Underwater Wireless Optical Communication Based on DPSK Modulation and Silicon Photomultiplier

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ABSTRACT In this paper, a promising phase-modulated underwater wireless optical communication (UWOC) system with silicon photomultiplier (SiPM) based receiver is proposed for the first time and its feasibility has been experimentally demonstrated in a laboratory environment. The phase modulation enables the additional degree of freedom available for encoding of information in UWOC, given that previous state-of-the-art systems mainly employ intensity modulation (IM) schemes with direct detection (DD).

The proposed UWOC system, the information is encoded in the phase of light wave carrier based on differential phase-shift keying (DPSK). A highly sensitive receiver is built from SiPM, which is able to compensate the transmission loss and dramatically enhances the performance of the DPSK UWOC system.

We experimentally show the feasibility of the proposed system at a data rate of 200 Mbps. For comparison, the commonly used avalanche photodiode (APD) based receiver is also tested. Comparing with the APD, the use of SiPM reduces the BERs by about two orders of magnitudes. The minimum required optical power for achieving a BER below the FEC threshold is about -$40.2$ dBm, which is about $11.6$ dB lower than the case of APD.

INDEX TERMS Underwater wireless optical communication, differential phase-shift keying, phase modulation, silicon photomultiplier.

I. INTRODUCTION

Advanced underwater wireless communication (UWC) techniques are highly demanded for the significantly increased human activities in underwater such as ocean exploration, marine environmental monitoring and oceanography research [1], [2]. Traditionally, UWCs are mainly implemented through the use of acoustic waves. However, acoustic communication experiences limited bandwidth (kHz) and relatively high latency, which are not suitable for practical high-speed data transmission applications, such as real-time video transmission [3], [4]. In recent years, the underwater wireless optical communication (UWOC) has been shown as an attractive alternative due to its advantages of high data rate, low latency, low power consumption, and small volume [3]. Accordingly, significant progress has been achieved in the performance of UWOC demonstrations [1], [5], [6].

To the best of author’s knowledge, the current UWOC systems mainly utilize intensity modulation (IM) schemes with direct detection (DD). The commonly used modulation schemes include On/Off Keying (OOK), Pulse Position Modulation (PPM), Pulse Width Modulation (PWM), etc [3].

Intensity modulated systems are based on the use of optical pulses, of which the increase of data rate requires a higher repetition rate, shorter pulse width and sufficient peak power [7]. In addition, they allow the information to be encoded in only one degree of freedom [8]. There have also been a few studies on the alternative modulation techniques. In [7], the...
use of binary phase shift keying (BPSK), quadrature PSK (QPSK), and quadrature amplitude modulation (QAM) in a UWOC system have been presented. However, they are actually conducted by imposing intensity modulation on the pre-modulated signals but not changing the phase of the light [3], [7]. A binary polarization shift-keying (PolSK) UWOC system was also demonstrated, in which the optical signal is modulated by varying the polarization of the transmitting laser beam [9].

Apart from the above modulation schemes, phase coherent schemes can be implemented with continuous-wave laser sources and electro optic phase modulators such that the phase of optical signal is exploited to carry information in UWOC. The investigation of the modulation techniques using the phase of light wave carrier would have the great potential to increase the degrees of freedom available for encoding of information in UWOC systems, and hence open the possibility for higher spectral efficiency. It can also mitigate the nonlinear effects due to the reduction of peak power [10], [11]. Phase modulation is a promising technique for the underwater data transmission and can be even used in underwater quantum communications [12].

Typical phase modulations include phase-shift keying (PSK) and differential phase-shift keying (DPSK). PSK format carries the information in optical phase itself, but requires coherent detection which suffers from higher implementation complexity and higher cost [3]. The DPSK is based on the interference of two successive signal bits. It can be much simpler to implement and offers higher tolerance to transmission impairments [10], [11]. Unlike the PSK modulation with coherent detection, which benefits from higher receiver sensitivity due to the use of a local oscillator (LO) laser, DPSK is normally directly detected by a balanced receiver or a single-ended receiver after an optical delay line interferometer (DLI) without the improvement in the receiver sensitivity [11], [13]. A single-ended receiver is formed by connecting one of the output ports of the DLI with a single photodiode, while a balanced receiver is formed from two matched photodiodes connected to the both output ports of the DLI [11], [14]. A balanced receiver offers about 3dB higher detection sensitivity at the cost of higher implementation complexity [11], [14].

