NLC: Natural Light Communication using Switchable Glass

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***Abstract*—Switchable glass, which can electronically change its state between opaque and transparent, is finding applications in modern buildings as a replacement for traditional curtains or blinds to enable dynamic privacy control in physical spaces. In this work, we propose to exploit the electronic configurability of switchable glass to modulate natural light, which can be demodulated by a nearby receiver with the light-sensing capability to realise data communication over natural light. We call this natural light communication (NLC). A key advantage of NLC is that no energy is used to generate light, as it simply modulates the existing light in nature. The slow response rate of the switchable glass, however, limits the achievable data rates for NLC. We propose and optimise an ON-OFF modulation/demodulation technique for such slow-response switchable glass and implement it using off-the-shelf Polymer Dispersed Liquid Crystal (PDLC) glass. We demonstrate that the proposed NLC can achieve 33.33 bits per second communication with a bit error rate below 1% under a wide range of ambient luminance.**

***Index Terms*—Switchable Glass, Natural Light Communication, Visible Light Communication.**

I. Introduction

Switchable glass is an emerging technology that can electronically switch the state of the glass from opaque to transparent by simply applying a voltage to it [1]. By removing the voltage, the glass can be brought back to its transparent state. Switchable glass, therefore, can block sunlight out, regulate indoor luminance and temperature, and serve as a replacement for traditional curtains or blinds as well. As it can also help electronically configure and control the privacy level on-demand, it is rapidly finding applications as 'electronic privacy screen' in meeting rooms, bathrooms, and even cars [2].

In this paper, we propose to exploit the electronic configurability of switchable glass to realise what we call **natural light communication (NLC)**. Specifically, we propose to convert a switchable glass into a data transmitter that can transmit a digital stream by controlling the voltage and thus modulating the light-emitting states of the glass under the control of a microprocessor. Then any nearby object with light-sensing capability can demodulate the light and hence act as a receiver. NLC, therefore, can add value to existing switchable glasses by enabling them to communicate with other objects in the smart Internet of Things environment.

As current switchable glass technology is primarily designed to support privacy screens, it has a relatively slow response raising a challenge for data communications. Specifically, although the glass can switch from opaque to transparent in just a few ms when the voltage is applied, it takes hundreds of ms to become opaque again when voltage is removed. Our goal, therefore, is to communicate only small packets of information. Of course, this will not match the high data rates that are possible with existing visible light communication (VLC) [3] [4], which takes advantage of the extremely high response rates of light-emitting diode (LED). NLC, however, can take advantage of the ambient lights in nature to communicate without having to generate artificial lights as used in LED-based VLC. As such, NLC can potentially provide a low-energy communication solution for switchable glass and may enable many interesting new applications despite the low data rates.

Using commercial off-the-shelf switchable glass, we demonstrate that NLC is feasible. Our contributions in this paper can be summarized as follows:

- We experimentally characterise natural light modulation capabilities of existing Polymer Dispersed Liquid Crystal (PDLC) switchable glass,
- We design an ON-OFF modulation technique optimized for PDLC switchable glass. We propose and compare two different demodulation techniques for receivers that use commercial off-the-shelf low-cost photosensors to detect natural light.
- We implement the proposed modulation/demodulation techniques in a complete end-to-end NLC prototype and evaluate their performance experimentally. We demonstrate that the proposed NLC concept is feasible and achieves a data rate of 33.33 bits per second with a bit error rate below 1% under a wide range of ambient luminance.

The rest of the paper is structured as follows. We provide a preliminary on PDLC-based switchable glass in Section II. Experiments to characterise natural light modulation capabilities of PDLC switchable glass is presented in Section III. The proposed ON-OFF modulation and demodulation techniques are explained in Section IV, followed by their implementation and evaluation in Section V. We discuss limitations and research challenges in Section VI and conclude the paper in Section VII.

