PROGRESS REPORT

Progress in the development of the display performance of AR, VR, QLED and OLED devices in recent years

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ABSTRACT

The remarkable progress of virtual reality, augmented reality, quantum dot light-emitting diode, and organic light-emitting diode as next-generation displays has overcome the leadership of the liquid crystal display during the last two years. This paper discusses the key technological advancements and performance of these new-generation display devices.

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1. Introduction

During the last two years, four next-generation displays—namely the augmented reality (AR) display, the virtual reality (VR) display, the quantum dot light-emitting diode (QLED), and the organic light-emitting diode (OLED)—have been making remarkable progress and drawing great attention in the industry, even overcoming the performance and market leadership of liquid crystal display (LCD). The AR and VR displays, which are the major platforms of near-eye display (NED) devices, have been expanding the application field. The OLEDs are at present the dominant display technology in the market owing to several features that give them built-in advantages over the other displays. In particular, OLEDs have a highly flexible display platform that gives them wide compatibility to play a much stronger role in next-generation display. Indeed, OLEDs are quickly penetrating the market for all sizes of display applications, from small-size, mid-size, and large-size devices. Among the four next-generation displays, QLEDs with their remarkably high color purity give them the strongest potential to compete with the OLEDs. Recognizing their importance to the industry, this study has tracked the progress of all four of these next-generation displays for insights on their business and market prospects.

2. Recent progress of augmented reality and virtual reality

NEDs are eyeglass-type wearable displays that present to a user images from a far distance through optics that form the virtual image of a micro display panel. As shown in Figure 1(a), VR NEDs show the virtual images while blocking the real-world scene around it. In contrast, as shown in Figure 1(b), AR NEDs make use of image-combiner optics to present virtual images on top of the see-through real-world scene.

As the main display platform of VR and AR applications, NEDs are worn like eyeglasses to enable users to navigate and interact with the virtual or augmented world. The micro display panel in NEDs is located close to the user’s eye (typically within a few centimeters), unlike usual displays that are physically located at a comfortable viewing distance from the user and are seen directly without any optics. Indispensable to the functioning of NEDs is the optics device that forms the virtual images of the micro display panel at a far distance from the user. It is this device that largely enables how well NED devices work.

Figure 2 illustrates the key performance elements of AR and VR NEDs, namely the field of view (FOV), or the angular extent of the displayed virtual image, which is
shown in Figure 2(a); the eyebox, or spatial range where the eye can be positioned to watch the entire FOV of the NED, Figure 2(b); the angular resolution, or angular size of a single pixel in the virtual image, Figure 2(c); the focus cue, which is the monocular eye accommodation distance or virtual image plane distance, Figure 2(d); and the occlusion, or the masking of the real-world scene by the displayed virtual image, Figure 2(e). These factors are crucial to the performance of the AR and VR NEDs in giving the viewer an immersive feeling (FOV), comfortable eye positioning (eyebox), high-resolution images with no screen-door effect (angular resolution), fatigue-less natural viewing experience (focus cue), and high outdoor visibility (occlusion).

AR and VR NEDs are continually evolving with a wider FOV, larger eyebox, and smaller form factor [1, 2]. The metaverse, as the more recent emerging concept that uses NEDs as visual display platform, has been further accelerating the development of NEDs. To provide the natural and immersive user experience that enables vivid interaction between the real world and virtual space, the NEDs has to fulfill not only the traditional FOV, eyebox, and form factor requirements but also the monocular focus cues and mutual occlusion between the virtual images and the real objects. Some examples of the recently reported or commercialized NEDs are shown in Table 1, which lists in addition to the FOV and resolution their other notable key features like the focus cue mechanism and the image combiner optics configuration.

### 2.1. FOV and angular resolution

The FOV, eyebox, and angular resolution are the most important performance features of a NED. Ideal NEDs should have an FOV larger than 160° to cover the FOV of the human visual system [22], an eyebox wider than 10mm to accommodate eye rolling and the inter-pupillary distance discrepancy [1], and an angular resolution higher than 60 pixels per degree (PPD) to match the human visual acuity [1]. There should be a close trade-off relation between the FOV and the eyebox dictated by the étendue, or the property of light that characterizes how spread out the light is in area and angle. The FOV and the angular resolution likewise need to be balanced with the given resolution of the micro display panel. The precision of these trade-off relations are crucial to simultaneously achieving the required FOV, eyebox, and angular resolution.

