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Aggregation-Induced Emission Luminogens as Color Converters for Visible-Light Communication

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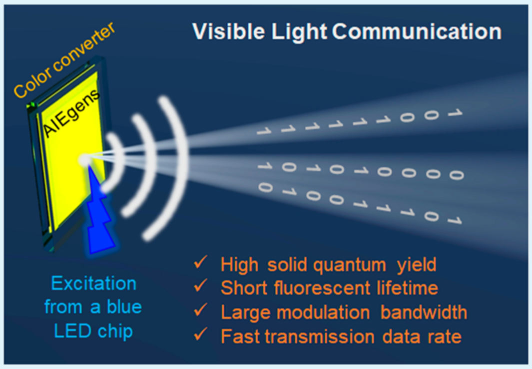
Supporting Information

ABSTRACT: In this work, we report the application of the aggregation-induced emission luminogens (AIEgens) as color converters for visible light communication (VLC). In the form of pure solid powder, the AIEgens studied herein have demonstrated blue-to-red full-color emissions, large −6 dB electrical modulation bandwidths up to 279 MHz (∼56× that of commercial phosphor), and most of them can achieve high data rates of 428−493 Mbps (up to ∼49× that of commercial phosphor) at a maximum bit error rate of 3.8×10^{-3} using on−off keying. Their data communication performances strongly suggest that AIEgens are very promising candidates as color converters for VLC applications, together with their unique AIE properties that will benefit usage in high concentration. Based on the comprehensive experimental results, we further propose some insights into improving data rate of the color converter in VLC: the data rate limit is influenced by modulation bandwidth and signal-noise ratio (SNR). We have experimentally proved that the −6 dB electrical modulation bandwidth f_c can be estimated from the effective lifetime τ of the color converter with the theoretical prediction of $f_c = \sqrt{3}/(2\pi\tau)$ within experimental uncertainties, while theoretically derived that the SNR is proportional to its PL quantum efficiency. These observations and implications are very profound for exploring materials as color converters and improve the data transmission performance in VLC.



KEYWORDS: *color-converting materials, optical wireless communication, solid-state lighting, organic semiconductor, LED, channel capacity*

■ INTRODUCTION

Visible light communication (VLC, also known as optical wireless communication, OWC or Li-Fi) is an emerging technology for simultaneous illumination and data transmission, which supplements the existing radio frequency communication approaches, such as Wi-Fi. Carrying the modulated signal via the unlicensed visible-light spectrum, a VLC system basically consists of a modulated visible light source (such as a white-light-emitting diode, denoted as wLED) as the transmitter, air in free space rather than fibers as the propagating media, and a photodetector like a photodiode or a camera as the receiver. It has many advantages, such as higher energy efficiency, better environmental friendliness, greater security, and no RF interferences over the common radio frequency approaches.[1,2] VLC can not only augment the Wi-Fi technology in indoor communication scenarios, but also facilitate communication in special scenarios, such as hospital, airplane, underwater, and vehicle-to-vehicle.[3] However, the conventional wLED usually consists of a blue LED chip and a longer-wavelength color converter. The color converter is usually made from phosphorescent material like Ce^{3+}: YAG with a long photoluminescence (PL) lifetime of >50 ns and a narrow modulation bandwidth of only a few megahertz (MHz) (Figure S1 in the Supporting Information (SI)), greatly

