Customizing Tactile and Visual Perceptions of Organic Light–Emitting Diodes by Surface Coatings

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1. Introduction

The organic light-emitting diode (OLED) is a promising technology for numerous applications, some of which are unimaginable without its unique properties. OLEDs are thin-film devices comprising a multilayer stack of organic semiconductors between two electrodes on a (generally transparent) carrier substrate. Due to their architecture, OLEDs possess several advantages compared with traditional light sources such as inorganic LEDs or fluorescent lamps. Employing light-transmissive electrode materials enables the fabrication of semitransparent or even completely see-through modules.[15–3] In addition, OLEDs can be processed on flexible plastic substrates allowing for the realization of light sources that can be bent, rolled, or folded like a newspaper.[4–6] However, the use of transparent or foldable OLED displays has recently led to the commercialization of highly futuristic television and smartphone devices, conventional OLED displays have been used for more than 10 years.[7] As OLEDs are inherent surface emitters requiring no backlight source, they typically show low power consumption, high color contrast, and wide viewing angles.[8]

The usage of OLEDs is not limited to display technology, though. Their highly customizable properties make them ideal light sources for other applications such as optical biosensing in lab-on-a-chip devices, electronic packaging and labels, and wearable lighting.[9–14] OLED technology also shows huge potential for general (indoor) lighting but has yet to gain notable market share.[13] Despite significant improvements in efficiency and long-term stability due to extensive research both in academia and industry, OLEDs are almost exclusively found in very particular product sectors, most of them limited to display applications.[16] One of the main reasons for this phenomenon may be the comparatively high fabrication costs of high-performance devices. In contrast, many research endeavors have primarily aimed toward performance increase. Record luminous efficacies of more than 100 lm W−1 have been demonstrated for white OLEDs in recent years, closing the gap to their inorganic counterparts.[17–19] Alongside the development of new generations of OLED emitter compounds based on phosphorescence or thermally activated delayed fluorescence, optimization of the OLED architecture has played a major role in enhancing device performance.[20] The introduction of light guiding or light coupling structures in the layer stack or on the substrate may not only increase light outcoupling but also offers means to tune emission spectra attaining higher color purity or directing light in specific directions.[21–23]

Most of these factual metrics such as efficiency, color contrast, emission characteristics, and device lifetime are of fundamental relevance for the use in display applications. While they are no less important for general lighting applications, additional product features have to be accounted for as well. Taking advantage of mechanical flexibility and transparency, OLED light sources can...
be installed in windows or as wallpapers, integrated in fabrics for clothing or wearable accessories, utilized as luminous indicators for hybrid haptic-visual interfaces or simply as luminous accents or art. In most of these cases, the resulting products fulfill several purposes additional to illumination, potentially requiring haptic or optical recognition of object properties. As a result, OLED illuminants may frequently be touched or consciously observed and consequently, design aspects including tactile and visual product perceptions may be of considerably higher significance than in other application areas.

Visual perception of OLED devices is mainly determined by the emission color and product shape. However, it may be altered by external or internal light guiding structures such as photonic crystals or lenses. Usually, these structures are designed to enhance performance by increasing light outcoupling from the substrate. In the case of large-area lighting panels, which often require highly conductive metallic grid electrodes to prevent brightness gradients, scattering layers are used to cloak undesired shadows and homogenize light emission.

Haptic perception, in contrast, has rarely been studied in OLEDs. It is dependent on the macroscopic form of an object along with its microscopic surface properties—surface roughness and friction coefficient being two important factors. However, an OLED’s shape and size are in principle only restricted by manufacturing constraints, the introduction of additional surface roughness to the emission side of the device substrate might influence light transmission and change emission characteristics. Due to these potential implications on device performance, haptic OLED surface characteristics cannot be evaluated independently from optical properties. Instead, tactile and visual device perceptions must be controlled simultaneously to determine the applicability in practical scenarios.

