10m/500Mbps WDM visible light communication systems

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Abstract: A wavelength-division-multiplexing (WDM) visible light communiction (VLC) system employing red and green laser pointer lasers (LPLs) with directly modulating data signals is proposed and experimentally demonstrated. With the assistance of preamplifier and adaptive filter at the receiving sites, low bit error rate (BER) at 10m/500Mbps operation is obtained for each wavelength. The use of preamplifier and adaptive filter offer significant improvements for free-space transmission performance. Improved performance of BER of $<10^{-9}$, as well as better and clear eye diagram were achieved in our proposed WDM VLC systems. LPL features create a new category of good performance with high-speed data rate, long transmission length (>5m), as well as easy handling and installation. This proposed WDM VLC system reveals a prominent one to present its advancement in simplicity and convenience to be installed.

OCIS codes: (060.2605) Free-space optical communication; (060.4510) Optical communications; (140.7300) Visible lasers.

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1. Introduction

Visible light communication (VLC) systems are presently being developed by researchers seeking to create high-speed, high security, and friendly communication networks using large

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bandwidth visible light instead of radio-frequency (RF) and microwave signals. It has many attractive features, such as worldwide available and unlicensed bandwidth, non-interference with radio bands, and the potential of spatial reuse of operating frequencies in adjacent communication cells. Moreover, VLC systems can provide many benefits, like: providing communication link in specific areas in which RF communication is prohibited, such as in a hospital or in an aircraft; providing a secure link channel since the light beam is visible and directional [1–6]. VLC systems use modulated light wavelengths emitted and received by a variety of suitably adapted standard sources, such as indoor and outdoor lighting, display, illuminated sign, television, computer screen, digital camera and digital camera on mobile phone for communication purposes, primarily through the use of light emitting diode (LED). With the rapid progress of VLC systems, the increasing requirements raise the needs for high-speed transmission rate. LED VLC systems are recognized as creating a possible valuable addition to future generations of technology, which have the potential to use light for the purposes of advanced technical communication at high-speed surpassing that of current wireless communication systems. In the previous studies, high-brightness LED (HB-LED) is employed not only as the lighting devices but also as the light sources for LED VLC systems [7, 8]. However, the performances of the LED VLC systems can be further improved by using laser pointer laser (LPL) as the light source. The dual functions of HB-LED, for lighting and communication, emerges many new and interesting applications. Nevertheless, HB-LED array and convex lens are required for longer free-space link [9, 10]. As the light source is deployed toward VLC systems, installation simplicity and convenience are beyond disputed issues needed to be solved. To overcome the limitations, in this paper LPL is applied in the VLC systems. A LPL is a small portable device with a power source (usually a battery) and a laser emitting a very narrow coherent beam of visible light, intended to be used to highlight something of interest by illuminating it with a small bright spot of colored light. LPL, with high optical power and light beam convergence characteristics, is expected to have good performances in VLC systems. To be the first one of employing LPLs (red and green lasers) as the light sources in VLC systems, the transmitting light signals are successfully directly modulated with data signals for free-space transmission. With the help of preamplifier and adaptive filter at the receiving sites, low bit error rate (BER) of $<10^{-9}$ at 10m/500Mbps operation is achieved for each wavelength. LPL features create a new category of good performance with high-speed data rate, long transmission length (>5m), as well as easy handling and installation. This proposed wavelength-division-multiplexing (WDM) VLC system is shown to be a distinguished one not only presents its simplicity in VLC applications but also reveals its convenience to be installed.