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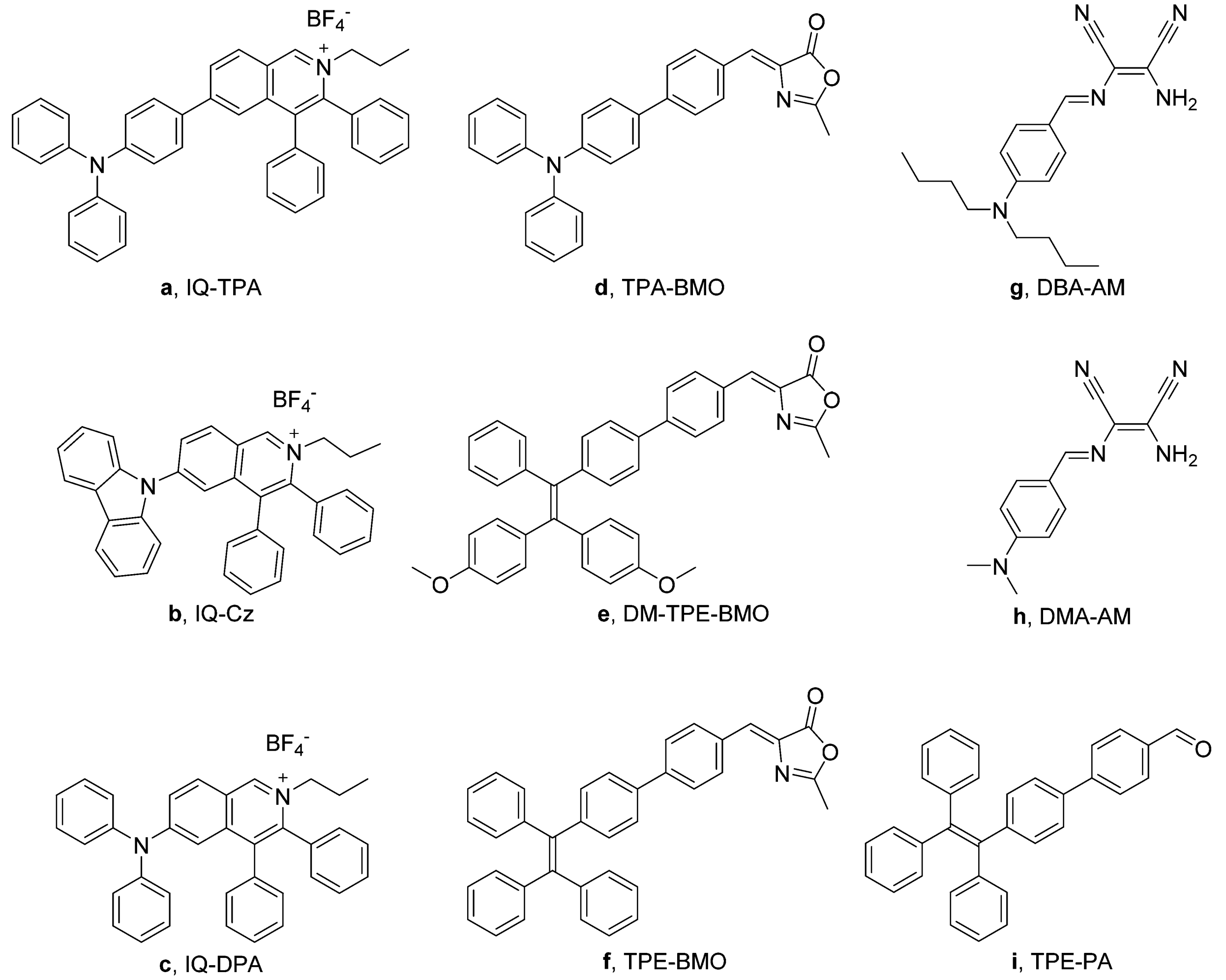

Figure 1. Molecular structures of the AIEgens studied in this work.

limiting the data rate of VLC.[4−6] Though this bottleneck can partially be overcome by using regions of small signals through advanced detection and signal equalizing circuits in conjunction with spectrally efficient encoding techniques,[7] color converters with larger modulation bandwidths are still highly favorable as they can lower the cost of signal detection and amplification and broaden the VLC applications.

To improve the modulation bandwidths in VLC, various fluorescence materials have been tested as color converters. For example, Xiao, Laurand, and Leitao implemented CdSe/ZnS quantum dots (QDs),[6,8,9] Dursun and Mei utilized perovskite nanocrystals,[10,11] and Sajjad, Chun, and Vithanage applied small organic dyes,[12] conjugated polymers,[13−15] and conjugated polymer blends.[15] Organic dye molecules are likely to have short PL lifetimes.[16] Conventional organic dyes were usually used in the form of solution[12,13] due to the aggregation-caused quenching (ACQ) effect. However, solution-based color converters are not satisfying for mass production as their performances may be influenced by the solvent evaporation and leakage. Therefore, multistep preparations and methods, such as luminescent microspheres,[13] guest−hosted polyimides matrix,[8] and metal−organic framework hybrid[17] have been developed to use these color converters in the solid state. Recently, having overcome the ACQ problem, aggregation-induced emission luminogens (AIEgens) have been developed.[18] These molecules show weak emissions in solution but intense emissions in the solid state, which have been used in various application fields, especially in OLED.[19,20] Moreover, these AIEgens might have short lifetimes of around several nanoseconds.[19,21−25] The emerging development of AIEgens has provided a new choice of color converters for VLC.

To prove the concept, in this article, nine AIEgens (as shown in Figure 1) with emission colors varying from blue to red were selected to investigate their VLC performances. In the form of pure solid powder, these AIEgens have demonstrated large −6 dB electrical modulation bandwidths up to 279 MHz. Most of the tested AIEgens can reach no less than 428 Mbps data rates at a maximum bit error rate (BER) of 3.8×10^{-3} using on−off keying (OOK), and the highest data rate can reach up to 493 Mbps. Besides, we have found that our experimental results well meet the theoretical prediction of $f_c = \sqrt{3}/(2\pi\tau)$ between the effective lifetime τ and −6 dB electrical modulation bandwidth f_c within experimental uncertainties. This consistency further confirms the possibility to forecast the modulation bandwidth of a color converter from its effective lifetime directly with reasonable accuracy. In addition, the Shannon-Hartley theorem on channel capacity indicates that the maximum data rate of a color converter in VLC is influenced by its photophysical properties like PL lifetime, PL quantum efficiency, and radiative decay rate. Above all, the data communication performance strongly