II. PDLC Switchable Glass Preliminary

As shown in Fig. 1, a PDLC glass is made up of liquid crystal particles. When there is no voltage applied, the liquid crystal particles are distributed throughout the polymer matrix randomly (left-hand side) and block most of the light causing a white milky surface on the glass. When a rated voltage is applied across the glass (the right-hand side), the liquid crystal particles orient themselves to allow light pass through them making the glass transparent [5] [6]. When used as a privacy screen, the device applies a rated voltage when a switch is turned on and removes the voltage (zero voltage is applied) when the switch is turned off. Thus, using a switch, the user can manually turn the privacy on and off.

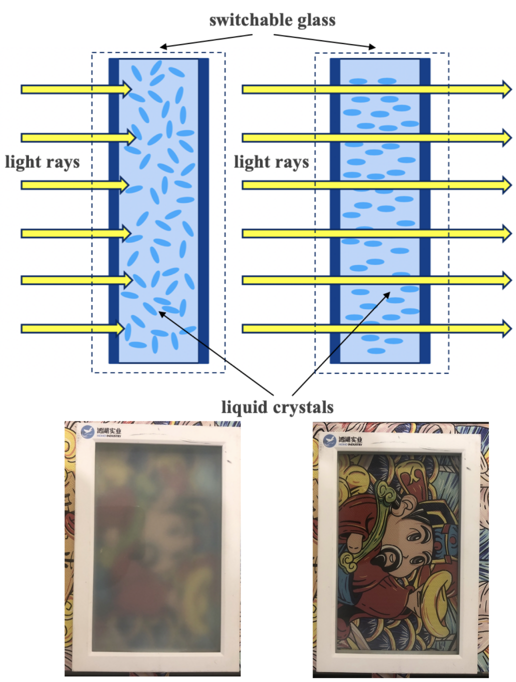


Fig. 1. Basic principles of PDLC switchable glass. Left: no voltage applied and Right: voltage applied

III. PDLC Switchable Glass Characterisation

Our goal in this section is to experiment with PDLC glass to find out its behaviour as a function of the applied voltage.

A. *Off-the-shelf PDLC Product*

In this work, we use a commercial off-the-shelf (COTS) PDLC switchable glass made by HoHo industry [7] (see Fig. 2). The size of the glass is 8cm*13cm, which is controlled using a rated voltage AC 48-75V, 50Hz. It comes with both DC and AC power supplies. The DC controller is driven by two 1.5V AA batteries. while the AC transformer is driven by 220V AC. The transformer transforms 220V AC to about 57.7V, so the glass could work properly. As the voltage in DC power supply varies with battery power consumption, we implement our prototype using the AC transformer as a power supply for a stable voltage output at all times.

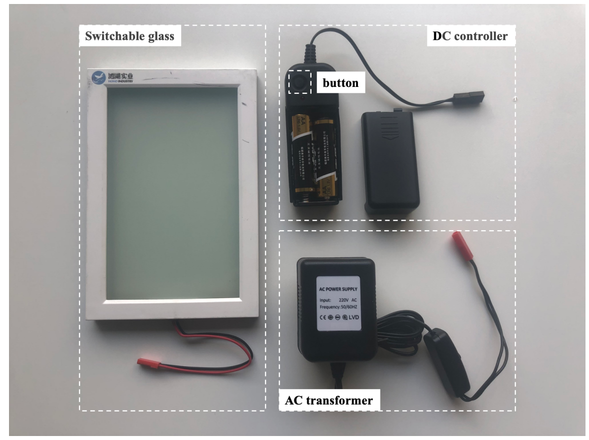


Fig. 2. A COTS PDLC glass with its AC and DC power supplies.

B. *Voltage Control Circuit*

The supplied switch only has two voltage values, 0V (opaque) and 57.7 (transparent). To experiment with different voltage values, we design and build our own circuit as shown in Fig. 3. The circuit works as follows.

