We experimentally demonstrate a 750 Mb/s real-time visible light communication (VLC) system based on non-return-to-zero on–off keying modulation by employing single commercially available monochromatic light-emitting diodes. To enhance the 3-dB bandwidth of the VLC link, we propose a low-complexity cascaded post-equalizer based on NPN transistors. With two different frequency-selecting networks in our post-equalizer, the highest achieved 3-dB bandwidth of the VLC link is 370 MHz. The highest achieved data rate is 750 Mb/s at a communication distance of 170 cm with a bit error rate below $1 \times 10^{-6}$, which is far below the forward error correction limit ($3.8 \times 10^{-3}$). Based on our monochromatic VLC system, a wavelength-division multiplexing VLC system could be designed with a higher data rate.

Light-emitting diodes (LEDs) can be used for both illumination and communication simultaneously and are considered an ideal source for visible light communication (VLC)\cite{1,2}. With wavelength-division multiplexing (WDM) technology considered as an important, promising approach to immensely improve the data rates of VLC systems\cite{3-5}, using monochromatic LEDs to achieve multi-channel communication and white lighting has gradually attracted researchers’ attention\cite{6}.

Monochromatic LEDs have finite bandwidths. Figure 1 shows the frequency response of four commercially available monochromatic LEDs belonging to the color LED family of LUXEON Rebel. They could be a good choice for a light source in a WDM-VLC system, for they have superior power efficacy, color stability, flux density, and color saturation. However, all of the 3-dB bandwidths are <30 MHz. Various driving modulation technologies can be used to further increase the bandwidths and equalization technology is one effective ones and was first used by Minh \textit{et al}. in 2008. They proposed a pre-equalizer to increase the bandwidth of a VLC system to 45 MHz and achieved an 80 Mb/s data rate with non-return-to-zero on–off keying (NRZ-OOK) modulation\cite{7}. After that, various equalizers was proposed and improved, and they had a better performance\cite{8-12}. In 2013, a 151 MHz bandwidth and 340 Mb/s real-time data rate were achieved by using a post-equalization circuit that contained two passive equalizers and one active equalizer\cite{10}. In 2014, by utilizing pre-emphasis and post-equalization circuits, a 3-dB bandwidth of a VLC link was extended from 3 to 233 MHz with a blue filter and a 550 Mb/s real-time data rate was achieved\cite{12}. In 2015, with a cascaded pre-equalizer, the 3-dB bandwidth of a VLC system was improved from 17 to 366 MHz, which is the highest 3-dB bandwidth achieved so far\cite{13}. The highest real-time data rate of 622 Mb/s was reported based on a blue LED by adopting a pre-equalization circuit and
post-equalization circuit simultaneously with a 112 MHz 3-
dB bandwidth. However, its communication distance was
only 15 cm. In this Letter, we propose a low-complexity post-
equalizer based on NPN transistors to enhance the 3-dB
bandwidth of VLC systems and experimentally demon-
strate a 750 Mb/s real-time VLC system based on NRZ-
OOK modulation by employing a single commercially
available monochromatic LED. With two different
frequency-selecting networks in the low-complexity cascaded
post-equalizer, its same frequency-selecting networks limit
Though the cascaded pre-equalizer enhances the 3-dB
frequency response of the post-equalizer and compensate
equalizers proposed in recent years, used as pre-equalizers or
frequency range, for they usually have a high transition
power of signal but also have better performance at a high
Transistor-based equalizers not only can increase the
The two-stage amplifying structure with different fre-
energy-selecting networks can not only easily adjust the
employed four different monochromatic LEDs are en-
hanced effectively, and their 3-dB bandwidths are 370, 347,
272, and 238 MHz for red, green, blue, and yellow LEDs,
respectively. Using a bit error rate (BER) test, their
real-time data rates are 750, 690, 730, and 650 Mb/s, re-
spectively, at a communication distance of 170 cm with
a BER below $1 \times 10^{-6}$. In addition, the communication
distance is longer than the VLC system mentioned above, and
it is more relevant to the actual distance between the light
source and desktop in a room. To our knowledge, 370 MHz
and 750 Mb/s are the highest 3-dB bandwidth and the highest
real-time data rate, respectively, ever achieved by using a
post-equalizer and a monochromatic LED. Furthermore,
based on our VLC system, if several monochromatic
LEDs are used simultaneously in a white LED source, a
much higher data rate WDM-VLC system can be expected.
If other complex modulation technologies are used at the
same time, the data rate can be further improved.
Comparing the proposed equalizers, passive RC-based
equalizers will decrease the sensitivity of the receiver.
Amplifier-based equalizers can increase the power of sig-
nal, but the finite gain bandwidth product (GBP) of ampli-
fiers limits their performance at a high frequency range.
Transistor-based equalizers not only can increase the
power of signal but also have better performance at a high
frequency range, for they usually have a high transition
frequency. There have been several transistor-based equal-
izers proposed in recent years, used as pre-equalizers or
post-equalizers, such as the pre-equalizer in Ref. [12].
Though the cascaded pre-equalizer enhances the 3-dB
bandwidth of a VLC link from 3 to 233 MHz with a
post-equalizer, its same frequency-selecting networks limit
the 3-dB bandwidth from being further enhanced. To
achieve a higher 3-dB bandwidth, we proposed a two-
cascaded NPN transistors-based post-equalizer with two
different frequency-selecting networks, shown in Fig. 2.
The two-stage amplifying structure with different
frequency-selecting networks can not only easily adjust the
frequency response of the post-equalizer and compensate
for the two different high-frequency points of a VLC link
via setting the proper parameters, but it will also ensure
the phase of the signal output is the same as that of the
input signal. Between these two transistor amplifier cir-
cuits, a capacitor $C_2$ is used as a blocking capacitor; it
is large enough (such as 10 μF) to ensure it will have little
influence on the AC signals.

