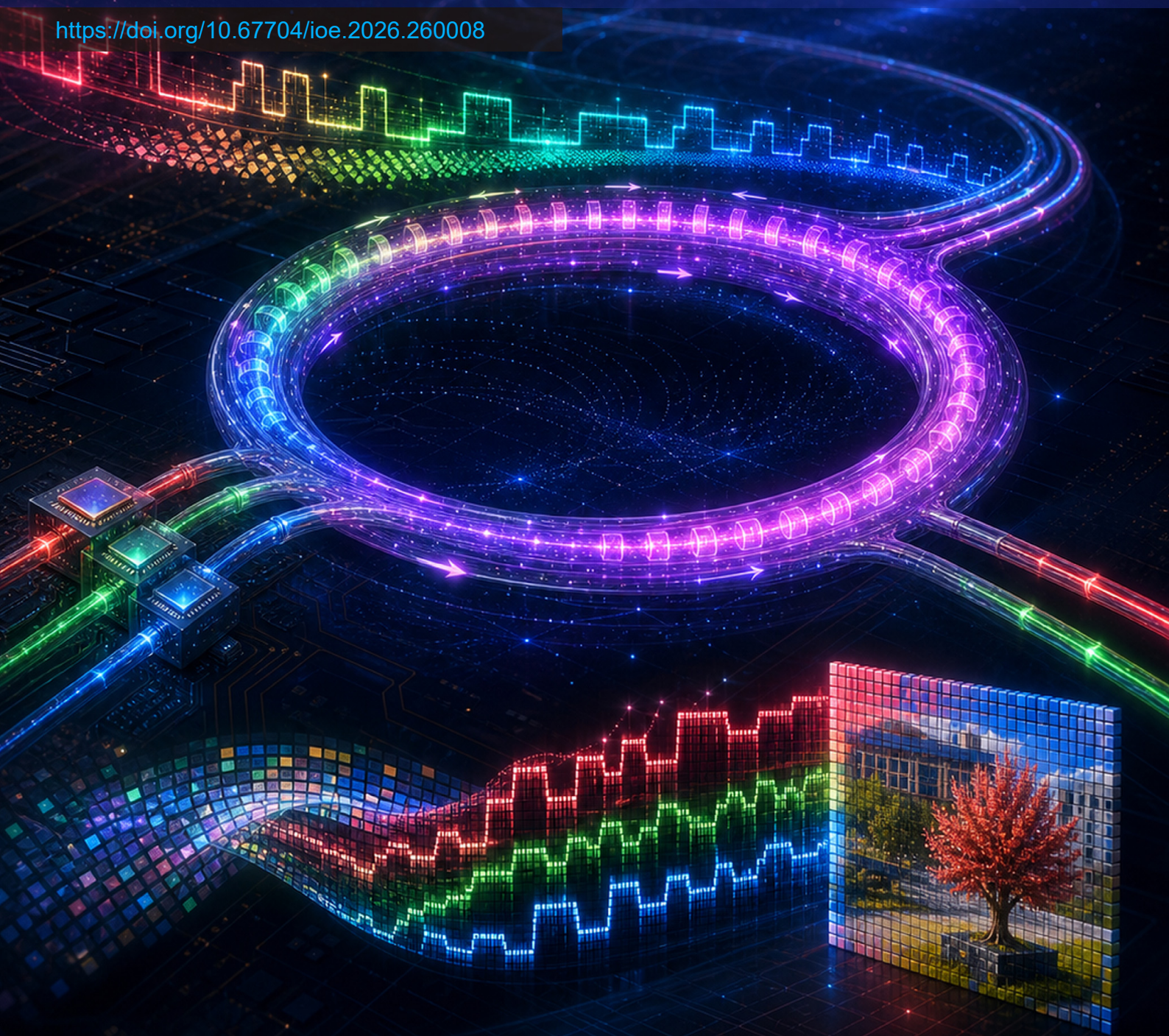


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Towards Gigabit-scale digital signal storage enabled by a distributed Raman-amplified optical memory

Wenxing Gong^{1,2†}, Chao Song^{1,2†}, Sheng Dong^{1,2}, Jingxu Chen^{1,2}, Yiran Guan³, Yuan Cao^{1,2}, Jiejun Zhang^{1,2*} and Jianping Yao^{1,2,3*}

Abstract: Optical computing promises ultrahigh-speed and energy-efficient information processing, offering unique advantages for data-intensive tasks such as machine-learning inference, image processing, and scientific simulations. Yet, the scalability of such systems remains fundamentally constrained by the absence of high-capacity optical memories capable of storing intermediate computational states without resorting to electronic conversions. Here we propose and experimentally demonstrate an all-optical digital memory based on a distributed Raman-amplified frequency-shifting loop, designed to function as an optical cache within large-scale photonic computing pipelines. The system enables long-duration, low-noise circulation of optical waveforms while maintaining high signal fidelity. We experimentally validate the storage of both grayscale and color image data and achieve an effective number of bits (ENOB) of 3 bits and a storage time of 20 ms. The experimental results show that for a single channel, the ideal maximum storage capacity is 3.2 Mbit and the effective storage capacity is 1.2 Mbit; for RGB channels, the ideal maximum storage capacity is 9.6 Mbit and the effective storage capacity is 3.2 Mbit. According to the theoretical calculations, the ideal storage capacity of the system can reach 3.84 Gbit, while the effective storage capacity is approximately 1.44 Gbit. These results establish a practical route toward scalable intermediate data storage in optical computing systems. By addressing one of the central bottlenecks in photonic computation, the lack of high-fidelity, high-capacity optical storage, this work advances the feasibility of fully optical computing architectures with substantial potential across domains requiring high-throughput, low-latency processing.