Fully achieving these ideal specifications has yet to be attained, but active research has led to their continuing enhancement, notable among which is the introduction of holographic optical elements (HOEs)—these are volume holographic gratings usually recorded in a photopolymer [23]—and liquid crystal (LC)-based holographic gratings. More versatile NED designs have been developed with these features—high diffraction efficiency, wavelength, and angle selectivity, multiplexing capability, and a more transparent thin-film form factor. More recent emerging innovations are LC-based holographic gratings that add polarization-dependent optical functions and further increases in the degree of freedom in design [2, 24, 25]. The development of holographic printers now likewise enables the creation of freeform HOEs that significantly enhance the image quality [26, 27]. Applications of the HOEs and LC-based holographic gratings to the NEDs have also been actively studied in the years 2020 and 2021 to further increase the FOV [28–30], the eyebox [31–35], and the angular resolution [36]. Table 2 summarizes some of these innovations.

### 2.2. Focal cue

The focal cue is required to mitigate the so-called vergence accommodation conflict (VAC), or the discrepancy between the stereoscopic image distance and the physical virtual image distance of a NED. This VAC is negligible when the stereoscopic image distance is far from the user,
but becomes significant at a closer distance within the arm’s length of the user. As the arm distance is of particular importance for user interaction in many AR and VR applications, the proper and better presentation of the focal cue continues to be a standing issue in NED research and development.

Various research efforts on this aspect of NED have been reported, among them the Maxwellian display [29, 32–34], the multi-plane display [36,37], the vari-focal display[38], the light-field display[39,40], and the holographic display [42–50]. This last advancement—holographic display—was the most notable in 2020 and 2021. Moreover, the application of deep-learning techniques to the computer-generated hologram (CGH), the image quality, and the CGH synthesis speed have been significantly enhanced [46–49], making one step forward in the

Figure 2. Performance parameters and features of AR and VR NEDs (a) FOV, (b) eyebox, (c) angular resolution, (d) focus cue, and (e) occlusion.
Table 1. Features of recently reported or newly commercialized AR and VR NEDs.

| Name            | FOV       | Resolution (in pixels) | Focus Cue   | Image Combiner        | Year | Ref. |
|-----------------|-----------|------------------------|-------------|-----------------------|------|------|
| Hu et al        | 33°x25°   | 1024 × 768             | varifocal   | Freeform half mirror  | 2014 | [3]  |
| Google Glass    | 13°x7.3°  | 640 × 360              | X           | Birdbath              | 2014 | [4]  |
| Yeom et al      | 30°x17.5° | 1366 × 768             | holography  | DOE                   | 2016 | [6]  |
| Hololens        | 55°x40°   | 960 × 540              | varifocal   | DOE                   | 2017 | [7]  |
| Magic Leap      | 40°x30°   | 1280 × 960             | two layers  | DOE                   | 2018 | [10] |
| Lee et al       | 90°(diag.)| 1080p                  | X           | BS + Metasurface lens | 2018 | [11] |
| Nreal           | 52°(diag) | 1080p                  | X           | Birdbath              | 2019 | [12] |
| Pimax 8K        | 170°x130° | 3840 × 2160            | X           | VR                    | 2019 | [13] |
| Lee et al       | 30°       |                        | X           | VR                    | 2019 | [14] |
| Kim et al       | 75°x78°   | 60 cdpi                | varifocal   | DOE                   | 2019 | [15] |
| Hololens 2      | 52°(diag) | 2048 × 1080            | X           | DOE                   | 2019 | [16] |
| Oculus Quest 2  | 89°(H)    | 1832 × 1920            | X           | VR                    | 2020 | [17] |
| Lee et al       | 80°(diag) | 30 cdpi in fovea, 5 cdpi in peripheral | holography | Polarization selective optics + HOE | 2020 | [18] |
| Tilt Five       | 110°      | 1280 × 720             | X           | Polarized projection + retro-reflector screen | 2021 | [19] |
| Bang et al      | 102°x102° |                        | X           | VR (lenslet array + Fresnel lens + polarized folding optics) | 2021 | [20] |
| Cakmakci et al  | 29°x12°   | 1920 × 1080            | X           | Lightguide + HOE + polarized folding optics | 2021 | [21] |

Table 2. AR NEDs with FOV and eyebox enhancement using HOE and LC-based holographic gratings (reported in 2020 and 2021).

| Feature                                      | Key element                                      | Ref. |
|----------------------------------------------|--------------------------------------------------|------|
| FOV enhancement of a Maxwellian NED          | GP lenses + Chromatic aberration compensating HOE | [29] |
| FOV doubling of a NED with far image plane   | Two PVLs                                         | [30] |
| Eyebbox replication of a Maxwellian NED      | PBD                                             | [32] |
| Eyebbox replication and switching of a Maxwellian NED | PBD + GP lenses + Multiplexed HOE               | [33] |
| Eyebbox expansion of a Maxwellian NED with multiple independent viewpoints | Spatially tiled HOEs                            | [34] |
| Eyebbox expansion of a NED with far image plane | Diffuser HOE + Lens HOE                          | [35] |

presentation of real-time photo-realistic holographic 3D images. Table 3 lists some of these notable achievements in 2020 and 2021.

