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REVIEW

Optical storage arrays: a perspective for future big data storage

Min Gu, Xiangping Li* and Yaoyu Cao*

The advance of nanophotonics has provided a variety of avenues for light–matter interaction at the nanometer scale through the enriched mechanisms for physical and chemical reactions induced by nanometer-confined optical probes in nanocomposite materials. These emerging nanophotonic devices and materials have enabled researchers to develop disruptive methods of tremendously increasing the storage capacity of current optical memory. In this paper, we present a review of the recent advancements in nanophotonics-enabled optical storage techniques. Particularly, we offer our perspective of using them as optical storage arrays for next-generation exabyte data centers.
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Keywords: big data centers; optical data storage; optical storage arrays; super-resolution

INTRODUCTION

Historically, the recording and storage of information have undergone a technological evolution from paintings to carvings, scribing and digitization, as illustrated in Figure 1. The major revolution in this developmental history is digitization, which allows music, sounds, pictures, words and movies to be stored in a binary form. The invention of optical compact discs (CDs), where a laser beam was adopted to store the binary data, was one of the major milestones in digital information technology. Together with magnetic storage devices, CDs have played a crucial role in the digital life of human beings.

Digital information technology has significantly boosted both economies and societies. Therefore, the storage of information from every sector, including education, entertainment, health, business and so on, has already become an indispensable part of the many activities of human beings in the information era. Consequently, humans are entering an era of information explosion. It has been estimated that the information generated by the major sectors is nearly doubled each year. According to a report prepared by International Data Corporation (IDC) in 2011, the total amount of data generated globally will reach 35 ZB (1 ZB$=10^3$ EB$=10^6$ PB$=10^{12}$ GB) by 2020,[1] as shown in Figure 2. Like the information recorded in cave paintings, carvings and printings, the vast amount of digital information that has been stored constitutes a core portion of our civilization and history. However, there is a growing gap between the amount of digital data being created and the extent of available storage capacities. Big data centers with petabyte (PB) and even exabyte (EB) capacities have emerged as the key enabling techniques and core platforms for cloud computing and storage, which have been heralded as the primary technical solution for the next generation of big data storage.[2,3] However, the infrastructure of current information technology has been increasingly challenged by the limited storage capacity of current digital media as well as the shortcomings associated with the high energy consumption and short lifetime of such media.

As shown in the right-hand panel of Figure 2, current methods of data storage and archiving rely primarily on magnetization-based storage technologies, such as hard disk drives (HDDs) and magnetic tapes. To store vast amounts of information generated by clients, data centers composed of arrays of thousands of HDDs have been built. The sustainability of this technology is confronted by several crucial problems. First, the capacity of HDD units, which is less than 1 TB (1000 GB) per disk, is far below the requirements of next-generation information storage. To increase the capacity to the PB scale, thousands of HDD units must typically be assembled, which means that the footprint of such a typical big data center is similar to that of a football stadium in size. Second, HDD-based data centers are not energy efficient. According to a statement issued by the US Environmental Protection Agency, data centers in the US alone consumed a significant amount of energy, accounting for 1.5% of the total US electricity consumption in 2010 at a cost of $4.5 billion annually. Moreover, the amount of energy consumption is expected to nearly double within the next 5 years. Third, the limited lifetime of HDD technology requires data migration every 2 or 3 years to avoid any data loss. This significantly increases the energy-consumption burden, as a considerable amount of energy is consumed during such data migration. These challenges constitute fundamental obstacles to the longevity and sustainability of current information technology. Accordingly, technologies with capacities greater than PBs, ultralow energy consumption and ultralong lifetimes are in high demand to support big data centers.

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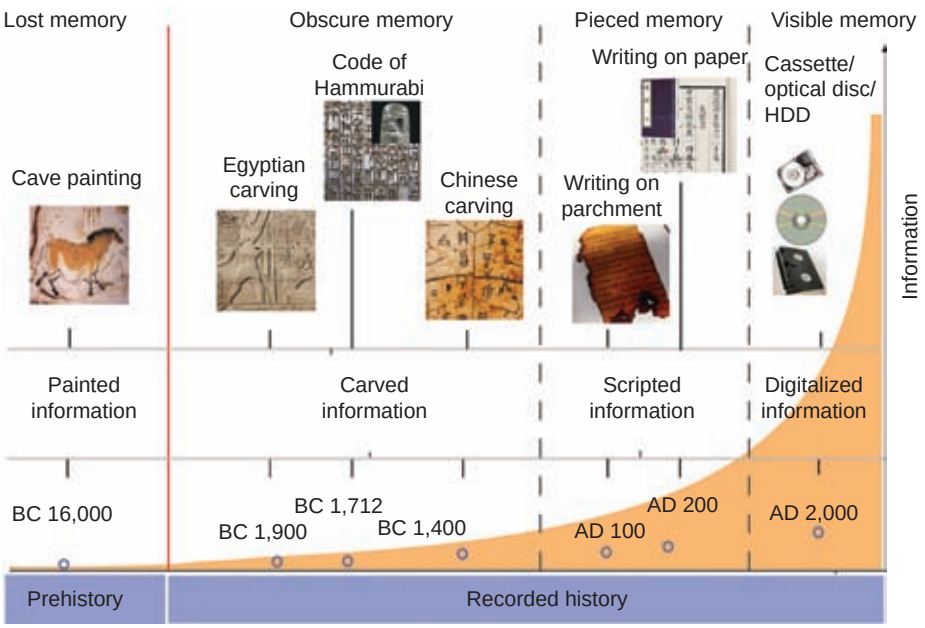

Figure 1 Historical evolution of the recording of information in human society. AD, Anno Domini; BC, Before Christ; HDD, hard disk drive.

On the other hand, optical data storage (ODS), which first emerged as CDs in the 1980s, is well known for its green features, including high storage capacities and high energy efficiencies compared with its counterparts. Unfortunately, current optical storage devices, including digital video discs (DVDs) and Blu-ray discs, can only record information in a diffraction-limited region within a layer beneath the surface of the disc. Therefore, their maximum capacity is limited to a few tens of gigabytes (GBs).[4] As a matter of fact, optical discs have been sparsely used in current approaches to big data storage. Although tremendous research and development efforts have been expended on exploiting the volume of recording media for volumetric or multilayer memories facilitated by nonlinear excitation using a pulsed laser beam,[5–7] the diffractive nature of light restricts the smallest recording bit to approximately half the wavelength of the light, and hence, the theoretical storage capacity in volumetric memories is limited to a few terabytes (TBs) per DVD-sized disc,[8,9] which is still far below the requirements for massive data storage.