In this paper, we propose a UWOC scheme based on DPSK modulation and highly sensitive SiPM, and experimentally demonstrate its feasibility by the investigation of the BER performance at different optical power. We also investigated the performance with an APD based receiver for comparison. The improvement of receiver sensitivity and hence the system performance of the proposed DPSK UWOC system by the use of SiPM is presented. Section II introduces the operation principle of the proposed system. Section III illustrates the detailed experimental setup of the proposed system with a water tank. Experimental results are shown and discussed in Section IV. A brief conclusion of this paper is drawn in Section V.

II. OPERATION PRINCIPLES

In DPSK, the intensity of the carrier wave remains unchanged in each bit interval, and binary data is encoded as the optical phase difference between two successive bit intervals. Bit ‘1’ is transmitted by a phase of ‘π’ relative to the phase of the optical signal in the previous bit interval, while bit ‘0’ is transmitted without a phase difference between two adjacent bit intervals [25]. The implementation of DPSK modulation and demodulation can be illustrated in the schematic diagram shown in Fig.1 (a) and Fig.1 (b) respectively.

For DPSK modulation, the signal which represents the phase difference between every two successive bit intervals is generated from the baseband signal by a delayed-XOR precoder (also known as the differential encoder). The DPSK encoding operation can be expressed mathematically as [25]:

\[
H(\tau) = S(\tau) \oplus H(t - T_b)
\]

where \(S(t)\) is the baseband signal, \(H(t)\) is the encoded signal, \(T_b\) is the bit duration, and \(H(t - T_b)\) is the adjacent encoded signal at a time interval of \(T_b\). \(\oplus\) denotes the Boolean XOR operator. Then the phase of the carrier wave (ie. the continuous-wave laser beam) is modulated based on \(H(t)\) by the use of a phase modulator. The modulated optical signal \(E_{DPSK}(t)\) is given by [13]:

\[
E_{DPSK}(t) = A \cos (\omega_0 t + H(t) \pi)
\]
TABLE 1. Coding process of DPSK system.

| Coding process of DPSK system | 1 0 1 1 0 1 1 1 0 0 |
|-------------------------------|---------------------|
| Baseband signal               |                     |
| Delay-XOR (DPSK signal)       | 1 1 0 1 1 0 1 0 0 0 |
| Phase signal                  | π π 0 0 π 0 0 0 0 0 |
| Delayed phase                 | 0 π π 0 π 0 0 0 0 0 |
| Phase difference              | π 0 π 0 π π π π 0 0 |
| Recovered signal              | 1 0 1 1 0 1 1 1 0 0 |

where \( A \) and \( \omega_0 \) are the amplitude and frequency of the carrier wave, respectively. \( \theta(t) = H(t)\pi \) is the DPSK phase signal. Thus, the phase of the optical signal is modulated in a DPSK format. On the other hand, the demodulation is generally realized by the DLI of which one arm has a delay being equal to the duration of one bit \( (T_b) \) relative to the other arm [13], [26]. As shown in Fig.1 (b), the DLI is composed of a splitter, an optical delay line and a coupler [11]. The incoming optical signal is split into two parts, which travel through upper and lower arms of the DLI. As a result, one part of the signal would experience a delay of a time \( T_b \) relative to the other part. The interference of two adjacent bits occurs when the two parts of the signals are combined at the coupler with two output ports, and the phase information of the incoming signal is therefore converted to the intensity of the output optical signal [13], [25]. Thus, the signal can be recovered back to the baseband signal. It can be concluded as [13]:

\[
\begin{align*}
\text{bit 0:} & \quad \theta(t) - \theta(t - T_b) = 0 \\
\text{bit 1:} & \quad \theta(t) - \theta(t - T_b) = \pi
\end{align*}
\] (3)

Since the full information is carried by both of the DLI output ports, the baseband signal can be translated into electrical domain by either a “balanced detection” scheme or by a “single-ended detection” scheme [11], [14], as shown in Fig.1(b).