Table 3. Focus Cues supporting AR and VR NEDs as reported in 2020 and 2021.

| Type                                      | Feature                                      | Ref. |
|-------------------------------------------|----------------------------------------------|------|
| Multiple plane                            | LC PVLs with different focal length          | [37] |
| Multiple plane                            | Polarization grating and angle multiplexed HOEs | [38] |
| Varifocal                                 | 64 depths using 6 PBLs with time-multiplexing | [39] |
| Light field                               | Integral imaging + waveguide + elemental image compensation | [40] |
| Light field                               | Integral imaging + freeform prism + digitally controllable dual-focus lens array | [41] |
| Holographic                               | Continuous eyebbox expansion using 2D replication and angular spectrum wrapping | [43] |
| Holographic                               | FOV expansion using random phase mask        | [44] |
| Holographic                               | Foveated display by locating the SLM image to eyeball rotation center | [45] |
| Holographic                               | Foveated display using MEMS mirror and a PBD | [18] |
| Holographic                               | Deep learning based CGH using SLM and camera-in-the-loop calibration | [46,47] |
| Holographic                               | Deep learning based CGH + camera-in-the-loop calibration | [48,49] |
| Holographic                               | Vision correction by pre-compensated hologram | [50] |

*Foveated display is a rendering technique which uses an eye tracker integrated with a virtual reality headset to reduce the rendering workload by greatly reducing the image quality in the peripheral vision.

2.3. The form factor

A prerequisite to the widespread adoption of NEDs is their compactness, lightness in weight, and socially plausible form. Although the form factor remains a standing issue in both AR and VR applications [21, 51], its most notable advancement in 2020 and 2021 was in the VR NED sector. In VR NEDs, the thickness of the device is mainly determined by the focal length of the optics forming the virtual image. The VR optics need to be large enough to offer an adequately wide FOV to enhance the
immersive experience. However, such large optics usually require a long focal length that substantially increases the thickness of the device.

Two novel approaches to this design situation recently attracted great attention. One is the use of a lenslet array [20, 52] in place of the single large optics to form the virtual image. The smaller size of the individual lens in the lenslet array results in a shorter focal length, thus reducing the overall device thickness while maintaining the wide FOV. The lenslet array, moreover, can also be curved to give an even wider FOV [52]. The second emerging approach is the use of polarization folding optics, which is also called pancake optics [21, 53]. These polarization devices fold the optical path, thus reducing the system thickness by as much as half; in recent years, in fact, VR NEDs of a sub-centimeter thickness have been developed [20, 53]. Still another potential candidate for the slim VR NED in the metasurface lens owing to its large numerical aperture (NA) [54]. Table 4 summarizes the recent developments in the research for slim VR NEDs.

### 2.4. Occlusion

Occlusion-capable AR NEDs are in their infancy and research to develop them are still on-going. The usual AR NEDs have optical combiners that simply add the displayed virtual images to the see-through real view, thus making the virtual images translucent. As mutual occlusion between the displayed virtual images and the real objects is not provided, users typically find the the depth order between them ambiguous. For good visibility, the virtual images should also be bright enough to stand out in the real environment, which then requires a display panel of very high luminance. Occlusion-capable AR NEDs solve these problems by masking the real-world view at the point where the virtual images appear. It is not a simple thing to realize this degree of occlusion capability. It usually needs multiple spatial light modulators (SLMs) to mask the real scene and a separate imaging optics for the virtual image display, thus significantly increasing the system's volume. Moreover, the additional image optics reduces the system's FOV.

Indeed, for ideal occlusion, a 3D mask should be imposed on the real-world scene, a situation that would require a system complexity equivalent to the NEDs with natural focus cues as previously taken up in Section 1.2. Even with these constraints, however, the recent research in 2020 and 2021 have made significant progress, coming up with a single SLM occlusion optics [55, 56], a masking scheme free of the screen-door effect [57], enhanced FOV [58], and 3D occlusion [59]. Table 5 lists the recent occlusion-capable AR NEDs.

### 3. Progress of QLEDs

Colloidal quantum dots (QDs) have received great attention owing to their superb properties: size-dependent bandgap tunability, high photoluminescence (PL) quantum yield (QY), and saturated colors from band-edge emission. These excellent characteristics make QDs practically adoptable in light-emitting diodes (LEDs), solar cells, photo detectors, biomarkers, and other optoelectronic applications [60–69]. Among these applications, their potential use of QLEDs in full-color displays have been widely investigated. The device structure and the operating principle of QLEDs are almost identical to that of OLED, except that the former's emission layer is comprised by QDs.