Keywords: optical computing; all-optical memory; Raman-amplified loop; photonic cache; optical data storage

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1 Introduction

Advances in optical computing over the past decade have revealed a strong demand for accelerating core computational primitives, including optical arithmetic operations, matrix-vector multiplication, and convolutional processing^{1–4}. Both photonic integrated circuits (PICs) and free-space optical platforms have been reported to enable high-throughput implementations of these operations, positioning optical computing as a promising candidate for next-generation information processing solutions^{5,6}. Leveraging

the intrinsic properties of photonics, such as ultralow latency, massive spatial-temporal parallelism, and minimal energy dissipation, optical systems can offer orders-of-magnitude improvements in bandwidth and power efficiency compared with their electronic counterparts^{7–13}. These capabilities make optical approaches attractive for computationally intensive tasks such as deep neural network inference, image processing, and large-scale scientific simulations.

Despite the rapid progress in optical processors, the development of an accompanying high-performance optical

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¹International Cooperation Joint Laboratory for Optoelectronic Hybrid Integrated Circuits, Jinan University, Guangzhou 510632, China; ²College of Physics & Optoelectronic Engineering, Jinan University, Guangzhou 510632, China; ³Microwave Photonics Research Laboratory, School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, ON K1N 6N5, Canada.

[†]These authors contributed equally to this work.

*Correspondence: JJ Zhang, E-mail: zhangjiejun@jnu.edu.cn; JP Yao, E-mail: jpyao@uottawa.ca

memory, which is crucial for buffering intermediate data and enabling complex multi-stage computations, has significantly lagged behind¹⁴. A scalable "compute-in-light, store-in-light, and flow-in-light" architecture remains elusive, as current systems rely heavily on electronic memory to store intermediate results^{15–18}. The lack of robust all-optical storage critically limits the attainable size, depth, and functionality of photonic computing pipelines. Addressing this gap is essential for realizing fully optical computational systems capable of operating without optoelectronic bottlenecks.

Frequency-shifting loops (FSLs) have emerged as a versatile platform for optical waveform generation, analog signal buffering, and image-domain operations such as optical convolution in convolutional neural networks^{19–23}. However, their application as digital memories has been hindered by several limitations due to the use of erbium-doped fiber amplifiers (EDFAs) for loss compensation. These include significant noise that degrades the waveform fidelity over multiple circulations, transient gain dynamics that restrict the storage duration^{24,25}, and loop-length constraints that limit the accessible data record length. Collectively, these challenges have so far prevented FSL-based architectures from serving as practical high-capacity optical memories.

In this paper, we introduce a Raman-amplification-assisted frequency-shifting loop designed for high-fidelity digital data storage²⁶. By incorporating a distributed Raman fiber amplifier (DRFA) and employing wavelength-division multiplexing, the system achieves stable, low-noise circulation of optical signals over extended durations²⁷. Compared with an EDFA, a DRFA has much lower noise, better gain flatness^{28,29}, and broader amplification bandwidth, which enable multi-wavelength operation with a substantially increased storage capacity^{30,31}. These properties make Raman-amplification-assisted loops particularly suited for digital memory applications where long-term stability and high fidelity are paramount. The proposed system is experi-

mentally demonstrated. Storage of both grayscale and color image data with an effective number of bits (ENOB) of 3 bits is experimentally demonstrated. The experimentally measured effective storage capacity is 1.2 Mbit for a single grayscale channel and that for the RGB channels is 3.6 Mbit, whereas the ideal storage capacity is up to 3.84 Gbit, with an effective storage capacity of 1.44 Gbit.

2 Principle

Figure 1 illustrates the proposed all-optical digital signal storage system implemented based on a distributed Raman-amplification-assisted FSL. An optical carrier generated by a laser diode (LD) is directed into a Mach-Zehnder modulator (MZM) through a polarization controller (PC). The polarization state of the optical carrier is adjusted by the PC to minimize the polarization-dependent loss at the MZM. A digital signal to be stored in the memory is loaded to an arbitrary waveform generator (AWG), to generate an electrical waveform, which is subsequently amplitude modulated on the optical carrier at the MZM. To increase the data storage capacity, wavelength-division multiplexing can be employed. To do so, multiple digital signals are modulated on different wavelengths, which are then combined at a dense wavelength-division multiplexing (DWDM). The combined signal is sent to an acousto-optic modulator (AOM1), which functions as an optical switch to allow the signal with a duration smaller than the round-trip time of the FSL to be injected into the FSL.