As an example, a bit sequence ‘1011011100’ is used as the transmitting data, which is pre-coded into a DPSK format. The underlying coding/decoding process of the DPSK modulation scheme can be concluded in Table 1 [13]. The DPSK signal can be obtained as a bit sequence ‘1101101000’ based on (1), which corresponds to the phase information ‘π π 0π 0π 0π 0π 0π 000’ based on (2). The waveform of the corresponding DPSK signal to be used for phase modulation is shown as the blue curve in Fig. 1(c). The received phase-modulated optical signal is demodulated by the DLI and then detected by the detector. The recovered signal is shown as the green curve in Fig.1(c), indicating the complete demodulation operation at the DPSK receiving site when compared with the baseband signal.

In the paper, our proposed system with SiPM employs the single-ended detection scheme which has lower implementation complexity. The sensitivity of a SiPM depends on the photon detection efficiency (PDE), which is a function of wavelength. It has been recently reported that SiPM based receivers with (PDE) higher than 14% are more sensitive than APD based receivers [21]. In this paper, a commercially available SiPM (SensL J series 30035) which contains an array of 5676 SPADs with a 32% PDE at 532nm has been investigated [27]. The SiPM employs the passive quenching scheme and the output signal is generated by adding all SPADs’ signal together at the common output.

When using the SiPM based receiver, each detected photon generates a single pulse and the pulses are isolated at the very low light level. SiPM is then working in a “digital mode”. The output of SiPM can be processed by counting the number of pulses by the photon counting method reported in [28]. However, when the detected photon rate is increased above a certain level \( (PR_{max}) \), the output pulses become overlapped and the photons cannot be accurately counted by the photon-counting method. For the SiPM tested in this work, \( PR_{max} \) is measured about \( 4.9 \times 10^7 \) photons per second, corresponding to a maximum optical power of 0.062nW. Fortunately, SiPM would also operate in the “analog mode” at higher light levels, in which the amplitude of the output signal can be directly measured instead of counting pulses [29]. The different output of SiPM in two modes are illustrated in Fig.2.

In addition, when the pulse repetition rate is higher than the bandwidth of SiPM, the impaired performance may arise from enhanced distortion due to the overlapping detected signal pulses. Such an effect is known as the Inter-symbol interference (ISI), in which the spreading of the pulses due to the bandlimited receiver results in interference between neighboring symbols [30], [31]. Therefore, decision feedback equalizer (DFE) is employed to mitigate ISI in our proposed system. The block diagram is shown in Fig. 3 [32]. The DFE is composed of a transversal feedforward filter and a feedback filter. The received signal \( x \) is firstly input to the feedforward filter with \( N_F \) steps of delay with constant tap delay \( T \). At the
n_{th} \text{ step, the magnitude of the delayed signal is weighted with a factor } a_n. \text{ The sequence of decisions on previously detected symbols are then input to the feedback filter with weights } [b_1 b_2 \ldots b_{ND}]. \text{ As a result, the impairments caused by ISI in the received signal can be overcome. The output from a DFE can be expressed as [32]:}

\[ z_k = \sum_{n=0}^{N_{F}} a_n \cdot x_{k-n} + \sum_{n=1}^{N_{D}} b_n \cdot y_{k-n} \quad (4) \]

where \( x_k \) is the received signal and \( y_k \) is the estimated symbols. The optimal weights \( a_n \) and \( b_n \) are found based on the least mean square (LMS) algorithm, which minimizes the mean square error between the actual output and the desired output from DFE [32]. In LMS, the weights are computed iteratively based on the equation below [32]:

\[ W_N(i+1) = W_N(i) + \mu \left[ y_k(i) - W_N^T(i) X_N(i) \right] X_N(i) \quad (5) \]

where \( W_N \) is the weight vector, \( N \) is the number of delay stages, \( X_N \) is the input signal vector, \( i \) indicates the sequence of iteration, and \( \mu \) is the step size which controls the rate of convergence.