How can TB- or even PB-scale information be accommodated by a single DVD disc, and how can optical storage technology eventually overtake the storage capabilities of current HDDs? Revolutionary innovations in storage techniques are in high demand to transform conventional GB optical discs into ultrahigh-capacity storage media. In recent decades, nanophotonics has emerged as a rapidly expanding new field of light–matter interaction, largely owing to recent advances in nanotechnology that permit better control of material properties at the nanometer scale as well as the availability of sophisticated nanophotonic probes. As such, studies based on the new photonic principles have led to the development of artificial materials with negative refractive indices,[10–12] nano-optical circuits,[13,14] nanoscale light-emitting sources,[15,16] imaging beyond the diffraction limit[17–19] and super-resolution optical lithography.[20,21] These studies have laid the physical

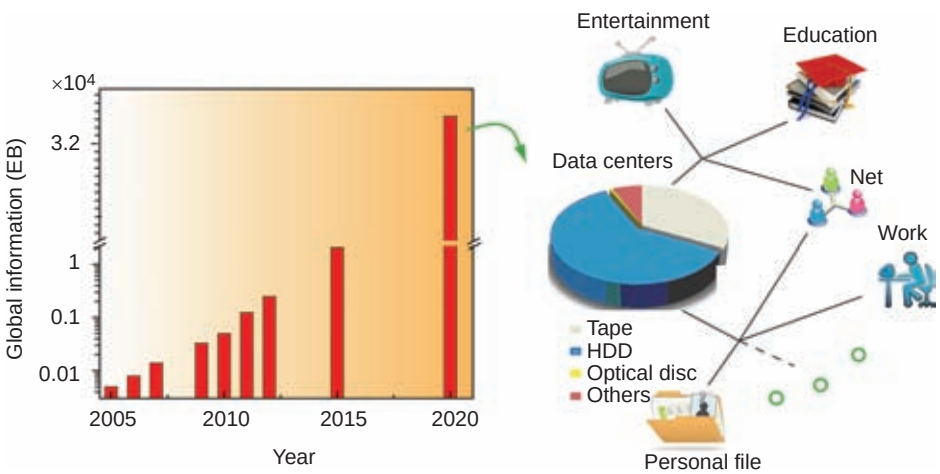

Figure 2 Global information generated each year. The right-hand panel shows the percentage of different storage methods used for storing large amounts of data (source data from IDC). HDD, hard disk drive; IDC, International Data Corporation.

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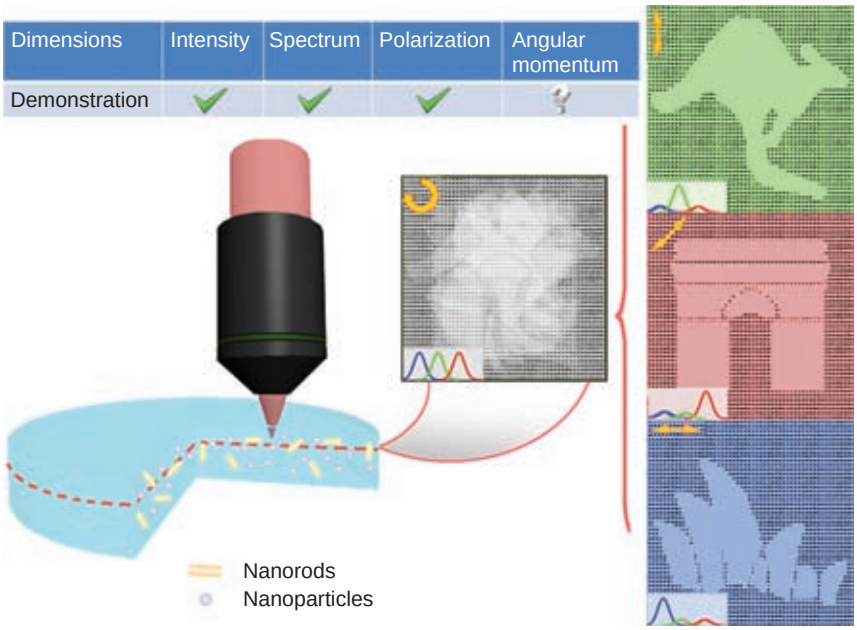

Figure 3 Scheme of multidimensional optical data storage. In the case of 5D data storage, the information bits are multiplexed in the polarization and spectrum domains of the writing beam and in multiple layers inside the medium. One recorded layer, indicated by the red dashed line and accessed using a randomly polarized broadband source as illustrated in the middle, cannot separate the polarization- and spectrum-coded information. The multiplexed information can be individually addressed by using the appropriate polarization state (indicated by the arrow) and wavelength, as illustrated in the right-hand column.[4] The inset table lists four physical dimensions of the writing beam that could be employed for multiplexed storage. 5D, five-dimensional.

groundwork for the confinement of light–matter interactions to the nanometer scale, which paves the way toward breaking or circumventing the diffraction barrier and thus increasing storage capacity by using entirely new nanophotonic approaches.

FEATURES OF NANOPHOTONICS-ENABLED OPTICAL DATA STORAGE

Ultrahigh density

As has been known for some time, the limit on the optical resolution of a high-numerical-aperture (high-NA) objective, which was discovered by the German physicist and entrepreneur Ernst Abbe, sets a fundamental barrier that limits the smallest size of a recorded bit to approximately half the wavelength of the light used for recording in the lateral direction and approximately one wavelength in the axial direction. Hence, the theoretical maximum storage density for an aberration-free objective with a high NA of 1.4 is only on the order of TB per disc.[8,9] Recent advances in nanophotonics can facilitate either the encoding of information in physical dimensions, such as those defined by the frequency and polarization parameters of the writing beam, or the achievement of three-dimensional (3D) super-resolution recording, breaking the conventional storage-capacity limit.

Multidimensional storage

Nanophotonics allows for sharp color and polarization selectivity in light–matter interactions at the nanometer scale. For example, light can couple to surface plasmons, the collective oscillations of free electrons in metallic nanoparticles, which yield deterministic spectral responses associated with their sizes and shapes.[22] These appealing properties make nanoparticles suitable for the implementation of spectrally encoded memory. Consequently, based on the principle of light-induced shape transitions, three-color spectral encoding by using gold nanorods of various sizes has been demonstrated.[23] Similarly, polarization anisotropy can be created in nanocomposite materials by means of selective excitation by different polarization states of a writing beam.[24,25] It has been recently demonstrated that when such polarization selectivity is combined with the sharp spectral selectivity of nanophotonics, gold nanorods can enable information recording in five dimensions, encoded across three wavelengths and two polarization states with an equivalent capacity of 1.6 TB in a single disc,[23] as illustrated in Figure 3. Another possible dimension that can be exploited, which is also the most straightforward to control, is the intensity of the optical beam; control of the beam intensity forms the basis of the principle of gray-scale-encoded ODS. Instead of recording binary information, each voxel stores a range of gray-scale values by varying the discrete intensity levels of the writing beam. With a precise control of its focal intensities through vectorial Debye focusing of the beam using a high-NA objective, up to eight levels can be recorded and distinguished in photobleaching polymers[26] and glass materials.[27,28]