The Raman-amplification-assisted FSL is the core module of the system which consists of an optical coupler (OC), a DRFA, a dispersion-shifted fiber (DSF), an AOM (AOM2), and an optical bandpass filter (OBPF). The DRFA is implemented using a DSF with near-zero chromatic dispersion, which simultaneously serves as the Raman gain medium and a dispersion-managed delay line. Several kilometers of DSF

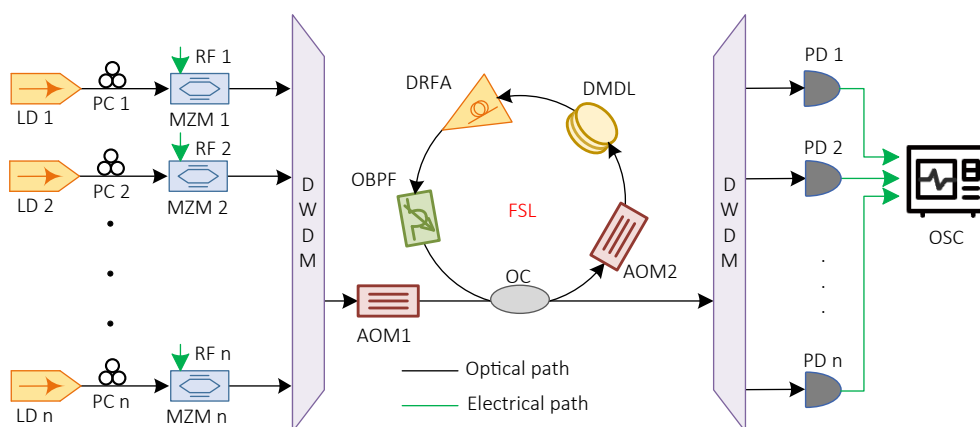


Fig. 1 | Schematic diagram of the proposed all-optical digital signal storage system based on Raman-amplification-assisted FSL. LD: laser diode; PC: polarization controller; MZM: Mach-Zehnder modulator; DWDM: Dense wavelength division multiplexer; AOM: acousto-optic modulator; OC: optical coupler; DMDL: dispersion managed delay line; DRFA: distributed Raman fiber amplifier; OBPF: optical bandpass filter; PD: photodetector; OSC: oscilloscope.

are employed to provide sufficient distributed Raman gain for compensating the loop loss while introducing a long round-trip delay. Owing to the near-zero dispersion of the DSF, dispersion-induced power fading and inter-symbol interference are effectively suppressed during repeated circulation, ensuring that the overall dispersion of the FSL remains close to zero. The key advantage of using distributed Raman amplification is that the low added amplification noise, making the noise figure (NF) of the FSL low. To avoid lasing, a second AOM (AOM2) is introduced in the FSL to produce a frequency shift³². The OBPF in the loop is employed to remove the out-of-band amplified spontaneous emission (ASE) noise. After each circulation, part of the optical signal is coupled out of the FSL via the OC, and the remaining optical signal continues to circulate in the FSL. The optical signals at the output of the FSL are sent to a second DWDM where the optical signals on different wavelengths are demultiplexed and are applied to an array of photodiodes (PDs) where the stored signals are restored. An oscilloscope (OSC) is used to monitor the restored signals.

To store an image, we first convert the image to a one-dimensional temporal signal. Figure 2 shows the process where a color image is converted to a one-dimensional temporal signal. As can be seen, a color image in Fig. 2(a) is converted into an 8-bit grayscale image, shown in Fig. 2(b), where the intensity of a pixel is from 0 to 255. A locally enlarged view of the grayscale image is presented in Fig. 2(c). In this way, the grayscale image is transformed into a digital-signal matrix, as shown in Fig. 2(d). Since the digital signal must be modulated on an optical carrier, the matrix is vectorized and appended with a short synchronization header, yielding a final PAM-256 digital signal that is loaded to an AWG, as illustrated in Fig. 2(e). When an 8-bit grayscale image is converted into a digital data array, the grayscale value of each pixel is represented by 8 bits, corresponding to $2^8 = 256$ intensity levels (0–255). To load this

digital signal onto an optical carrier via intensity modulation, PAM-256 modulation can be used, where each grayscale value is directly represented by one of 256 distinct signal levels.

Since the DRFA offers a flat gain profile with a wide bandwidth exceeding 40 nm and a low NF, wavelength-division multiplexing can be employed to greatly increase the storage capacity of the system. The theoretical maximum storage capacity of the proposed all-optical digital signal storage system S_{ideal} is given by

$$S_{ideal} = N_{\lambda} f_s N_{bit} \left(\frac{n_0 L}{c} \right), \quad (1)$$

where N_{λ} is the number of multiplexing wavelengths, which is a key factor for capacity expansion, N_{bit} is the number of bits carried by each symbol. For a PAM-256 signal, the number of bits is 8, n_0 is the effective refractive index of the optical fiber, f_s is the sampling rate of the AWG, c is the speed of light in vacuum, and L is the physical length of the FSL. The round-trip time delay is given by $\tau = n_0 L/c$, which determines the maximum storage time of a data packet without overlap.