After the first demonstration of QD-based electroluminescence devices [70], multilateral efforts were likewise conducted to develop high-performance QLEDs. The synthesis methods developed for QDs were to improve their PL QY and colloidal stability by tailoring their core/shell structures and engineering surface ligands. In particular, the synthesis strategies included reducing the Auger process and surface defects that arise from exciton quenching, like adopting a gradient core/shell structure as well as QD surface passivation methods.

The device structures for QDs have also been significantly improved in the next decade. For example, an inverted structure with a ZnO electron transport layer was first introduced in 2012 [71], leading to highly

### Table 4. Slim VR NEDs as reported in 2020 and 2021.

| Features | Thickness | FOV     | Ref. |
|----------|-----------|---------|------|
| Lenslet array + Fresnel lens + polarization based folding optics | 8.8mm | 102°(H) | [20] |
| Curved lenslet array + curved screen | 9mm | 102°(H) | [52] |
| HOE + polarization based folding optics | 9mm | 90°(H) | [53] |
| Achromatic Metalens | | | [54] |

### Table 5. Occlusion-capable AR NEDs as reported in 2020 and 2021.

| Features | Number of SLMs | Ref. |
|----------|----------------|------|
| DMD + further optimization using occlusion factorization | 1 (single DMD for both masking and display) | [55] |
| DMD + polarization based double pass optics | 1 (single DMD for both masking and display) | [56] |
| Occlusion without screen door effect using a photochromic mask | 2 (a DMD for mask pattern UV projection + a panel for virtual image display) | [57] |
| Wide FOV using paired conical reflectors | 2 (a LCoS for masking + a panel for virtual image display) | [58] |
| 3D occlusion mask | 3 (a LCoS for masking + a PSLM for mask depth modulation + a panel for virtual image display) | [59] |
improved efficiency and operational stability of QD devices. Because inorganic nanocrystal QDs intrinsically possess deeper valence band (VB) energy levels than those of typical organic molecules, it was also thoroughly considered for injecting holes from the hole transport layer (HTL). For efficient hole injection into QDs as a hole transport layer, typically used were organic hole transporting materials that possess a deep or highest occupied molecular orbital (HOMO) energy level; e.g. 4,4′-bis(N-carbazolyl)-1,1′-biphenyl (CBP) and tris(4-carbazoyl-9-ylphenyl)amine (TCTA)) as well as polymers; e.g. polyvinylcarbazole (PVK), Poly(N,N'-bis-4-butylphenyl-N,N'-bisphenyl)benzidine (poly-TPD), and poly(9,9-di-octylfluorene-alt-N-(4-sec-butylphenyl)-diphenylamine) (TFB). The most widely used as electron transport layer are ZnO and ZnMgO nanoparticles owing to their decent ability of supplying electrons into QDs and their solution processibility. Typical organic electron transport materials like 2,2',2”-(1,3,5-benzinetriyl)tris(1-phenyl-1-H-benzimidazole) or TPBi are also adopted frequently. As a result of these research development efforts, the external quantum efficiencies (EQEs) of QD devices, have been improved close to the theoretical maximum values as plotted in Figure 3.

The next section discusses the research and development progress on QLEDs with Cadmium-containing QDs and Cd-free QDs.
In coordination chemistry, a ligand is an ion or molecule that binds to a central atom to form a coordination complex.

An exciton is a bound state of an electron and an electron hole that are attracted to each other by the electrostatic Coulomb force. It is an electrically neutral quasi-particle that exists in insulators, semiconductors, and some liquids.

The external quantum efficiency of a semiconductor device is defined as the ratio of the total number of photons extracted outward to the number of injected electrons to the device.

### 3.1. Cadmium-based QLEDs

Great efforts on material engineering led to the development of Cadmium (Cd)-containing QDs that show high PL QY close to unity, narrow emission spectra (FWHM < 30 nm), and high stability. Device structures and fabrication processes have been also improved continuously: The highest EQEs of red, green, and blue QLEDs reached 30.9%, 25.04%, and 19.8%, respectively [76, 80, 83], which are comparable to that of OLEDs. They were achieved by adopting a composition gradient core/shell structure and by controlling the size of ZnO nanoparticles. Also, the maximum luminance of red and green QLEDs were raised to as high as 3,300,000 cd/m² and 1,680,000 cd/m², respectively [81, 91], by minimizing exciton quenching processes and by optimizing thermal dissipation and light outcoupling that are hardly achievable in OLEDs. Furthermore, an unprecedented high operational lifetime of 125,000,000 h at 100 cd/m² was recently reported in red-emitting QLEDs [91]. Table 6 summarizes the device performance of recent Cd-based QLEDs.

