Bandwidth Extension of an Enhanced SNR with a higher Light Uniformity of a Phosphorescent White LED Based Visible Light Communication System

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***Abstract*—This paper increases the bandwidth of a phosphorescent white light emitting diode (LED) employed in an indoor visible light communication (VLC) system. A new distribution pattern for the same number of used LEDs increased the signal to noise ratio (SNR) and enhanced the uniformity of the illumination. The indoor VLC system is modelled using the proposed pattern and the theoretical analysis is presented. Compared to other studied patterns, the average power received was increased from 1.62 dB_m to 3.17 dB_m, simulations using MATLAB show the improvement in the power received distribution within the room. The maximum bit error rate (BER) at a data rate of 30 Mb/s was also reduced from 3.26×10^{-25} to 1.59×10^{-25}. A proposed design to the equalization circuit at the transmitter end was also presented that was able to extend the VLC link bandwidth from a few Megahertz (MHz) to 325 MHz.**

Keywords—bandwidth; equalization; phosphorescent white light emitting diode (LED); visible light communications (VLC)

I. INTRODUCTION

Solid-state lighting is currently revolutionizing indoor illumination. Incandescent and fluorescent lamps are now being replaced by Light Emitting Diodes (LEDs) due to numerous reasons. Compared to other luminaries, LEDs are more efficient, have longer life spans, improved color rendering, and lower heat generation. On the other hand, LEDs unparalleled benefit is their ability to switch to different light intensities at a rate undetectable by the human eye (i.e. can be modulated at high speeds) [1]. This functionality allowed the evolution of a communication technology known as Visible Light Communication (VLC), where LED luminaries are used for high speed data transfer.

There are two types of visible LEDs; single colored LEDs such as red, green, blue, yellow,…etc., and white colored LEDs [1]. Considering an indoor environment that uses LEDs for illumination, white LEDs are used. Currently, white light using LEDs is generated using two main technologies; either by combining red, green, and blue light emitters or, by using a blue emitter coated with a phosphor layer that emits yellow light, this mixture produces white light [2]. Due to their lower complexity and cost, phosphorescent white LEDs are often favored for general illumination [2] and for that reason, this paper uses such technology. However, since the modulation bandwidth of these phosphor based emitters is very limited, high data rate transmission is becoming a challenge for VLC [2]. Several research groups tried to overcome this problem by developing different techniques, such as: pre-equalization at the LED driving module at the transmitter end, blue filtering, post equalization at the receiver end or by even combining the previous three techniques, in addition to that, it can be solved by using complex modulation schemes [1].

In this paper, we propose an analog pre-emphasis circuit that is able to extend the 3-dB bandwidth of the VLC link to 325MHz with the aid of blue filtering, which is, to the best of the authors' knowledge, the widest bandwidth reported in literature. This design is implemented in an indoor VLC system model lit by phosphorescent white LEDs. To achieve a wide modulation bandwidth using equalization circuit, the system requires high power signal to noise ratio (SNR) [3]. For that reason, this paper modifies the VLC indoor lighting configuration model presented in [4-7]. The proposed model maintains the same number of LEDs with a different distribution pattern and viewing angles. The power received and the uniformity of illumination of the proposed model are simulated.

The remainder of the paper is organized as follows. In Section II, the VLC communication system using white phosphorescent LEDs is described, the simulations of the channel model using the software MATLAB is presented. Then, in Section III, the equalization to this link is shown using the simulations. Finally, we conclude the paper in Section IV.

II. INDOOR VLC MODEL

We have developed an indoor VLC simulation model represented by a ($5x5x3$ m^3) room as in [4-7]. In order to provide uniform illumination within the room, arrays of low intensity white LEDs are distributed along the ceiling area. Due to technological limitations, a single LED cannot provide the sufficient illumination for an indoor environment [8]. On the other hand, an extremely high-brightness LED luminary can compromise eye safety. Accordingly, having a large number of spatially distributed LEDs is an inevitable solution. The model presented in [4-7] illuminated the room using four 2-D

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rectangular arrays of LEDs. However, the illuminance requirement for a typical office environment is between 200 and 1000 lx [3]. This luminance constraint was met in [6,7] where each array contains 60 x 60 LEDs (i.e. total number of LEDs within the room is 14400). In this study, we have proposed a new distribution pattern of 30 x 30 LEDs per array maintaining the same total number of LEDs within the room (i.e. sixteen equal arrays). This proposed indoor VLC system model is illustrated in Fig. 1.