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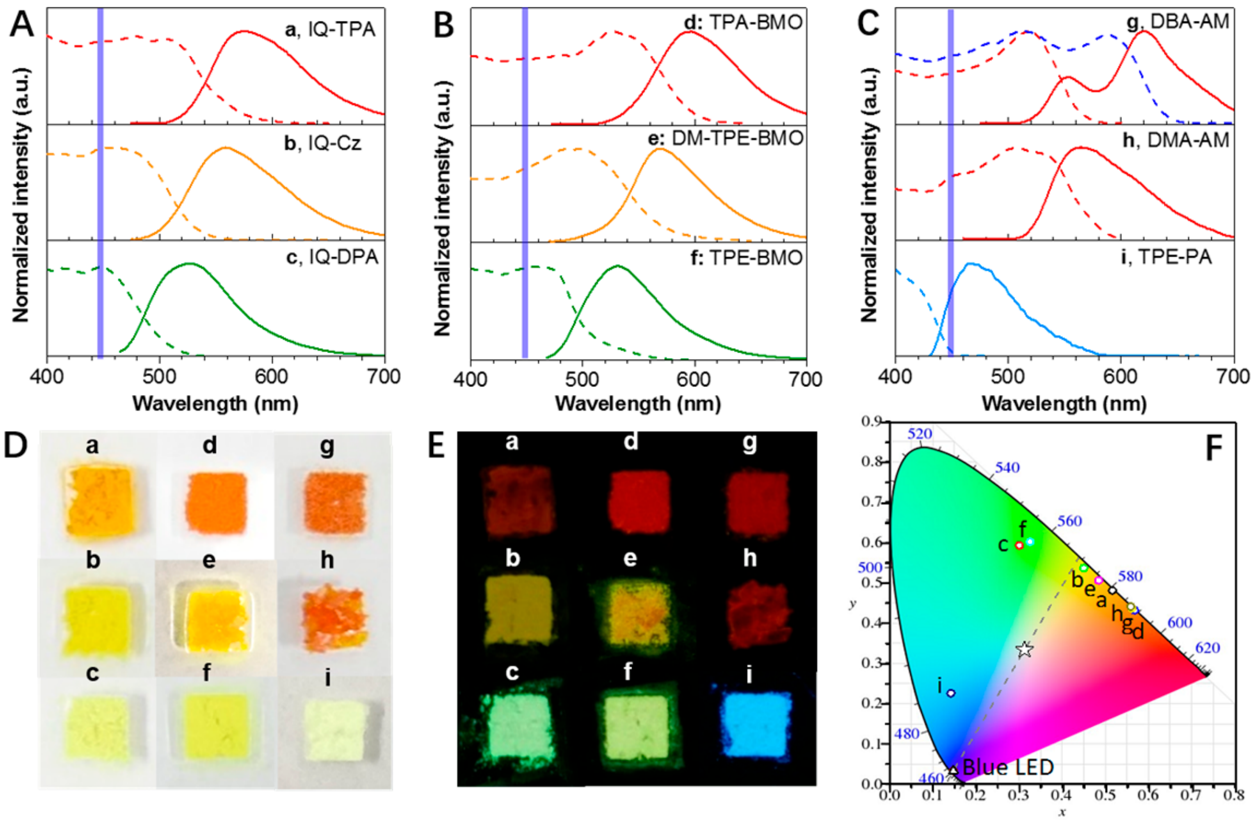

Figure 2. (A−C) Normalized excitation and emission spectra of the AIEgens in solid state. The vertical blue lines show the 450 nm excitation of the blue laser diode (denoted as LD, whose wavelength is same as the blue LED chip). (D) Bright-field photo of the AIEgens in solid state. (E) Dark-field photos of the AIEgens in solid state under the 365 nm excitation of UV analyzer. (F) CIE coordinates of the AIEgens generated on CIE 1931 chromaticity diagram according to their emission spectra.

Table 1. Photophysical Properties, Modulation Bandwidths, and Data Rates[a]

AIEgen	λ_{em} [nm]	CIE coordinate	Φ_{solid}	τ [ns]	k_r [10^8 s^{-1}]	k_{nr} [10^8 s^{-1}]	f_c [MHz]	Data rate [Mbps]
a, IQ-TPA	576	(0.514, 0.482)	0.19	0.97	1.96	8.35	279	439[b]
b, IQ-Cz	559	(0.448, 0.538)	0.09	3.38	0.27	2.69	77	<256
c, IQ-DPA	525	(0.299, 0.594)	0.33	2.20	1.50	3.05	119	433[c]
d, TPA-BMO	597	(0.566, 0.433)	0.19	2.22	0.86	3.65	110	444
e, DM-TPE-BMO	568	(0.483, 0.507)	0.59	1.99	2.96	2.06	128	493
f, TPE-BMO	531	(0.324, 0.603)	0.50	2.69	1.86	1.86	125	466
g, DBA-AM	589	(0.559, 0.438)	0.06	2.69	0.22	3.49	103	<256
h, DMA-AM	584	(0.557, 0.442)	0.07	14.7	0.048	0.63	26	<256
i, TPE-PA	471	(0.141, 0.227)	0.41	2.44	1.68	2.42	158	428

