Design and experiment of post-equalization for OOK-NRZ visible light communication system*

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Considering that the white LED's spectral response decreases exponentially with the increase of carrier frequency for the on-off-keying non-return-to-zero (OOK-NRZ) visible light communication (VLC) data links, a first-order RC high-pass filter is designed and fabricated as a post-equalizer (PE) to compensate the LED spectral response. Formulation and simulation are both available for illustrating the VLC performance with and without PE. Experiments are performed in detail for the fabricated OOK-NRZ VLC system integrated with PE. The data transmission results show that by using PE, the measured carrier bandwidth is enhanced from 0.8 (0.4−1.2) MHz to 1.7 (0−1.7) MHz, and the bit-error-rate (BER) is less than 10^{-9}. It proves the feasibility of the proposed scheme in OOK-NRZ VLC data links.

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Compared with other communication approaches, the visible light communication (VLC) technology based on white LED takes the advantages of high speed, no electromagnetic interference and environmental protection, and it shows potential prospects in hospital, indoor and outdoor short-distance communications, intelligent transportation and other areas[1-5]. Many researches have been carried out in the aspects of modulation, key technology, lighting layout, hardware and equipment, etc, and much progress has been made in such areas[6,7]. Based on the discrete multitone (DMT) modulation, a VLC system with high bit rate more than 500 Mbit/s has been reported[8]. Compared with orthogonal frequency division multiplexing (OFDM)[9], though the on-off-keying non-return-to-zero (OOK-NRZ) is restricted by the ability of multipath interference suppression, it is still one of the common ways used in VLC system due to its simple implementation and easy development[10]. With a single white LED, an OOK-NRZ VLC system has been numerically simulated and reported by our research group[11]. However, we have found from experiment that as the carrier frequency increases, the magnitude response of the white LED decreases exponentially, and the threshold voltage of the OOK-NRZ VLC system cannot function normally within a wide bandwidth. So in this paper, an approach, which can broaden the OOK-NRZ operation bandwidth, is presented by introducing a post-equalizer (PE), and related experiments are carried out to prove the proposal.

Although much improvement has been achieved on the aspects of power consumption, thermal design and luminous efficiency[12,13], the response bandwidth is narrow because of long response time of phosphor. The white LED with the power consumption of 3 W, which is shown in the inset of Fig.1, is modulated by using a sine-wave signal source (0−2 MHz). The LED response is measured with a PIN detector with nanosecond response time, as shown in Fig.1, where the measured signal has been amplified. We can observe that as the increase of f_c, its magnitude response decreases exponentially from 0 dB to -20 dB. Because the threshold voltage is usually set at a certain frequency f_0, when $f_c \gg f_0$, the high and low voltages cannot be judged correctly, which leads to a narrow operation bandwidth. The exponential fit equation of the LED response versus the carrier frequency f_c is decided by

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$$|H_{\mathrm{LED}}(f_{\mathrm{c}})|=1.948\times\exp(-1.1468 f_{\mathrm{c}}) \ . \tag{1}$$

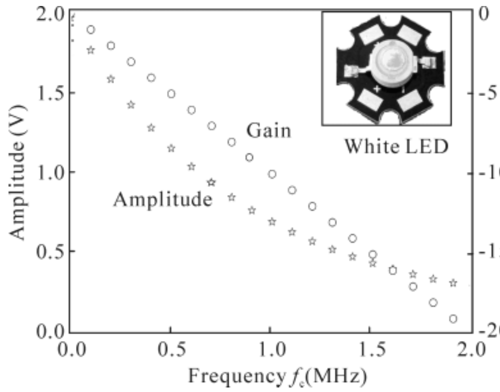

Fig.1 Experimental results of frequency response of the used white LED measured by a high-speed PIN detector

In our previous published work[11], the response (E-O-E transfer function) of the VLC channel is derived as

$$i=\int_{\lambda_{\min}}^{\lambda_{\max}}\int_{S\in A}\frac{1}{r^2}I_{\mathrm{o\,max}}T(\lambda)R(\lambda)\cos^m(\varphi_{\mathrm{d}s})\times$$
$$\cos(\theta_{\mathrm{d}S})g(\theta_{\mathrm{d}S})\,\mathrm{d}S\,\mathrm{d}\lambda \ , \tag{2}$$

where $R(\lambda)$ is the responsiveness of the detector at λ, I_{omax} is the maximum output intensity, $T(\lambda)$ is the normalized spectral response, m is the luminous order determined by $m=-\ln2/\ln[\cos(\varphi_{1/2})]$, and $\varphi_{1/2}$ is the half-value angle of white LED[14].