The dimension of the beam that has received the least attention is the angular momentum (AM), which can be carried by photons in the forms of spin AM and orbital AM. As a demonstration of the principle of AM information multiplexing, the AM of light has been used to create orthogonal and spatially distinct streams of data-transmitting channels multiplexed in a single fiber.[29] It is therefore expected that AM can be used to multiplex information and thereby boost the storage capacity. On the other hand, circularly polarized beams with different handedness (spin states) can be employed to introduce different magnetization orientations in all-optical magnetic recording.[30] In this case, if the recording spots could be reduced to their smallest, diffraction-limited size,[31] the optical magnetic response could act as another dimension to allow for further increase in the storage capacity. Limited by the material response, the multiplexing of information in six individual dimensions has never been achieved. Recent advances in nanotechnology, which have enabled a variety of new nanocomposites, such as nitrogen vacancy centers in diamonds[19,32,33] with optically detected magnetic resonance,[34,35] might provide a solution for

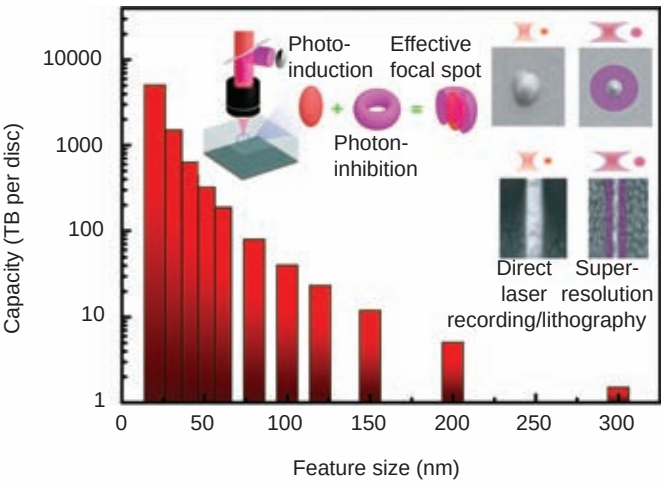

Figure 4 Projection of the maximal capacity that a single disc can hold as a function of the feature size of the recorded bits. In the projection, the lateral separation and the axial separation are set to 2.5 times and 8 times the feature size, respectively. The insets illustrate the principle underlying SPIN's ability to break the diffraction barrier and achieve super-resolution recording/lithography. Top inset: comparison of direct laser recording and super-resolution recording by using SPIN methods. Bottom inset: comparison of conventional laser lithography and super-resolution lithography. SPIN, super-resolution photoinduction-inhibition nanolithography.

exploiting the maximal number of information channels by simultaneously employing all physical dimensions of the writing beam.

3D super-resolution recording

A variety of methods have been proposed and demonstrated to break the diffraction barrier in the near-field region and achieve super-resolved areal memories.[36,37] However, these approaches do not exhibit the ability to record information in the volume of a medium. Recently, inspired by a diffraction-unlimited far-field imaging approach,[38] scientists have developed super-resolution photoinduction-inhibition nanolithography (SPIN), which can break the diffraction barrier and achieve 3D super-resolved writing.

In contrast to conventional optical memory, SPIN is achieved by employing dual beams during recording; the behavior of each beam is still governed by its diffraction. In general, the two beams operate at different frequencies enduing different functions, as illustrated in the insets of Figure 4. One of the two beams, with a Gaussian shape, falls within the transition bands of the materials and thus is responsible for photoinduction. The other beam, with a spatially modulated intensity distribution that is usually a doughnut shape (with zero light intensity in the center), is responsible for inhibiting photoinduction everywhere in the focal region except at its center. Consequently, the effective focal spot can be made much smaller than the diffraction barrier by the spatial superposition of the two beams and varying the intensity ratio between the two beams.

By employing the principle of SPIN, researchers have successfully demonstrated super-resolved line fabrication as well as dot recording in a variety of photoinduction systems, as schematically illustrated in the right-hand panel of insets in Figure 4. Table 1 summarizes the state of the art of SPIN-based super-resolution recording methods for the production of ultrafine features. In general, photoinduction can refer to any photoinduced chemical or physical processes that initiate a change in material properties, such as photochromism,[39] photopolymerization[20] and photoreduction,[48] and that can also be terminated by an inhibition beam operating at a different wavelength. As such, the photochromism process has been used to inhibit photoabsorption, and the smallest line-feature size of 30 nm (approximately one-tenth of the wavelength λ) has been successfully demonstrated.[39] Recently, a photopolymerizable material with improved photosensitivity and mechanical stability has been developed and successfully applied in using the SPIN method for the fabrication of suspended lines with the smallest feature size down to 9 nm, or $\lambda/42$.[20] These exceptional features open a new avenue toward diffraction-unlimited laser fabrication, as well as for the development of ultrahigh-density optical memory.

The development of 3D super-resolved writing methods will enable further decrease in the effective size of recorded bits to below 50 nm and will eventually boost disc capacity to approach or even surpass the PB scale in the near future, as projected in Figure 5. In the meantime, sophisticated techniques for light manipulation on the focal plane are necessary to maintain an effective focal spot smaller than the diffraction limit with enriched physical dimensions. The combination of super-resolution techniques and multiplexing in the physical dimensions can further expand disc storage capacity beyond hundreds of PBs. Clearly, nanophotonics-enabled storage techniques are far superior to the current HDD and flash memory techniques, which are encountering density bottlenecks (Figure 5).

Ultrahigh throughputs

Another challenge confronting big data storage is low writing and reading throughputs. Based on the current throughput ($\sim$20 MB s^{-1}) of Blu-ray discs, it might take more than one and a half years to access 1 PB of information.[3] Even taking the current HDD technique into consideration ($\sim$100 MB s^{-1}), it would still require more than 100 days to access such a massive amount of data. Therefore, it is equally as

Table 1 The development of SPIN methods

Photoinhibition methods	Wavelength of photoinduction (nm)	Wavelength of photoinhibition (nm)	Lateral feature size (nm)	Pattern
Photodeactivation[21]	800	800	$\sim$100 ($\frac{1}{8}\lambda$)	Dots
Photochromism[39]	325	633	30 ($\frac{1}{10}\lambda$)	Lines
Photoradical[40]	473	364	64 ($\frac{1}{8}\lambda$)	Dots
Photoluminescence[41]	800	532	65 ($\frac{1}{12}\lambda$)	Lines
Photoradical[42]	488	375	40 ($\frac{1}{12}\lambda$)	Dots
Photodeactivation[43]	800	800	$\sim$150 ($\frac{1}{6}\lambda$)	Lines
Photoluminescence[44]	800	532	$\sim$120 ($\frac{1}{7}\lambda$)	Lines
Photoabsorption[45]	800	642	$\sim$120 ($\frac{1}{7}\lambda$)	Dots
Stimulated emission depletion[46]	780	532	55 ($\frac{1}{14}\lambda$)	Lines
Photoradical[20]	800	375	9 ($\frac{1}{42}\lambda$)	Lines
Photoswitching[47]	405	491	200 (resolution)	Dots

*SPIN, super-resolution photoinduction-inhibition nanolithography.