[a] λ_{em} is the emission peak wavelength of a certain AIEgen in solid powder. For DBA-AM with dual emission peaks, its effective peak wavelength λ_{em} is estimated from the nearest wavelength coordinates on CIE 1931 chromaticity diagram. Φ_{solid} is the solid-state quantum efficiency measured by an integrating sphere (see details in SI). τ is the PL effective lifetime whose details can be found in the *Photoluminescence Decay Curves* and *Calculation of the Effective Lifetime* section in the SI. k_r is the radiative decay rate determined by Φ_{solid}/τ, and k_{nr} is the nonradiative decay rate determined by $(1 - \Phi_{solid})/\tau$. f_c is the modulation bandwidth at −6 dB electrical response. Data rate refers to the highest data rate achieved at a maximum BER of 3.8×10^{-3} using OOK. Without extra notation, the data rate is measured at an incident power of P_i = 6.12 mW. [b]IQ-TPA was measured at an incident power of ∼14% P_i. [c]IQ-DPA was measured at an incident power of ∼50% P_i.

indicated that AIEgens are very promising candidates as color converters for VLC.

■ EXPERIMENTAL SECTION

Details can be found in the Supporting Information (SI).

■ RESULTS AND DISCUSSION

1. Photophysical Properties of the AIEgens. Figure 1 shows the chemical structures of nine AIEgens used in this work. Among them, TPA-BMO, TPE-BMO, TPE-PA, IQ-TPA, IQ-DPA, DMA-AM, and DBA-AM have been synthesized and reported in our previous reports.[21,23,26−29] Figure 2A-C shows the steady-state excitation and emission spectra of these AIEgens. Their excitation spectra are relatively broad, allowing a wide range of possible excitation wavelengths.[16] Except TPE-PA, they show excitation peaks at wavelengths around or longer than 450 nm (labeled with blue bold vertical lines in Figure 2A-C) and can be efficiently excited by the 450 nm blue LED chip. As for TPE-PA, its excitation strength at 450 nm is relatively weak, but it can be easily excited by the

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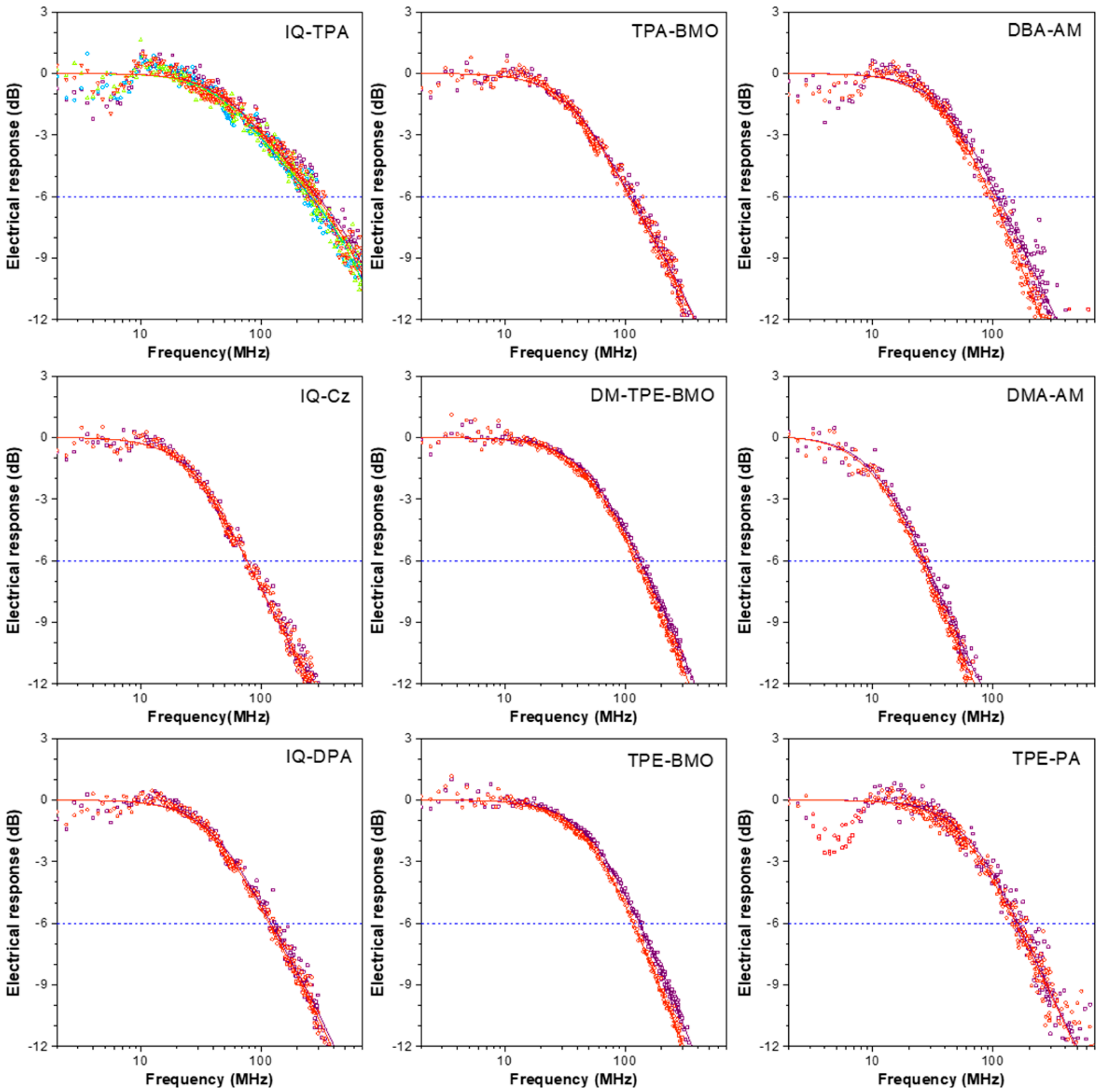