In the first-stage amplifier circuit, $R_4$, $R_5$, and $C_1$
constitute the first frequency-selecting network which can
initially adjust the frequency responses. The response
function of the first stage amplifier circuit can be expressed by

$$H(j\omega) = \frac{R_3}{R_4/(R_5 + 1/j\omega C_1)}$$

$$= \frac{R_3}{R_4} \left(1 + \frac{R_4}{R_5(1 + 1/j\omega R_5 C_1)}\right).$$

(1)

Therefore, the amplitude response function is

$$|H(j\omega)| = \frac{R_3}{R_4} \sqrt{1 + \omega^2 (R_4 + R_5)^2 C_1^2} \sqrt{1 + \omega^2 R_4^2 C_2^2},$$

(2)

When $\omega$ is zero, we know the DC gain is $R_4/R_1$, and when $\omega$
is large enough, the amplitude gain will converge at a certain constant $R_4/(R_5 + R_4)$ $R_5 R_4$.

According to Eq. (2), the 3-dB point above the DC gain
can be computed as

$$\omega_{3\text{-}dB} = \frac{1}{R_4 C_1 \sqrt{1 + 2(R_5/R_4) - (R_5/R_4)^2}}.$$  

(3)

From Eqs. (2) and (3), the magnitude response of the
first-stage amplifier circuit can be calculated.

In the second-stage amplifier circuit, there is a different
frequency-selecting network constituted by $R_6$ and $C_3$. It
is set to compensate for a higher frequency range of the
system. The response function of the second-stage ampli-
circuit could be expressed by

$$H(j\omega) = \frac{R_8}{R_6/(1/j\omega C_3)} = \frac{R_8}{R_6} (1 + j\omega R_6 C_3),$$

(4)

and the amplitude response function is

$$|H(j\omega)| = \frac{R_8}{R_6} \sqrt{1 + \omega^2 R_6^2 C_3^2}.$$  

(5)
Obviously, the DC gain is $\frac{j_0}{R_0}$ and the 3-dB point above the DC gain can be computed as

$$\omega_{3\text{-dB}} = \frac{1}{R_3 C_3}. \tag{6}$$

Equation (5) shows that the amplitude response of the second-stage amplifier circuit is approximately linear versus frequency $\omega$, which differs from that of the first stage, which converges at a certain constant. Therefore, at a certain high frequency range, the second-stage amplifier structure will have a better amplitude gain than the first-stage amplifier structure, which can compensate well for the weak response of the LEDs.