### III. EXPERIMENTAL SETUP

A DPSK UWOC system with SiPM based receiver is proposed and its feasibility is experimentally investigated. The detailed experimental setup is shown in Fig. 4. In the transmitting site, a 532nm single frequency laser (linewidth < 150kHz) is used to emit the continuous-wave (CW) light which is then modulated using the phase modulator (Junoptik PM532, maximum modulation frequency > 500MHz). The DPSK precoder is realized in the offline MATLAB program, which generates the DPSK signal from a pseudorandom binary sequence (PRBS) in advance, and the corresponding voltages for phase modulation are pre-stored in the AFG (Tektronix AFG31252) and used upon request. Owing to the limited bandwidth of the AFG available, the data rate is set to 200Mbps in demonstrating the feasibility of our proposed system. A fiber collimator (FC) is connected to the output port of the phase modulator, therefore the phase-modulated optical signal is sent out as a parallel wireless optical beam. The output power of the optical signal at the output of the transmitter is fixed at 0dBm (1mW). The underwater channel is simulated by a glass water tank (1.6 m × 0.25 m × 0.25 m) filled with tap water, of which the attenuation coefficient is measured as about 0.15m⁻¹. The measured water temperature is 25°C.

In the receiving site, a variable neutral density filter is used at the end of the water tank to achieve different channel attenuation and hence the different optical power of the received signal. Another FC is used to collimate the receiving phase-modulated optical signal into a fiber-based DLI, which is used to conduct the DPSK demodulation based on the interference of every two adjacent bits. A delay line is used to set the delay of \( T_p = 5 \text{ns} \) (ie. The duration of one bit at the data rate of 200Mbps) between the two paths of DLI which is implemented by a one-meter fiber. Another phase modulator is placed in one of the arms of DLI and driven by a programmable DC voltage source based on the monitored signal amplitude from the detection, to compensate the slow relative phase drift between the two paths of the DLI due to the temperature and other environmental fluctuation. The demodulated signal is then detected by a SiPM (SensL J series 30035) in the “single-end detection” scheme. The APD (Thorlabs APD210), which is commonly used in UWOC experiments, is also tested here. In order to minimize the background noise, the SiPM is covered with a black box during the experiments. The measured ambient light is about 1nW. The detected signal is then captured by a 20GS/s software controlled oscilloscope (Keysight DSOS254A). The parameters are summarized in Table 2.

The data acquisition, synchronization and the bit error rates (BERs) calculation are conducted in an offline Matlab program via the data transferred from the oscilloscope to a computer. Specifically, the captured signal is decoded back into the binary bits with a searched optimum decision threshold after the synchronization. The alignment between the received and transmitted signal is conducted via the use of cross-correlation [33]–[35]. The BER is then calculated by the comparison between the decoded bits and the transmitted bits.
IV. RESULTS AND DISCUSSION

In our experiment, the 532nm phase modulator (Jenoptik PM532) is implemented using integrated-optical waveguide and the modulation is based on the linear electro optic effect, which describes a change of the refractive index of an optical medium in response to an electric field [36]. The change in refractive index is proportional to the strength of the applied electric field [36]. Materials exhibiting this effect are known as electro optic materials and Lithium niobate (LiNbO₃) is normally the preferred material for the fabrication of integrated optical modulators [36], which is also used for the phase modulator in this work. When an electric field is applied to the phase modulator, the change in refractive index results in a phase shift of the propagating light beam [36]. Therefore, the transmitted optical beam is phase modulated by this modulator in our experiment with the applied electric signal from AFG.

In order to obtain the optimized performance of the proposed system for underwater transmission, we firstly test the operation of the phase modulation and find the optimum operation point of the phase modulator in use. Therefore, an interferometric setup is built as shown in Fig. 5 (a), which converts the phase modulation into an amplitude modulation and detected by the APD. A 200MHz square-wave signal generated from AFG is applied to the electrodes of the phase modulator which is then detected as the modulated intensity at the input of APD. The normalized peak power of the output pulses ($P_{\text{out}}$) is plotted in Fig. 5(b) as a function of the peak-to-peak voltage of the modulation signal ($V_{\text{pp}}$). It can be seen that $P_{\text{out}}$ is maximized when the $V_{\text{pp}}$ is at about 2.6V, which is fixed at the following experiments as the optimum DPSK drive voltage.
Then, based on the setup shown in Fig. 4, the performance of the DPSK UWOC system with SiPM is investigated. The SiPM operates in the “analog mode”. The 3dB bandwidth of SiPM available in our experiment is tested as about 107MHz (as shown in Fig. 6(a)). The presence of ISI in the SiPM based detection can be observed from Fig. 6(b), which shows the transmitted signal input to the phase modulator and the recovered signal. DFE is realized in the offline Matlab program in our experiment. Fig. 7 shows the eye diagrams with and without DFE, indicating the effective mitigation of the ISI by using DFE in the detection.