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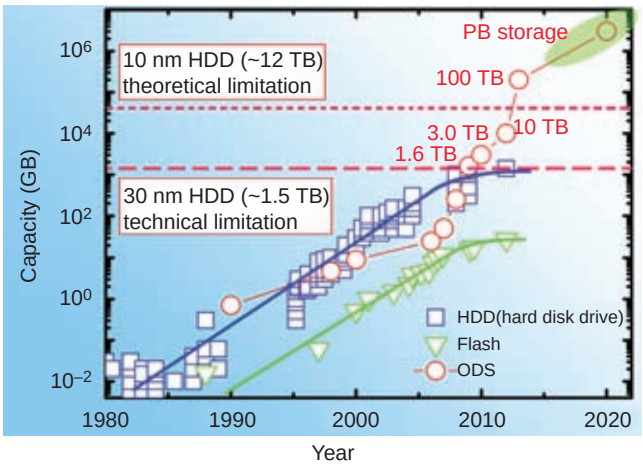

Figure 5 Comparison of the development of storage capacities using the HDD (squares), flash (triangles) and ODS (circles) techniques. The capacity of flash memory is calculated based on a storage area of 1 cm^2. The HDD technique is currently subject to a 30 nm technical limitation (~1.5 TB) and is expected to approach its theoretical limitation of 10 nm (~12 TB). However, 5D storage has already broken the technical limitation of the HDD technique, achieving a capacity of 1.6 TB in 2009.[23] The super-resolution focal-volume technique has pushed the capacity further to 3 TB.[9] Moreover, the application of the SPIN method in 3D optical storage has enabled a feature size below 100 nm with an equivalent capacity of approximately 10 TB.[49] The latest result of a recorded bit size of 32 nm has surpassed the theoretical limitation of the HDD technique and demonstrated a new world record with an equivalent capacity of approximately 100 TB.[50] 3D, three-dimensional; 5D, five-dimensional; HDD, hard disk drive; ODS, optical data storage; PB, petabyte; SPIN, super-resolution photoinduction-inhibition nanolithography.

important to boost writing/reading throughputs as it is to increase storage capacity.

Various optical parallelism methods for generating multifocal arrays in single laser shots have been proposed and experimentally demonstrated, including microlens arrays,[51] diffractive optical elements,[52] Debye-based Fourier transformation[53] and dynamic computer-generated holograms.[54] Among these methods, Debye-based Fourier transformation enables the formation of diffraction-limited multifocal spots using a high-NA objective wherein each focal spot can be dynamically programmable, which is a necessity for ultrahigh-density optical recording. The implementation of this method by using a spatial light modulator for parallel recording is illustrated in Figure 6a.[53] The single beam carrying the modulated phase pattern calculated by the Debye-based Fourier transform can be diffracted into the designed multifocal array in the focal plane of the objective. With a few hundred programmable focal spots for parallel writing, the throughput of optical storage could be significantly increased to ~10 GB s^{-1}; therefore, the accessing time for 1 PB could be dramatically reduced to only a few days. The Debye-based Fourier transform method can generate not only in-plane multifocal arrays but also high-quality 3D multifocal arrays for volumetric parallel writing,[55] and it can even be integrated with other physical parameters to increase the throughput beyond tens of GB s^{-1}, as illustrated in Figure 6b. Thus, polarization states of individual focal spots in 3D multifocal arrays have been controlled to achieve parallelism in the dimension of the polarization states. As an example, the generation of cylindrically polarized multi-focal arrays has been demonstrated by applying the vectorial Debye-based Fourier transform method.[56] Furthermore, the combination of polarization-controllable multifocal arrays with SPIN methods can allow for super-resolution parallel recording and readout, which will therefore be a core platform for the development of PB optical discs (Figure 6c).

Ultrahigh security

The physical dimensions of a writing beam can be used not only as information channels to increase the storage capacity but also as versatile means to encrypt information for data security, which is one of the most important aspects of any memory system.

As an electromagnetic wave, light can selectively interact with optical materials with physical anisotropic properties *via* its polarization, or the oscillation of its electric fields. The response of optical materials strongly depends on the orientation of the electric dipoles with respect to the polarization state of the light. As such, information can be encrypted using a specific polarization state of a writing beam, which cannot be retrieved without pre-knowledge of the polarization key. By rotating the polarization orientation, flexibility of the encryption key can be achieved, and multiple states of information can be encrypted in the same spatial region. Thus, information can be

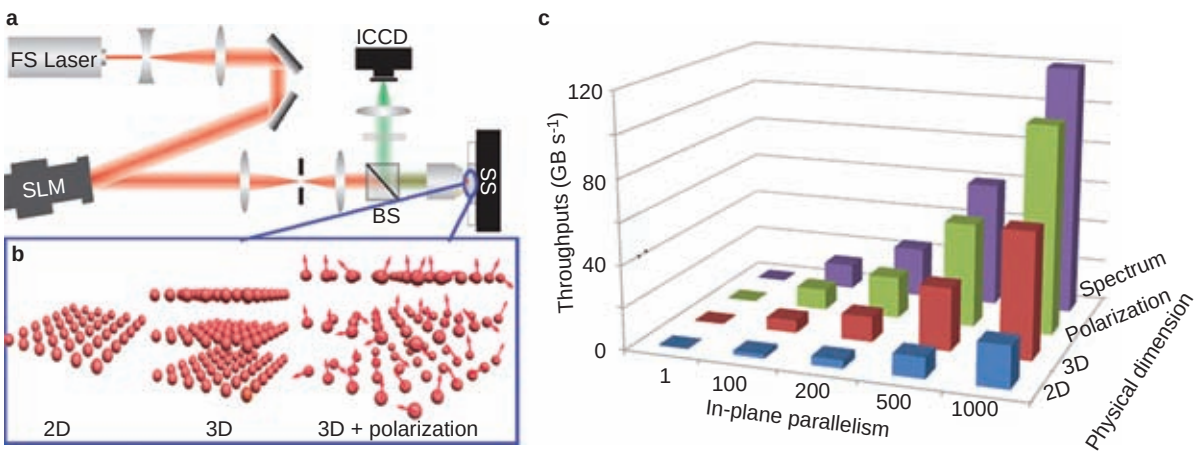

Figure 6 (**a**) Scheme for parallel optical recording using an SLM. (**b**) Schematic illustrations of in-plane parallel (2D) recording, volumetric 3D recording and 3D-combined-with-polarization parallel recording. The arrows indicate the polarization orientations. (**c**) The overall throughput as a function of the in-plane parallelism and physical dimensions. BS, beam splitter; 2D, two-dimensional; 3D, three-dimensional; FS, femtosecond; ICCD, intensified charge-coupled device; SLM, spatial light modulator; SS, scanning stage.