PDLC glass is in effect a capacitor, which must be activated by an AC source. In order to control high volt AC by low volt DC, we put two Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFET) in serial connection back to back and connect a diode in parallel for rectification of each. When the Arduino outputs a 5V DC on gates of both MOSFETs, there is a closed circuit between these two MOSFETs and the voltage applied on PDLC glass is 57.7V, which we will call *turn-on* voltage. When there is no voltage output from the Arduino, the circuit between MOSFETs is open and the voltage applied on PDLC glass is the *turn-off* voltage. We achieve different turn-off voltages by applying different combinations of capacitors C1 and C2. As a result, the turn-off voltage depends on selected capacitors and cannot be an arbitrary value.

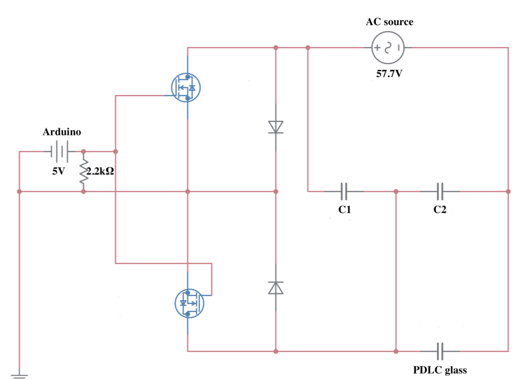
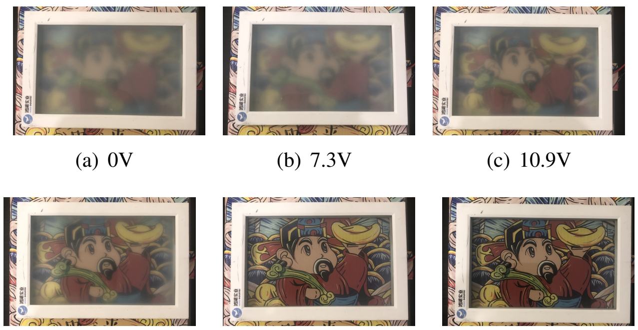


Fig. 3. Diagram of voltage control circuit.

C. *Transparency Control*

Armed with the voltage control circuit, we explore the transparency levels of the PDLC glass as a function of the voltage applied. As can be seen in Fig. 4, different levels of transparency can be easily obtained by simply supplying a different voltage to the glass. A key outcome of this experiment is that when used for data communication, we do not necessarily want to switch between the highest transparency and completely opaque states to modulate the natural light, which may take a long time to transition. Rather, two different transparency levels close to each other could be used to reduce transition times, thereby increasing the data rates. We study the transit/response times next.



(a) 0V (b) 7.3V (c) 10.9V

(d) 13.8V (e) 26.8V (f) 57.7V

Fig. 4. Appearance of PDLC glass under different voltages

D. Signal Transition Analysis

The received light signal for different turn-off voltages are shown in Fig. 5. Initially, the highest voltage of 57.7V (turn-on voltage) is applied for 25 ms. At time 0, we apply the turn-off voltage and observe the signal for a long time, up to 475ms, then apply turn-on voltage again. We make the following observations: low-to-high transition is very quick, only about 5ms, but the high-to-low transition is much slower and depends on the turn-off voltage applied. Specifically, the higher the turn-off voltage, the higher the steady-state value, and the quicker the signal reaches its steady-state value. These observations suggest that if quicker high-to-low transition is desired, which is required for achieving higher data rates, then a higher turn-off voltage should be selected.

To see whether indeed higher turn-off voltage would provide higher data rates without sacrificing reliability, we study the distribution of mean light intensity of the received signal for high and low for different lengths of signal durations, or symbol lengths. Note that shorter the symbol length, the higher the data rate, but the distributions for high and low should not have overlap to avoid errors in symbol detection. These results are shown in Fig. 6 for three different turn-off voltage values, 0V, 7.3V and 26.8V. We can clearly see that with the restriction of no overlap for the distributions, the higher the turn-off voltage, the lower the acceptable symbol durations. Specifically, we find that for no overlap, the shortest symbol durations are 50ms (Fig. 6.a), 30ms (Fig. 6.e), and 25ms (Fig. 6.i), respectively, for turn off voltages of 0V, 7.3V and 26.8V.