The BER performance of the 200Mbps DPSK UWOC with SiPM is experimentally investigated by the proof-of-concept experiment featuring additional emulated channel losses. After transmission along the water tank, the optical power is further varied by adjusting the variable neutral density filter. The measured BERs are plotted in Fig. 8 as a function of the optical power monitored at the input of the detector. The forward error correction (FEC) limit of 3.8 × 10⁻³ [6] is shown as a blue dashed line in Fig. 8. This is the maximum BER level which a standard FEC code can operate. The BER performance of the system using an APD based receiver is also plotted for comparison. For the case of APD-based detection, the BER increases with the transmission loss, and it is increased from 1.44 × 10⁻⁴ to 1.35 × 10⁻¹ when the received optical power is reduced from −22.2 dBm to −35.2 dBm.

In order to obtain BERs below the FEC threshold, the minimum required optical power at the APD for a feasible 200Mbps DPSK UWOC system is about −28.6 dBm. On the other hand, it can be seen from Fig. 8 that the system using the SiPM offers much better system performance in term of BER than the case with APD based receiver. This is due to that the use of SiPM provides a significant enhancement in the sensitivity of the receiving site. The overall reduction in BERs is approximately two orders of magnitudes. At the optical power of −32.2 dBm, the BER of the DPSK system is reduced from 4.16 × 10⁻² to 5.38 × 10⁻⁴ by replacing APD with SiPM, and the corresponding eye diagrams are plotted as the insets in Fig. 8. Much more clear eye diagram is obtained with SiPM. Moreover, the minimum required optical power at the SiPM for achieving a 200Mbps DPSK UWOC transmission with BER below the FEC threshold is approximately −40.2 dBm, which is about 11.6 dB lower than the case of APD. The results suggest that the proposed UWOC system based on DPSK modulation is feasible with either the commonly used APD or the more sensitive SiPM, and the DPSK UWOC system using SiPM is able to work under 11.6 dB more transmission loss than using APD.

In addition, we also estimate the achievable distance of the proposed system based on the above results. The maximum acceptable total attenuation of the tested system is about 40.2dB for achieving a BER below the FEC threshold, given that the output power from our transmitter is 0 dBm. Due to the imperfection of this homemade DLI, the detection system in this feasibility study has a total insertion loss of about 8 dB. Therefore, the maximum allowed channel loss can be calculated as about 32.2dB, corresponding to 49m in the tested tap water (attenuation coefficient of 0.15m⁻¹) or 132m in pure sea water (attenuation coefficient of 0.056 m⁻¹ [3]). With an integrated DLI dedicated to DPSK demodulation and a higher power laser, the maximum communication distance can be further improved.

V. CONCLUSION

In this work, the feasibility of a 200Mbps DPSK UWOC system using SiPM based receiver is experimentally demonstrated, which enables underwater data transmission based on modulating the phase of light wave carrier. The minimum required received power for achieving 200Mbps DPSK UWOC transmission with a BER below the FEC threshold is about −28.6 dBm and −40.2 dBm for the APD and SiPM based receiver, respectively. The use of SiPM in the detection significantly enhances the performance of the proposed DPSK UWOC system, compared with the commonly used APD. With SiPM, the BERs are reduced by two orders of magnitude, and the minimum required received power for achieving 200 Mbps DPSK UWOC transmission with BER below the FEC threshold is reduced by nearly 12 dB. The data rate of the tested system can be further increased with a wider bandwidth signal generator and a shorter delay line.

To the best of our knowledge, this work experimentally demonstrated a phase-modulated UWOC system with SiPM for the first time. The possible performance degradation of the
proposed system caused by environmental dynamics, such as turbulence and bubbles, would be investigated in the future work. We hope this work will also encourage research to explore the application of higher order phase modulation schemes with higher spectral efficiency in UWOC.