Figure 3. Plots of the electrical responses of these AIEgens versus frequency (scatter). The nonlinear fitting curves are performed with two-component model as shown in eq S19 (line). The modulation bandwidths f_c are calculated and averaged at −6 dB electrical response.

405 nm violet LED.[30] Their emission spectra show emission peaks ranging from 471 to 597 nm with the full width at half maximums (fwhm's) of around 80−100 nm. Their large fwhm's in emission spectra suggest these AIEgens are very suitable for lighting or illuminating applications.[31] Figure 2D,E shows the bright and dark field photos of the AIEgens, respectively. Their colors appear from milky-white to orange-red under room light and their luminescence varies from light-blue to red under 365 nm excitation of UV analyzer. The CIE coordinates of the AIEgens lie on the edge of the chromaticity diagram (Figure 2F), indicating that their colors are relatively pure.[32]

Further, the PL quantum efficiencies were measured and listed in Table 1. With various colors, most of these AIEgens show high solid-state quantum efficiencies of 19−59%, except IQ-Cz, DBA-AM, and DMA-AM. Moreover, PL decay curves of the AIEgens around their emission peaks were captured as shown in Figure S2 and their effective lifetimes were estimated and listed in Table 1. The much quicker instrumental response (Figure S3) imply the accuracy of lifetime measurements. The amplitude average lifetimes as described in SI were used due to their better fitting to the experimental results (Figure S4). These AIEgens show lifetimes within 0.97−3.38 ns, except DMA-AM. These short lifetimes are comparable to those of other organic materials (0.37−4.06 ns), and relatively shorter than those of QDs (11−29 ns) and perovskite nanocrystals (7−44 ns) in the previous reports.[6,8−15,17,33]

2. Modulation Bandwidth and Data Rate. After investigation of the photophysical properties, we further test the frequency response properties of the AIEgens. Figure S5 shows the photo and schematic picture of the experimental setup. Since the frequency where the optical response reduces

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3 dB is corresponding to the one where the electrical response reduces 6 dB from its maximum, therefore, the frequency where the electrical response is decreased to −6 dB was defined as the modulation bandwidth f_c (the responses at frequency lower than 2 MHz of the curves in Figure 3 have been adjusted to zero). All the frequency response curves are repeated at least 2 times for each compound to check the accuracy and repeatability of the results. The average modulation bandwidths are shown in Table 1. Almost all the AIEgens tested show large f_c above 100 MHz except IQ-Cz and DMA-AM, and the largest is IQ-TPA with f_c of 279 MHz, which is ∼56 times the bandwidth of commercial phosphors (Figure S1). Although this is smaller than the over 470 MHz −6 dB electrical modulation bandwidth of the specifically designed polymer BBEHBO-PPV film,[14] it is larger than most of the color converters reported in previous publications.[6,8,12,17,33,34]

Then, we further tested the data transmission performance of the AIEgens. Figure 4 and Figure S6 show the BERs at different data rates of the AIEgens using OOK. The BERs increase with the increasing of data rates, showing a similar trend to Yin's experimental and Akbulut's numerical results.[35,36] At the forward error correction (FEC) limit of BER = 3.8×10^{-3}, which is more commonly used as error floor in recent reports,[9,10,14,17,37,38] the data rates are over 428 Mbps for most of the AIEgens. The highest data rate is 493 Mbps for DM-TPE-BMO and it is much higher than that of the yellow phorphors in commercial LEDs (∼10 Mbps),[15] and only slightly smaller than the BBEHBO-PPV film (>550 Mbps).[14] The eye diagrams were also captured for these AIE color converters as shown in Figure S7 and a typical example of DM-TPE-BMO is shown in Figure 4. For compounds with high data rates (a, c−f, and i), their widely open eyes at 256 Mbps indicate that the bit symbol 1 and 0 can be reliably distinguished, and these eyes are nearly closed at the data rates close to BER = 1.2×10^{-3} (which was used as error floor in Sajjad's reports[12,15]).

