Is blue optical filter necessary in high speed phosphor-based white light LED visible light communications?

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Abstract: Optical blue filter is usually regarded as a critical optical component for high speed phosphor-based white light emitting diode (LED) visible-light-communication (VLC). However, the optical blue filter plays different roles in VLC when using modulations of on-off keying (OOK) or discrete multi-tone (DMT). We show that in the DMT VLC system, the blue optical filter may be unnecessary, and even degrade the transmission performance (by reducing the optical signal-to-noise ratio (SNR)). Analyses and verifications by experiments are performed. To the best of our knowledge, this is the first time the function of blue filters in VLC is explicitly analyzed.

OCIS codes: (230.3670) Light-emitting diodes; (060.4510) Optical communications; (060.4080) Modulation.

References and links

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1. Introduction

Prosperous development of light emitting diode (LED) technology makes LED an economical choice of light source. Compared to traditional fluorescent lamp, LED has higher modulation bandwidth; hence the integration of illumination and visible light communication (VLC)

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using LED has attracted many attentions recently [1–7]. Phosphor-based white-light LED is typically used for lighting owing to the lower cost when compared with the red-green-blue (RGB) LED. The phosphor-based LED is typically consisted of a blue LED chip covered by a yellow phosphor layer. However, when this phosphor-based LED is used for the VLC, the modulation bandwidth is limited by the long relaxation time of the phosphor; hence limiting the transmission capacity of the VLC. In order to increase the LED modulation bandwidth, it is claimed to use a blue filter before the photo-diode (PD) in the VLC system to eliminate the slow-response yellow light component [8–10].

Using high spectral-efficient modulation formats is one common approach to mitigate the bandwidth starvation issue of LED VLC systems. Among these spectral-efficient modulation formats, discrete multi-tone (DMT) is a popular choice since adaptive bit-loading and simple equalization can be used to highly utilize the available bandwidth of the LED; hence higher capacity and acceptable bit error rate (BER) can be obtained [10–12].

In this work, we analyze for the first time whether a blue optical filter is necessary for the high-speed phosphor-based LED VLC. In the analysis, we can observe that the use of blue optical filter does not enhance the "practical" LED modulation bandwidth. It only enhances the "normalized" LED modulation bandwidth at the expense of introducing optical power drop (since the yellow-light component is removed). We explicitly point out that the blue optical filter does contribute for increasing the maximum data rate of the conventional on-off keying (OOK) VLC system owing to signal equalization. On the other hand, for DMT signal, the benefit brought by the blue filter is limited. This is because the DMT signal is consisted of many narrow-band subcarriers. Each DMT subcarrier experiences a quasi-flat frequency response whether the total frequency response of the channel is flat or not. The optical blue filter has negligible contribution to the equalization of the DMT subcarriers since the blue filter has a much wider bandwidth. Besides, the multiple subcarrier-based DMT signal can be easily equalized by using digital signal processing (DSP) in the transmitter (Tx) and/or receiver (Rx). Hence, in the DSP-based VLC system, the blue optical filter may be unnecessary, and may even degrade the transmission performance (by reducing the optical signal-to-noise ratio (SNR)). To the best of our knowledge, this is the first time the function of blue filter in VLC is explicitly analyzed.

2. Model and discussion

The proposed model for a phosphor-based LED VLC system with optical blue filter is shown in Fig. 1. The blue LED chip is properly biased and directly modulated by the electrical signal $s_i(t)$ produced by an arbitrary waveform generator (AWG). Linear approximation is assumed while the modulation amplitude is small. Hence, the optical signal intensity from the blue LED chip is approximately equal to $s_i(t)$. Figures 1(a) and 1(b) show the corresponding schematic electrical spectra. The electrical spectrum of an optical signal is determined by the corresponding electrical current of a PD stimulated by the optical signal. Some of the blue light emitted from the LED chip is absorbed by the phosphor layer to produce yellow light, $s_y(t)$. The bandwidth of the received yellow light is limited by the slow response, $h_y(t)$ of the phosphor, and its schematic electrical spectrum is shown in Fig. 1(c). On the other hand, the electrical spectrum of the blue light is shown in Fig. 1(d), which is similar to the electrical spectrum after the blue LED chip as shown in Fig. 1(b) but with attenuation. Then, the blue and yellow lights are mixed to become white light during transmission. Assume the blue and yellow lights pass through a channel with flat frequency response, which denotes a channel response of $h_{air}(t) = \delta(t)$, where $\delta(t)$ is the delta function.

