When the texture period is comparable to the emission wavelength, the structure behaves as a diffraction grating. The strength and angular distribution of scattering depend on the P , h and profile of the texture, as well as the wavelength, refractive indices, and angle of incidence. The number of propagating diffraction orders is governed by the ratio of P to the effective wavelength in the medium and by the angle of incidence; as P approaches the effective wavelength, higher orders are progressively cut off. Consequently, decreasing P reduces the number of propagating orders and limits far-field scattering, although the detailed efficiency still depends on the texture profile and height. Interference between scattered and reflected fields can further enhance or suppress extraction.

For larger textures (e.g., $P = 1500$ nm), the surface becomes locally flatter, reducing scattering. Conversely, textures with very small periods (e.g., $P = 450$ nm) begin to lose scattering efficiency, as the features become too small for light to interact with effectively.

Ultimately, despite these opposing trends, textures with periods between 600 and 1000 nm and AR values between 0.2 and 0.3 consistently yield high outcoupling efficiency across all red, green, and blue emission colours. This simplifies the selection of effective light extraction textures, as multiple configurations within this range perform well across a broad spectral range.

5. Conclusions

Using advanced optical simulations, we examined the relationship between different sine corrugations and specific general orientations of the emission dipoles for three emission colour OLED devices, aiming to enhance light extraction efficiency. Across red, green, and blue devices, the texture aspect ratio ($AR = h/P$) emerges as the principal control parameter, while actual P and height h exert only secondary influence. For horizontally oriented

dipoles, extraction increases up to a texture AR of approximately 0.2, then starts to decrease, whereas for vertically oriented dipoles it improves up to a texture AR of approximately 0.5. For isotropic emission ($a = 1/3$), an optimum near-texture AR ≈ 0.3 is observed, and periods between 600 and 1000 nm consistently deliver high extraction across all red, green and blue devices. Absorption analysis by layers attributes the primary gains to reduced Ag-related (SPP) losses for vertical dipoles, with smaller contributions from mitigation of waveguide losses for both horizontal and vertical dipoles.

Electric field $|E|$ simulations clarify the mechanisms underpinning these trends to a combination of different causes, local dipole reorientation, where increasing AR modifies the angular intensity distribution, enhancing extraction for vertical dipoles and increasing waveguiding for horizontal ones; enhanced extraction due to waveguide bending introduced by corrugation, which is stronger for higher AR (smaller bend radii); and light scattering due to the texture itself.

Crucially, practical texturing can locally reorient emitting dipoles via surface inclination, altering anisotropy. Shifts towards vertical alignment diminish extraction, whereas shifts towards horizontal alignment enhance it. In the absence of reorientation, AR ≈ 0.2 – 0.3 is broadly optimal for $a \leq 1/3$; if $a \approx 0$ (strongly horizontal), AR ≈ 0.1 is preferable and, for $a > 0.35$ (more vertical), higher ARs yield superior performance. Considering possible reorientation of emission dipoles, following the texture shape, highly horizontal dipole distributions already exhibit strong extraction without texturing, and the marginal benefit of corrugation may be outweighed by increased fabrication complexity or defect risks.

Together, these results provide general design guidelines: target AR ≈ 0.2 – 0.3 and $P \approx 600$ – 1000 nm for broadband; colour-independent (including white emission) gains in OLED devices with isotropic or moderately horizontal dipole distributions; tailor AR upward for vertically dominated emission and downward for strongly horizontal emission; and explicitly account for fabrication-induced orientation changes and dipole position on the corrugation. These insights chart a practical route to next-generation, high-efficiency OLEDs by co-optimising corrugation geometry and general emission dipole orientation.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/photonics13030287/s1>, Figure S1. Cross-sectional view of layer growth on a regular 2D sine-shaped texture ($P = 800$ nm, $h = 400$ nm). Shown is the stack configuration for a blue OLED, with layer thicknesses of 90, 12, 30, 54, and 100 nm. The figure highlights the transition from the original sine-shaped surface (yellow line) to the altered final layer profile (red line). Figure S2. (a) Light extraction, for blue OLED with $P = 800$ nm and different heights, for the case with 3 or 15 selected dipoles and 3 preferential dipole orientations. (b) Representation of 3 selected dipole positions (a, b, c) and a collection of 15 dipoles. Figure S3. Light extraction (blue OLED with $P = 800$ nm, $h = 240$ nm and $\lambda = 460$ nm) for horizontally oriented dipoles on a corrugated structure, evaluated at three discrete positions (a, b, c—see Figure S2b) as used in the simulations. The dashed lines show the in-plane orientation average corresponding to a random (azimuthally uniform) horizontal distribution; this average is accurately captured by the mean of two orthogonal horizontal dipoles (values marked with triangular symbols). Figure S4. (a) Extraction efficiency (blue OLED with $P = 800$ nm, $h = 240$ nm and $\lambda = 460$ nm) for multiple emitter orientations (each orientation is presented by one of 100 dipole directions presented on the right side), shown for three discrete texture positions (a, b, c—see Figure S2b). The dashed lines denote the orientation-averaged response computed from all 100 orientations or from three orthogonal dipoles, demonstrating that the reduced-basis averaging accurately represents the ensemble and validating our approach. The actual data are provided in the inset. (b) Illustration of a uniform (isotropic) distribution of dipole orientations (100 points), corresponding to random orientation across multiple periods. Simulations show that the orientation-averaged response is accurately reproduced by averaging over three orthogonal

basis dipoles (red, green and blue arrows in the figure). Same set of basis dipoles was used in our simulations. Figure S5. Emission spectra of used materials. Figure S6. Complex refractive indices of used materials. (a) Refractive indices, (b) Extinction coefficient. Figure S7. Validation of the FEM implementation by comparison with the exact TMM for planar stacks (red, green and blue device). TMM has been repeatedly verified against experimental data. No separate external benchmark was performed for the corrugated case; however, the same physical assumptions, boundary conditions, and material models apply, and prior work (Zschiedrich, L. et al.—Refs. [50,51]) establishes the suitability of FEM for periodically textured optical structures. Figure S8. Power mode analysis of flat devices separated for different anisotropy values. Figure S9. Light extraction regarding to initial anisotropy values for different periods of corrugation. Figure S10. Angular intensity distribution of horizontally and vertically oriented dipoles, with illustration of escape cones (2α) according to interface between two materials.

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