The scope of this work is to demonstrate an OLED substrate coating allowing for specific tailoring of tactile and visual device perceptions. To the best of our knowledge, no investigations on haptic surface coatings considering OLED emission characteristics and coating color perception have been published in the literature so far. Mixing different contents of zinc oxide (ZnO) nanoparticles into a poly(methyl methacrylate) (PMMA) coating matrix provides a mean to modify surface roughness, effectively changing haptic surface impression. As those particles, which act as additional scattering centers, may potentially influence device performance, the relationship between surface roughness parameters and light transmission via the coating as well as device efficiency of coated OLEDs is investigated. Although the coatings presented in this work are not optimized toward improved light outcoupling, increased external quantum efficiency (EQE) is observed at low-to-medium particle content. Furthermore, it is shown that by adding colored pigment particles to the coating, the perceived surface color of a powered off OLED light source is altered without significantly changing its emission spectrum (see exemplary OLED photographs in Figure 1). The application of such a coating allows researchers and product engineers to customize haptic and visual perception of their devices to match appliance requirements. Potential use cases may range from increased haptic pleasantness to slip resistance or tactile identification of control elements.

2. Results and Discussion

To adjust tactile and visual device perceptions, we show the integration of (nano)particles into a polymer matrix which is applied as a coating. Surface roughness parameters and color impression of this coating are varied independently by choosing specific particle compositions and contents. The matrix material itself has to meet several requirements so that OLED device applicability is not restricted by the coating. To allow for the utilization of all potentially advantageous properties, the coating must feature high transparency over the entire visible spectral range as well as mechanical flexibility. In addition, cost-efficient high-throughput processing of the coating is essential for the integration in low-cost products such as wearable lighting or disposable luminous packaging. This requires the coating to be solution processable, as suitable

![Figure 1. Schematic representations and digital photographs of OLEDs coated with haptic surface coatings or covered with separate coating samples illustrating two different experimental arrangements: Flexible OLEDs fabricated on PET substrates coated with a polymer film incorporating a) 7.5% tetrapodal ZnO particles and b) 23.1% Pigment Red 101 particles; the same OLED device fabricated on a glass substrate covered with separate coating samples comprising c) pigment green 50 and d) Pigment Red 101 particles at a concentration of 37.5%. The coatings allow for modification of haptic perception and surface color impression. While no emission color change is observed, light homogenization due to scattering results in cloaking of dark spots. Substrate staining visible in e,f) is due to the device encapsulation glue and not connected with to the substrate coating.](image-url)
fabrication techniques such as ink-jet printing, slot-die coating, or spray coating are typically wet processes. Here, we used the transparent thermoplastic PMMA as the coating matrix material because of its excellent optical and mechanical properties. The properties of thin PMMA layers, however, may greatly vary upon the deposition method and parameters including the solvent which is used and the molar mass distribution of the solute.[29]

We therefore investigated the thickness and surface roughness of films fabricated by spin coating, using different solvents as well as PMMA samples with different mass average molar masses (M_w). Comparing the film properties (see Table S1, Supporting Information) we decided to use a solution of PMMA with high average molar mass of 120 000 in toluene. The layers fabricated from this solution not only exhibited the highest layer thickness (2 μm) but also low average roughness of around 80 nm, making intentional changes to the surface roughness distinctly perceivable.

Sample coatings were applied to plain glass substrates to evaluate haptic and optical properties of the coating layers individually. Device integration is possible by either OLED layer deposition on precoated substrates or subsequent coating after OLED encapsulation.

2.1. Haptic Surface Impression

Tactile perception of external objects plays a major role in human interaction with the surrounding environment. The complex physiological processes underlying the conversion of sensory stimuli to sensation have been studied for several centuries and are now better understood than ever before.[30] However, quantifying the impact of specific physical surface characteristics on tactile perception remains challenging, not least due to subjective perceptual experience.

Surface roughness and texture are two essential attributes influencing haptic impression and thus judgment of material composition, slipperiness, and comfort.[31,32] A rough surface can be described by a multitude of independent parameters emphasizing different characteristics related to amplitude and spatial distribution of the height profile. In many applications, surface roughness is described only as the arithmetical mean height S_a or the root mean square height S_q:

\[
S_a = \frac{1}{A} \int_A |z(x, y) - \langle z \rangle| \, dx \, dy
\]

(1)

\[
S_q = \sqrt{\frac{1}{A} \int_A (z(x, y) - \langle z \rangle)^2 \, dx \, dy}
\]

(2)