2. Experimental setup

The experimental configuration of our proposed WDM VLC systems employing red and green LPLs with directly modulating data signals over a 10-m free-space link is shown in the Fig. 1. The LPLs, with wavelength/color/power of 671nm/red/5mW and 532nm/green/5mW, were directly modulated by a 500 Mbps pseudorandom binary sequence (PRBS) of 2^{10}-1 generated by a Tektronix arbitrary waveform generator (AWG) with a 1 × 2 splitter. The modulated red and green lights were transmitted over a distance of 10 m, and then reached to the PIN-photodiodes (PIN-PDs). The PIN-PD has the detection wavelength range of 350-1100 nm, with a responsivity of 0.65 mA/mW. The received signals were then amplified by the preamplifiers with low noise figure of around 4.5 dB, and passed through the adaptive filters for errors corrections. The performance and accuracy of the adaptive filter depends on the data length. In this experiment, we use 2^{10}-1 PRBS length (not 2^{15}-1 or 2^{23}-1); for the same number of filter taps, lower data length results in better performance and accuracy. The two 500 Mbps data signals were multiplexed together by a 2 × 1 multiplexer. Finally, the data signals were fed into a BER tester (BERT) for BER analysis and an oscilloscope for eye diagram evaluation.

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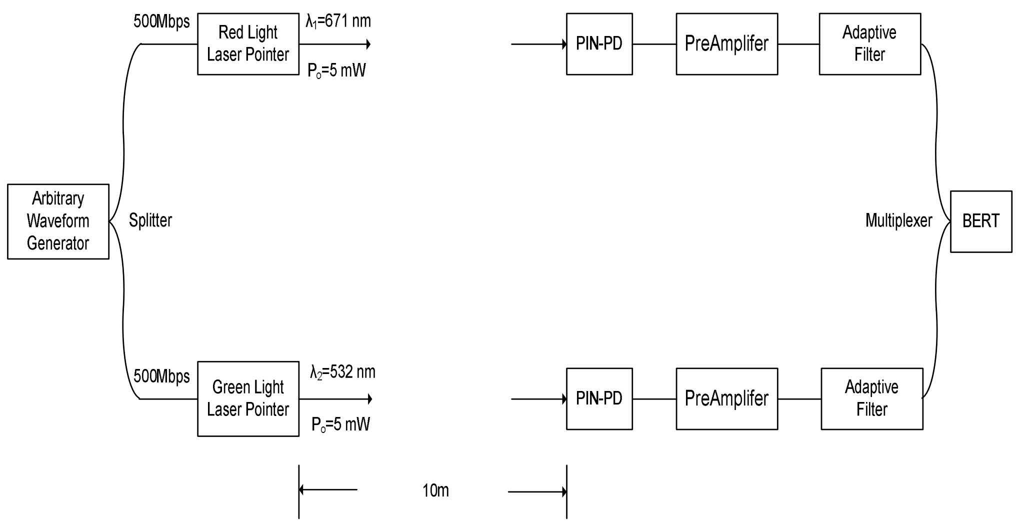

Fig. 1. Experimental configuration of our proposed WDM VLC systems employing red and green LPLs with directly modulating data signals over a 10-m free space link.

3. Experimental results and discussions

A schematic diagram of the preamplifier, in which a push-pull amplifier with bandwidth of 600 MHz, is illustrated in the Fig. 2. Since the even-order harmonic distortions of systems can be eliminated dramatically by the push-pull amplifier, the preamplifier output can be given by

$$v_o = a_1 \cdot v_i + a_3 \cdot v_i^3 + a_5 \cdot v_i^5 \tag{1}$$

where v_o is the preamplifier output voltage, v_i is the preamplifier input voltage, and a_1, a_3, a_5 are the amplitude coefficients (a_3 and a_5 are coefficients characterize nonlinearities). A VLC system with high order nonlinear distortions is expressed as

$$q = b_1 \cdot m + b_3 \cdot m^3 + b_5 \cdot m^5 \tag{2}$$

where q is system's output voltage detected from PIN-PD, m is system's input voltage, and b_1, b_3, b_5 are the amplitude coefficients (b_3 and b_5 are coefficients characterize nonlinearities). It is clear that q is equal to v_i, substituting Eq. (2) into Eq. (1) and neglecting higher order nonlinear terms, then yields

$$v_o = (a_1 \cdot b_1) \cdot m + (a_1 \cdot b_3 + a_3 \cdot b_1^3) \cdot m^3 + (a_1 \cdot b_5 + a_5 \cdot b_1^5) \cdot m^5 \tag{3}$$