However, we also notice that the signal is noisy behaving like a sine wave. This can be attributed to the cyclic nature of the AC voltage. The presence of noise also means that for high turn-off voltage we may not get a clean transition from low-to-high or high-to-low, which could make it challenging for synchronising the transmitter and the receiver. This effect is analysed in Fig. 7, which shows that there is a clear detectable low-to-high transition for turn-off voltage 7.3V, but it is not detectable for 26.8V. Without good synchronisation, clocks can drift very quickly making symbol detection highly unreliable. Indeed, our experiments show that with a turn-off voltage of 26.8V, the bit error rate is too high. Therefore, we can conclude there exists an optimum turn-off voltage to balance between short symbol duration (high data rate) and synchronisation (reliability). We leave the analytical study of this interesting optimisation problem for future work, but choose 7.3V as the turn-off voltage for evaluating the proposed ON-OFF modulation in the following sections.

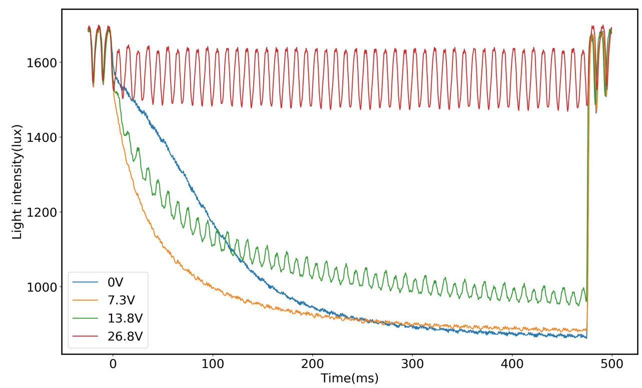


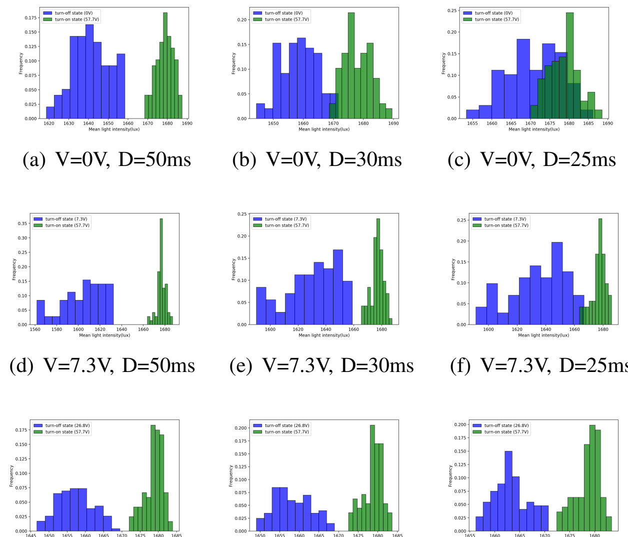
Fig. 5. High-to-low and low-to-high transitions of received light signals with different turn-off voltages. Ambient light intensity is between 3200-3400 lux.

IV. ON-OFF Modulation and Demodulation

A. Modulation

On-Off Keying (OOK) [8], Pulse-width modulation (PWM) [9] and Pulse-position modulation (PPM) have already been universally employed on VLC. Since PDLC glass always need a period of time for state transformation, we employ OOK for modulation. We utilise different states of PDLC glass, ON and OFF to represent data bits '1' and '0' respectively. For the data bit '1', set the output pin of Arduino to 5V, so that it could drive MOSFETs and activate PDLC glass. For the data bit '0', set the output pin of Arduino to 0V, the circuit between MOSFETs will be open and PDLC glass will switch to turn-off state.

