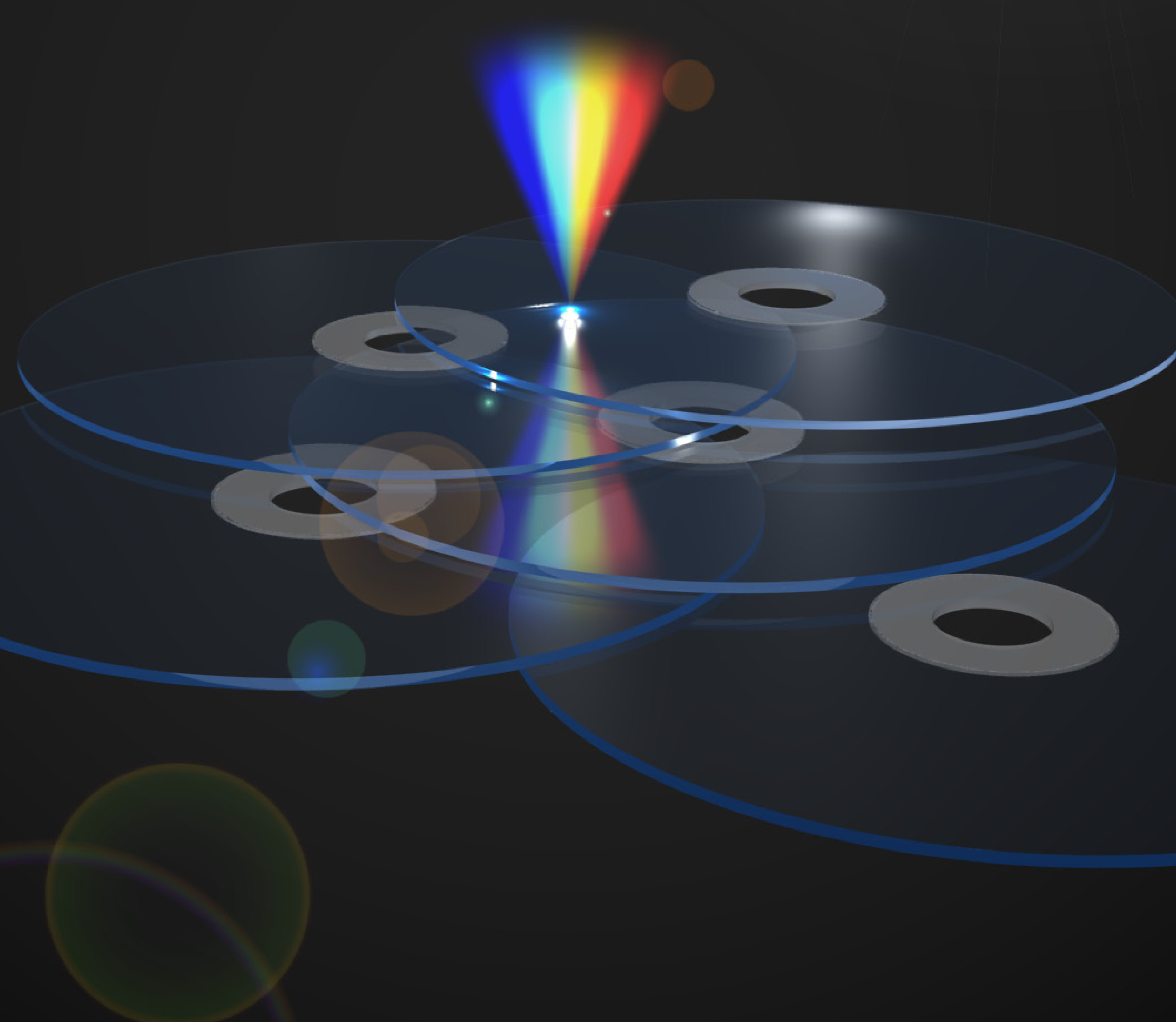
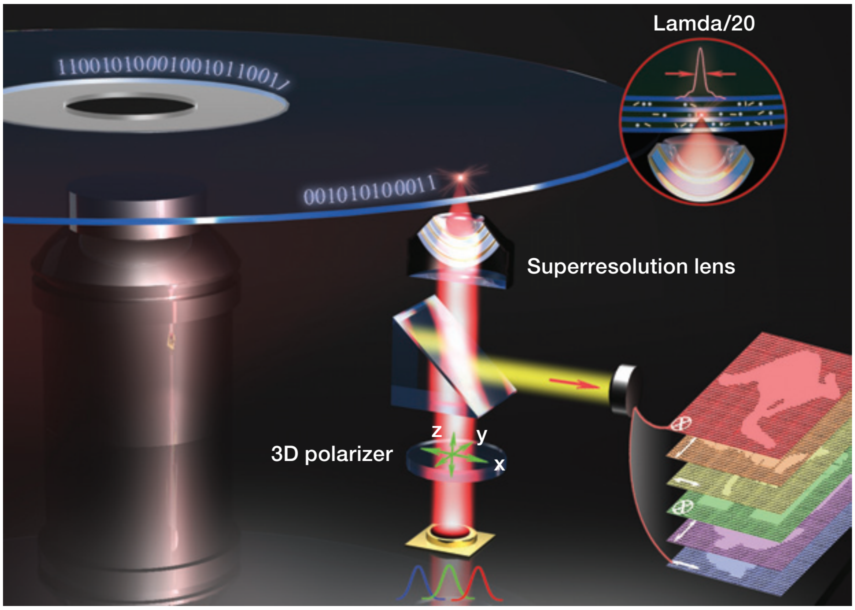
The Road to Multi-Dimensional Bit-by-Bit Optical Data Storage