If no blue filter is used, the schematic electrical spectrum after PD is shown in Fig. 1(e), which is a superposition of the spectra shown in Fig. 1(c) and Fig. 1(d). Figure 1(f) shows the received schematic electrical spectrum when a blue filter is applied. Only the blue light can be received by the PD. As shown in Fig. 1(e) and 1(f), the use of a blue optical filter does not really enhance the "practical" LED modulation bandwidth. It only enhances the "normalized" LED modulation bandwidth at the expense of introducing high optical power drop (since the yellow-light component is removed). The optical power drop will result in SNR degeneration.

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If we focus on the "practical" LED modulation bandwidth, an absolute peak reference should be first defined (the dash line marked by "Peak" in Fig. 1 (e) and 1(f)). It is clear that Fig. 1(e) and 1(f) have the same bandwidths with respect to the same "Peak" level. Hence, we can conclude that the use of optical blue filter theoretically cannot influence the available bandwidth of the VLC system. Further analyses are carried out in two cases.

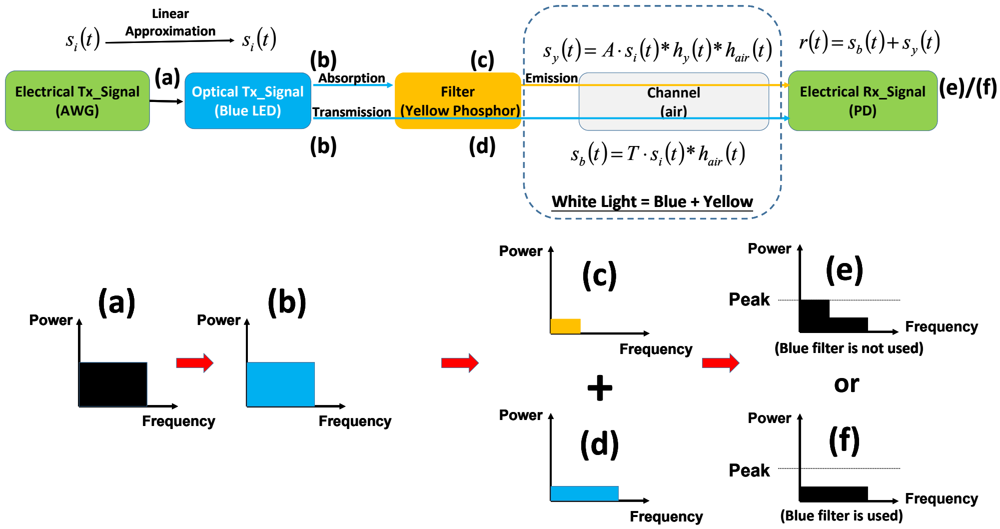

Fig. 1. The model for phosphor-based LED VLC system with optical blue filter. A: absorptance; T: transmittance. Insets: schematic electrical spectra of (a) input signal, (b) blue light if received by a PD, (c) yellow light component if received by a PD, (d) blue light transmitted through the yellow phosphor, (e) received white light without using a blue filter, and (f) received white light using a blue filter.