While S_a is the most common metric used to specify surface roughness, it is not sufficient to adequately represent surface roughness with respect to tactile perception. Sample surfaces with fundamentally different surface structure, resulting in different tactile stimuli, might possess identical mean roughness. Similarly, surfaces with vastly different mean roughness may induce comparable haptic interaction. Here, we determined the arithmetical mean height as well as skewness (S_k) and kurtosis (S_ku) of the height distribution to compare surface roughness characteristics of the investigated samples. S_k is defined as the third standardized moment of the height distribution and represents the degree of asymmetry around the mean plane. A positive value (S_k > 0) therefore indicates a surplus of elevations and peaks, whereas a negative value (S_k < 0) hints at a surplus of recessions or scratches in the surface.

\[
S_k = \frac{1}{S_q^4} \left[ \frac{1}{A} \int_A (z(x, y) - \langle z \rangle)^3 \, dx \, dy \right]
\]

(3)

S_ku is the fourth standardized moment of the height distribution quantifying the sharpness of the roughness profile with a value of S_ku = 3 being the sharpness of a univariate normal distribution.

\[
S_{ku} = \frac{1}{S_q^6} \left[ \frac{1}{A} \int_A (z(x, y) - \langle z \rangle)^4 \, dx \, dy \right]
\]

(4)

In this work, we demonstrate the modulation of surface roughness characteristics by incorporating different types of nanoparticles into a PMMA matrix. To achieve high roughness variations at low particle content, we utilized 3D tetrapodal-shaped ZnO particles, referred to as t–ZnO. The particles were synthesized by Phi–Stone AG (Kiel, Germany) using the flame transport method, yielding arm lengths ranging from 0.5 to 150 μm and an arm diameter between 24 and 850 nm (see Figure S2, Supporting Information).[33] When incorporated in the coating, the particles are partly immersed in the polymeric host with sharp features protruding from the surface. The outcome is a distinct surface morphology characterized by narrow peaks with large height differences. The microscopic images and 3D height representations shown in Figure 2 reveal evident differences in surface roughness characteristics depending on the particle content. Comparison of the optical surface images suggests the presence of few high-amplitude spikes for samples with t–ZnO concentrations of 0.4 and 3.9%, whereas a more homogeneous spreading of the particles is observed at a t–ZnO concentration of 7.5%. This observation indicates that aggregation, which is expected to increase at high particle content, may not be the major factor determining peak heights. However, it is also possible that large clusters are spun off the sample surface during the coating process resulting in a large number of low-amplitude peaks mostly formed by individual particles. High-magnification differential interference contrast (DIC) images also display aciculate particle fragments inside the coating. Particle fragmentation supposedly arises due to the fragile 3D shape, which is prone to fracturing during particle dispersion and spin coating.

The initial assessments are confirmed by the surface roughness parameters shown in Table 1. The mean surface roughness increases with increasing t–ZnO content as opposed to skewness and kurtosis both of which are significantly higher on sample surfaces comprising low particle concentration. This effect can simply be explained by the fact that a lower number of particles results in fewer peaks and asperities, finally leading to larger height differences with respect to the mean plane. Nevertheless, those differences in surface roughness characteristics are clearly perceivable by touch, thus allowing for modulation of tactile surface perception.
In host–guest configurations like the one described here, surface roughness characteristics mainly depend on particle size and shape. In addition to the ZnO tetrapods, we also incorporated commonly used color pigments into the PMMA coating matrix. Apart from providing a way to change the coating color, the pigment particles alter the surface structure and tactile perception. We used the green colorant pigment green 50 (cobalt titanate green spinel) and the red colorant pigment red 101 (iron(III) oxide) at varying concentrations, investigating the influence on surface roughness characteristics. Images of the colored coating surfaces and 3D representations of the surface structures are shown in Figure 3. As the pigment particles exhibit different geometrical dimensions and features compared with the t–ZnO, significantly lower mean roughness of spin-coated films was observed at similar particle content. Comparable roughness characteristics could only be attained at high pigment contents of up to 37.5%.