While achieving linearity means cancelling out the nonlinear terms, an amplifier would have to cancel out the third-order nonlinear term. Setting the appropriate nonlinear coefficient to eliminate the third-order nonlinear term:

$$a_1 \cdot b_3 = -a_3 \cdot b_1^3 \tag{4}$$

Then Eq. (3) can be changed as

$$v_o = (a_1 \cdot b_1) \cdot m + (a_1 \cdot b_5 + a_5 \cdot b_1^5) \cdot m^5 \tag{5}$$

It is obvious that, from Eq. (5), third-order nonlinear distortion can be eliminated by proper adjusting the nonlinear coefficient. Furthermore, the amplitude of harmonic distortion decreases with the increasing of the harmonic. Thus, the 5th harmonic distortion has a very small amplitude, so it will not induce any distortion in the VLC systems.

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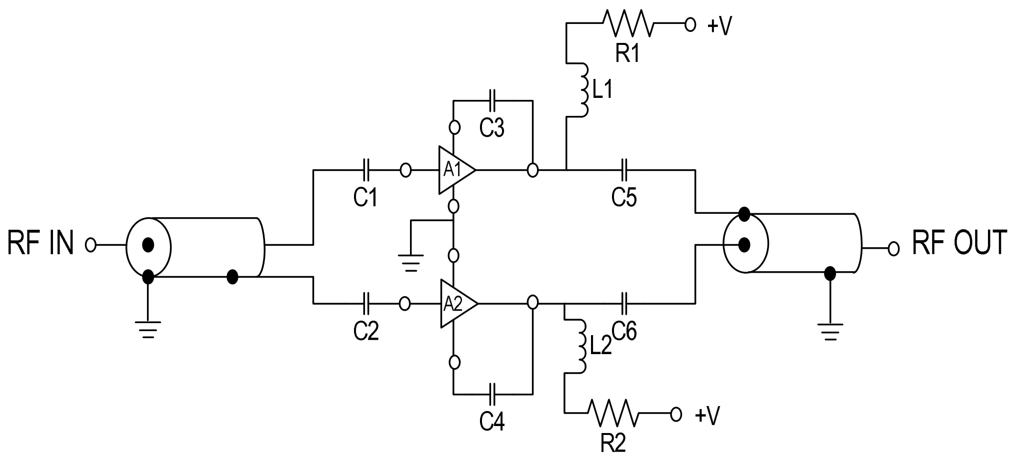

Fig. 2. A schematic diagram of the preamplifier (push-pull amplifier).

A functional block of the adaptive filter is illustrated in the Fig. 3, in which including an amplitude/phase comparator. In implementing the adaptive filter, first the transmitter send a data pattern with an arbitrary data length as a protocol; and at the receiving site, the adaptive filter has a stored copy of data signal in the adaptive filter before starting communication. The output of the adaptive filter scheme with amplitude and phase without any nonlinear distortion is transmitted. Let $d(n)$ has an amplitude $a(n)$ and phase $\theta(n)$:

$$d(n) = a(n)e^{j\theta(n)} \tag{6}$$

After transmission through free-space links, the received signal $d_{er}(n)$ has a distorted amplitude $a_{er}(n)$ and phase error $\theta_{er}(n)$:

$$d_{er}(n) = a_{er}(n)e^{j\theta_{er}(n)} \tag{7}$$

The power of a transmitted symbol is $P(n)$, and a received symbol is $P_r(n)$:

$$P(n) = a^2(n)/2 \tag{8}$$

$$P_r(n) = a_r^2(n)/2 \tag{9}$$

The adaptive filter has to estimate $d(n)$ from $d_{er}(n)$ by error feedback. For amplitude compensation, the output of the amplitude compensator is compared with a stored copy of $a(n)$ to create an amplitude error. For phase compensation, the output of the phase compensator is compared with a stored copy of $\theta(n)$ to create a phase error. An adaptive algorithm updates amplitude and phase errors every time so that the errors are minimized. Amplitude and phase errors compensation are crucial for ensuring maximum nonlinear distortion suppression, the use of adaptive filter offers significant amplitude and phase errors compensation.