Since NLC could work under various light conditions between 200lux to 3600lux, receiver cannot simply recognize a mean light intensity of symbol duration representing a turn-on or turn-off state. A preamble is necessary for the receiver to record mean values of light intensity for both states for demodulation. Preamble consists of continuous alternate '1' and '0' so that we can get the mean value of both states for

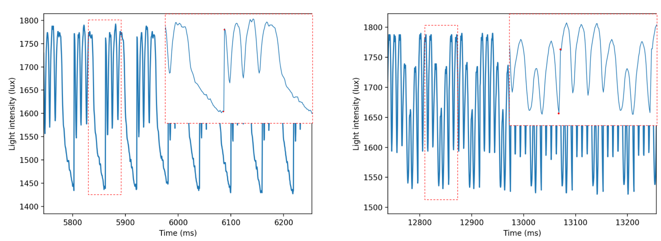


(a) V=0V, D=50ms (b) V=0V, D=30ms (c) V=0V, D=25ms

(d) V=7.3V, D=50ms (e) V=7.3V, D=30ms (f) V=7.3V, D=25ms

(g) V=26.8V, D=50ms (h) V=26.8V, D=30ms (i) V=26.8V, D=25ms

Fig. 6. Mean light intensity distributions with different turn-off voltages (V) and symbol durations (D), external luminance is 3400lux



(a) 7.3V (b) 26.8V

Fig. 7. Detectability of low-to-high transitions with different turn-off voltages. The transition is very clear for 7.3V, but almost undetectable for 26.8V.

multiple times. We transmit 1000 random bits with different lengths of preamble and repeat 10 times, use mean value demodulation and record average bit error rate (BER) of them, the result is stated in Table II. We can find that a 10-digit preamble, which is ’1010101010’, can achieve a BER about 1%. So, we set preamble as ’1010101010’. Another effect of preamble is to determine when the transmission starts. For example, PDLC glass keeps opaque and receiver keeps listening before transmission when the light intensity increases suddenly at a time, the receiver can detect this increase of light intensity and start collecting data.

B. Demodulation

1) Mean value demodulation: Mean value demodulation uses the mean light intensity of each symbol duration. As we have got preamble already, we can calculate the mean value for each bit ’1’ and bit ’0’, $Mean_1$ and $Mean_0$ in preamble. It is a challenge to determine a suitable threshold for demodulation. As Fig. 6 (e) shows, the mean value of bit ’1’ is Gaussian distributed and the mean value of bit ’0’ is

TABLE I
BER WITH DIFFERENT LENGTH OF PREAMBLE

length of preamble	average BER
2-digit	34.4%
4-digit	18.6%
6-digit	8.2%
8-digit	3.6%
10-digit	1.4%
12-digit	1.6%
14-digit	1.3%
16-digit	1.4%

distributed arbitrarily. We calculate a threshold by the formula below with a 10-digit preamble and repeat 1000 times, there is 98.7% probability that threshold is in the blank gap of two distributions.

$$Threshold = \frac{min(Mean_1) + max(Mean_0)}{2} \tag{1}$$

For each symbol received, we calculate its mean light intensity and compare it with the threshold. If the mean value is greater, it means this symbol is bit ’1’, otherwise, it is bit ’0’. An example of mean value demodulation is shown in Fig. 8.

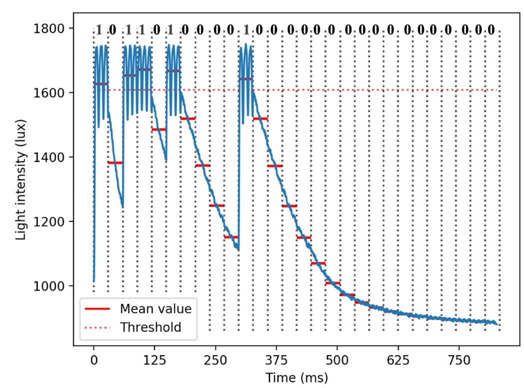


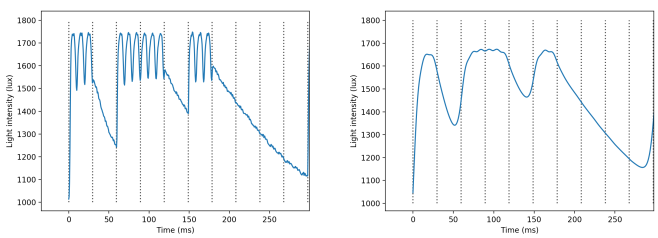
Fig. 8. Received symbols and mean values of each of them