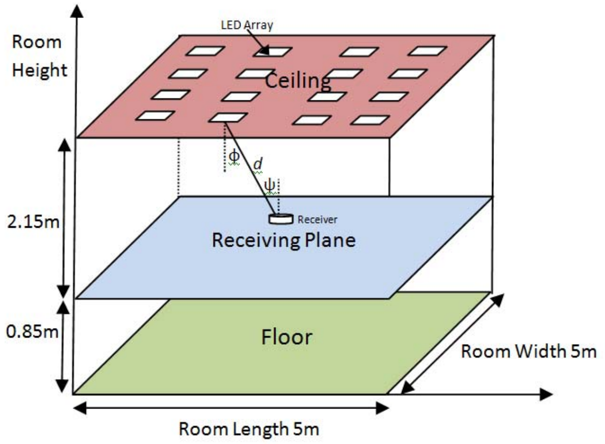

Fig. 1. Indoor VLC System Model

The used phosphorescent white LEDs are assumed to have Lambertian radiation pattern [3]. The radiation intensity at the receiving plane is given by

$$I(\emptyset) = I(0)cos^{m_l}(\emptyset) \qquad (1)$$

where $\emptyset$ is the angle of irradiance with respect to the axis normal to the transmitter surface (as shown in Fig. 1). *I(0)* is the centre luminous intensity and m_l is the order of Lambertian emission which is defined by

$$m_l = \frac{ln\,(2)}{ln\left(cos\,\emptyset_{1/2}\right)} \qquad (2)$$

where $\emptyset_{1/2}$ is the semi-angle at half illuminance of the LED.

The received power P_r is given by

$$P_r = P_t\frac{(m_l+1)}{2\pi d^2}cos^{m_l}(\emptyset).T_s(\varphi).g(\varphi).\cos(\varphi) \qquad (3)$$

where P_t is the transmitted power, φ is the angle of incidence with respect to the axis normal to the receiver surface (see Fig. 1), given that $0 \le \varphi \le \varphi_{con}$ where φ_{con} is the receiver Field-of-view (FOV). $T_s(\varphi)$ is the filter transmission, $g(\varphi)$ is the concentrator gain, and d is the distance between the LED and the detector surface. The receiver is assumed to be placed on a horizontal plane 0.85 m above the floor level, which is the average height of a desk [11] making $\emptyset = \varphi$. However, equation (3) calculates the power received only from a direct path, and not those reflected from other surfaces. For more accuracy, this paper also evaluates the power received due to the first reflection from walls.

Our proposed model aims to achieve a higher received average power and SNR across the room compared to the model used in [6, 7] in order to overcome the attenuation caused by the equalization process. To do so, this section first studies the four 60 x 60 arrays of LEDs scenario. The semi-angle at half luminance, $\emptyset_{1/2}$ is the angle from the axis normal to the LED by which the luminous intensity drops to 50% [9]. This angle is also known as half-intensity beam angle or the viewing angle. The half-intensity beam angle value is about 10-12^0 with no diffusant, which is controlled by the reflector cup that surrounds the LED chip. However, at maximum diffusant, this value reaches up to 70^0 which is the case described in many scenarios. All the system parameters used for simulating the VLC link are given in Table I.

TABLE I. SYSTEM PARAMETERS FOR THE VLC LINK

	Parameters	***Values***
Room	Size	5 x 5 x 3 m^3
	Walls Reflection Coefficient	0.8
Source	Number of LED arrays	16
	Transmitted power per LED	20 mW
	Number of LEDs per array	30 x 30 = 900
Receiver	Receiver plane above the floor	0.85 m
	Active area	1 cm^2
	Half – angle FOV	70°
	Lens refractive index	1.5

The power distribution among the room from both LED patterns are simulated and illustrated in Fig. 2. The figure compares the received power from the four 60 x 60 arrays model in 2(a) to our proposed sixteen 30 x 30 arrays in 2(b) with half-angle FOV of 70^0. The received power varied between -1.51 and 2.57 dB$_m$ with an average value of 1.62 dB$_m$ in the four array model. These powers were -1.30 and 2.53 dB$_m$ with an average value of 1.48 dB$_m$ for the proposed model. From these results, the four arrays model showed better (i.e. higher) received powers using the 70^0 FOV angle.