Although Cd-based QLEDs generally outperform Cd-free QLEDs, the fact that Cd-containing QDs are environmentally harmful raise the possibility of their exclusion from the industry in the near future. In contrast, researches in support of Cd-free QDs and QLEDs have been increasing gradually.

### 3.2. Cadmium-free QLEDs

For practical uses of QDs in industry, heavy metal ions need to be substituted for the Cadmium in QDs to avoid environmental issues. Although Cd-free QDs that contain InP and ZnSe have not been studied as much as those that contain Cd, their use and market demand in the industry are increasing rapidly. For instance, in 2019, InP-based red-emitting QLEDs showed a maximum EQE of only 21.4% by precisely controlling the defects of their core, reducing their shell thickness and their surface ligands [96]. In 2021, this group also reported highly bright, red-emitting InP QLEDs capable of showing a maximum luminance of > 120,000 cd/m² by using a QD–organic blended emissive layer [104]. For green emission with InP QDs, much smaller QD cores need to be synthesized than the red QDs; however, since it is not that easy to synthesize smaller QD cores uniformly and to grow shell layers precisely, this makes the green InP QLEDs perform lower than red QLEDs. Nevertheless, a red QLED with high EQE of 16.3% has recently been reported; this performance was achieved by modifying surface ligands and optimizing the electron transport layer [102].

| QD structure | Peak wavelength (nm) | FWHM (nm) | Max. Luminance (cd/m²) | Max. EQE (%) | Max. CE (cd/A) | Ref. |
|--------------|----------------------|-----------|------------------------|--------------|---------------|------|
| Red InP/ZnSe/ZnS | 607 | 48 | 1,600 | 6.6 | 13.6 | [93] |
| InP/ZnSeS | 623 | 38 | 27,800 | 4.4 | 8.5 | [94] |
| InP/ZnSe/ZnS | 618 | 42 | 10,000 | 12.2 | 14.7 | [95] |
| InP/ZnSe/ZnS | 630 | 35 | 100,000 | 21.4 | – | [96] |
| InP/ZnSe/ZnS | 630 | 34 | 128,577 | 18.6 | – | [104] |
| InP | 632 | 40 | – | – | 19.6 | – |
| InP/ZnSe/ZnS | 632 | – | 23,300 | 21.8 | 23.46 | [106] |
| Yellow InP/ZnSeS/ZnS | 545 | 56a | 10,490 | 1.5a | 4.44 | [97] |
| InP/ZnSeS/ZnS | 565 | 65 | 1,900 | 5.1 | 18 | [98] |
| Green InP/ZnSeS | 539 | 37 | 17,400 | 3.4 | 21.6 | [94] |
| InP/ZnSeS | 518 | 64 | 3,900 | 3.46 | 10.9 | [99] |
| InP/GaP/ZnSe/ZnS | 527 | 58 | 2,938 | 6.3 | 13.7 | [100] |
| InP/ZnSeS/ZnS | 531 | 34 | 13,900 | 13.6 | – | [101] |
| InP/ZnSeS/ZnS | 545 | 39 | 12,646 | 16.3 | 57.5 | [102] |
| InP/ZnSeS/ZnS | 533a | 31 | 3,000a | 4.2 | 30.1 | [103] |
| InP | 532 | 39 | – | 17.6 | – | [105] |
| Blue ZnSeTe | 453 | 29 | – | 11.5 | – | [105] |
| ZnSeTe | 441 | 32 | 1,195 | 4.2 | 2.4 | [107] |
| ZnSeTe | 445 | 27 | 2,904 | 9.5 | 5.3 | [108] |
| ZnSeTe | 457 | 35 | 88,900 | 20.2 | – | [109] |

*aEstimated from the graph*
it is hard to obtain efficient blue emission in InP-based QDs, blue QD emitters use different chemical compositions in the core, such as ZnSe and ZnSeTe. In 2020, ZnSeTe-based blue QLEDs showed a high EQE of as much as 20.2% via Cl\(^-\) passivation of QDs and Te doping optimization [108]. Table 7 summarizes the comparative performance of Cd-free QLEDs.

### 3.3. Inkjet-printed QLEDs

To implement full-color displays using QLEDs, they should be patterned with red, green, and blue subpixels. Among the various patterning techniques, the inkjet printing of QDs is considered the most promising technology owing to their cost-effectiveness, high throughput, and large-area compatibility. Nevertheless, their relatively low performance that is caused mainly by their non-uniform surface morphology has been delaying the commercialization of QLED displays.