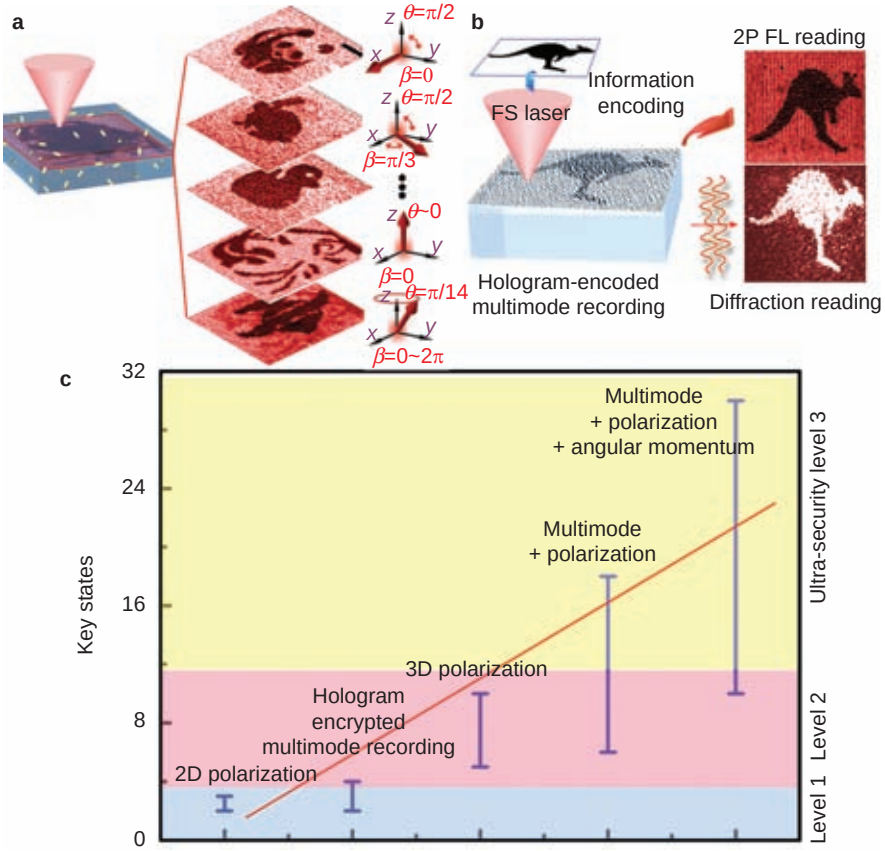

Figure 7 (**a**) Scheme for 3D polarization encryption using 3D oriented polarization states.[60] (**b**) Illustration of hologram-encoded multimode recording for enhanced data security. Information bits can be randomly accessed through the 2P fluorescence readout and retrieved in the diffraction mode of the recorded holograms.[61] (**c**) Projection of levels of information security by combining multimode recording with other physical dimensions. 3D, three-dimensional; FL, fluorescence; FS, femtosecond; 2P, two-photon.

encrypted in the two polarization states of writing beams at 0°- and 45°-oriented polarizations through polarization-induced birefringence.[24] Recently, it has been demonstrated that by employing the depolarization effect through the tight focusing of a radially polarized beam, one can generate a longitudinal polarization state within the focal region.[57,58] Through the superposition of weighted radially and azimuthally polarized beams, a 3D arbitrary polarization orientation can be achieved in the focal region of a high-NA objective. In combination with the sharp polarization sensitivity of gold nanorods, 3D polarization encryption within a solid angle in the focal plane has been demonstrated for ultrahigh security,[59] as illustrated in Figure 7a.

Additionally, the enrichment of the physical dimensions for light–matter interactions offered by nanophotonic approaches enables information to be recorded in multimode material responses, which opens a new avenue toward a high level of information security. For example, simultaneous changes in the refractive index and fluorescence intensity of graphene-based materials have been demonstrated to hold the potential for hologram-encoded multimode recording,[61] as shown in Figure 7b. On the one hand, the information can be randomly accessed through two-photon fluorescence readout. On the other hand, the information can be simultaneously encrypted in holograms, ensuring its integrity and durability. It is possible to integrate hologram-encrypted multimode recording with other physical dimensions, such as polarization and AM, to achieve an even higher level of information security, as illustrated in Figure 7c. However, the experimental achievement of such a high level of security strongly depends on material properties of the recording medium, specifically, its deterministic responses to light with various characteristics. Nanotechnology that offers the ability to engineer and control material properties on the nanoscale may provide a solid platform for future ultrahigh-security optical storage.

Ultralong lifetime

As we have noted, magnetization-based HDD techniques have a limited lifetime of 2–5 years, and therefore, frequent data migration is needed to avoid potential data loss. However, ODS has a longer lifetime than HDDs, which dramatically reduces the required frequency of data migration. In addition, ODS only consumes energy when the data are written or read out and does not consume any energy when the optical disc is in idle state. For comparison, Figure 8 illustrates the power consumption and operational cost of information storage incurred by a single HDD (4480 kWh) and a single disc (35 kWh) over 50 years. Clearly, optical technology greatly reduces the waste generated by frequent data migration, reduces the energy consumption in idle status and reduces the cost for the replacement of new units associated with short lifetimes. Moreover, increasing the lifetime of ODS to greater than 50 years can dramatically increase the savings in overall expenditures, including electricity and costs for storage devices, by more than 96% compared with HDD techniques.