As the optical signal recirculates within the FSL, the accumulated ASE noise progressively degrades the SNR of the optical signal, thereby limiting the maximum number of circulations. The ASE noise mainly originates from the optical amplifier within the FSL. The ASE noise power generated by the DRFA can be expressed as

$$P_{DRFA,ASE} = h\nu B_0 \int_0^L C_R P_{p0} \exp \left\{ \begin{aligned} & -(\alpha_s + \alpha_p) \xi \\ & + \frac{C_R P_{p0}}{\alpha_p} [1 - \exp(-\alpha_p \xi)] \end{aligned} \right\} d\xi, \quad (2)$$

where B_0 is the bandwidth of the optical filter, $P_{DRFA,ASE}$ is the ASE power of the DRFA within the bandwidth B_0 , h is the Planck's constant, ν is the optical frequency of the

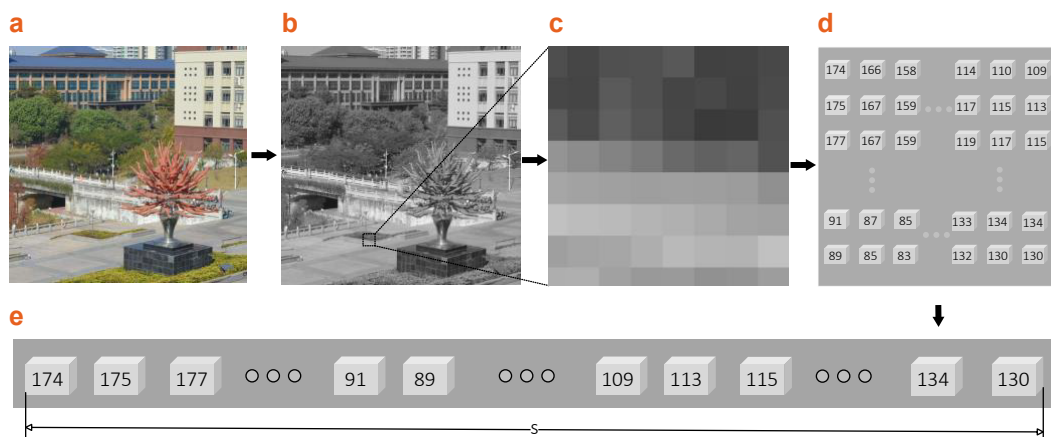


Fig. 2 | Process to show a color image converted to a PAM-256 digital signal. (a) A color image. (b) Converted to an 8-bit grayscale image. (c) Locally enlarged view of the grayscale image. (d) Corresponding PAM-256 digital signal matrix. (e) Vectorized PAM-256 digital signal.

optical carrier, C_R is the effective Raman gain coefficient of the fiber span, P_{P0} is the injection optical pump power, and α_s and α_p are the attenuation coefficients of the optical signal and the optical pump, respectively. Equation (2) indicates that the noise is continuously generated and simultaneously attenuated along the propagation path, allowing the signal to maintain a relatively high SNR.

In the FSL, the decrease in the SNR of the PAM-256 signal is primarily determined by two factors, the ASE noise and the transient effects of the DRFA³³. But these two factors differ fundamentally in their physical mechanisms and manifestations. The ASE noise originates from the spontaneous emission process of the Raman amplification, characterized by its randomness and broadband nature. The ASE noise accumulates continuously in the FSL circulations, causing a gradual increase in signal noise, resulting in a decrease in the SNR, which will cause image reconstruction errors. On the other hand, the transient effects of the DRFA are time-dependent gain fluctuations caused by the dynamic response of the gain, primarily manifested as slow gain drift and amplitude inhomogeneity. For a signal with a long duration, the impact of this transient effect is relatively limited in the first few cycles, but over multiple circulations, the accumulated gain fluctuations lead to a decrease in the relative amplitudes between different levels of the PAM-256 signal. When reconstructing the signal into an image, this level fluctuations introduce additional reconstruction errors. Based on the above analysis, the ASE noise and DRFA transient effects function jointly to degrade the signal quality through random noise accumulation and amplitude fluctuations. In addition, the dark noise of the PD and the AWG quantization noise also contribute to the total noise. Thus, the total SNR, which is defined as the ratio of the original signal power to the noise power in the received signal, is given by

$$\text{SNR}_{\text{image}} = 10\log_{10} \left(\frac{P_{\text{signal}}}{P_{\text{noise}}} \right) = 10\log_{10} \left(\frac{\frac{1}{M} \sum y_i^2}{\text{MSE}} \right), \quad (3)$$

where P_{signal} is the average power of the signal, M is the total number of pixels, y_i is the original image data, P_{noise} can be approximated by the mean square error (MSE) given by

$$\text{MSE} = \frac{1}{M} \sum_{i=1}^M (\hat{y}_i - y_i)^2, \quad (4)$$

where $\hat{y}_i$ is the restored image data.

In a reconstructed image, a decrease in SNR manifests as a loss in the fine image details, leading to a reduction in the quality of the recovered image. This degradation trend becomes increasingly pronounced with repeated circulations, reflecting the combined impact of accumulated noise and loop loss on image quality. From a quantitative analysis perspective, the difference between the reconstructed image and the original image can be characterized by the root

mean square error (RMSE), given by

$$\text{RMSE} = \sqrt{\text{MSE}}. \quad (5)$$

For a signal that undergoes multiple circulations, a small RMSE indicates that the effective information in the original signal is well preserved. This preservation is manifested as a higher effective number of bits (ENOB). Consequently, ENOB serves as a crucial metric for assessing the overall fidelity of the system. In the context of optical storage, ENOB can be used as a quantitative indicator to evaluate the storage accuracy and information retention ability. Specifically, it measures how much true, effective data that the system retains after multiple circulation cycles. Here the ENOB is defined as

$$\text{ENOB} = \frac{10\log_{10} \left(\frac{1}{m} \sum y_i^2 / \text{MSE} \right) - 1.76}{6.02}. \quad (6)$$

From the above equation, the ENOB ultimately determines the practically recoverable storage capacity. As the MSE increases, the ENOB gradually decreases. This reduction in ENOB, in turn, lowers the effective storage capacity of the signal in each circulation, thereby limiting the overall storage capacity of the system. Thus, the recoverable storage capacity of the system is given by

$$S_{\text{real}} = N_{\lambda} f_s \tau \frac{\text{ENOB}}{N_{\text{bit}}}, \quad (7)$$

where the round-trip time $\tau = n_0 L / c$ is approximately 100 μs for the 20 km FSL.