**Table 8. Device Performance of Inkjet-printed QLEDs.**

| QD structure | Peak wavelength (nm) | FWHM (nm) | Max. Luminance (cd/m\(^2\)) | Turn-on Voltage (V) | Max. EQE (%) | Max. CE (cd/A) | Ref. |
|--------------|----------------------|-----------|-----------------------------|---------------------|--------------|----------------|-----|
| Red          | 630                  | 35        | 12,100                      | 2                   | 1.34         | 4.44           | [110]|
|              | 628                  | 36        | 4,680                       | 2.2                 | 2.24         | 2.54           | [111]|
|              | 640\(^a\)            | –         | 10,000                      | 1.4                 | 16.6         | –              | [112]|
|              | 632                  | 32        | 8,533                       | 3                   | –            | 0.55           | [113]|
|              | 628                  | 27        | 30,000                      | 2.7                 | 7.52         | 10.03          | [114]|
|              | 630                  | 30        | 73,360                      | 2.3                 | 2.8          | 3.3            | [115]|
|              | 624                  | 27        | 10,000\(^a\)               | 2.2                 | 18.3         | 26.6           | [116]|
|              | 630                  | –         | 104,826                     | 2.2\(^a\)           | 19.3         | –              | [117]|
| Green        | 530                  | 30        | 89,500                      | 3.4                 | 3.31         | 13.9           | [118]|
|              | 530\(^a\)            | 29        | 12,000                      | 5.1                 | –            | 4.5            | [119]|
|              | 548                  | 33        | 3,000\(^a\)                | 6                   | 2.4          | 2.8            | [120]|
|              | 525                  | –         | 13,445                      | 4                   | 1.29         | 4.21           | [121]|
|              | 530                  | –         | 283,996                     | 3\(^a\)             | 18           | –              | [122]|
| Blue         | 462                  | 24        | 1,990                       | 3.6                 | 0.6          | 0.3            | [123]|
|              | 465                  | –         | 2,367                       | 3.5\(^a\)           | 4.4          | –              | [124]|

\(^a\)Estimated from the graph

**Figure 4.** EQEs of fluorescent, phosphorescent, and TADF OLEDs.

To improve their performance, several methods have been proposed for QLED displays, such as using co-solvents, additives, and post-annealing [109, 111, 114]. Still, because of recent several efforts to improve ink formulation and morphology, improvements, the EQE performance of red-, green-, and blue-emitting inkjet-printed QLEDs has already reached 19.3%, 18.0%, and 4.4%, respectively [119]. Table 8 summarizes their performance.

### 4. Progress of OLEDs

In the field of OLEDs, device and material technologies that utilize triplet excitons for high EQE have been mainly developed. To improve efficiency, triplet exciton utilizing such mechanisms as phosphorescence, thermally activated delayed fluorescence (TADF), and hyperfluorescence (HF) have been mostly investigated. Improvements...
Table 9. Device Performance of Fluorescent OLEDs and TADF OLEDs in 2021.