Min Gu and Xiangping Li



Recent advances in optical data storage have led to the development of a five-dimensional device that could hold up to 2,000 times more data than a conventional DVD. These authors discuss this and other milestones on the road to multi-dimensional optical memory with petabyte capacity.



Bit-by-bit optical data storage. Inset: Bits are pre-recorded by a photoinduced physical or chemical change in a recording medium. Information is retrieved back by detecting the intensity variation of a reading beam when the optical disc is scanned.

Optical data storage has led to revolutionary advances in information technology and storage. One of the challenges in this field is to meet the rapid growth in demand for storage capacity. Bit-by-bit optical data storage systems such as compact discs (CDs), digital video discs (DVDs) and Blu-ray discs (Blu-rays) have emerged as compact, portable devices that have high memory density and high resistance to intense electromagnetic radiation. Given its high tolerance to vibration and robust reliability, bit-by-bit optical storage has been shown to be superior to holographic memory.

Each technological breakthrough comes with a new expansion of the storage capacity but also with its own limitations. Bit-by-bit optical data storage uses photons to introduce a localized physical or chemical property change—such as photoinduced fluorescence or reflectance modulation—as information storing processes. When an optical disc is scanned, pre-stored information can be retrieved back by detecting the intensity variation of the reading beam; the "on" or "off" state corresponds to a "1" or "0."

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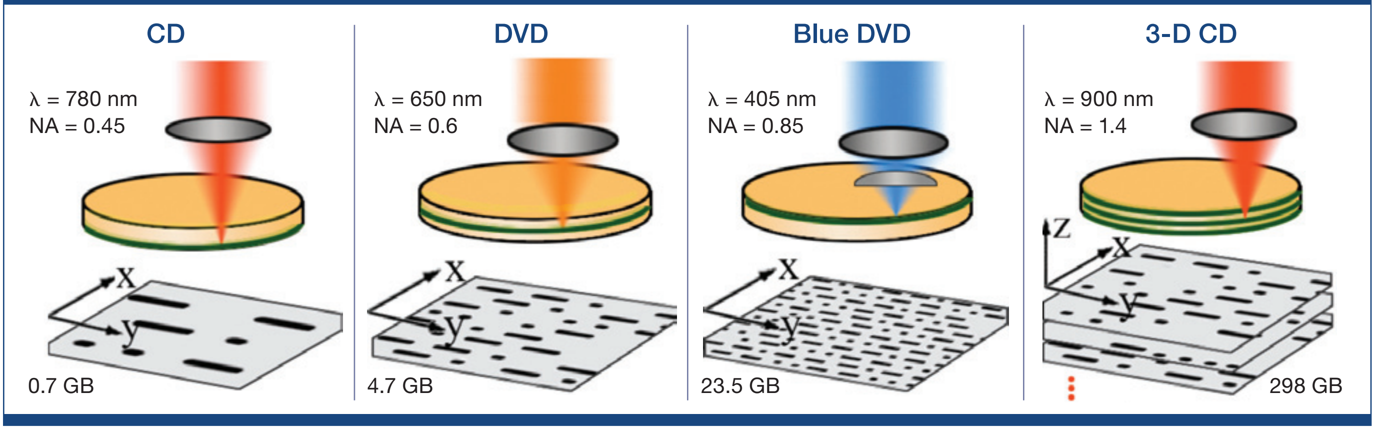
[Optical setups and optical discs]