Taking the frequency response of the white LED into account, the amplified voltage signal to be processed by the demodulator is

$$u'(f_{\mathrm{c}},t)=(KR_{\mathrm{L}})'ps(t)\cos(2\pi f_{\mathrm{c}}t)\,|H_{\mathrm{LED}}(f_{\mathrm{c}})|\times$$
$$\int_{\lambda_{\min}}^{\lambda_{\max}}\int_A\frac{1}{r^2}I_{\mathrm{o\,max}}T(\lambda)R(\lambda)\cos^m(\varphi_{\mathrm{d}S})\cos(\theta_{\mathrm{d}S})\,\mathrm{d}S\,\mathrm{d}\lambda \ , \tag{3}$$

where K is the gain of the amplifier, R_{L} is the load resister, $s(t)$ is the binary baseband signal, and $\cos(2\pi f_{\mathrm{c}}t)$ is the carrier signal. Neglecting the multipath effect, the total output signal from the detector is

$$u(t)=u'(t)+n(t) \ , \tag{4}$$

where $n(t)$ is the induced white Gaussian noise. We define the signal-noise-ratio (SNR) as

$$SNR=10\lg\frac{P[u'(t)]}{P[n(t)]} \ . \tag{5}$$

To demodulate the signal, the threshold voltage is

$$V_{\mathrm{ref1}}=0.4\times\mathrm{Amp}[u'(f_c,t)]_{f_c=1\ \mathrm{MHz}} \ , \tag{6}$$

where Amp[•] represents getting the amplitude of [•].

Using the parameters listed in Tab.1, simulation is performed for the VLC system without PE as shown in Fig.2, where the threshold voltage is obtained from the voltage at 1 MHz. It can be seen that the effective bandwidth is only 1.3 MHz (0.3−1.6 MHz) around 1 MHz. It limits the applications of such VLC system.

Tab.1 Related parameters of the white LED and VLC detector in simulation and experiment

Parameter	Value
LED central emitting intensity I_{omax}	0.73 cd
LED half-value angle $\varphi_{1/2}$	70°
Sensing area diameter of the detector d	5 mm
Distance between source and detector	0.5 m
Detector responsiveness R	0.34 A/W
Amplifying gains $(KR_{\mathrm{L}})'$ / $(KR_{\mathrm{L}})''$	50 kÙ / 3 MÙ
Modulation parameter p	1.0
Signal-to-noise ratio (SNR)	10 dB
f_{c}:f_{b}^*	2

* f_{b} is binary data rate.

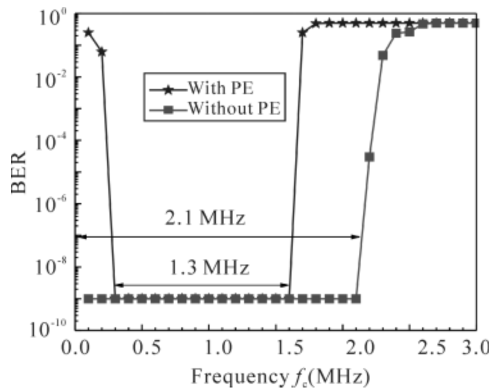

Fig.2 Simulated results of bit-error-rate (BER) versus the carrier frequency f_{c} with and without PE