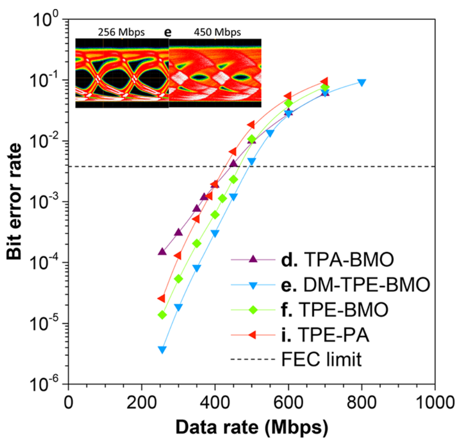

Figure 4. BERs versus data rates of the AIEgens measured at an incident power of P_i = 6.12 mW using OOK. The forward error correction (FEC) limit is BER = 3.8×10^{-3} (dashed line). The eye diagrams of DM-TPE-BMO at 256 and 450 Mbps are inserted.

Above all, these AIEgens achieve large modulation bandwidths up to 279 MHz and high data rates up to 493 Mbps. These results strongly indicate that AIEgens can serve as promising candidates of the color converters to further improve the performance of VLC. Although the AIEgens presented here have not achieved the best modulation bandwidth and data rate reported in color converters for VLC, the Φ_{solid} of our AIEgens can be up to 59% in solid state powders, attributing to their unique AIE property, overcoming the ACQ problem of conventional dyes (for example, the Φ of BBEHBO-PPV in forms of film (45%) is smaller than that of its solution (67%)). This AIE property could be crucial for color converters used in VLC when the high concentration of dye molecules need to be used to improve the SNR.

3. Relationship between the PL Lifetime and Modulation Bandwidth. The relationship in which the PL lifetime of the color converter highly affects the frequency response (or modulation bandwidth) of the VLC has been discussed in Laurand's work with colloidal QD nanocomposites,[8] and the quantitative relation $f_c = \sqrt{3}/(2\pi\tau)$ was proposed[4] (theoretical derivation can be found in the SI). However, few works have experimentally verified the accuracy of the equation above. Here, we plot the reciprocal of the effective lifetime $1/\tau$ and the −6 dB electrical (−3 dB optical) modulation bandwidth f_c of the color converters in Figure 5,

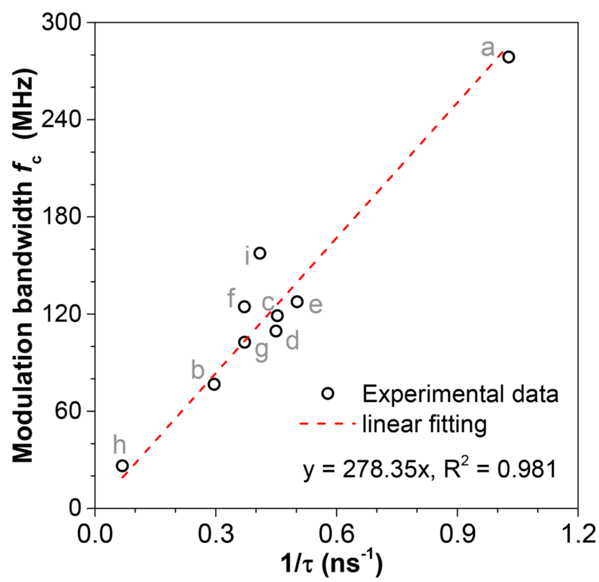

Figure 5. Plot of the relation between effective lifetimes τ and modulation bandwidths f_c of these AIEgens. The red-dashed line is the linear-fit line of the scattered sample points with the intercept set as zero ($f_c = k \times 1/\tau$).

where f_c is in the unit of megahertz (MHz) and τ is in the unit of nanosecond (ns). When the intercept of the linear fit to the scattered sample points in Figure 5 is set to zero, the slope k of $f_c = k/\tau$ is obtained as 278.35 ± 12.74 with a fitting correlation coefficient of R^2 = 0.981, which is very close to the slope of theoretical prediction $f_c = 275.66/\tau$ under the current units. Therefore, the result strongly suggests that it is possible to predict the f_c of a certain color converter from its effective lifetime τ with reasonable accuracy. This was further verified by the recent reported BBEHBO-PPV solution.[14] The predicted bandwidth of BBEHBO-PPV solution (424 MHz) from its lifetime (0.65 ns) deviates only ∼10% from its experimental −6 dB electrical modulation bandwidth (∼470 MHz). Therefore, the radiative lifetime is a reasonable indicator of bandwidth of color converters for VLC.