Evolution of optical data storage systems

Two-dimensional systems

Compact discs, the first-generation optical data storage devices, emerged in the 1980s. They use a focused laser beam to induce a localized change within a two-dimensional (2-D) layer near the surface of a recording medium. The information occupies less than 0.01 percent of the volume of a CD. Due to the limitation of the recording wavelength and the numerical aperture (NA) of the recoding lens, the maximum data capacity of the first-generation optical data storage systems is approximately 650 to 750 Megabytes (1 MB = 1 million bytes; 1 byte = 8 bits) for each CD.

The development of DVDs was aimed at breaking this limit. DVDs marked the beginning of the second generation of optical data storage technology. Because of the diffraction-limited feature after the beam passes through the objective, the resolution of such a system can be written as $r = 0.61 * \lambda/NA$, where λ is the wavelength and *NA* is the numerical aperture of the objective. This technological development involved the recording of information while reducing the recording wavelength to 650 nm and increasing the NA of the recording lens to 0.6.

In a 2-D optical data storage system, where information is recorded only in one layer inside the medium, 99.99 percent of the volume of the optical disc has not been used.

The diffraction-limited resolution of the DVD system has been improved 40 percent compared to the CD technique, therefore greatly enhancing storage density to 4.7 GB/disc. Blue DVDs, or so-called Blu-rays, operate at a much shorter wavelength of 405 nm. They also increase the NA to 0.85, allowing more information to be stored in the same area with a smaller focal spot size. Therefore storage capacity has been greatly expanded to 23.5 GB/disc.

Three-dimensional systems

In a 2-D optical data storage system, where information is recorded only in one layer inside the medium, 99.99 percent of the volume of the optical disc has not been used. Researchers have pursued further research to explore the feasibility of three-dimensional (3-D) optical data storage, such as double-layer DVDs and double-layer Blu-ray discs.

Some have tried adding an axial dimension, where information is recorded in the *x-y-z* space. However, when a recording beam is focused deep into the volume of an optical medium, scattering loss occurs. The shorter the wavelength, the stronger the loss. The energy cannot be delivered efficiently for multilayer recording. In addition, it is very difficult to manufacture three-layer DVDs or Blu-Ray discs.

This challenge has spurred the revolutionary idea of two-photon (2P) excitation by an infrared femtosecond (fs) pulsed laser beam with a pulse width of 100 fs. Due to its highly confined properties and high efficiency of penetration into the volume of a recording medium using infrared beams, the information can be recorded in multiple layers of the recoding medium. This approach is sometimes called 3-D CD technology.

The 2P excitation technique has been widely applied to a variety of materials for high-density memories, including photopolymerizable materials, photochromic materials, photorefractive materials, photobleaching materials, void-fabricatable materials and nanoparticles dispersed materials. The important milestones that scientists have achieved toward the development of high-density 3-D storage systems are summarized in the table on the facing page.

In a 1989 study in the journal *Science*, researchers described introducing the 2P excitation technique into 3-D optical data storage with two orthogonal beams intersecting inside the focuses of two objectives. The elegance of this approach is highly localized recording and random access to data.

However, the recording and reading system was quite complicated for the implementation of 3-D storage devices.

Researchers reached an important milestone in the single-beam 2P recording the following year. They found that the 2P absorption occurs inside the tight focus of a single objective of a large NA instead of two. Since 2P absorption is a highly nonlinear process, a high-power pulsed laser is generally required to facilitate the 2P process. This, of course, significantly increases the cost for the device application. Another important milestone is the discovery that 2P-induced 3-D recording can be introduced using a high-power continuous wave (CW) laser in photochromic and photorefractive materials as a replacement for a femtosecond pulsed laser.