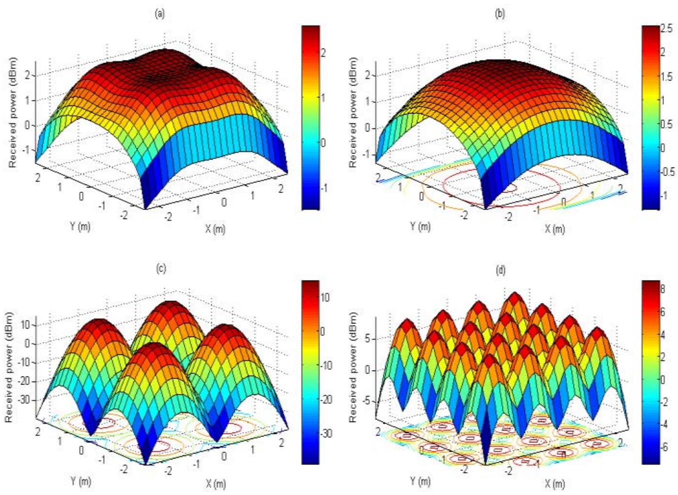

Fig. 2. Received power from (a) Case of 4 Tx and $\emptyset_{1/2} = 70°$ (b) Case of 16 Tx and $\emptyset_{1/2} = 70°$ (c) Case of 4 Tx and $\emptyset_{1/2} = 10°$ (d) Case of 16 Tx and $\emptyset_{1/2} = 10°$

The main aim in this study is building a VLC system that provides higher signal powers. For that reason, we have carried out a new investigation using LEDs with a smaller half-intensity beam angle of 10^0. Employing these LEDs with such viewing angle resulted in a huge increase in the received powers for both compared models in Fig. 2. Even though the four arrays model shown in Fig. 2(c) reached a maximum power of 14.64 dB_m, yet, the minimum power was -39.17 dB_m resulting in an average power of just -7.34 dB_m (which is inadequate for a practical VLC system). Alternatively, the proposed model was able to achieve a significant average power of 3.17 dB_m, with maximum and minimum powers of 8.65 and -7.54 dB_m, respectively as shown in Fig. 2(d).

The illuminance distribution across the room is another factor that is directly affected by decreasing the viewing angle to 10^0 according to (1). The maximum obtained illuminance of 146.54 lux was still below the minimum required level for a typical office environment (see section II). The minimum and average levels were 3.37 and 53.43 lux, respectively. For that reason, we have increased the viewing angle to 30^0 as a tradeoff between increasing the received power and meeting the illuminance requirements. Simulated results showed that employing the 30^0 angle radically improved the luminance level to meet the illumination requirements. The average level was 325.6 lux which fluctuates from 115.54 to 439.77 lux. The illuminance distribution across the room for both the four arrays and the proposed model are depicted in Figs 3(a) and 3(b) respectively. Although the four arrays model achieved higher luminance, the proposed model offered more uniform distribution which is clear from Fig. 3. The four arrays model illuminance ranged between 81.47 and 628.84 lux with an average level of 356.03 lux. On the other hand, even though the maximum received power is lower than using the 10^0 angle (as expected), the results show an improved average power of 3.17 dB_m. The power varied between -0.97 and 4.49 dB_m and hence, the more power uniformity results in reduced SNR fluctuations to the VLC system. Not only did our model provide higher spatial diversity, by being more evenly distributed across the room hence avoid blocking, it also allowed the use of LEDs with smaller viewing angles, providing a higher average received power across the room, yet maintaining the same total number of LEDs and their driving currents.

The performance of the proposed model is further investigated by evaluating the bit error rate (BER), utilizing on-off keying scheme. The BER and SNR are given by [3]:

$$BER = Q(\sqrt{SNR}) \tag{4}$$

and

$$SNR = \frac{(RP_{rx})^2}{\sigma_T^2} \tag{5}$$

respectively, where R is the photodiode responsivity and P_{rx} is the received optical power. The total noise variance σ_T^2 is given by the analysis presented in [10] as

$$\sigma_T^2 = 2qRP_{b,i}I_2B + \frac{8\pi kT}{G}\varepsilon AI_2B^2 + \frac{16\pi^2 kT\beth}{g_m}\varepsilon^2A^2I_3B^3 \tag{6}$$

where q is the electronic charge, k is the Boltzman's constant and $P_{b,i}$ is the ambient light power detected by the i^{th} detector. The values of the parameters used to calculate the BER are given in Table II.