The resulting surface roughness parameters for colored coating samples are shown in Table 2. Again, at increasing particle content, the samples show higher mean roughness but lower kurtosis due to less sharp surface features. Comparing both pigment types, the samples comprising red iron oxide (Fe₂O₃) generally exhibit higher roughness metrics and in particular higher sharpness than the ones with cobalt titanate (Co₂TiO₄).

To further modify the tactile impression of the colored coatings, we combined the employed particle types by blending pigment particles with t–ZnO. The addition of t–ZnO leads to an increment in mean surface height which is explicable in terms of increased particle content and the tetrapodal geometry of the ZnO. Surprisingly, a large discrepancy in behavior is observable for the sharpness of the height profiles. Mixing Co₂TiO₄ with t–ZnO yields sharp surface features similar to the samples containing only t–ZnO, resulting in a significant enhancement of $S_{ku}$. In contrast, sample coatings containing Fe₂O₃ already exhibit sharp high-amplitude elevations indicated by the high skewness and kurtosis, which are almost identical to the values observed for samples containing only t–ZnO. In this case, the addition of acicular particles reduces the sharpness of surface features considerably. While this observation may seem unintuitive, possible explanations considering the decreased skewness of the height distribution appear likely. A higher density of surface features may increase not only the arithmetical mean surface height but also the height of the calculated mean plane, leading to smaller relative height differences. The overall appearance of

| ZnO content [%] | $S_a$ [nm] | $S_{sk}$ | $S_{ku}$ |
|-----------------|------------|----------|----------|
| 0               | 80         | −0.26    | 2.7      |
| 0.4             | 150        | 8.8      | 180      |
| 3.9             | 205        | 7.7      | 115      |
| 7.5             | 255        | 3.9      | 31.0     |
the surface then changes from a plane with occasional peaks toward a more balanced distribution of elevations and valleys, yielding values of $S_k$ close to zero.

Predicting the implications of specific combinations of roughness characteristics for haptic impression is difficult due to the complexity of tactile interaction with external objects. Multiple interdependent factors such as surface morphology, friction, and elasticity influence tactile perception, preventing the isolated evaluation of a single parameter. Despite those limitations, we have demonstrated the targeted modulation of surface roughness characteristics of OLED devices by incorporating nanoparticles in a polymer matrix coating. The fabrication of samples with variable combinations of the surface roughness parameters $S_a$, $S_k$, and $S_u$ is possible by blending specific types of particles at different concentrations. This method may enable product engineers to tailor haptic properties of OLED light sources for particular applications.

### 2.2. Visual Surface Impression and Device Performance

The optical properties of an object are strongly associated with its surface morphology. Smooth surfaces often show high reflectance, whereas surface roughness induces light scattering and haze. In the case of the coatings described here, t–ZnO and color pigment particles incorporated into the polymer matrix act as scattering centers altering light propagation inside the layer and at the air interface. Interfacial light scattering in the OLED stack is generally considered beneficial for device performance as it increases light outcoupling efficiency through the extraction of optical modes which would otherwise be guided in the high-index organic layers or the substrate.\cite{34,35} Moreover, scattering layers are often used in large-area light sources to conceal electrical contacts and spatial irregularities.\cite{28} Homogenization of angular emission characteristics may decrease emission directionality, though, making it unfavorable for specific applications such as high-resolution displays. In addition to scattering, particles may also introduce additional light absorption in the coating layer, reducing OLED efficiency. Scattering and absorption intensity mainly depend on the number of light–particle interactions. Hence, high variability of haptic

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**Figure 3.** a–d) Laser DIC images, e–h) digital photographs, and i–l) 3D height representations of sample surfaces coated with PMMA layers incorporating color pigments (pigment green 50 and pigment red 101) at different concentrations.