Besides the amplitude average lifetime, we also check the fitting plot by using the effective lifetime interpolated from

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intensity average lifetime (as shown in Figure S8). The result shows the effective lifetime interpolated from amplitude average lifetime fits better with the theoretical prediction than intensity average lifetime in our case. However, it should also be noted that the intensity average lifetime might became suited at lower frequency region. (Detailed discussion on their difference can be found in SI.)

It should be noted that for fluorescent dyes, their PL lifetimes often vary with their local microenvironments, such as whether they are in solution or film,[14] and what kind of solvent is used in solution.[21,39] Therefore, the measurement of the PL lifetime in situ is necessary to estimate the −6 dB electrical modulation bandwidth from the above equation more accurately. Also, the aggregation state of the AIEgen influences its VLC performance. DBA-AM, whose aggregate state was reported to have a great influence on its emission properties,[27] was used as an example. As its aggregation state changed from crystalline to amorphous, the apparent color and emission color were both blue-shifted (as Figure S10 A-D). The fraction corresponding to the 550 nm emission band became relatively larger in the emission spectra of the amorphous state (Figure S10C). The PL decay in Figure S10E and frequency response in Figure S10F curves showed that the effective lifetime decreased and the −6 dB electrical modulation bandwidth increased as the aggregation state changed from crystalline to amorphous. It should be noted that the f_c = 116 MHz of the amorphous state is smaller than that estimated from its lifetime (∼207 MHz) as its signal intensity dropped when the frequency response curve was scanned from low frequency to high frequency, probably due to the poor photostability of its amorphous solid. These results suggest that the control of the morphology is important for the reproducibility of the experimental results. Fortunately, throughout the experiments, we tested the same solid sample for the collection of all data and thus they kept in good accordance.

4. Relation between the Data Rate Limits and Photophysical Properties. Based on the comprehensive results concluded above, we would like to derive a broader implication, i.e., not only the lifetime is related to the performance of VLC, but other photophysical properties, such as quantum efficiency or radiative decay rate, are of concern. According to the Shannon's channel capacity theorem,[40] it is possible to predict an upper bound on the maximum data rate that can be transmitted by the color converter. Assuming the noise is white noise with a power N and uncorrelated to signal with a power S, the channel capacity C is bounded by

$$C = f_c \log_2\left(1 + \frac{S}{N}\right) \tag{1}$$

if the signal is pure PL from the color converter captured by the photodiode, in a unit of time

$$S = \int P(\lambda)G(\lambda)R(\lambda)\,\mathrm{d}\lambda \tag{2}$$

where $P(\lambda)$ is the optical power distribution of the PL emitted and scattered from color converter, $G(\lambda)$ is the optical collection efficiency of the optical system, $R(\lambda)$ is the response of the photodiode at wavelength λ.[41]

In PL quantum efficiency characterization, the quantum efficiency can be described as[42]

$$\phi = \frac{N_{\text{emit}}}{N_{\text{abs}}} \tag{3}$$

wherein N_{emit} and N_{abs} refer to the number of photons emitted and absorbed by the color converter, and they can be described by

$$N_{\text{emit}} = \int N_{\text{emit}}(\lambda)\,\mathrm{d}\lambda = \int \frac{P(\lambda)}{E_{\text{ph}}(\lambda)}\,\mathrm{d}\lambda = \int \frac{P(\lambda)\lambda}{hc}\,\mathrm{d}\lambda \tag{4}$$

$$N_{\text{abs}} = f(\varepsilon(\lambda_0)A)\frac{P_i}{E_{\text{ph}}(\lambda_0)} = \frac{\lambda_0}{hc} f(\varepsilon(\lambda_0)A)P_i \tag{5}$$

$E_{\text{ph}}(\lambda)$ is the energy of the photon at wavelength λ, P_i is the power of the incident light from the LED or laser diode on the color converter (incident power), $f(\varepsilon(\lambda_0)A)$ is the fraction of absorption which can be expressed by $f(\varepsilon(\lambda_0)A) = 1 - \exp(-\varepsilon(\lambda_0)A)$, where $\varepsilon(\lambda_0)$ is the absorption coefficient of the color converter at the wavelength of the LED/LD device (denoted as λ_0), A is other factors that may influence the absorption of the color converter, such as the area of incident spot that can be collected by the photodiode and the concentration of the color-converting molecules, and hc is Planck's constant. Hence,

$$\begin{aligned}\frac{S}{N} &= \frac{\int P(\lambda)G(\lambda)R(\lambda)\,\mathrm{d}\lambda}{\int \frac{P(\lambda)\lambda}{hc}\,\mathrm{d}\lambda}\,\frac{\int \frac{P(\lambda)\lambda}{hc}\,\mathrm{d}\lambda}{\frac{\lambda_0}{hc} f(\varepsilon(\lambda_0)A)P_i}\,\frac{\frac{\lambda_0}{hc} f(\varepsilon(\lambda_0)A)P_i}{N}\\ &= \frac{\lambda_0}{N}\,\frac{\int P(\lambda)G(\lambda)R(\lambda)\,\mathrm{d}\lambda}{\int P(\lambda)\lambda\,\mathrm{d}\lambda}\phi f(\varepsilon(\lambda_0)A)P_i\end{aligned} \tag{6}$$