Consequently, the development of ODS with ultralong lifetimes has been a subject of intensive research. Permanent laser-induced physical changes, such as voids in polymers[62] and glass materials,[63] provide an

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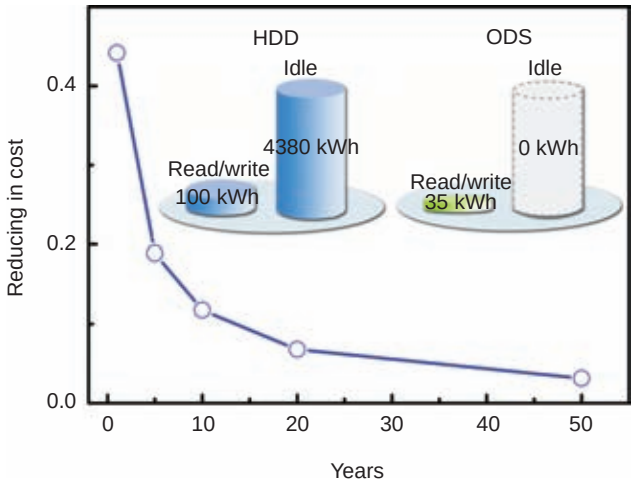


Figure 8 Reduction in the operational cost for a single ODS unit compared with that of a single HDD unit as a function of years elapsed. The inset shows a comparison in terms of the electricity consumption for reading/writing and in idle status for a single unit over 50 years. In this comparison, a single HDD unit typically consumes 20 W for reading/writing, and it is used in this manner for 100 h per year. In the idle status, it consumes 10 W per hour. A single ODS unit consumes 7 W for reading/writing and is used in this manner for 100 h per year. The cost is calculated based on an assumption of $0.12 per kWh, and the unit prices of the HDD and the ODS are $80 and $40, respectively. HDD, hard disk drive; ODS, optical data storage.

approach to long-lifetime storage without information degradation. Laser inscriptions in glass materials[27,28] can withstand temperatures of up to 1000 ℃ and maintain data stability and readability for up to thousands of years, in principle. The demonstrated physical changes including voids and inscription are limited by a low capacity of approximately 50 GB per disc because the physical size of each bit cannot be smaller than the diffraction barrier. The top-down nanocomposite approach offers an alternative method that may allow the development of SPIN methods to break the diffraction limit for ultrahigh capacity ODS with thousands of years of lifetime.

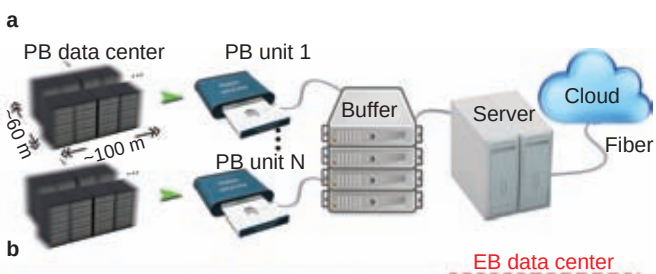
OPTICAL STORAGE ARRAYS: A PERSPECTIVE FOR EB DATA CENTERS

The question of how to store the vast amount of data generated each year completely and efficiently is an urgent challenge confronting current information technologies. For example, the Australian telescope generates more than 700 TB of data every day. Scientists must selectively store only a portion of these valuable data. The US national priority project to map the human brain to gain an understanding of the cell types present in the brain, how they are connected and how they communicate is expected to generate more than 1000 ZB of data. It is impossible to store such a vast amount of information using current technologies, even the cloud computing and storage have emerged as technical solutions for future big data storage, in which PB data centers provide key enabling platforms. Since the capacity of a single HDD is no larger than 1 TB, PB data centers must typically be built on arrays of thousands of HDDs. Because of the low capacity and high energy consumption of HDD techniques, the resources necessary to store large amounts of data require inordinate amounts of power and rack space. A typical PB data center occupies a stadium-sized space, including the racks and cooling accessories, which represents a significant overhead for such a data center. According to the IDC report,[1] the annual electricity consumption and maintenance costs for such a PB data center based on HDD arrays could even surpass the cost of the hardware itself.

Recent advances in nanophotonics-based ODS have exhibited the ability to address the bottlenecks that confront current HDD techniques, including storage capacity, lifetime, energy consumption and data-transfer rates. In particular, the SPIN method has enabled ODS with a capacity approaching PBs per disc. Each such disc may potentially replace a stadium-sized PB data center in terms of capacity, as schematically illustrated in Figure 9. The integration of a single nanophotonics-based ODS unit with PB-scale capacity into multiple-unit arrays will provide a new platform for EB-scale big data centers to cope with vast amounts of information being produced in the digital era. Combined with its green features in energy conservation, nanophotonics-enabled optical storage arrays (OSAs) hold the potential to switch from the current magnetization-based approach to big data storage to the use of optical discs.

Most importantly, photonics has been heralded as a sustainable information technique to replace its current electronic- and magnetic-based counterparts for big data era. It is believed that optical chips will emerge in the following 5–10 years to replace electronic chips for ultrafast and ultralow-energy-consumption optical computing. The optical fiber has already replaced copper-based wires for ultrahigh speed and ultrahigh-energy-efficiency communication. The emergence of OSAs for ultrahigh-capacity information storage will complete the optical information-technology chain to create an entirely new approach to all-optical cloud computing/storage toward a sustainable future. Once that day comes, the efficient and complete storage of big data will affect every aspect of a normal person's life, including e-health, e-banking, e-education and e-defense. It will completely change the way people consume and store information.

The core of the OSA system is based on nanophotonics-enabled PB ODS units. The system consists of N units of PB drives and discs controlled by a server through a buffer, as schematically illustrated in Figure 9a. The capacity of the entire array system is the product of the total number of PB units and the capacity of each single disc. For example, the storage capacity of such an array system can be significantly increased to the EB or even zettabyte (ZB) scale by increasing the number of PB ODS units present in the array, as shown in



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EB data center

PB units	10	50	100	200	500	1000	2000	5000
Capacity (PB)	10	50	100	200	500	1000	2000	5000
Throughput (TB s^{-1})	0.1	0.5	1	2	5	10	20	50

Figure 9 (**a**) Schematic illustration of an OSA based on integrating N units of nanophotonics-enabled PB ODS devices, where each single PB ODS unit is capable of replacing a conventional PB-scale big data center based on HDD arrays of ~100 m by 60 m in size. (**b**) The capacity and throughput of the storage array system as a function of the number of ODS units. Big data centers with a capacity approaching EBs become possible using the new OSA technique without any increase in the infrastructure size of the data centers. EB, exabyte; HDD, hard disk drive; ODS, optical data storage; OSA, optical storage array; PB, petabyte.

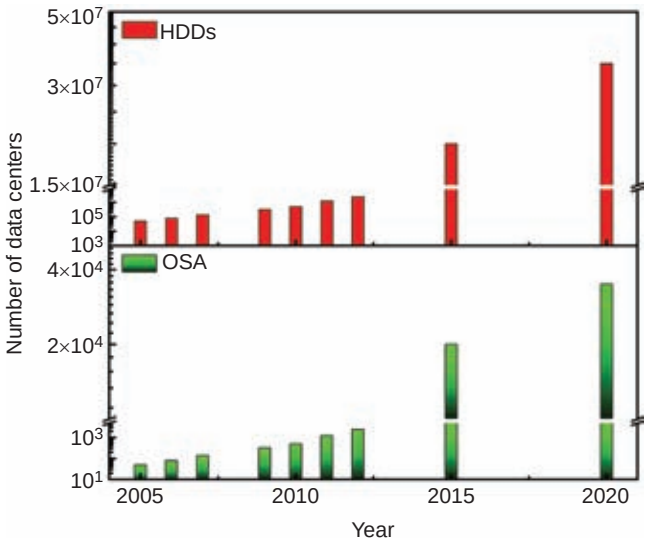

Figure 10 Number of data centers based on 1000 HDD units (red bars) and 1000 OSA units (green bars) required to store the global information generated each year. HDD, hard disk drive; OSA, optical storage array.