**Table 2.** Surface roughness parameters of PMMA layers incorporating color pigments (pigment green 50 and pigment red 101) and t–ZnO particles at different concentrations.

| Particle content | $S_a$ [nm] | $S_k$ | $S_u$ |
|------------------|-----------|------|------|
| Pigment Green 50 Co$_2$TiO$_4$ 5.6% | 80 | 4.8 | 66.3 |
| 23.1% | 230 | 2.0 | 9.8 |
| 37.5% | 75 | 1.7 | 11.1 |
| 37.5% + 7.5% t–ZnO | 480 | 3.3 | 40.9 |
| Pigment Red 101 Fe$_2$O$_3$ 5.6% | 90 | 8.3 | 185 |
| 23.1% | 300 | 3.8 | 40.0 |
| 37.5% | 450 | 4.1 | 34.2 |
| 37.5% + 7.5% t–ZnO | 540 | 2.2 | 14.7 |
surface characteristics at low particle content is preferable to maintain visual device impression. In contrast, distinguishable variation of the surface color impression requires not only high particle concentration but also wavelength-dependent optical properties. However, ZnO particles are expected to show little wavelength dependency in the visual spectral range, color pigments are specifically used to change the perceived color of coated objects. Their impact relies on a combination of wavelength-dependent light absorption and diffuse reflection (backscattering), changing spectral characteristics of the light reflected from a surface. Light transmitted through the coating is also affected by absorption and scattering, causing diffuse transmission. However, as these effects may exhibit disparate spectral behavior, the resulting spectra of reflected and transmitted light may vary significantly.

Modification of OLED emission and color impression may be achieved by different color-converting materials such as color filters or phosphors similar to the ones used in conventional inorganic white LEDs.[36–39] Opposing to such approaches, the scope of this work is the specific variation of OLED surface color impression without altering emission characteristics. Using color pigments with low transmission dispersion allows for the modification of surface color impression when the device is turned off while maintaining the original OLED emission color. White-light reflection spectra of OLED substrate surfaces coated with PMMA layers incorporating color pigment particles are shown in Figure 4. Wavelength dependency of the reflection spectra at low particle content is low, indicating little change to the color impression. At high pigment contents, however, the coatings show obvious reflection dispersion, resulting in intense color impression. These results are consistent with the subjective color impression overserved for the sample surfaces shown in Figure 3.

Apart from visual impression induced by external illumination, OLED color impression was investigated by measuring emission spectra through the coated substrates. To account for potential impacts on the angular emission characteristics due to light scattering, measurement conditions were chosen to resemble human vision. Light from an OLED comprising the emissive material Flrpic (bis[2-(4,6-difluorophenyl)pyridinato-C2,N][picolinato]iridium) was collected using an optical fiber placed above the emissive area. Normalized emission spectra of a single OLED device covered with different sample coatings incorporating high particle concentrations are shown in Figure 5. The emission spectrum of the uncoated OLED and the same device placed underneath a coated substrate using t-ZnO particles are undistinguishable, implying no color change caused by the coating. Emission spectra measured through colored coatings in contrast show slight distortions around 470 and 600 nm for the green and red coatings, respectively. However, as these changes in spectral shape are very small, we do not expect variations in color impression to be recognizable in actual applications.

The overall agreement of all OLED emission spectra indicates that diffuse transmission through the coating exhibits low wavelength dependency for the particles used in these experiments. Nevertheless, absorption and scattering intensity may vary significantly and impede light emission. Evaluation of OLED efficiency as well as coating transparency and translucency are necessary to assess implications on device performance for practical applications. The simplified schematics shown in Figure 6 illustrate the experimental setups utilized for the determination of OLED device efficiency and coating transmission spectra. Separate measurements of directly and total transmitted light allow for an estimation of the optical haze which is close to the amount of diffuse transmission. The precise haze value may be determined considering the angular distribution of the light transmission, distinguishing between narrow-angle scattering and wide-angle scattering.[40]

The EQE of OLEDs coated with polymer layers incorporating different particle types and concentrations after device fabrication is shown in Figure 7. Application of haptic coatings comprising only t-ZnO particles can lead to an efficiency increase of almost 10% at 1000 cd m−2 due to outcoupling of substrate modes induced by scattering at the substrate-air interface. A similar impact is observable for Co2TiO4 (pigment green 50) particles at a low concentration of 5.6%, where absorption is negligible. At higher particle contents increased light absorption dominates the beneficial scattering effects resulting in efficiency reduction due to the coating. As absorption is higher for Fe2O3 (pigment red 101) particles a slight decrease in EQE is observable even at low content. To evaluate the limitations of the proposed haptic coatings with respect to device performance a sample device comprising a very high concentration of pigment red 101 particles was prepared. As the dispersion was prone to

![Figure 4](image-url)  
**Figure 4.** Diffuse reflection spectra of coatings incorporating different contents of color pigments (green curves: pigment green 50, red curves: pigment red 101). Spectra were recorded with an optical fiber placed perpendicular above the sample surface and white light illumination at 45°.