(i) In an OOK-based VLC system, it is evident that blue filter contributes for increasing the maximum data rate of the VLC system [9]. Based on the above model, this does not benefit by the bandwidth enhancement. The enhancement of the maximum data rate is due to equalization. Refer to Fig. 1(e), the power of all the received signal mainly locates at the low frequency band because of the slow response of the yellow phosphor. The low-frequency-dominant spectrum shown in Fig. 1(e) will result in a distorted signal, which has expanded signal waveform in time domain. This induces interference among consecutive symbols and may degrade the BER. When a blue filter is used, the received signal spectrum will be shaped to be the one shown in Fig. 1(f), which has a more flat frequency response. The flat frequency response reduces the signal distortion and symbol interference. This is the main reason for BER enhancement. Any equalization process that flattens the frequency response may have similar or even better contribution to the optical blue filters [8], which increases the system data rate, rather than the system available bandwidth.

(ii) In a DMT-based VLC system, the use of optical blue filter may be unnecessary. Any DMT signal is consisted of many narrow-band subcarriers. Each DMT subcarrier experiences a quasi-flat frequency response. The blue filter, which has a much wider bandwidth, can have negligible contribution for equalizing the DMT subcarriers. Besides, the DMT-based signal can be easily equalized by using DSP in the Tx and/or Rx. The use of blue filters will reduce the received optical power. Hence, in typical DMT-based VLC system, blue filter may be unnecessary.

3. Experimental verification

We can consider an OOK signal as a set of "On" pulses. If we can further emulate each "On" pulse as a DMT symbol, then we can verify our model by performing only the DMT experiment. The experimental setup to verify the model is shown in Fig. 2. A low-cost commercially available phosphor-based white light LED (LUXEON Rebel) was electrically driven by sinusoidal signals with different frequencies via a bias-tee. The optical signal emitted by the LED was received by a silicon PD (Thorlabs PDA10A) with 150 MHz bandwidth, 0.8 mm^2 active area, and 0.45 A/W peak response at 750 nm. The PD was directly connected to a real-time oscilloscope.

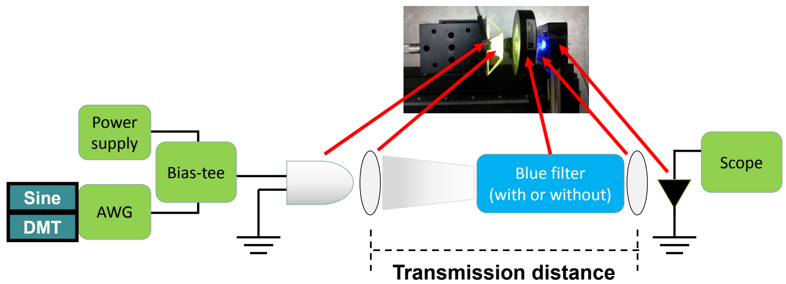

Fig. 2. Experimental setup to evaluate the necessity of the optical blue filter.

Figure 3 shows the measured frequency response of the LED. We can observe that the use of an optical blue filter makes the frequency response at low frequency band to be more flat by removing the yellow light component as expected in our model discussed in Section 2. For the high frequency band, the curve slopes with and without using the optical blue filter gradually become identical since the blue filter introduces equal attenuation to the blue light component as expected in our model. In the experiment, the insertion loss of the blue filter is approximately 3 dB, which causes lower receiving power when blue filter is used. Moreover, to ensure the above conclusion is not influenced while a lens is used for focusing the optical power, the frequency responses with and without using focusing lenses are also measured and included in Fig. 3. It can be observed that the use of lenses mainly results in linear shift of power level for both cases.