Figure 9b. In the meantime, each unit has the ability to write and read in optical parallelism to maximize the throughput. The overall throughput of the array system is a product of the total number of units and the optical parallel throughput of each single drive, which can far exceed TB s^{-1}, as shown in Figure 9b.

Ultrahigh capacity and ultrahigh throughput of big data centers enabled by OSA

According to the IDC's projections of the global information generated each year in Figure 2, millions of PB data centers are required to store such vast amounts of information based on the current HDD technique. By switching the future big data centers to the approach of nanophotonics-enabled OSA, each single disc will be able to achieve PB capacity and will therefore replace one PB-scale data center based on HDD arrays. With a similar number of discs, an OSA can reach far beyond PB-scale and even EB-scale capacity. For comparison, an HDD array consisting of 1000 units has a maximum capacity of 1 PB, whereas a nanophotonics-enabled OSA with the same number of units can exceed 1 EB, and even approaching the ZB scale is possible. It can be seen that OSAs can significantly reduce the number of big data centers required to satisfy the capacity requirement by more than three orders of magnitude, as shown in Figure 10.

In addition to their exceptionally high capacity, future big data centers based on OSAs enabled by nanophotonic parallel recording and reading techniques will permit ultrahigh throughput beyond the TB s^{-1} level. As shown in Figure 6, if the multifocal array technique were integrated with the technique of multiplexing in physical parameters, the throughput of each single PB unit disc could exceed 10 GB s^{-1}. A typical OSA with 1000 units could easily achieve a throughput of greater than 10 TB s^{-1}, which is far superior to the current HDD array technique with its typical throughput of a few tens of GB s^{-1}. Unlike its counterparts, OSA-based big data centers are fully compatible with the optical-fiber communication technique, which is ubiquitously used in big data centers. By removing the necessity of electrical-to-optical converters, the data transfer between remote terminations and storage media could be made even faster.

Ultrahigh energy efficiency

In addition to the question of how to accommodate an explosively increasing amount of information in current storage devices, another major challenge confronting the current big data centers based on HDD arrays is the question of how to store information in an energy-efficient manner. Because of the low areal density of present technology, current data centers must be built on arrays of thousands of HDDs in order to reach a capacity of PBs. Moreover, HDD arrays consume energy during both operating and idle states and produce a significant amount of heat, which must be dissipated by gigantic accessorial cooling systems that consume a tremendous amount of electricity. On the one hand, this means that a single HDD-based data center occupies a footprint comparable to that of a stadium (~100 m by 60 m). On the other hand, the high energy consumption raises a number of serious concerns regarding the sustainability of big data centers, including the vast costs of the infrastructure and environment pollution as well as the ever-increasing cost of maintenance. By contrast, nanophotonics-enabled OSAs of ultrahigh capacity, approaching the PB scale in a single DVD-sized disc, can dramatically ameliorate these concerns.

The ultrahigh capacity and compactness of OSAs can dramatically alleviate the costs for the infrastructures of such stadium-sized big data centers. It is reasonable to project that a PB-scale optical storage unit based on nanophotonics-enabled recording methods will be developed in dimensions of 200 mm×125 mm×36 mm within the following 5–10 years. Most importantly, OSAs do not consume energy, while they are in the idle state, which eliminates the necessity for cooling accessories. For the same capacity of 1000 PB, the use of OSAs can reduce the data-center size compared with that required for a data center based on HDD arrays by three orders of magnitude. As shown in Figure 11a, OSA technology represents a tremendous reduction in the infrastructure required for big data centers to satisfy the demands of storing vast amounts of information newly generated each year. Taking as an example an electricity consumption of 1.0 kWh per effective TB for current HDD-based data centers (0.8–1.8 kWh TB^{-1}, including storage and cooling costs) and assuming that the infrastructural development of a new PB data center will consume ~50% of the yearly operating cost, Figure 11b and 11c represents the reduction of the infrastructural development of new PB data centers, in terms of equivalent electricity consumption as well as CO_2 emission by switching to the OSA technique to satisfy the requirement of the global data consumption. Indeed, the OSA enabled by nanophotonic approaches can save trillions of kWh of electricity per annum on the infrastructure development of new data centers, as well as eliminate millions of tons of CO_2 emission for a greener future.

In addition, OSAs can significantly reduce the annual electricity consumption required to store vast amounts of information generated each year. Per effective TB of data, current HDD-based data centers consume ~1.0 kWh of electricity for data storage. Based on IDC projections, more than 300 trillion kWh of electricity will be consumed to store the newly generated data in the year 2020 if HDD technology is used, as shown in Figure 11d. For comparison, the OSA technique, with its ultralow energy consumption per writing cycle and zero consumption, while in the idle state, can significantly reduce the electricity consumption and increase the efficiency of energy usage. The electricity conserved in the year 2020 by switching to OSA techniques could be equivalent to one thousand times the US residential electricity consumption in 2011.

Ultralong-lifetime archiving

The permanent archiving of information that is generated annually is another important aspect of big data storage. Typically, data stored