![Figure 5](image-url)  
**Figure 5.** OLED emission spectra recorded in transmission through substrates coated with different particle types. Spectral distortions caused by the coatings are negligible, indicating no observable color change.
sedimentation due to the high particle content, it was not possible to determine the precise concentration before coating of the OLED substrate, however, it is estimated to be above 50%. High light absorption in the coating layer is already obvious from the very low maximum luminance of only 300 cd m\(^{-2}\). In addition, the EQE is lowered by more than 70% making the coating unsuitable for practical applications.

Apart from OLED efficiency, determination of light transmission spectra of the coatings is an important aspect to assess the applicability to see-through devices or large surfaces which may not be entirely covered with light emissive areas. Figure 8 shows transmission spectra of glass samples coated with the PMMA matrix containing t-ZnO particles at different concentrations. Overall, no wavelength dependency of transmitted light is observable as the slight curvature in the graphs can be attributed to the glass substrate. Forward scattering of incident light increases with particle concentration leading to a significant reduction in direct transmission. Considering the total transmitted light, though, only a small part of no more than 5% of the incident light is lost due to the coating even at high t-ZnO concentrations. It should also be noted that the amount of diffusely transmitted light is expected to be even larger when the coating is applied onto an OLED stack due to reflection of backscattered light at the metallic top electrode of the device. For a t-ZnO content of 0.4%, no decline in total light transmission compared with an uncoated reference glass substrate is measured, meaning the coating is barely visible, causing only minor haze on the sample surface.

Similar transmission spectra for coatings containing the two color pigments investigated in this work are shown in Figure 9. Although the total light transmission still features comparatively low wavelength dependency, distinct deviations arise at high pigment concentrations. The evident spectral variations in scattering intensity are associated with the spectral positions of the pigment colors. Furthermore, they accurately account for the deviations observed in the OLED emission spectra.

Comparing the amount of total transmitted light displays a trade-off between visual surface color impression and translucency which is reflected in the OLED device efficiency. Clearly, high color pigment content results in intensive surface color impression and high opacity. Meanwhile, diffuse reflection of incident light and absorption inside the coating increase as well, impairing light outcoupling from the OLED device. However, due to additional light outcoupling, OLED EQE is not reduced by the same amount and may even be increased by the coating at low
Furthermore, surface color impression of OLED devices can be tuned independently of their emission color. Using color pigment particles with low wavelength dependency in light transmission we are able to obtain coatings with an intensive color impression causing only minor shifts in OLED emission color. While device efficiency is increased at low particle content due to additional light outcoupling from the substrate, high coating opacity inherently leads to significant absorption, reducing light outcoupling efficiency from the coated substrate. Nevertheless, we believe haptic and visual customizability of device coatings to be a promising concept for a range of different OLED applications. In many potential applications, such as indirect ambient lighting or the usage of OLEDs as luminous wearable accessories, high brightness may not be required, making customizable color impression more appealing than maximum light emission.

3. Conclusion

In conclusion, we demonstrate a surface coating for OLEDs providing customizability to haptic and visual device perception. We use a highly transparent and comparatively smooth PMMA matrix as the coating base, immersing different types of particles to change surface roughness and color impression. Incorporation of tetrapodal ZnO particles yields distinct changes to surface morphology, increasing mean surface height and sharpness of the height profiles. Specific combinations of surface roughness parameters are accessible by varying particle content and blending particles of different shapes and dimensions. As the t-ZnO particles exhibit acaulcute geometric features, substantial modification of surface roughness is possible at low particle concentrations, leading to marginal changes in OLED emission. Although the particles introduce increased scattering at high concentrations, no spectral deviation is observable, allowing for the application as scattering layers in large-scale light sources. Furthermore, surface color impression of OLED devices can be tuned independently of their emission color. Using color pigment particles with low wavelength dependency in light transmission we are able to obtain coatings with an intensive color impression causing only minor shifts in OLED emission color. While device efficiency is increased at low particle content due to additional light outcoupling from the substrate, high coating opacity inherently leads to significant absorption, reducing light outcoupling efficiency from the coated substrate. Nevertheless, we believe haptic and visual customizability of device coatings to be a promising concept for a range of different OLED applications. In many potential applications, such as indirect ambient lighting or the usage of OLEDs as luminous wearable accessories, high brightness may not be required, making customizable color impression more appealing than maximum light emission.