TABLE II. BER PARAMETERS

Parameters	***Values***
Photodiode Responsivity, R	0.54
Bandwidth Factor, I_2	0.562
Bit Rate, B	30 Mb/s
Absolute Temperature, T	298 K
Fixed Capacitance per unit area, ε	112 pF/cm^2
Detector Area, A	1 cm^2
FET channel noise factor, $\beth$	1.5
FET transconductance, g_m	30 mS
Bandwidth Factor, I_3	0.0868

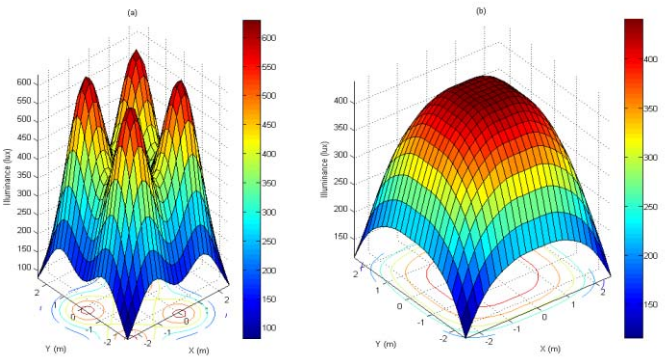

Fig. 3. Illuminance of (a) Case of the studied 4 Tx model and $\emptyset_{1/2} = 30°$ (b) Case of the proposed 16 Tx model and $\emptyset_{1/2} = 30°$

A comparison between the BER of the four arrays and the proposed models is plotted in Fig. 4. The maximum BER (which is obvious at the corners) of the four arrays model was 2.634 x 10^{-13}, while that of the proposed model was just 5.8386 x 10^{-14} which highlights the improvement offered by the the proposed pattern.

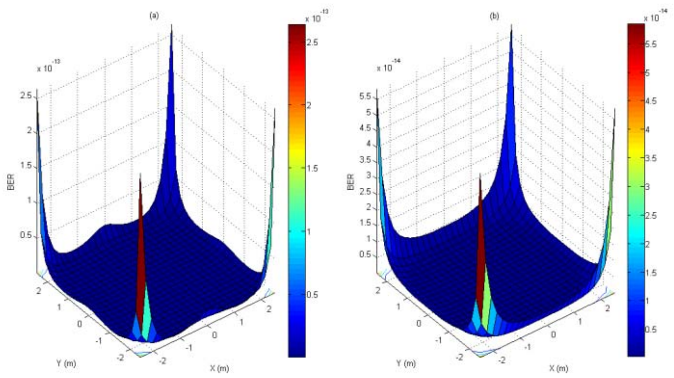

Fig. 4. BER of (a) Case of the studied 4 Tx model and $\emptyset_{1/2} = 30°$ (b) Case of the proposed 16 Tx model and $\emptyset_{1/2} = 30°$

III. VLC EQUALIZATION

To a great extent, the performance and speed of the VLC system is determined by LEDs. The block diagram of the VLC system including the entire transmitter and receiver ends is shown in Fig. 5. A DC-biased ON-OFF keying (OOK) modulation scheme is used where; the transmitting element is the proposed array of LEDs in the previous section. The optical power radiated by the LED is modulated by a driving circuit and driven using a fixed bias current I_{DC}. At the receiving end, a blue optical filter is placed prior to the photodiode (PD) in order to remove the slow phosphorescent component from the modulated signal [11]. For amplifying the small output electrical signal, it is then launched to a trans-impedance amplifier (TIA).