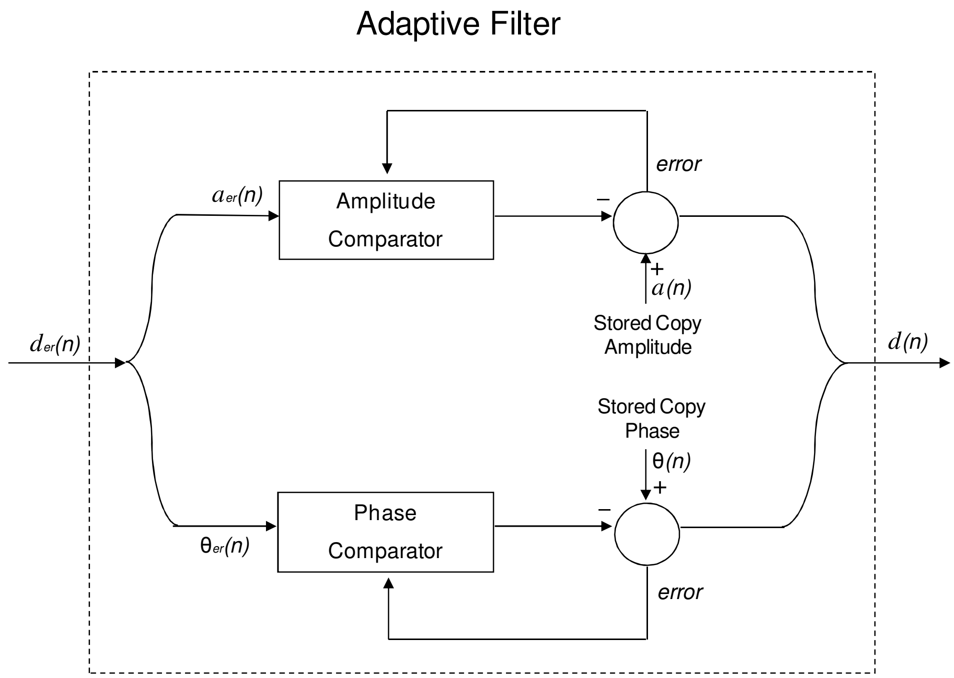

Fig. 3. A functional block of the adaptive filter, in which including an amplitude/phase comparator.

The measured BER curves of red light LPL channel as a function of the free-space transmission distance are plotted in the Fig. 4. At a free-space transmission distance of 10 m; without employing the preamplifier and the adaptive filter, the BER is around 10^{-5}; with employing the preamplifier and the adaptive filter, the BER is reached to 10^{-9}. It is clear that as the preamplifier and the adaptive filter are employed simultaneously, large BER performance improvement (10^4 order) can be achieved. In order to know how much BER performance improvement is based on each scheme, VLC systems employing the preamplifier alone have been used to evaluate the BER performance. At a free-space transmission distance of 10 m, the measured BER is about 10^{-7}. And VLC systems employing the adaptive filter alone have been used to measure the BER value. At a free-space transmission distance of 10 m, the measured BER is also about 10^{-7}. It means that the VLC systems employing the preamplifier alone or the adaptive filter alone to improve the BER performance, the BER performance improvement is limited. The results indicate that the preamplifier and the adaptive filter play important roles for error correction functions, and they can further improve systems' signal-to-noise ratio and BER performance.