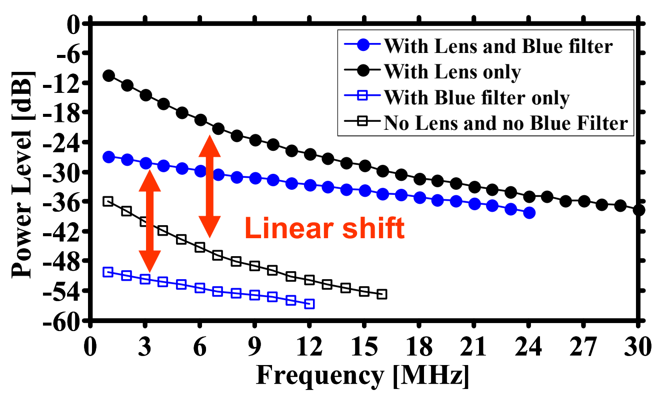

Fig. 3. The measured frequency response of VLC with and without using optical blue filters and lenses.

After the frequency response analysis, we then drove the LED with DMT signal. The DMT signal was generated offline using Matlab program. The DMT generation consisted of serial-to-parallel (S/P) conversion, quadrature-amplitude-modulation (QAM) symbol encoding, inverse fast Fourier transform (IFFT), CP insertion and digital-to-analog conversion (DAC) as similarly described in ref [7]. The DAC used was the AWG with sampling rate of 100 MS/s. FFT size of 512 was used. The electrical signal generated by the AWG was launched into the LED using a bias-tee. The peak-to-peak voltage was adjusted to satisfy the linear small signal condition. At the receiver end, the silicon PD was directly connected to the real-time oscilloscope and the signal decoding was performed offline. The

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demodulation process included the synchronization, FFT, and QAM symbol decoding. Zero-forcing was used for the equalization. The BER was obtained according to the measured SNR of each DMT subcarrier. Figure 4(a) shows the SNR performance at different DMT subcarriers. As expected in the model, the SNR performance without a blue filter is much better than that with a blue filter.

To further investigate how the blue filter induces power degradation and affects the VLC system capacity, comparison for these two cases was performed. The subcarriers of the DMT signal were bit-loaded according to their SNR performance to nearly optimally use the LED bandwidth. The optimized bit-loading schemes with and without using a blue filter are shown in Fig. 4(b). For the case of without using a blue filter (case BL_1), the achievable net data rate is ~71 Mb/s. For the case of using a blue filter (case BL_2), the achievable net data rate is ~63 Mb/s. Hence 8 Mb/s data rate gain can be achieved while the blue filter is not used. It can be observed that more than 20 MHz bandwidth can be used for transmission even though the measured 3-dB bandwidth shown in Fig. 3 is about 2.5 MHz.

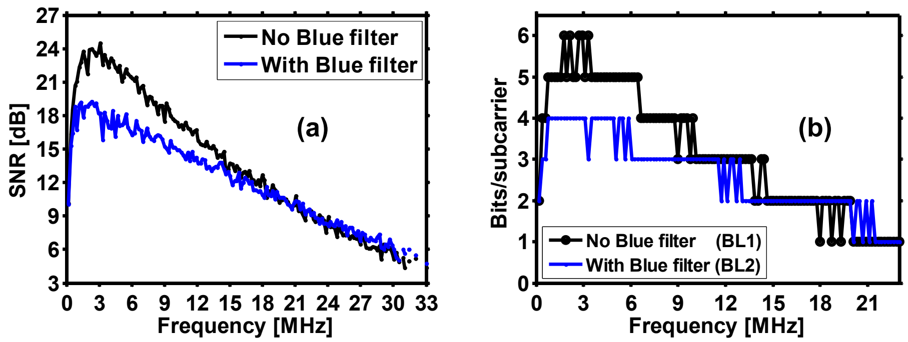

Fig. 4. (a) The measured SNR for the VLC transmission without and with optical blue filter, and the (b) bit loading schemes used.

Figure 5 shows the measured constellations of different symbols loaded on the DMT subcarriers according to the $\underline{BL_1}$ bit-loading scheme shown in Fig. 4(b). The constellations were measured without and with using an optical blue filter under the same VLC transmission distance. We can observe that while a blue filter is used in the VLC system, the constellation diagrams are more diverse, particularly at higher-level modulation formats (used in low-frequency band). This is because the optical power at the low frequency band is highly attenuated by the optical blue filter. At higher frequency DMT subcarriers, which are loaded with lower-level formats, the constellation diagrams are more condensed. The constellation diagrams with and without optical blue filter are similar because the optical power attenuation owing to the optical blue filter at these subcarriers is small. Owing to the 3-dB blue filter insertion loss, the constellations at these high-frequency subcarriers are slightly worse than that without using the optical blue filer.