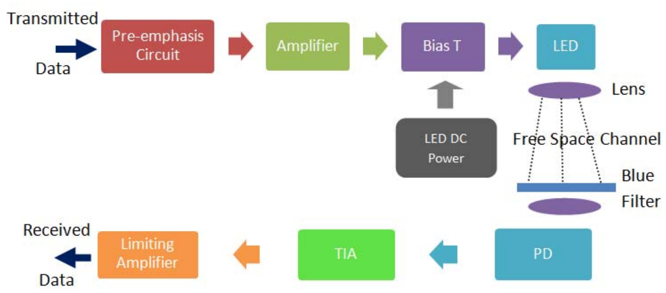

Fig. 5. Block diagram of a VLC system

In a practical experimental setup, at the transmitter end, the signal is generated by a pattern generator before propagating through a pre-emphasis circuit; this signal is clearly AC in nature. This pre-emphasis circuit is designed to overcome the limited bandwidth of the phosphorescent LED and thus enhance the 3-dB channel bandwidth. The signal is amplified and is superimposed on the LED driving current by means of the Bias T [12]. In this section, we first describe the limitations of phosphorescent white LEDs followed by our proposed design that is used to equalize the response of these LEDs and extend the bandwidth of the VLC system.

A. LED Response

The modulation bandwidth of LED is restricted by the minority carriers' lifetime in semiconductors [13]. Theoretically, this bandwidth is limited below 2 GHz; however, currently the bandwidth of available LEDs is far below this theoretical value. Its frequency response is dependent on a number of factors such as, the emitting size and the driving current of LED. Consequently, in order to find an accurate model for a specific LED, few simulations were run to obtain the desired optical response. To determine the pre-emphasis circuit (i.e. equalizer) parameters, this paper used the measured optical response of the phosphorescent white LED presented in [14]. The bandwidth of the white light response was about 3 MHz, whereas that of the blue response was approximately 12 MHz. However, since blue filtering is used in the proposed model, and the slow phosphorescent component is removed, the blue response is equalized in our design as presented in Fig. 6. Since the response of the embedded blue LED in the simulation program we used did not match the measured results in [14], additional components were integrated to create a model that would accurately represent it. The simulated results showed similar outputs to [14] regarding the 12 MHz 3 dB frequency (using a 400Ω resistance) and the gain magnitude of the LED response (applying a controlled voltage source). After the response of the LED was accurately modeled, a pre-emphasis circuit was essential to equalize such response.

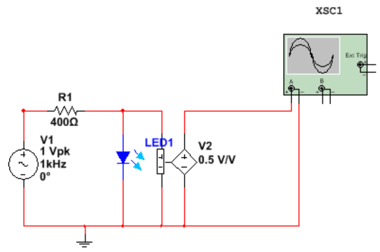

Fig. 6. Blue light response equivalent model

B. Equalization

Equalization is the process of adjusting the balance between the frequency components of a signal, which happens by strengthening or weakening the energy of specific bands. By adding an equalization stage, which is the pre-emphasis circuit in our system, the response of this stage will be multiplied with that of the LED resulting in a combined response with a wider bandwidth than that of the LED alone [15]. To achieve this, we designed a circuit similar to that in [14], but the pivotal difference between both designs is that in our design we combined the pre-emphasis and post equalization circuits presented in [14] into a single pre-emphasis circuit, hence reducing the receiver's complexity. In addition to that, after extensive trials we modified the values of the key parameters of the circuit, which allowed us to achieve unprecedented bandwidth enhancement.

Our circuit is made up of two segments; the first is shown in Fig. 7 and the second in Fig. 8. The first segment is composed of three transistors connected in cascade, unlike [14], we used 2N2222 transistors for our simulations. The first two transistors are connected in common emitter mode, and they are the main controllers of the signal amplitude range and the slope of the pre-emphasis curve, while the third transistor is connected in emitter follower mode and its main function is impedence matching. This segment enhances the bandwidth to about 200 MHz, and then the second segment is responsible for further bandwidth enhancement and amplification of the signal.

The output of the first segment is fed to the input of the second segment, which is made up of a differential amplifier (ADA4937). This segment has a massive capability of flattening the response of the system; however, the values of the parameters of this segment have to be carefully chosen as they can easily cause the amplifier to become unstable.