| EQE (%) | CE (cd/A) | Color coordinates | Lifetime (h) | Ref. |
|---------|-----------|-------------------|--------------|------|
| [1000 cd/m²] | (Max) | [1000 cd/m²] | (Max) | x | y | | |
| **Fluorescent** | | | | | | | |
| Blue | – | 17.4 | – | 26.2 | 0.14 | 0.22 | – | [121] |
| Red | 8.3 | 10.7 | – | – | 0.15 | 0.09 | – | [122] |
| Green | 6.4 | 31.7 | 14.2 | 71.0 | 0.55 | 0.45 | – | [123] |
| – | 19.5 | 30.3 | – | 13.4 | 0.69 | 0.31 | – | [124] |
| – | 16.4 | 33.7 | – | – | 0.54 | 0.46 | – | [125] |
| – | 29.1 | 39.1 | – | – | 0.38 | 0.55 | – | [126] |
| – | 21.2 | 29.8 | – | 71.9 | 0.13 | 0.53 | – | [127] |
| – | 22.3 | 24.5 | 75.3 | 79.6 | 0.34 | 0.57 | 93.4 | 99.4 | [129] |
| **TADF** | | | | | | | | |
| Red | 6.4 | 31.7 | 14.2 | 71.0 | 0.55 | 0.45 | – | [123] |
| Green | 19.5 | 30.3 | – | 13.4 | 0.69 | 0.31 | – | [124] |
| – | 16.4 | 33.7 | – | – | 0.54 | 0.46 | – | [125] |
| – | 29.1 | 39.1 | – | – | 0.38 | 0.55 | – | [126] |
| – | 21.2 | 29.8 | – | 71.9 | 0.13 | 0.53 | – | [127] |
| – | 22.3 | 24.5 | 75.3 | 79.6 | 0.34 | 0.57 | 93.4 | 99.4 | [129] |
| **Green** | | | | | | | | |
| Blue | 29.1 | 39.1 | – | – | 0.15 | 0.09 | – | [121] |
| – | 19.5 | 30.3 | – | 13.4 | 0.69 | 0.31 | – | [124] |
| – | 16.4 | 33.7 | – | – | 0.54 | 0.46 | – | [125] |
| – | 29.1 | 39.1 | – | – | 0.38 | 0.55 | – | [126] |
| – | 21.2 | 29.8 | – | 71.9 | 0.13 | 0.53 | – | [127] |
| – | 22.3 | 24.5 | 75.3 | 79.6 | 0.34 | 0.57 | 93.4 | 99.4 | [129] |
| **Blue** | | | | | | | | |
| – | 26.0 | 34.4 | 23.2 | 31.0 | 0.12 | 0.11 | – | [136] |
| – | 26.0 | 34.4 | 23.2 | 31.0 | 0.12 | 0.11 | – | [136] |
| – | 17.2 | 19.4 | 24.0 | 26.0 | 0.64 | 0.36 | 37.000 | 37.000 | (1,000 cd/m², LT95) | (1,000 cd/m², LT95) | [137] |
| – | – | 32.0 | – | – | 0.56 | 0.35 | 37.000 | 37.000 | (1,000 cd/m², LT95) | (1,000 cd/m², LT95) | [137] |
| – | 20.6 | 19.0 | – | – | 0.26 | 0.18 | 41.9 | 41.9 | (1,000 cd/m², LT90) | (1,000 cd/m², LT90) | [138] |
| – | 18.9 | 19.0 | – | – | 0.26 | 0.18 | 41.9 | 41.9 | (1,000 cd/m², LT90) | (1,000 cd/m², LT90) | [138] |
| – | 34.5 | 39.3 | – | – | 0.12 | 0.15 | – | [132] |
| – | 34.5 | 39.3 | – | – | 0.12 | 0.15 | – | [132] |
| – | 26.6 | 27.0 | – | – | 0.15 | 0.29 | 275 | 275 | (1,000 cd/m², LT90) | (1,000 cd/m², LT90) | [132] |
| – | – | 43.0 | – | – | – | – | – | – |
| – | 29.1 | 38.8 | 22.5 | 30.0 | 0.12 | 0.15 | – | [134] |
| – | 32.0 | 41.0 | 59.0 | 72.0 | 0.13 | 0.16 | – | [134] |
| – | 25.2 | 33.0 | – | – | 0.14 | 0.23 | – | [134] |
| – | 21.4 | 29.3 | – | 32.8 | 0.12 | 0.09 | – | [134] |
| – | 21.9 | 34.4 | – | 38.9 | 0.12 | 0.09 | – | [134] |
| – | 23.3 | 27.3 | 27.9 | 31.2 | 0.13 | 0.16 | – | [134] |
| – | 14.3 | 16.9 | 24.6 | 28.9 | 0.13 | 0.27 | – | [134] |
| – | 25.4 | 32.2 | 25.1 | 32.0 | 0.11 | 0.14 | – | [144] |
| – | 25.4 | 32.2 | 25.1 | 32.0 | 0.11 | 0.14 | – | [144] |

in their external quantum efficiencies (EQEs) are plotted in Figure 4.

4.1. Fluorescent OLEDs

Development of fluorescent OLEDs has been focused on the use of thermally activated delayed fluorescence (TADF) compounds as the emitters or assistant dopants of hyperfluorescence (HF) devices. For fluorescence devices, only singlet excitons can generally be utilized for light emission with a maximum exciton utilization efficiency of 25%. To improve this, assistant dopant that can harvest generated triplet excitons as radiative excitons is being co-doped in the emission layer to harness all the singlet excitons of the final fluorescent dopant. This emission process is called hyperfluorescence.
Table 10. Device Performance of PhOLEDs in 2021.