The storage capacity and the storage time of the digital signal storage system are primarily limited by the MSE. The accumulated ASE noise introduced by the DRFA, the amplitude fluctuations introduced due to the transient effects, the detector dark noise, and the AWG quantization noise all contribute to the MSE. As the number of circulation increases, the continuous accumulation of noise amplifies the signal noise and distortions, manifested as an increase in the MSE or a decrease in the ENOB. Consequently, the number of effective cycles is limited, which determines the storage capacity and storage duration. The storage capacity is also determined by the gain bandwidth of the DRFA. For a wider gain bandwidth, a larger number of multiplexing wavelengths can be supported, leading to a higher storage capacity. Thus, to increase the storage capacity and storage time, the MSE should be minimized. In addition, the gain bandwidth can be maximized to further increase the storage capacity. Since a DRFA has inherently a small ASE noise and a wide bandwidth, the use of it in an FSL is an ideal device for loss compensation.

3 Results

A proof-of-concept experiment is conducted based on the setup shown in Fig. 1. A PAM-256 signal corresponding to a

grey-level image is generated by an AWG, which is then modulated on a single-wavelength optical carrier at a 10-GHz MZM. The wavelength of the optical carrier is set at 1550.12 nm, and its optical power is 20 dBm. Prior to entering the MZM, the polarization direction of the optical carrier is adjusted to ensure it is well aligned with the principal axis of the MZM to minimize the polarization-dependent loss. An AOM (AOM1), driven by rectangular pulse train at a repetition rate of 25 Hz and a pulse width of 80- μ s, is employed as an optical switch to allow the signal with a duration smaller than the round-trip time of the FSL to be injected into the FSL. The gated signal is coupled into the FSL through a 90:10 OC. With the FSL length set to 20 km, the maximum storage duration of the optical signal in the loop is approximately 100 μ s. Considering that the sampling rate of the AWG is 5 GSa/s, according to Eq. (1), the maximum storage capacity of the digital signal for the FSL is about 4 Mbit if only a single wavelength is used. To avoid lasing, AOM2 is used in the FSL to introduce a 80-MHz frequency shift. In addition, AOM2 is also used to electronically controlling its attenuation to balance the loop gain, thereby maximizing the achievable number of circulations. The DRFA provides in-loop amplification to compensate for the propagation losses, while a 100-GHz bandwidth OBPF with a center wavelength of 1550.12 nm is used to suppress the out-of-band ASE noise. After each circulation, 90% of the optical power is recirculated for the next round-trip, and the remaining 10% is coupled to a PD, where the stored signal is recovered. The recovered signal is sampled by a high-speed OSC and processed to reconstruct the original image.

Figure 3(a) shows the temporal waveform of the initial stored digital signal. According to Eq. (1), the original grayscale image is converted into a PAM-256 signal of 2.88 Mbit. At the same time, a 0.32 Mbit flag sequence is added at the beginning of the PAM-256 waveform. The total stored digital data is 3.2 Mbit. Figure 3(b) shows the details of the flag sequence. The flag sequence has two functions: i) defining the maximum and minimum amplitude of the subsequent PAM-256 data; ii) providing a time stamp to ensure that AOM1 only shapes a single PAM-256 frame, even though the AWG is operating to provide continuous output.

Figure 3(c) shows the storage performance of the proposed all-optical memory. The PAM-256 signal remains detectable after more than 200 circulations, corresponding to a storage duration exceeding 20 ms. Fig. 3(d) and 3(e) present the measured PAM-256 waveforms after the 1st and 100th circulations, respectively. Compared with the waveform after the first circulation, the waveform after the 100th circulation exhibits significantly reduced amplitude, accompanied by enhanced pulse leading edge and weakened trailing edge. This degradation arises due to the four factors: i) The RFA gain is intentionally set below the total loop loss to suppress self-oscillation. ii) Accumulation of ASE noise from the RFA over multiple cycles, the dark noise of the PD

and the AWG quantization noise contribute to degrade the optical SNR; iii) After >200 circulations, cumulative frequency drift introduced by repeated frequency conversion exceeds the 3-dB bandwidth of the OBPF, pushing the signal spectrum into the filter falling edge and causing additional attenuation; iv) the transient effect of the RFA is weak and slightly enhances the leading edge of the signal, but this tiny enhancement accumulates over multiple circulations, eventually causing signal distortions. These combined effects ultimately limit the maximum achievable circulation number and the storage duration.