Thus, the total AC gain of the two-cascaded NPN transistors-based post-equalizer is

$$|H(j\omega)| = \frac{R_3}{R_4} \left(\frac{\sqrt{1 + \omega^2 (R_4 + R_5)^2 C_3^2}}{\sqrt{1 + \omega^2 R_3^2 C_1^2}}\right) \cdot \frac{R_8}{R_9} \sqrt{1 + \omega^2 R_7^2 C_5^2}. \tag{7}$$

In our proposed post-equalizer, the high-frequency triode BFR520 (transition frequency: 9 GHz) was used as the transistor. According to impedance matching principle, the input impedance and output impedance were both set at 50 $\Omega$. The value of $R_3$ was set much smaller than $R_4$ because in this case, it would have little influence on the first corner frequency on the basis of Eq. (3) and still have a significant effect on the amplitude response of the circuit according to Eq. (2). Therefore, the 3-dB frequency point of the first-stage amplifier circuit can be estimated according to Eq. (3). In order to obtain a high 3-dB frequency point, the value of $C_3$ can be set small, but it will cause the signal to be excessively restrained. Therefore, the value of $C_3$ was set to not only compensate for the low frequency range, but also to enhance the high frequency range. Meanwhile, it is necessary to set a proper static operating point of the high-frequency triode. The proper parameters for the post-equalizer are listed in Table 1. As these four LEDs have different frequency responses, the set parameters are also different.

The setup of the proposed monochromatic LED-based VLC system is shown in Fig. 3. As is shown in Fig. 3(a), at the transmitting terminal, the signal generated by a signal generator was firstly processed by a power amplifier (Mini-Circuits ZHL-6 A-S+, 500 MHz bandwidth). Then, the amplified signal was superimposed onto the LED bias current, supplied by a DC power, via a bias tee (Mini-Circuits ZFBT-4R2GW+, 4200 MHz bandwidth). The hybrid output of the bias tee was directly supplied to the monochromatic LED. A 18° full opening angle collimating lens was fixed in front of the LED at an appropriate distance to ensure the light transmits directionally. Meanwhile, at the receiving terminal, a designed receiving antenna was fixed in front of the detector, whose specifications are shown in Table 2. These two lenses constituted an optical system helping to ensure the high communication performance of the VLC system. The detector was an avalanche photodiode (APD) detector (Menlo System, FPD 310-FV), which had a 900 MHz transition frequency. Another power amplifier was used to amplify the light current outputted by the APD. Then, the signal was improved by a post-equalization process using the proposed post-equalizer. Finally, a signal analyzer followed to analyze the communication performance. Based on the block diagram, we set up the VLC experimental link, shown in Fig. 3(b), whose communication distance is up to 1.7 m.

Based on the VLC experimental link in Fig. 3(b), we firstly performed measurements for the frequency responses of the four monochromatic LEDs and tested

<table>
<thead>
<tr>
<th>LED</th>
<th>R-LED</th>
<th>G-LED</th>
<th>B-LED</th>
<th>Y-LED</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_1$, $R_6$</td>
<td>150 $\Omega$</td>
<td>150 $\Omega$</td>
<td>150 $\Omega$</td>
<td>150 $\Omega$</td>
</tr>
<tr>
<td>$R_2$, $R_7$</td>
<td>75 $\Omega$</td>
<td>75 $\Omega$</td>
<td>75 $\Omega$</td>
<td>75 $\Omega$</td>
</tr>
<tr>
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<td>100 $\Omega$</td>
<td>83 $\Omega$</td>
<td>83 $\Omega$</td>
<td>100 $\Omega$</td>
</tr>
<tr>
<td>$R_4$, $R_9$</td>
<td>100 $\Omega$</td>
<td>83 $\Omega$</td>
<td>83 $\Omega$</td>
<td>100 $\Omega$</td>
</tr>
<tr>
<td>$R_5$</td>
<td>10 $\Omega$</td>
<td>11 $\Omega$</td>
<td>7 $\Omega$</td>
<td>11 $\Omega$</td>
</tr>
<tr>
<td>$C_1$</td>
<td>5 pF</td>
<td>12 pF</td>
<td>15 pF</td>
<td>9 pF</td>
</tr>
<tr>
<td>$C_2$</td>
<td>100 pF</td>
<td>100 pF</td>
<td>100 pF</td>
<td>100 pF</td>
</tr>
<tr>
<td>VCC</td>
<td>7.8 V</td>
<td>7.8 V</td>
<td>7.8 V</td>
<td>7.8 V</td>
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</tbody>
</table>
the performances of the proposed post-equalizers. In the measurements, an arbitrary waveform generator (Agilent N9310A) was used as a signal generator, and an MXA signal analyzer (Agilent N9020A) was used as the signal analyzer. The frequency responses of post-equalizers and LEDs with and without post-equalizers are shown in Fig. 4.