In view of the low-pass filtering characteristic of white LED, a first-order high-pass RC filter is designed to compensate the LED response for obtaining a flat response within 0 and 2 MHz. The circuit is named PE, as included in Fig.3. Based on the lumped parameter circuit theory, the transfer function of the PE can be written as

$$H_{\mathrm{p}}(f_{\mathrm{c}})=l\frac{1+\mathrm{j}(2\pi f_{\mathrm{c}})\tau_{\mathrm{P}}}{1+\mathrm{j}(2\pi f_{\mathrm{c}})\tau_{\mathrm{P}}l} \ , \tag{7}$$

$l=R_{\mathrm{L}}/(R_{\mathrm{L}}+R_{\mathrm{p}})$, and $\tau_{\mathrm{p}}=R_{\mathrm{p}}C_{\mathrm{p}}$. The corresponding amplitude-frequency response is

$$\left|H_{\mathrm{p}}(f_{\mathrm{c}})\right|=l\frac{\sqrt{1+(2\pi f_{\mathrm{c}}\tau_{\mathrm{p}})^2}}{\sqrt{1+(2\pi f_{\mathrm{c}}\tau_{\mathrm{p}}l)^2}} \ . \tag{8}$$

To effectively compensate the LED frequency response, we have

$$20\log10[|H_{\mathrm{LED}}(f_{\mathrm{c}})|\times|H_{\mathrm{p}}(f_{\mathrm{c}})|]=const \ , \tag{9}$$

where the value of *const* should be properly selected for achieving a flat response, which is taken as −30 dB in the design.

After introducing the PE, the amplified voltage signal should be modified to be

$$u''(f_c,t)=(KR_L)''ps(t)\cos(2\pi f_c t)\,|H_{LED}(f_c)\|H_P(f_c)|\times \int_{\lambda_{min}}^{\lambda_{max}}\int_A \frac{1}{r^2} I_{o\max} T(\lambda)R(\lambda)\cos^m(\varphi_{dS})\cos(\theta_{dS})\,\mathrm{d}S\,\mathrm{d}\lambda \quad , (10)$$

and the threshold voltage is modified to

$$V_{ref\,2}=0.4\times \mathrm{Amp}[u''(f_c,t)]_{f_c=1\ \mathrm{MHz}} \ . \quad (11)$$

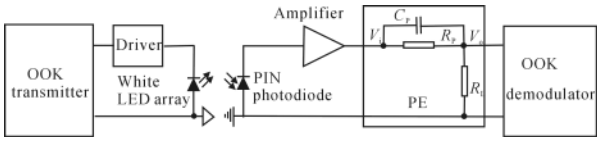

Fig.3 OOK-NRZ VLC system containing a PE for compensating the LED response

In order to use Eq. (9) for optimizing the parameters of the PE, by utilizing the nonlinear least mean square optimization algorithm, the parameters τ_p and l are optimized as τ_p= 0.5967×10^{-6} and l = 0.0311. The frequency response of the PE, the original response without PE, and the total response with PE are shown in Fig.4. We observe that compared with the original response without PE, the total response becomes extremely flat by use of PE, which is beneficial for expanding the operation bandwidth of the OOK-NRZ VLC system.

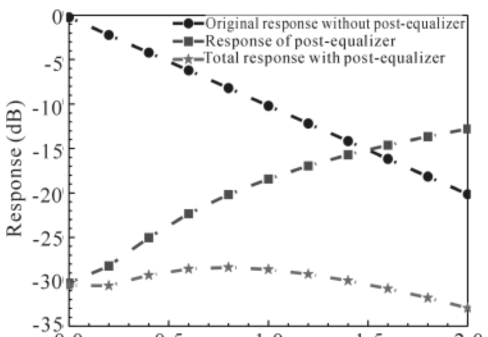

Fig.4 Freequency response of the designed PE,original response without PE, and the total response with PE

The simulation is also performed by using the optimized PE, for example the first-order high-pass filter, to compensate the LED frequency response, and the relation between the BER and carrier frequency f_c is also shown in Fig.2. When the threshold voltage is set less than 1 MHz, a rather low BER below 10^{-9} can be achieved within a wide frequency range of 0−2.1 MHz.