2) Slope demodulation: Based on Mean value demodulation, slope also utilizes the slope of each symbol duration. Similar to mean value demodulation, we should get the slope and mean value of bit ’1’ and ’0’ first. However, the original symbol has too much background noise, we have to implement a low pass filter before calculating slopes. We use a one-order filter with a $\frac{100}{\text{sample rate}}$ critical frequency for each bit in preamble and every symbol in the payload. After filter, the inflection may be advanced or delayed slightly, to be more accurate, we discard the first 30% and last 30% values for each duration and just calculate the slope of the middle part. Like Fig. 8, due to the slope will flat after about 15 consecutive ’0’, which is similar to the slope of ’1’, we also use mean value as the second parameter of determination. Similar to threshold for mean value, the formula of slope threshold is as below, and we determine the bit through Algorithm 1.

$$Threshold = \frac{min(Slope_1) + max(Slope_0)}{2} \quad (2)$$

Algorithm 1 Slope demodulation

```
if slope < slopeThreshold then
    return bit '0'
if slope >= slopeThreshold then
    if meanValue > meanValueThreshold then
        return bit '1'
    else
        return bit '0'
```



(a) Unfiltered (b) Filtered

Fig. 9. Received symbols and filtered symbols

C. Synchronisation

Since the transmitter and the receiver have separate clocks, we need to synchronise them regularly. We find that without synchronisation, bit error rate (BER) increases rapidly with time. Because light intensity rises rapidly from low-to-high voltage application, we choose low-to-high transition for synchronisation.

V. Implementation and Performance Evaluation

A. Prototyping

As we expect to control PDLC glass by the program automatically in a high switch frequency, we design and implement a control circuit which allows PDLC glass switch in a specific pattern controlled by a microcontroller (Arduino Uno board). As we mentioned before, we require a PDLC glass switch between turn-on and turn-off voltage to reach transparent and opaque state continuously.

To explore the feasibility and performance of Natural Light Communication (NLC), we design and implement a simulated box as Fig. 10 for experiment. We use a cardboard box (30cm*18cm*20cm) to pretend a closed room and embed a commercial on-the-shelf PDLC glass (8cm*13cm) as its only window. The transmitter is composed of A PDLC glass and a control circuit, the receiver is a photosensor (OPT101 [10]) which we collect light intensity from it and processed by Arduino. The distance between transmitter and receiver is 9.5cm. For each bit '1' we assign a transparent state to PDLC glass and an opaque state for '0'. When the window stays in a transparent state, natural light will pass through the window and light up the room. When the window keeps in the opaque state, most of the natural light will be blocked by the window and the intensity of light inside will decrease apparently. This kind of difference could be exploited to do an On-Off Keying (OOK) modulation by natural light and a photosensor as a receiver could easily catch the switch pattern inside and demodulate these light signals to original bits.