4. Experimental Section

Sample Preparation: Coating solutions were prepared by solving poly(methyl methacrylate) (Mn = 120,000, Sigma Aldrich) in toluene (Carl Roth) with a concentration of 100 mg mL⁻¹. Tetrapodal zinc oxide particles (Phi–Stone AG) or color pigments (Pigment Green 50: Mason Color, Pigment Red 101: Lanxess) were dispersed in the solution by ultrasonic treatment. Glass substrates (25 x 25 mm²) were cleaned in acetone and isopropyl alcohol and dried at 130 °C on a hotplate. Oxygen plasma treatment was carried out for 3 min at 8 sccm gas flow rate and an radio frequency power of 300 W to improve surface wettability. The coating process was conducted using the spin-coating method. After the dispensation of 200 μL of the corresponding solution, the sample was first rotated at 500 rpm for 5 s to achieve homogeneous wetting, followed by rotation at 1000 rpm for 60 s. Thermal annealing was carried out at 140 °C for 15 min, yielding a solid polymer coating.

OLED fabrication was carried out on glass and polyethylene terephthalate (PET) substrates coated with indium-doped tin oxide (ITO) by spin coating the conducting polymer poly(3,4-ethylenedioxythiophene) (PEDOT): polystyrene sulfonate (PSS), followed by thermal evaporation of the remaining organic layers and the metal cathode. The used layer stack was ITO (140 nm) | PEDOT:PSS (~60 nm) | 1,3-bis([11-4-(tris(4-methylphenyl)phosphinyl)phenyl]cyclo-hexane (TAPC) (20 nm) | 1,3-bis(N-carbazolyl)benzene (mCP) (10 nm) | 3,3′-bis(NH4-pyrido[2,3-b]indol-9-yl)-1,1′-biphenyl (C6BbpC8):10 wt% FIrpic (25 nm) | diphenyl[4-(triphenylsilyl)phenyl]phosphine oxide (TSPO1) (35 nm) | LiF (1 nm) | Al (170 nm). Active emission area size was 5 x 5 mm². The completed OLED devices were encapsulated in a nitrogen-filled glovebox to allow for optical measurements in air.

Surface Roughness Characterization: 3D surface analysis was conducted using a laser scanning confocal microscope (Keyence). Optical microscope images were used to assess coating homogeneity along with general surface impression and morphology, whereas quantitative surface roughness parameters Sq, Sw, and Sk were calculated from 3D-height measurements taking into account a surface area of 1.14 mm².

Optical Characterization: OLED emission spectra were recorded with an optical spectrometer (Horiba) by placing an optical fiber (numerical aperture: 0.48, core diameter: 1000 μm) perpendicular above the active area at a distance of ~20 mm. This measurement setup was designed to resemble observation of a luminous area with the human eye from an intermediate distance, collecting some but not all of the diffusely transmitted light. OLED EQE was measured by placing the active device area very close to a large-area photodiode (FDS1010, Thorlabs) to collect only light emitted in forward direction through the OLED substrate. The EQE was then calculated from the OLED current and the induced photocurrent which were measured simultaneously with two source measure units (SourceMeter 2400, Keithley).

Coating reflection spectra were measured using the same setup for light collection as for the recording of the OLED emission spectra. A sunlight LED (SAWS0661A, Seoul Semiconductor) was used as a broadband
white illumination source placed at an angle of 45°, resembling illumination by sunlight or ceiling lights during coating observation. Coating transmission spectra were recorded in two separate experimental setups. Regular transmission was measured using a UV–vis spectrophotometer (Perkin Elmer) collecting only directly transmitted light. Total light transmission was measured using an in-house built setup comprising an integrating sphere (Opsytec Dr. Gröbel) to collect diffusely transmitted light.

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

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Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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