Figure 4 shows the grayscale images reconstructed from the stored signals after the first, 50th, 150th, and 200th circulations. The corresponding RMSE values are also shown. As can be seen, the restored images remain visually faithful to the original image within the first 50 circulations, which are consistent with the low RMSE value. After more than 150 circulations, the accumulated ASE noise within the DRFA reaches a critically significant level. This excessive noise manifests through a progressive degradation of image quality, characterized by an increase in image noise, a gradual loss of sharpness leading to blurring, the irreversible loss of fine details, and a continuously escalating degree of image distortion. This image quality degradation leads to an increase in the RMSE and a significant reduction in the image fidelity. Such deterioration fundamentally reflects the cumulative nature of noise accumulation during extended long-term storage, wherein each circulation incrementally contributes to the irreversible degradation of signal integrity. Fig. 4(d) shows significant transient effects. Because the image is restored column-by-column from left to right, the leading edge of the PAM-256 signal has a higher amplitude, appearing as a brighter region in the reconstructed image; conversely, the trailing edge had a lower amplitude, corresponding to a darker region. This brightness distribution characteristic is consistent with the amplitude variation trend of the unrestored signal, verifying the impact of transient effects on image reconstruction quality.

The system performance is further evaluated by examining the RMSE and the ENOB. Figure 5 shows the dependence of the RMSE and the ENOB on the number of circulations. The RMSE increases approximately linearly, with an average increment of 6.2×10^{-4} per cycle. This small growth rate indicates that noise accumulation within the loop is small, which is consistent with the prediction given by Eq. (2). Although the error gradually accumulates, the system maintains stable operation and good robustness over the first few circulations. The ENOB, shown as the orange curve in Fig. 5, quantifies the effective resolution of the stored signal. During the first ten circulations, the ENOB remains near 3 bits. As the number of circulations exceeds 100, the ENOB decreases significantly and approaches 1 bit. According to Eq. (7), based on the experimental results, although the loop can ideally support storage 3.2 Mbit of signal, the noise and distortion limit the ENOB to around

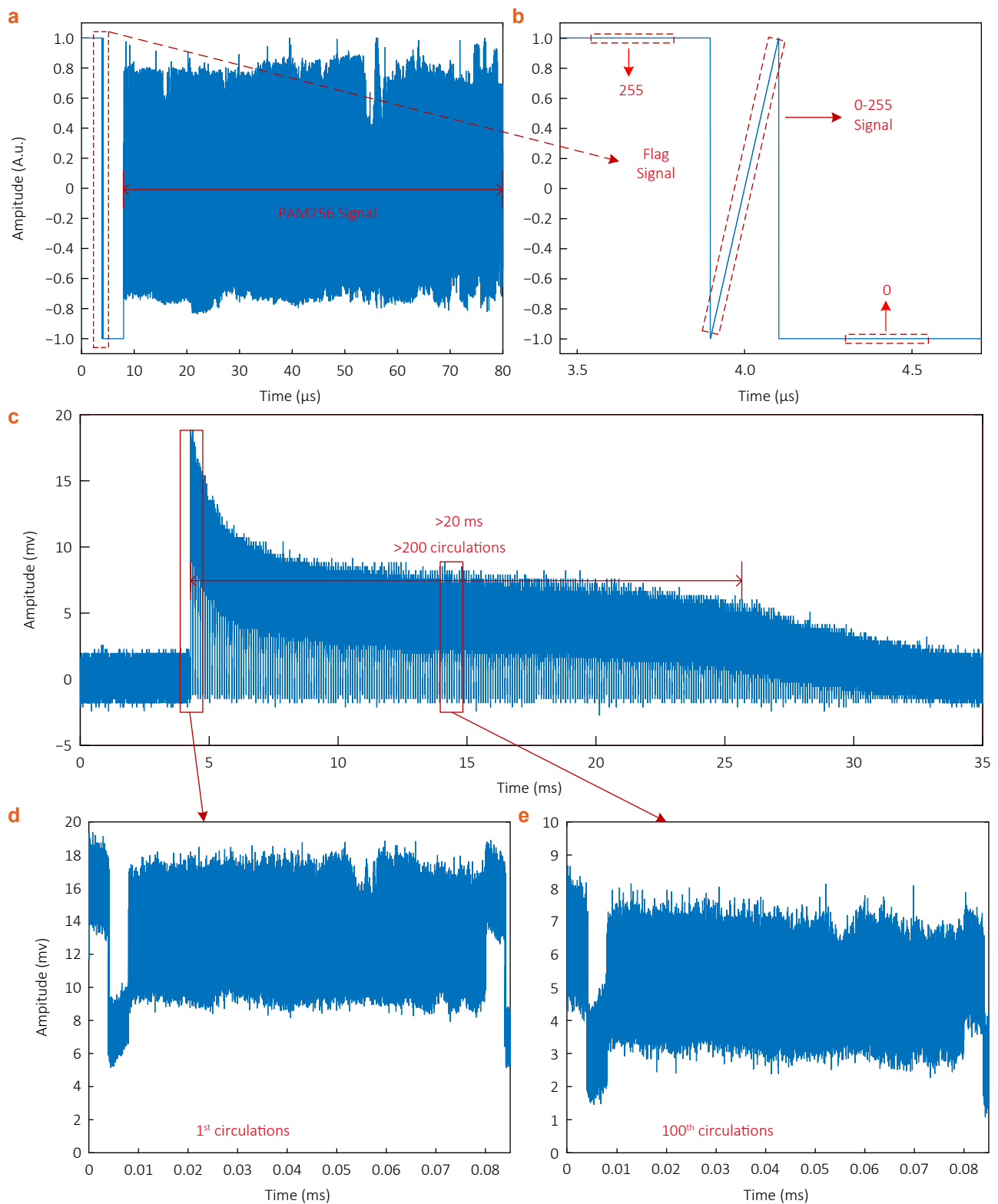


Fig. 3 | (a) The temporal waveform of the initial digital signal, including the flag sign and the PAM-256 digital signal. (b) The zoom-in view of the flag sign in (a). (c) The detected PAM-256 digital signals stored by the proposed system. (d) The temporal waveform of the stored signal after the first circulation. (e) The temporal waveform of the stored signal after the 100th circulation.