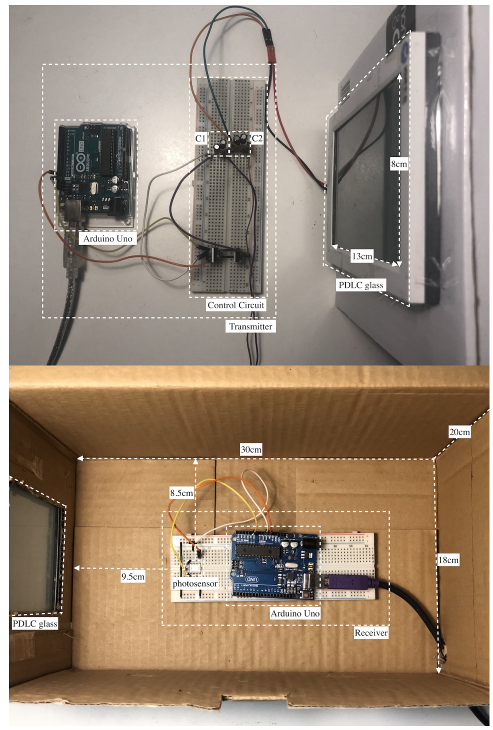


Fig. 10. Transmitter and receiver of prototype

B. Evaluation Results

In this section, we examine bit error rate (BER) of both demodulation with different ambient luminance. We use the prototype we introduced in V-A and conduct these experiments by varying external luminance to verify the capacity of NLC under different light circumstances (200lux, 1300lux, 2100lux, 3400lux and 4000lux). We measure external luminance by a TASI digital light meter [11] and put it besides the glass. In each of these experiments, we use 7.3V as turn-off voltage and 30ms as symbol duration. Transmitter generates and transmits 1000 random bits, repeats 10 times, which are 10000 bits in total. We apply both demodulation methods and compared against the transmitted bit to compute the total BER, BER with '1' (original bit is '1' but we demodulate it to '0') and BER with '0' (original bit is '0' but we demodulate it to '1') as results are stated in Table III.

For both demodulation, BER decreases when external luminance increases, except of 4000lux. The reason is the photosensor we use in prototype, OPT101 has a measuring range between 0lux to 2000lux. When external luminance is 4000lux,

TABLE II
BER WITH DIFFERENT EXTERNAL LUMINANCE

External luminance	Mean value/Slope demodulation		
	Total BER	BER with '1'	BER with '0'
200lux	1.41%/1.05%	0.63%/0.84%	2.18%/1.27%
1300 lux	1.08%/0.76%	0.49%/0.72%	1.71%/0.84%
2100 lux	1.07%/0.78%	0.55%/0.74%	1.59%/0.80%
3400 lux	1.02%/0.75%	0.51%/0.64%	1.53%/0.86%
4000 lux	23.0%/18.6%	12.6%/17.3%	34.2%/19.6%

the values that photosensor received inside may exceed its measuring range which causes BER to increase drastically. This prototype could work in a brighter circumstance by utilising another kind of photosensor with a higher measuring range. For mean value demodulation, because the impact of background noise, the mean value of bit '0' is distributed arbitrarily, the misjudgment of '0' to '1' is more likely than '1' to '0' in contrast. Slope demodulation performs better, it could reduce BER by 30% from mean value demodulation. With Table III, we can say using slope demodulation, NLC can achieve 33bit/s with a BER under 1% and external luminance between 200lux to 3400lux.

VI. DISCUSSION

This is the initial experiment to understand the opportunities and limitations for using the freely available ambient natural light as a medium for data communications using switchable glass. Here we discuss the limitations and research challenges for such NLC, which require further investigations by researchers from different disciplines.

First, existing switchable glasses take around 100ms to switch from transparent state to opaque state. This transition time is adequate for privacy applications, but becomes a bottleneck for high-speed data communications. Such long transition time also creates annoying visual effect for human eyes. New switchable glass technology must be developed to reduce transparent to opaque transition time significantly if it is to be used for data communications. In addition, the driving voltage of PDLC should be as low as possible to save energy.

Second, our current prototype has a single switchable glass controlling all the ambient light to the room. In reality, a room may have more than one window causing ambient light to enter a room from multiple locations. Thus, modulation of multiple switchable glasses must be optimised jointly to maximise decoding performance at the receiver at any given location in the room.

Third, we used photodiodes to implement our receiver, which worked well for indoor lighting conditions. Photodiodes, however, are known to saturate at extremely bright natural light environment, e.g., direct sunlight [12]. Thus solar cell should be investigated as a possible receiver technology for NLC. Indeed, for visible light communications, researchers have found organic solar cells to be effective for demodulation [13] [14].