|       | EQE (%) | CE (cd/A) | Color coordinates | Lifetime (h) | Ref. |
|-------|---------|-----------|-------------------|--------------|------|
|       | [1000 cd/m²] | [Max]      | [1000 cd/m²] | [Max] | x   | y   | (1,000 cd/m², LT95) |
| **Red** |          |           |                   |              |     |     |                        |
|       | 29.1     | 31.4      | –                  | 60.0         | 0.61 | 0.39 | –                       | [145] |
|       | 25.9     | 30.4      | –                  | 50.0         | 0.62 | 0.38 | –                       | [145] |
|       | 25.9     | 28.0      | 46.1               | 50.0         | 0.61 | 0.39 | –                       | [146] |
|       | 26.2     | 28.0      | 46.7               | 49.5         | 0.61 | 0.39 | –                       | [146] |
|       | –        | 25.0      | –                  | –            | 0.70 | 0.30 | 55,000                  | [147] |
| **Green** |         |           |                   |              |     |     |                        |
|       | 19.0     | 22.5      | 69.1               | 81.7         | –   | –   | 22755                   | [148] |
|       | –        | 25.0      | –                  | –            | 0.42 | 0.56 | (1,000 cd/m², LT50)     | [147] |
| **Blue** |          |           |                   |              |     |     |                        |
|       | 19.9     | 21.0      | –                  | 23.5         | 0.14 | 0.12 | 1.8                     | [149] |
|       | –        | –         | 47.0               | –            | 0.18 | 0.42 | (100 cd/m², LT50)       | [150] |
|       | 24.7     | 31.9      | 40.9               | 52.9         | 0.14 | 0.18 | 10,700                  | [152] |
|       | 25.6     | 27.6      | –                  | –            | 0.12 | 0.13 | (1,000 cd/m², LT50)     | [151] |
|       | –        | –         | 23.4 (500 cd/m²)   | 25.1         | –   | –   | 232                     | [153] |

Table 11. Performance of soluble OLED device in 2021.

|       | EQE (%) | CE (cd/A) | Color coordinates | Lifetime (h) | Ref. |
|-------|---------|-----------|-------------------|--------------|------|
|       | [1000 cd/m²] | [Max]      | [1000 cd/m²] | [Max] | x   | y   | (1,000 cd/m², LT95) |
| **Red** |          |           |                   |              |     |     |                        |
|       | 31.1     | –         | 40.0               | –            | 0.68 | 0.32 | 8,300                   | [154] |
| **Green** |         |           |                   |              |     |     |                        |
|       | 26.7     | –         | 108.7              | –            | 0.25 | 0.71 | 7,000                   | [154] |
| **Blue** |          |           |                   |              |     |     |                        |
|       | 7.5      | –         | 4.9                | –            | 0.13 | 0.07 | 510                     | [154] |
|       | 19       | 21.8      | –                  | 46.5         | 0.17 | 0.35 | –                       | [155] |
|       | 7.1      | 25.8      | 18.3               | 64.8         | 0.21 | 0.42 | –                       | [156] |

By employing narrow-emitting TADF or fluorescent materials as the final emitters instead of conventional fluorescence emitters, the progress of the device performance of hyperfluorescence devices has been remarkable during the last two years. For them, TADF or phosphors have been mostly employed as the assistant dopants. The external quantum efficiency (EQE) of the HF devices goes over 30% and their lifetime improvement was also significant. In the case of conventional blue fluorescence emitters using hot exciton channels, a record-breaking EQE of over 17% has been reported. Table 9 summarizes the performance of fluorescent OLEDs achieved in 2021.

4.2. Phosphorescent OLEDs (PhOLEDs)

Progress in the performance of PhOLEDs has been mostly achieved in the blue devices. The device lifetime of the blue PhOLEDs has been upgraded through better host and dopant engineering, but it is clear that further extension of the device lifetime is still needed. In case of hosts for long-lifetime blue PhOLEDs, mixed hosts such as exciplex host, electroplex host, and TADF host with high triplet energy have been investigated. Table 10 summarizes the EQE and lifetime data of PhOLED devices.

4.3. Soluble OLEDs

The industry has demonstrated gradual improvement in the performance of soluble OLEDs. Both spin-coating and ink-jet printing processes were used, but dramatic performance improvement of the devices was seen when they used ink-jet printing technology. The EQEs of the red, green, and blue ink-jet printed devices at 1,000 cd/m² reached 31.1%, 26.7% and 7.5%, respectively.
5. The outlook for AR and VR displays

In the last couple of years, AR and VR displays have achieved significant advancements. When they applied the HOEs and the LC-based holographic gratings in various configurations, the the FOV as well as the eyebox and angular resolution of the AR NEDs were significantly enhanced. The VR NEDs realized the polarization dependent optics and the sub-cm thickness of lenslet array they needed while maintaining their wide FOV. The image quality and the computation speed of holographic displays were enhanced significantly by their application of deep-learning techniques. The continuing development of the AR and VR displays is expected with the use of the non-conventional and multi-functional optical elements coupled with even better computational display techniques.

Owing to the recent advances in QDs and QLEDs, the performance of QLEDs—even those that use Cadmium-free QDs—are now almost comparable to the competing technologies. Furthermore, the continuing heightened research on inkjet-printed QLEDs is expected to further brighten the market prospects of full-color QLED displays. Significant progress was attained in phosphor or TADF sensitized fluorescent OLEDs with the development of new materials and device structures for them. The performance of the blue OLED has been dramatically improved, and it is anticipated that its further development will lead to a much wider commercialization of a high-efficiency blue OLED technology.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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