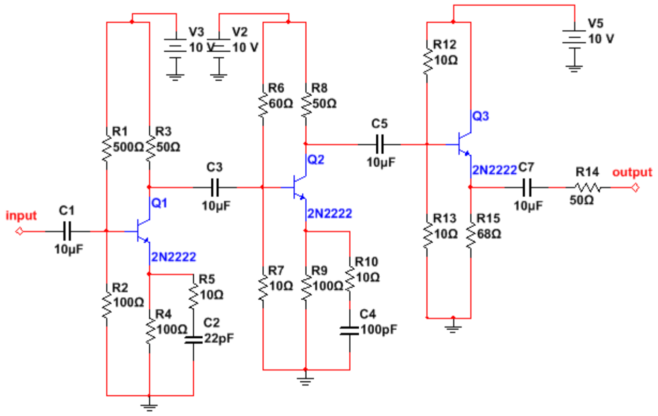

Fig. 7. First segment of the proposed pre-emphasis circuit

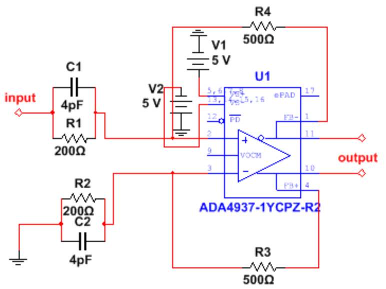

Fig. 8. Second segment of the proposed pre-emphasis circuit

C. Simulation Results

As mentioned earlier, our purpose was to design a circuit whose response when multiplied to that of the LED, the resultant response would be almost flat over the highest frequency range possible. In Fig. 9, three frequency responses are presented; the red curve is the frequency response of the LED, the blue is that of the pre-emphasis circuit response, and the green is the combined equalized response. To measure the 3 dB cut off frequency of the equalized response, we set a reference point at 1 MHz and observed the frequency at which the magnitude of the response falls by -3 dB, according to our simulations shown in Fig. 9, that occurred at 545 MHz. Unfortunately, this frequency cannot be exerted, as by observing the phase response, we found a rapid 180^0 phase reversal at 345 MHz, according to [16], that will cause instability. To avoid this from occurring, the bandwidth was set to 325 MHz, leaving 20 MHz as guard, the signal magnitude at this frequency is equal to -46.3 dB.

For the purpose of comparison, the simulation results of both the work done in [14] and our proposed circuit are presented in Fig. 10. As shown, the bandwidth of the work done in [14] is plotted as the red curve showing a bandwidth of only 235 MHz, our modification is plotted as the green curve, showing that the bandwidth was extended to 325 MHz, moreover, the rapid 180^0 phase reversal was shifted from 275 MHz to 345 MHz.

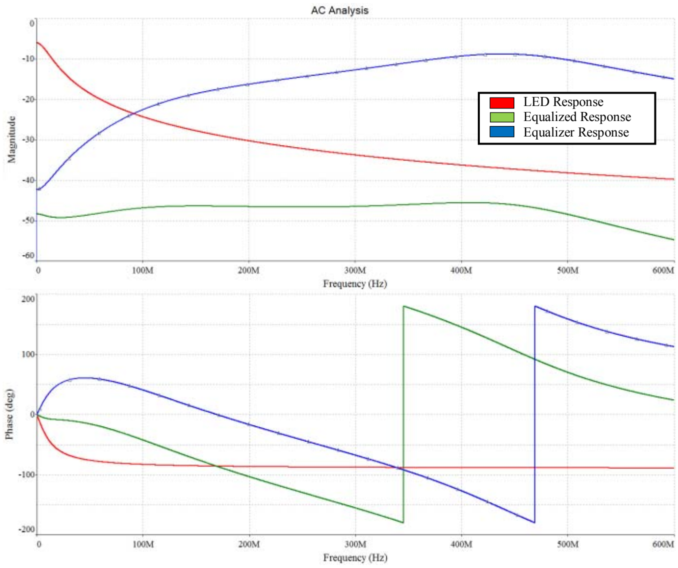

Fig. 9. Magnitude (dB) and Phase (degrees) versus Frequency (Hz) Simulation Results