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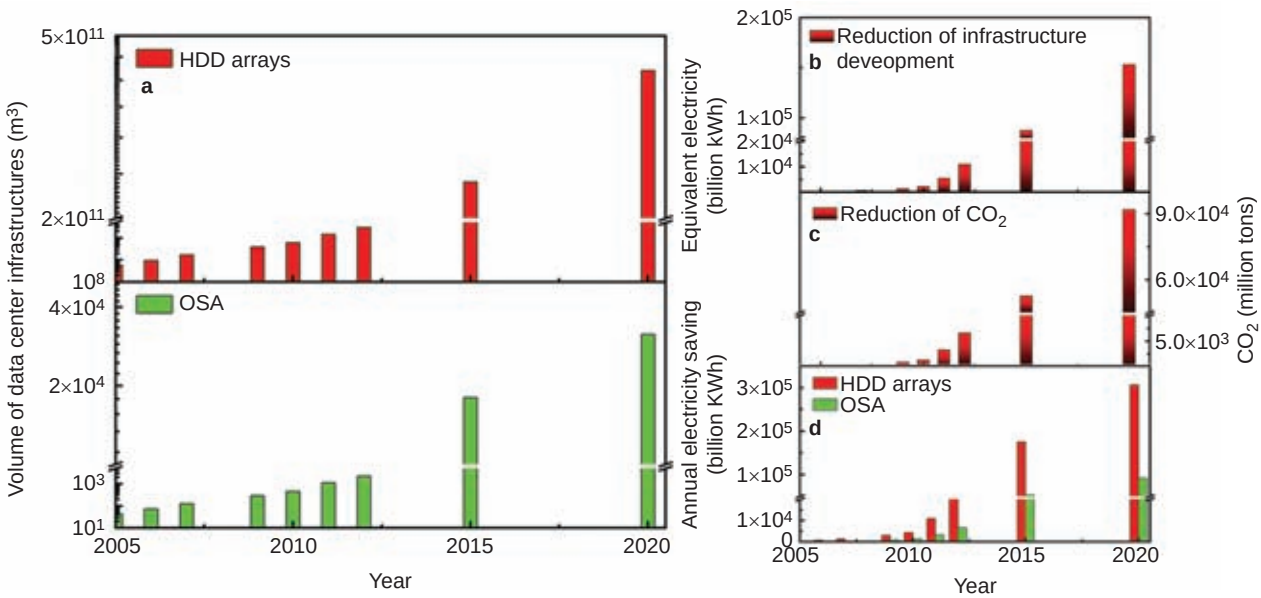


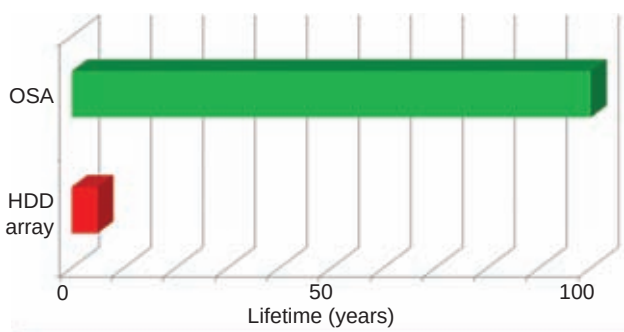
Figure 11 (**a**) Comparison of the infrastructure volumes of data centers based on HDD arrays and OSAs, which are required to store the information generated each year according to the IDC projection. The annual reduction offered by the infrastructural development of new PB data centers is expressed in terms of (**b**) equivalent electricity consumption and (**c**) CO_2 emissions (1 kWh electric power=0.6 kg CO_2 emission[64]). (**d**) Annual electricity consumption of data centers based on HDD arrays (red squares) and OSAs (green squares) for the storage of the information generated each year, according to IDC projections. HDD, hard disk drive; IDC, International Data Corporation; OSA, optical storage array; PB, petabyte.

using HDD-array techniques must be migrated every 2 or 3 years to prevent data loss. This requirement raises the concern of large amounts of energy consumed during such frequent data migration; as the capacity of data centers expands, this energy consumption becomes an increasingly significant obstacle to the longevity of current big data centers. Since nanophotonics-enabled storage methods allow write-once-read-many protocols, OSAs can alleviate the ongoing electricity demand of big data centers for long-lifetime data persistence. In addition, the data stored in optical discs does not consume any energy unless the information is written or read out during their lifetimes, which also tremendously reduces the operational and maintenance costs. For comparison, the storage of one effective TB of information in PB optical discs using nanophotonic approaches consumes less than 0.3 kWh,[4] which represents an energy savings of more than 70% in a single writing cycle. Optical storage discs with 100-year lifetimes can reduce the energy consumed for storage by more than 99.4% compared with HDD arrays, which require 50 data transfers in a 100-year information archive, as shown in Figure 12. This feature could result in astronomical figure of energy conservation if all data generated in the year 2020 could be stored using OSA techniques and archived for more than a century, and the energy conservation offered by OSAs with lifetimes of thousands of years or more could be even more pronounced.

OUTLOOK

In this paper, we have summarized the recent developments in nanophotonics-enabled optical storage techniques. Nanophotonic approaches enable light–matter interaction at the nanoscale and the enrichment of the physical dimensions used for encoding, thereby providing an avenue toward ultrahigh-density PB optical storage with ultrahigh security and ultrahigh throughput. The integration of single nanophotonics-enabled storage units offers new prospects for all-optical big data centers to address the bottlenecks in capacity and energy efficiency experienced by current big data centers based on HDD arrays. Because of their exceptional features, OSAs exhibit tremendous potential for big data storage and long-lifetime archiving.

Moreover, a data center based on OSAs is capable of maintaining higher standards of integrity and functionality for its stored information than its counterparts based on HDD arrays. Unlike electronic- or magnetic-based storage techniques, OSAs are robust to a variety of harsh environmental conditions (temperatures of 10–40 ℃, humidity of 20%–80%) and resistant to data corruption caused by radiation, making them ideal for many space and military applications. In particular, one potential application of such data centers is the storage of confidential information such as that related to banks, governments and national defense. To avoid malicious tampering with data integrity



Years	2	5	10	20	50	100
HDD (kWh)	8760	21900	43800	87600	219000	438000
OSA (kWh)	2628	2628	2628	2628	2628	2628
Saving	70%	88%	94%	97%	98.8%	99.4%

Figure 12 Comparison of typical lifetimes of OSAs (green) and HDD arrays (red) and the energy conservation offered by long-lifetime data storage and archiving. HDD, hard disk drive; OSA, optical storage array.

and breaches of information confidence, the enriched physical dimensions of light provide exceptional protocols for the encryption information in these physical parameters instead of the conventional binary information storage offered by HDD techniques. This intriguing feature of OSAs enables orders-of-magnitude-increased flexibility in the generation of encryption keys, opening a new avenue for information storage with ultrahigh security. Moreover, OSAs allow for write-once-read-many protocols in which information, once written, cannot be modified. This type of write protection affords reliability in information storage as well as the assurance that the data cannot be tampered with once written to the storage device.

In addition, the cost for information storage can be reduced from the current price of ~$1 per GB to well below $0.01 per GB by switching from HDDs to OSA techniques. Over the past two decades, ODS has proven to be a great success in the entertainment sector, with a global production of more than 2000 billion discs and a market size of multiple billions of US dollars per annum. The proposed OSA, with its exceptional capacity and energy efficiency, will become a key enabling platform for the sustainability of our digital economy and society powered by information technologies. It is reasonable to project that OSAs will gain a tremendous share in the big data technologies in the near future, with a global market on the scale of ~30 billion US dollars per annum.[65] Together with the booming optical chip and optical fiber techniques, OSAs functioning as relay stations for data streams or warehouses for information archiving will be able to promote a brand-new paradigm of all-optical information management toward a sustainable future for big data storage.

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