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REFERENCES
[1] X. Liu, S. Yi, X. Zhou, Z. Fang, Z. Qiu, L. Hu, C. Cong, L. Zheng, R. Liu, and P. Tian, “34.5 m underwater optical wireless communication with 2.70 Gbps data rate based on a green laser diode with NRZ-OOK modulation,” Opt. Express, vol. 25, no. 22, pp. 27937–27947, Oct. 2017.
[2] M. Kong, W. Lv, T. Ali, R. Sarwar, C. Yu, Y. Qiu, F. Qu, Z. Xu, J. Han, and J. Xu, “10-m 9.51-Gb/s RGB laser diodes-based WDM underwater wireless optical communication,” Opt. Express, vol. 25, no. 17, pp. 20829–20834, Aug. 2017.
[3] Z. Zeng, S. Fu, H. Zhang, Y. Dong, and J. Cheng, “A survey of underwater optical wireless communications,” IEEE Commun. Surveys Tuts., vol. 19, no. 1, pp. 204–238, 1st Quart., 2017.
[4] H. Kaushal and G. Kaddoum, “Underwater optical wireless communica- tions,” IEEE Access, vol. 4, pp. 1518–1547, 2016.
[5] C. Shen, Y. Guo, H. M. Oudebi, T. K. N. G. Liu, K.-H. Park, K.-T. Ho, M.-S. Alouini, and B. S. Ooi, “20-meter underwater optical wireless communication link with 1.5 Gbps data rate,” Opt. Express, vol. 24, no. 22, pp. 25502–25509, Oct. 2016.
[6] J. Wang, C. Lu, S. Li, and Z. Xu, “100 m/500 Mbps underwater optical wireless communication using an NRZ-OOK modulated 520 nm laser diode,” Opt. Express, vol. 27, no. 9, pp. 12171–12181, Apr. 2019.
[7] B. Cochenour, L. Mullen, and A. Laux, “Phase coherent digital communica- tions for wireless optical links in turbid underwater environments,” in Proc. OCEANS, Vancouver, BC, Canada, 2007, pp. 1–5.
[8] J. M. Kahn and K.-P. Ho, “Spectral efficiency limits and modulation/detection techniques for DWDM systems,” IEEE J. Sel. Topics Quantum Electron., vol. 10, no. 2, pp. 259–272, Mar. 2004.
[9] W. C. Cox, B. L. Hughes, and J. F. Muth, “A polarization shift-keying sys- tem for underwater optical communications,” in Proc. OCEANS, Biloxi, MS, USA, Oct. 2009, pp. 1–4.
[10] Y. Fu and Y. Du, “Performance of heterodyne differential phase-shift- keying underwater wireless optical communication systems in gamma-delta-modulated turbulence,” Appl. Opt., vol. 57, no. 9, pp. 2057–2063, Mar. 2018.
[11] A. H. Gnauck and P. J. Winzer, “Optical phase-shift-keyed transmission,” J. Lightw. Technol., vol. 23, no. 1, pp. 115–130, Jan. 2005.
[12] S. Tarantino, B. D. Lio, D. Cazzolino, and D. Bacco, “Feasibility study of quantum communications in aquatic scenarios,” Optik, vol. 216, Aug. 2020, Art no. 164639.
[13] G. Xie, A. Dang, and H. Guo, “Effects of atmosphere dominated phase fluctuation and intensity scintillation to DPSK system,” in Proc. IEEE Int. Conf. Commun. (ICC), Kyoto, Japan, Jun. 2011, pp. 1–6.
[14] N. Chi, L. Xu, J. Zhang, P. V. Holm-Nielsen, C. Peucheret, S. Yu, and P. Jeppesen, “Improve the performance of orthogonal ASK/DPSK optical label switching by DC-balanced line encoding,” in Proc. Conf. Commun. (ICC), London, UK, Jun. 2012, pp. 181–185, 2013.
[15] C. Lu, J. Wang, S. Li, and Z. Xu, “60 m/2.5 Gbps underwater optical wireless communication with NRZ-OOK modulation and digital equalization,” in Proc. Conf. Lasers Electro-Opt. (CLEO), San Jose, CA, USA, 2019, pp. 1–2, Paper SM2G.6.
[16] W. Lyu, Y. Zhao, X. Chen, X. Yang, Y. Qiu, Z. Tong, and J. Xu, “Experimental demonstration of an underwater wireless optical communication employing spread spectrum technology,” Opt. Express, vol. 28, no. 7, pp. 10027–10038, Mar. 2020.

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