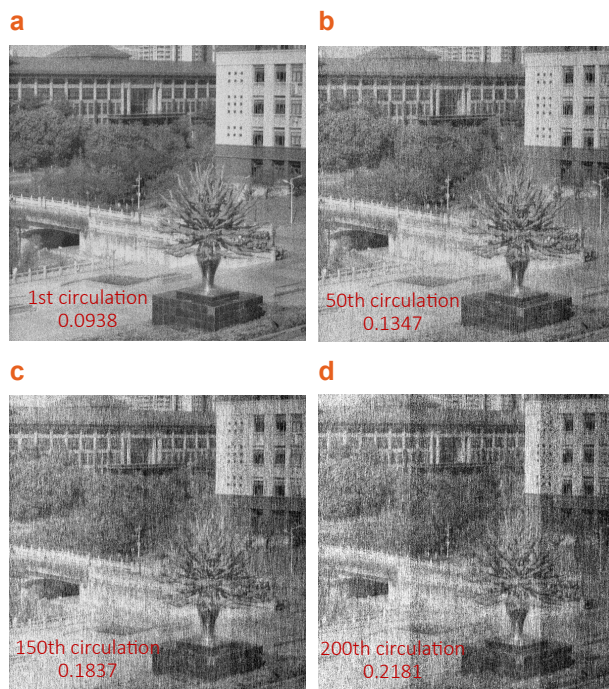


Fig. 4 | Grayscale images recovered from the storage digital signals. The grayscale images recovered from the (a) first, (b) 50th, (c) 150th, and (d) 200th circulations and the corresponding RMSE.

3 bits, thereby reducing the effective storage capacity to approximately 1.2 Mbit. These results indicate that while the proposed system exhibits good robustness over a limited number of circulations, the cumulative effects of noise and distortion ultimately constrain the achievable ENOB and, consequently, the effective storage capacity.

To evaluate the multi-channel processing capability, a multi-wavelength optical storage experiment is conducted in this study. Using the same modulation mechanism as single-channel storage experiment, the RGB components of an original color image are first converted into three one-dimensional PAM-256 signals. The data of each channel are

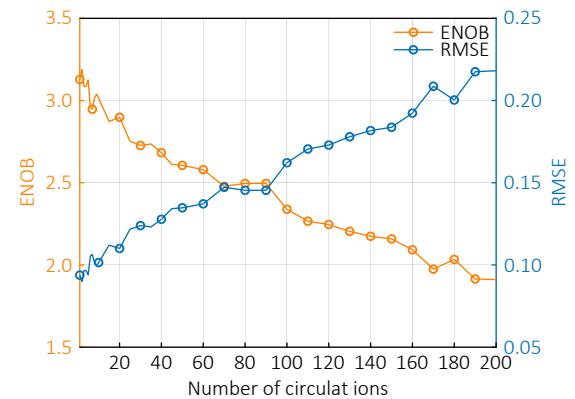


Fig. 5 | The RMSE and the ENOB (bit) values of the restored grayscale image versus number of circulations.

then modulated on three optical carriers at wavelengths of $\lambda_R=1550.12$ nm, $\lambda_G=1548.51$ nm, $\lambda_B=1546.92$ nm. The multi-wavelength optical signals at the output of the MZMs are wavelength-division multiplexed and jointly injected into the FSL. Finally, through wavelength-specific demodulation, the data of the three channels are detected and recovered to reconstruct the original color image.

Figure 6 shows the time-domain waveforms of the restored digital signals corresponding to the red, green, and blue channels. The signals for all three channels circulate over 200 cycles in the FSL, with a total storage duration greater than 20 ms per cycle. Based on these time-domain measurements, we successfully reconstructed the original color image through wavelength-resolved demodulation, channel reconstruction, and PAM-256 decoding, as shown in Fig. 7, where the reconstructed images after the 1st, 20th, 50th, and 100th circulations are presented. These results demonstrate that the proposed multi-wavelength optical storage scheme can reliably achieve the storage and recovery of multi-channel data over a relatively long cycle time.

Due to the 2.5 GHz bandwidth of the PD, the AWG used in the experiment was operating at a sampling rate of only