Figure 6 shows the measured BER-versus-distance curves for the four cases, which are respectively the BER performances of without and with using a blue filter under different bit loading schemes. From the results, in both BL_1 and BL_2 schemes, the signals without using a blue filter outperform the signals with a blue filter. When the blue filter is used in the system, the BL_2 outperforms BL_1 (the two blue curves). This comes from the high symbol format and low SNR at the low frequency subcarrier of BL_1 as shown in Fig. 4(b); hence according to our model, this results in a power drop. Moreover, for all cases, when the transmission distance increases, the received power decreases. For the system without the blue filter, the BER will satisfy the FEC requirement when the transmission distance is < 7 cm. If optical blue filter is used, the total power is reduced, and it support shorter transmission distance with lower data rate. At the transmission distance of 4 cm, the measured luminance is > 1000 Lux. The high luminance requirement in the proof-of-concept demonstration is due to the un-optimized focusing lenses used, and the very small active area PD used (0.8 mm^2). We believe by using

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a larger active area PD, the transmission distance can be enhanced with common luminance of 500 Lux.

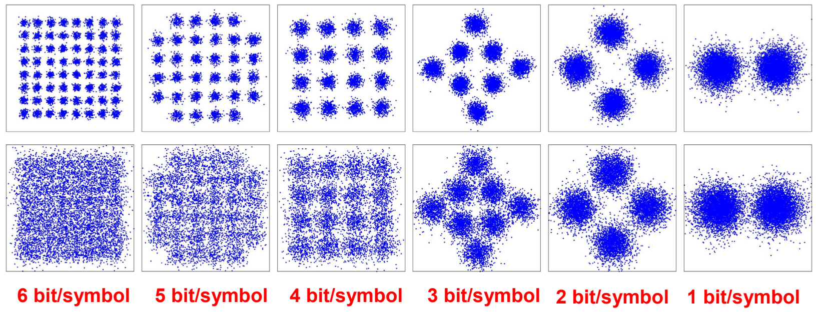

Fig. 5. Constellation diagrams of different bit-loading scheme. Upper rows: without using an optical blue filter. Bottom rows: using an optical blue filter.

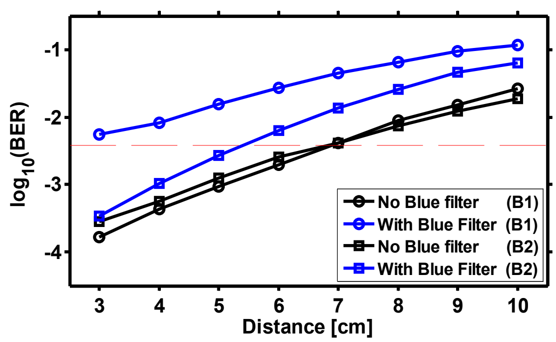

Fig. 6. BER performance against different transmission distances with and without using an optical blue filter.

4. Conclusion

Optical blue filter is usually regarded as a critical optical component for high speed phosphor-based white LED VLC. However, the optical blue filter plays different roles in VLC when using modulations of OOK or DMT. In this work, we analyzed for the first time whether a blue optical filter is necessary for the high-speed phosphor-based LED VLC. We modeled and illustrated by experiments showing that the optical blue filter did not enhance the white-light LED "practical" modulation bandwidth. The blue filter contributed for increasing the maximum data rate of the conventional OOK VLC system owing to signal equalization. However, for the DSP-based VLC system, the blue filter may be unnecessary, and even degrade the transmission performance.

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