According to the optimized parameters, the PE is fabricated (R_P=39.78 kΩ, C_P=15 pF, R_L=1.28 kΩ), and it is integrated with our previously developed VLC system. The photos of the fabricated VLC transmitter, VLC receiver (integrated with PE) and LED direct-current (DC) driver are all shown in Fig.5. With the developed devices, the experimental setup is established, as shown in Fig.5. The LED DC driver provides DC driving voltage to the bias-tee circuit, which is especially used for LED illuminating. The fabricated VLC transmitter generates the OOK-NRZ signal, which is superposed on the white LED along with DC bias through the bias-tee circuit. The VLC receiver with a distance of 0.5 m from the VLC transmitter is utilized to demodulate the OOK-NRZ signal. The encoded transmitted signal by the VLC transmitter and the demodulated signal by the VLC receiver are both measured with an oscilloscope (Tektronix 3014C). A computer is used to deal the data which are received by the VLC receiver, and the BER is calculated through comparison with the original transmitted data.

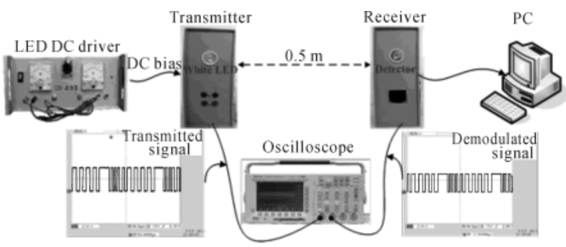

Fig.5 Photos of our fabricated VLC transmitter, VLC receiver (integrated with the fabricated PE) and LED DC driver, and the experimental setup for measurement (The white LED and detector are both integrated with a condenser.)

Fig.6(a) shows the measured frequency response of the fabricated PE, which is found to be in favorable agreement with the theoretical results. To prove the proposal, experiments are carried out by transmitting the same data for 10^9 times at a carrier frequency. After receiving the data from the transmitter, the receiver sends them again to the computer via universal asynchronous receiver/transmitter (UART) port. The data are verified, the numbers of wrong data and right data are counted, and the BER result is calculated at the end of data transmission. The experimental BER results versus the carrier frequency are shown in Fig.6(b). According to the measured results, due to the use of PE, the bandwidth is enhanced from 0.8 MHz to 1.7 MHz. Although the results are a little different from the simulation results shown in Fig. 2, because of the unpredictable noises and background light interferences, it can sufficiently prove that the proposal in this paper is useful in increasing the bit rate in OOK-NRZ

VLC systems.

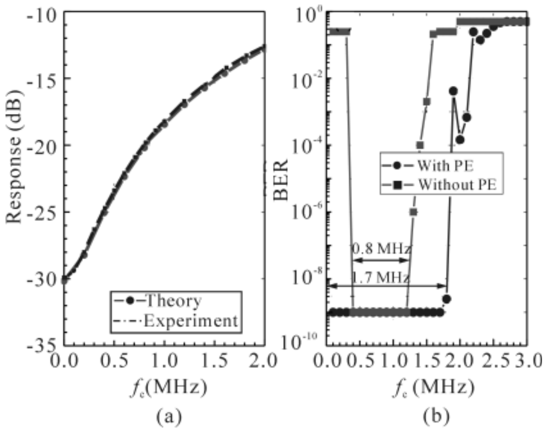

Fig.6(a) Measured and theoretical frequency responses of the fabricated PE; (b) Experimental BER results versus the carrier frequency

In summary, in this paper, the LED frequency response is firstly measured, and it decreases exponentially as the increase of the carrier frequency, which is a primary reason for the narrow operation bandwidth for the OOK-NRZ VLC system. So an RC high-pass filter as a PE is especially utilized for compensating the LED response. Furthermore, by using the nonlinear least mean square optimization algorithm, the parameters of the PE are optimized. The expressions of the signals to be demodulated are derived with and without PE, and the BER is simulated and analyzed under different threshold voltages with and without PE. Experiments using the fabricated VLC system integrated with PE show that owning to PE, the carrier bandwidth is enhanced from 0.8 MHz to 1.7 MHz, which verifies the feasibility of the proposed scheme in OOK-NRZ VLC data links.

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