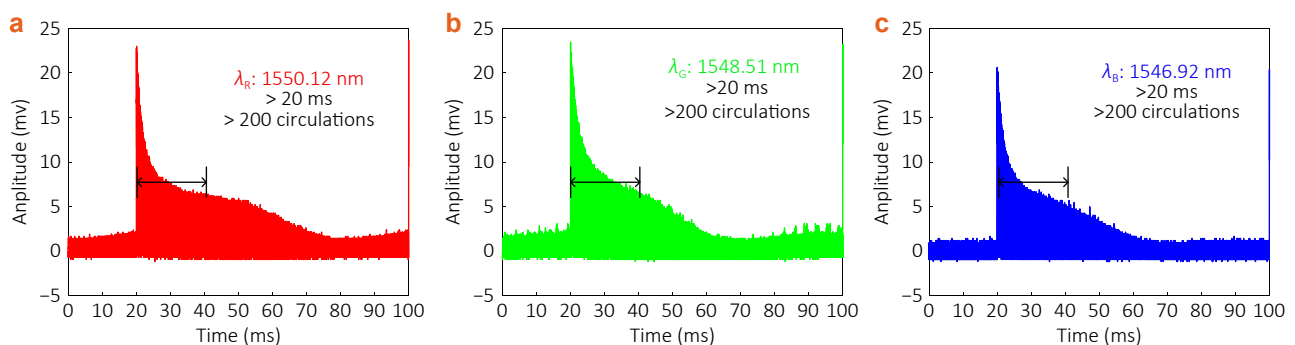


Fig. 6 | The stored digital signals. (a) Time-domain waveform of the digital signal corresponding to the red channel at 1550.12 nm. (b) Time-domain waveform of the digital signal corresponding to the green channel at 1548.51 nm. (c) Time-domain waveform of the digital signal corresponding to the blue channel at 1546.92 nm.

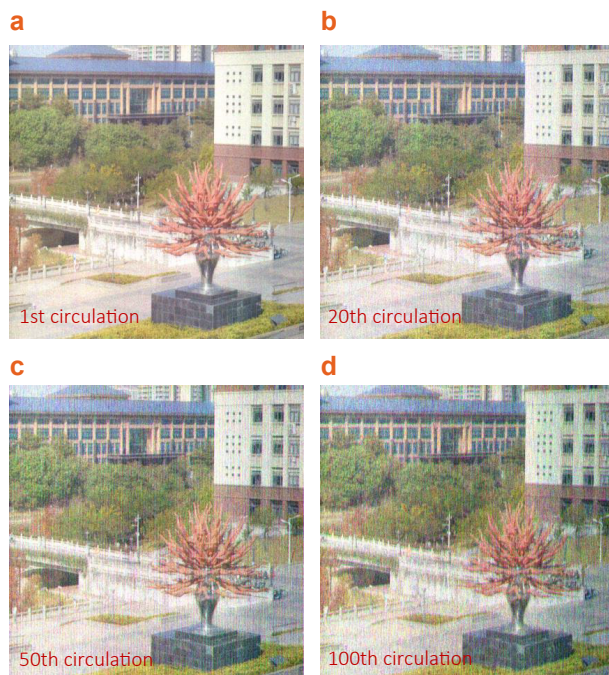


Fig. 7 | The color images recovered from the 1st, 20th, 50th, and 100th circulations.

5 GSa/s, and only three wavelength channels were activated. Consequently, the theoretical maximum storage capacity was 9.6 Mbit, and the effective storage capacity was approximately 3.2 Mbit. This result shows that the constructed FSL system exhibits excellent all-optical data storage performance. Considering that the DRFA used in the system achieves a gain bandwidth exceeding 40 nm around the 1550 nm band, when the wavelength spacing between adjacent channels is set to 125 GHz, up to 40 channels can be used. To avoid spectral overlap of the multi-wavelength signals during transmission, the maximum modulation signal bandwidth for each channel is set to 60 GHz, corresponding to a sampling rate of 120 GSa/s, with a 5 GHz guard band between the modulation sidebands of adjacent channels. Ultimately, under the PAM-256 modulation format, the theoretical maximum storage capacity of the system is 3.84 Gbit, while the actual recoverable storage capacity is approximately 1.44 Gbit. Therefore, the storage capacity of the current experimental system has not yet reached the gigabit level. Nevertheless, the proposed system demonstrates a feasible path toward gigabit-scale optical storage.

4 Discussion and conclusion

In summary, we have proposed and validated an all-optical digital storage system based on a distributed Raman amplification FSL. The architecture demonstrated in this work enables gigabit-scale optical storage with signal integrity, validating its viability as an intermediate buffer for optical

computing.

The key innovation enabling long time storage was the use of a DRFA with a low NF, which allows an optical signal to circulate in the FSL for a large number of circulations with minimal signal quality degradation. The operations of the system for both a single wavelength and multiple wavelengths were evaluated experimentally. In the single-wavelength experiment, the system achieved stable long-term storage of 3.2 Mbits PAM-256 data for 20 ms, with a minimum RMSE of 0.0938 and an ENOB greater than 3 bits. In the multi-wavelength experiment, the system was able to simultaneously process the RGB channels of a color image, with each channel stably recirculating more than 200 circulations, verifying its parallel processing capabilities. Beyond its relevance to optical computing, the proposed approach also holds promise for optical communication systems requiring temporary data buffering, data-center interconnects, and scalable optical information handling. By overcoming long-standing performance and stability challenges, the proposed Raman-amplification-assisted FSL platform provides a new pathway toward next-generation all-optical information storage technologies.

System storage capacity mainly depends on the length of the FSL, the modulation rate, the modulation order, and the number of WDM channels. Using the 40 nm flat gain bandwidth provided by the DRFA to support up to 40 wavelength channels increases the theoretical total capacity to 3.84 Gbit. Storage time is mainly limited by ASE noise and transient effects. Optimizing the pump configuration and adopting low-noise components can reduce noise and increase the number of circulations.

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Competing interests

The authors declare no competing financial interests.

Data availability

Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.



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