The frequency response curves of the post-equalizer in Fig. 4 indicate that our proposed post-equalizer has an excellent ability to restrain the low frequency response and enhance the high frequency response, which can compensate for the frequency response of each monochromatic LED at a large frequency range. However, because of the high suppression characteristic at low frequency ranges, our post-equalizer cannot be cascaded. Otherwise, the signal-to-noise ratio at a low frequency range would be too low to have a good communication performance. To ensure the preciseness and accuracy of the experiments, the 3-dB bandwidth is correctly defined as the 3-dB frequency point, where the power of the spectral response reduces by 3 dB compared with the maximum frequency response value. Therefore, the 3-dB points of monochromatic LED-based VLC links with and without post-equalizers can be read directly from Fig. 4. Just as shown in Fig. 4, all frequency response curves of monochromatic LED-based VLC links without post-equalizers drop in frequency rapidly at a low frequency range, and all of their 3-dB points are <30 MHz. In comparison, all of the 3-dB point of VLC link with post-equalizer are >233 MHz. With the proposed post-equalizers, the 3-dB bandwidth of the R-LED is extended from 14 to 370 MHz, that of the G-LED is extended from 26 to 347 MHz, that of the B-LED is extended from 20 to 272 MHz, and that of the Y-LED is extended from 22 to 238 MHz.

A BER measurement as a function of the data rate to evaluate the communication performance of the monochromatic LED-based VLC systems followed. Based on the VLC experimental link in Fig. 3(b), we used a signal analyzer (Tektronix BITALYZER1600) as both a signal generator and a signal analyzer. The BITALYZER1600 generated a pseudo-random binary sequence-7 \((2^7-1)\) OOK-NRZ data stream with a peak-to-peak voltage swing of 400 mV, whose data rate ranged from 1 to 800 Mb/s.

The measured BER experiment results of the four monochromatic LEDs are shown in Fig. 5. From Fig. 5, we know the VLC system we set up performed well at a data rate below 550 Mb/s, where the BER is no more than \(10^{-10}\). With a BER below \(1 \times 10^{-6}\), the achieved highest data rates of these LED-based VLC links can be as high as 750 Mb/s, which is the highest data rate in a VLC system using a monochromatic LED based on NRZ-OOK modulation at a communication distance of 170 cm. Both the data rate and communication distance are better than the best reported data. For the R-LED, the BER is \(6.64 \times 10^{-8}\) at a data rate of 750 Mb/s; for the G-LED, the BER is \(8.97 \times 10^{-7}\) at a data rate of 690 Mb/s. For the B-LED, the BER is \(5.81 \times 10^{-7}\) at a data rate of 730 Mb/s, and for the Y-LED, the BER is \(6.59 \times 10^{-7}\) at a data rate of 650 Mb/s. Their eye diagrams are also shown in Fig. 6. From the measured results, we know that the B-LED-based VLC link with a lower 3-dB bandwidth of 272 MHz still has a higher data rate of

<table>
<thead>
<tr>
<th>Table 2. Specifications of Receiving Antenna</th>
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<tbody>
<tr>
<td>System length/mm</td>
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<tr>
<td>System diameter/mm</td>
</tr>
<tr>
<td>Focal length of first lens/mm</td>
</tr>
<tr>
<td>Focal length of second lens/mm</td>
</tr>
<tr>
<td>Field of view/deg.</td>
</tr>
<tr>
<td>Relative illumination</td>
</tr>
<tr>
<td>Optical gain</td>
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<tr>
<td>Wavelength range/μm</td>
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</table>

Fig. 4. Frequency responses of post-equalizers and monochromatic LED-based VLC link with and without post-equalizers: (a) R-LED, (b) G-LED, (c) B-LED, and (d) Y-LED.

Fig. 5. BER versus data rate of monochromatic LED-based VLC links with post-equalizer.

![Image](image_url)
730 Mb/s when its BER is below $1 \times 10^{-6}$. In generally, the data rate achieved is not only related to the 3-dB bandwidth of the VLC link but also has a relationship with the signal amplitude of the receiver. The received signal amplitude is also influenced by several factors, such as the spectrum characteristic of the optical antennas, the spectrum response of the APD, and the performance of the post-equalizers. More studies are needed to elucidate how these factors have an effect on data rates. Based on our monochromatic LED-based VLC systems, if several monochromatic LEDs of appropriate colors are used simultaneously as a white lighting source and a communication system, a WDM-VLC system can be designed and a higher data rate will be expected. If additional complex modulation technologies, such as OFDM and MIMO, are used simultaneously, the data rate can be improved further.

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References