with the $f_c = \sqrt{3}/(2\pi\tau)$, the Shannon's channel capacity limit can be expressed by the photophysical properties as

$$C = \frac{\sqrt{3}}{2\pi\tau}\log_2\left(1 + \frac{\lambda_0}{N}\,\frac{\int P(\lambda)G(\lambda)R(\lambda)\,\mathrm{d}\lambda}{\int P(\lambda)\lambda\,\mathrm{d}\lambda} f(\varepsilon(\lambda_0)A)P_i\phi\right) \tag{7}$$

If the LD/LED light is fully absorbed by the color converter, then the $f(\varepsilon(\lambda_0)A)$ part will be a constant. It can be predicted from eq 7 that the channel capacity will increase with increasing ϕ or decreasing τ, if other factors remain the same. As it is the upper bound that can only be approached through a certain coding scheme for a certain channel that is represented by the Shannon's channel capacity limit C, we further checked whether the maximum data rate the color converter can achieve in our test may qualitatively follow the trend as described in eq 7 using OOK[43,44] with the photophysical properties in Table 1. The compounds with the larger data rates of 428−493 Mbps usually have larger quantum efficiencies (19−59%) and relatively shorter PL lifetimes (0.97−2.69 ns) than those of small data rates (IQ-Cz, DBA-AM, and DMA-AM). The short lifetime is essential to increase the modulation bandwidth while the large quantum efficiency in the solid state is crucial to improve the SNR in the VLC.

One may wonder why the highest achieved data rates for IQ-TPA, IQ-DPA, and TPE-PA are smaller than those expected from their ϕ and τ. For TPE-PA, it is because its weak excitation strength at 450 nm, the cutoff effect of 495 nm long-pass filter, and relatively weaker spectral responsivity of APD430A2 at the λ_{em} of TPE-PA result in a relatively smaller

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$\frac{\int P(\lambda)G(\lambda)R(\lambda)\,d\lambda}{\int P(\lambda)\lambda\,d\lambda} f(\varepsilon(\lambda_0)A)$ according to eq 7. For IQ-TPA and IQ-DPA, it is because in their data rate test, the incident power of blue LD, i.e., P_i in eq 7, is attenuated to 14% and 50% of original power as used for others, to alleviate their BER-data rate curve distortion to larger data rate side. As shown in Figure S10, their PL lifetime is shortened after shined by the focused blue laser for minutes under original incident power. Therefore, the smaller incident power P_i reduces their captured signal voltages, and the relatively lower SNR leads to smaller channel capacities according to eqs 1 and 7.

Given the radiative constants $k_r = \phi/\tau$, the k_r of these AIEgens are also calculated and listed in Table 1. It is found that the increasing order of k_r of TPA-BMO (0.86×10^8 s^{-1}), TPE-BMO (1.86×10^8 s^{-1}), and DM-TPE-BMO (2.96×10^8 s^{-1}) are in the same increasing order with their data rates (444, 466, and 493 Mbps), respectively. This result indicates that compounds with larger k_r are more likely to achieve larger data rates in VLC, which agrees with the trend predicted from eq 7.

In all, these implications provide a fundamental insight into the choice of color converters for VLC applications: to achieve large data rate, the photophysical properties of the color converter need to be tuned with short lifetime, high quantum efficiency, and large radiative decay rate.

■ CONCLUSION

In this work, we have performed a systematic investigation on the performance of AIEgens as color converters for VLC. With their blue-to-red full-color emissions, high solid-state quantum efficiencies of 19−59%, short effective lifetimes of 0.97−2.69 ns, large modulation bandwidths of 103−279 MHz, and fast data rates of 428−493 Mbps, together with their unique AIE properties that will benefit usage in high concentration, these AIEgens show great potential as color converters for VLC. Our experimental data well support the quantitative relation $f_c = \sqrt{3}/(2\pi\tau)$ between the −6 dB electrical modulation bandwidth f_c and the effective PL lifetime τ. Meanwhile the maximum data rate of a VLC system is influenced by the modulation bandwidth (effective lifetime τ) and SNR (PL quantum efficiency ϕ) of the color converter. In a simple way, compounds with large radiative constants $k_r = \phi/\tau$ are more favorable as color converters for VLC usage. These built relationships will provide insight and inspiration to design, develop, or select new materials in the future as color converters for VLC.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsami.8b05950.

> Experimental section including details on the materials and instrumentation, synthesis of the AIEgens, method of the photophysical property characterizations, frequency response and communication performance test data capture, processing and analysis, aggregation-state effect on the VLC performance of DBA-AM, thermal and photostability, etc., and supplementary figures (PDF)

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Notes

The authors declare no competing financial interest.

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