Figures 5(a) and 5(b) display the eye diagrams of red light LPL channel under 10 m free-space link for the conditions of without employing the preamplifier and the adaptive filter (Fig. 5(a)) and with employing the preamplifier and the adaptive filter (Fig. 5(b)), respectively. The amplitude and phase fluctuations in the signal are obviously observed in the without employing the preamplifier and the adaptive filter case (Fig. 5(a)). The signal distortion will give an increase in power penalty. For the case of employing the preamplifier and the adaptive filter (Fig. 5(b)), however, a better and clear eye diagram is achieved due to amplitude and phase fluctuations suppression.

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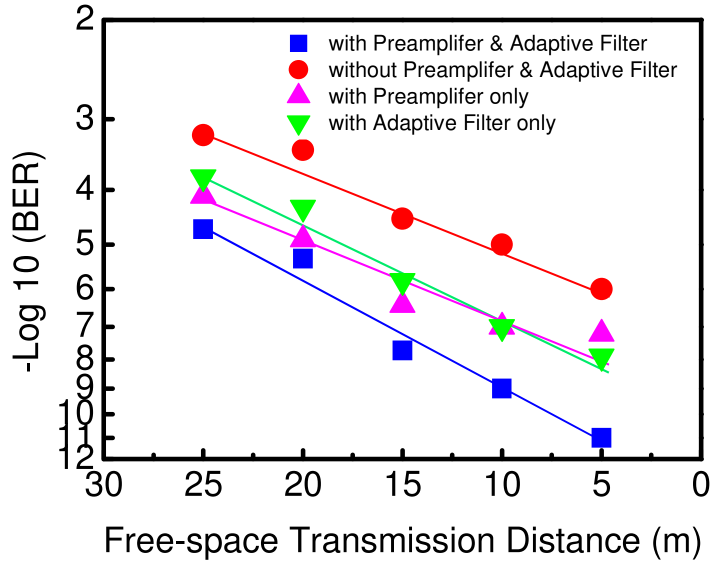

Fig. 4. The measured BER curves of red light LPL channel as a function of the free-space transmission distance.

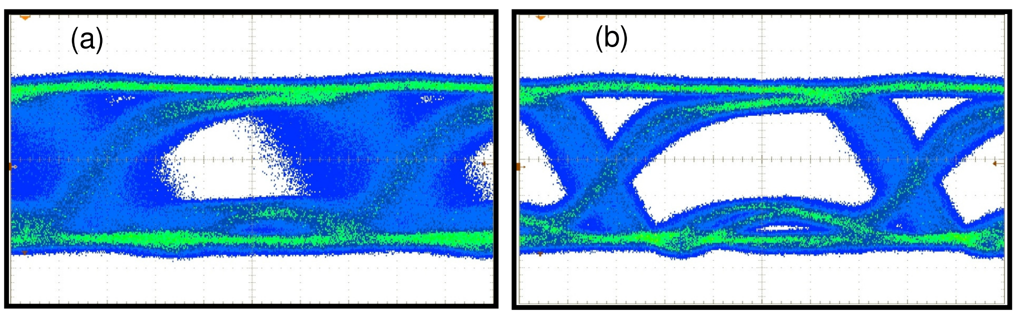

Fig. 5. The eye diagrams of red light LPL channel under 10 m free-space link: (a) without employing the preamplifier and the adaptive filter, (b) with employing the preamplifier and the adaptive filter.

4. Conclusions

We proposed and demonstrated a WDM VLC system using red and green LPLs with directly modulating data signals. With the help of preamplifier and adaptive filter t the receiving sites, low BER of $<10^{-9}$ at 10m/500Mbps operation is obtained for each wavelength. The use of preamplifier and adaptive filter offer significant improvements for free-space transmission performance. Improved performance of BER of $<10^{-9}$, as well as better and clear eye diagram were achieved in our proposed WDM VLC systems. Employing LPLs in VLC systems is a promising option, an attractive feature that could accelerate the VLC deployment. This proposed that such a WDM VLC system has been successfully demonstrated, which can inter-operate with free-space lightwave transport applications.

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