VII. CONCLUSION

Using COTS hardware, we experimentally characterise natural light modulation capabilities of existing PDLC switchable glass and designed an ON-OFF modulation technique optimized for it. We also implement the proposed modulation/demodulation techniques in a complete end-to-end NLC prototype and evaluate their performance experimentally. From this prototype, we demonstrate that the proposed NLC concept is feasible and achieves a data rate of 33.33 bps while keeping the BER below 1%. Although this is not a high data rate, we believe this will still help realise smart privacy screens that can not only switch between open and privacy modes dynamically but also 'talk' to other objects in the smart environment.

REFERENCES

[1] C.-C. Chen, L. Dou, R. Zhu, C.-H. Chung, T.-B. Song, Y. B. Zheng, S. Hawks, G. Li, P. S. Weiss, and Y. Yang, "Visibly transparent polymer solar cells produced by solution processing," *ACS nano*, vol. 6, no. 8, pp. 7185–7190, 2012.

[2] H. Alghamdi and A. Almawgani, "Smart and efficient energy saving system using pdlc glass," in *2019 Smart City Symposium Prague (SCSP)*. IEEE, 2019, pp. 1–5.

[3] X. Li, C. Min, S. Gao, G. Sun, X. Chen, and H. Chen, "A cdma-based high-speed multi-access vlc system with ook modulation," *Optics Communications*, 2019.

[4] H. Burchardt, N. Serafimovski, D. Tsonev, S. Videv, and H. Haas, "Vlc: Beyond point-to-point communication," *IEEE Communications Magazine*, vol. 52, no. 7, pp. 98–105, July 2014.

[5] K. V. Wong and R. Chan, "Smart glass and its potential in energy savings," *Journal of Energy Resources Technology*, vol. 136, no. 1, p. 012002, 2014.

[6] A. Ghosh, B. Norton, and T. K. Mallick, "Influence of atmospheric clearness on pdlc switchable glazing transmission," *Energy and Buildings*, vol. 172, pp. 257–264, 2018.

[7] S. H. industry, "HoHo Smart PDLC Film/Glass," http://www.hohotint.com/list-11-1.html.

[8] Z. Tian, K. Wright, and X. Zhou, "The darklight rises: Visible light communication in the dark," in *Proceedings of the 22nd Annual International Conference on Mobile Computing and Networking*. ACM, 2016, pp. 2–15.

[9] M. Basha, M. J. Sibley, and P. J. Mather, "Design and implementation of a long range indoor vlc system using pwm," *Annals of Emerging Technologies in Computing (AETiC)*, vol. 3, no. 1, 2019.

[10] Q. Wang, D. Giustiniano, and O. Gnawali, "Low-cost, flexible and open platform for visible light communication networks," in *Proceedings of the 2nd International Workshop on Hot Topics in Wireless*. ACM, 2015, pp. 31–35.

[11] TASI, "TASI TA8121 Light Meter," http://www.china-tasi.com/en/Product/Digital_Light_Meter/2014/0909/234.html.

[12] D. Ma, G. Lan, M. Hassan, W. Hu, M. B. Upama, A. Uddin, and M. Youssef, "Solargest: Ubiquitous and battery-free gesture recognition using solar cells," in *The 25th Annual International Conference on Mobile Computing and Networking (MOBICOM)*, 2019, pp. 1–15.

[13] S. Zhang, D. Tsonev, S. Videv, S. Ghosh, G. A. Turnbull, I. D. Samuel, and H. Haas, "Organic solar cells as high-speed data detectors for visible light communication," *Optica*, vol. 2, no. 7, pp. 607–610, 2015.

[14] Z. Wang, D. Tsonev, S. Videv, and H. Haas, "On the design of a solar-panel receiver for optical wireless communications with simultaneous energy harvesting," *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 8, pp. 1612–1623, 2015.