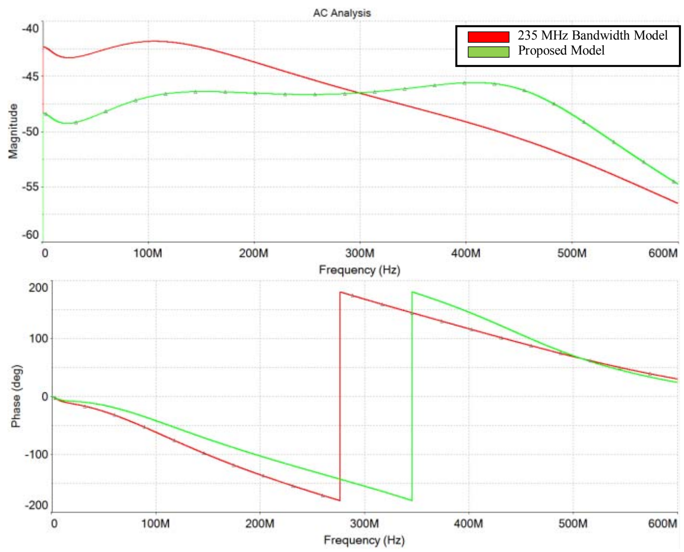

Fig. 10. Comparison between the 235 MHz Bandwidth model and the proposed circuit model

According to our simulations, it was found that by reducing the value of the differential amplifier's feedback resistance, the rapid 180^0 phase shift gets shifted to a higher frequency, and hence the bandwidth can be further extended, as shown in Fig. 11. However, the bandwidth enhancement occurs at the expense of the signal's magnitude, which is a very critical tradeoff to be considered when the system is practically demonstrated. A system designer needs to insure that the transmitted signal has sufficient power that wills it to be recovered at the receiver within the forward error correction (FER) limit of the BER. Moreover, the flatness of the gain magnitude is effected as well, as shown in Fig. 11, the less the feedback resistance R_f, the less flat the response becomes, meaning that not all frequencies will be multiplied by the same gain, causing SNR fluctuations among the VLC link, which is highly undesirable.

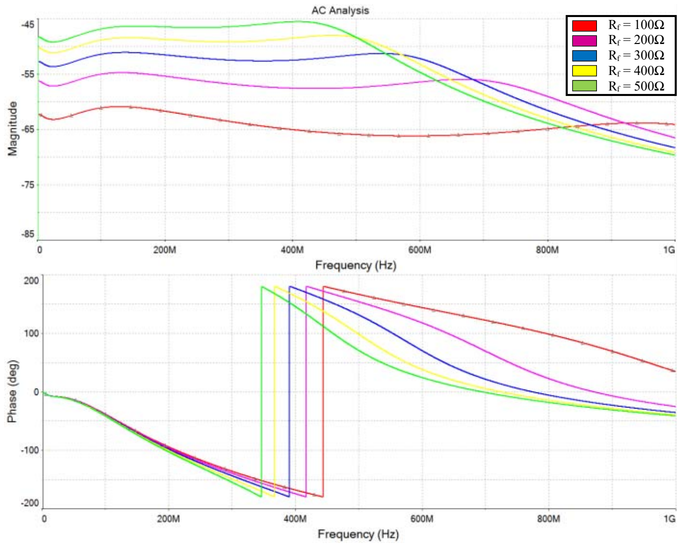

Fig. 11. The Effect of changing R_f at C = 4pF and R = 200Ω

The beneficial effect of changing R_f on bandwidth enhancement is also bounded, as when the feedback resistance R_f is reduced to less than 200Ω, the system response starts to deteriorate and the bandwidth starts to decrease, as its 3 dB cut off frequency in this case is not only limited by the phase reversal, it is also limited by the inadequate flatness of its magnitude response. So in order to achieve a functional system that can be practically demonstrated, we choose the feedback resistance R_f to be equal to 500Ω. The reason for our choice is that; firstly it provides the highest signal magnitude and it also has the flattest response in comparison with the other R_f values presented in Fig. 11.

IV. Conclusion

Visible Light Communication (VLC) is an uprising technology that uses white LEDs for illumination and communication simultaneously. LEDs have a modulation bandwidth of a few megahertz, thus severely limiting the data rate of the VLC system. In order to implement bandwidth enhancement techniques, the system needs to have a high signal to noise ratio. In this paper, we started by remodeling an indoor VLC environment. Aided by simulations, we were able to improve the signal power level of the system, create a more uniform illumination pattern, and decrease the BER by a percentage of 51.2%. Then, we designed a pre-emphasis circuit, if used with blue filtering it can increase the bandwidth of an LED from 3 to 325 MHz, which is the highest bandwidth enhancement reported. Simulations were used to validate this enhancement, in addition to that, models that offered further bandwidth enhancement were also shown, but at the expense of the decreasing the magnitude of the transmitted signal.

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