There has been intense research interest in developing various 2P-induced optical recording mechanisms—not only permanent ones such as photopolymerizing, photobleaching and photofabricating voids, but also rewritable ones, including photorefractivity and photochromism. In 1998, researchers introduced a rewritable 2P-induced recording in photorefractive crystals.

Later, Day et al. discovered a 2P-induced polymeric photorefractivity, achieving the world's first erasable 3-D device with a density of 5 Gbits/cm^3. In particular, this group discovered a polarization-sensitive polymeric photorefractivity in polymer-dispersed liquid crystal materials through a 2P-induced reorientation mechanism. This discovery builds the conceptual foundation for multi-dimensional optical storage.

The highly confined 2P fluorescence enhancement allows rewritable 3-D optical data storage up to 205 Gbits/cm^3. This result is equivalent to 50 times the current DVD capacity. It was the world's highest 3-D data storage density until 2008, when Walker and colleagues developed a photochromic polymer-based 3-D disc with a capacity of 1,000 GB/disc, as reported in a 2008 issue of *Nature Photonics*. In their system, the total number of layers is 200, and the capacity of each layer equals 5 GB.

The idea behind multi-dimensional optical data storage is to multiplex multiple states of information in the same 3-D spatial region of a recording medium.

Multi-dimensional systems

The storage capacity of 2P-excitation-based 3-D optical memory is still limited by the resolution of recorded bits, which is in turn confined by diffraction. The limit of 3-D storage capacity is approximately 3.5 Tbits/cm^3, as predicted by the diffraction theory after aberration correction is considered for an objective of NA=1.4. The ever-increasing demand for more data capacity is compelling the development of multi-dimensional optical data storage.

The idea behind multi-dimensional optical data storage is to multiplex multiple states of information in the same 3-D spatial region of a recording medium. The information can be encoded into additional physical dimensions of the writing beam, such as spectra or polarization, and then individually addressed. The ground-breaking techniques of polarization and spectral encoding are the core of third-generation optical data storage. These approaches, which are not limited by the spatial resolution of recorded bits, allow capacity to be expanded by orders of magnitude.

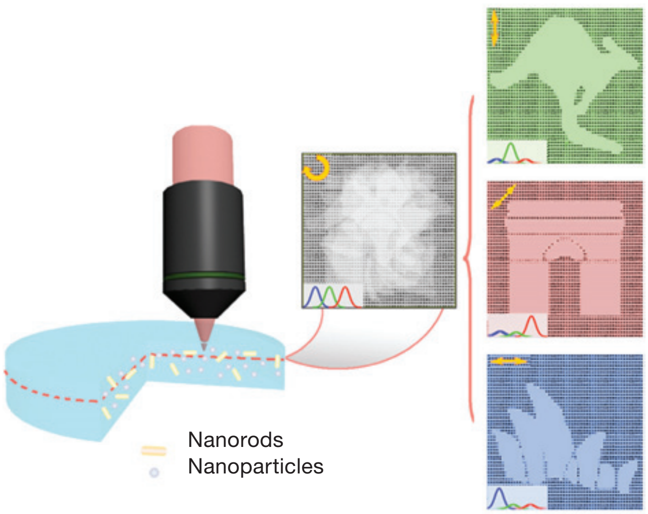
In 2007, Li et al. reported in *Optics Letters* that the world's first erasable four-dimensional (4-D) optical data storage device adopted the polarization-encoding technique. The two-state information was multiplexed in the two polarization states of the writing beams. Through the 2P-induced re-orientation of azo dyes inside a photopolymer, the researchers recorded a polarization-sensitive refractive-index change in the volume of a recording medium and retrieved it back individually. However, the realization of 4-D memory in such materials is limited by the weakness of 2P-absorption efficiency of azo dyes. This restriction has spurred a revolutionary idea: the 2P-induced photoreaction of nanoparticles.

When sizes shrink to the nanometer scale, intriguing

[Major achievements towards the development of 2P-induced 3-D optical data storage]

Group	Year	Achievements	Density
Parthenopoulos et al.	1989	Demonstration of 2P induced 3-D storage with a two-beam approach	--
Strickler et al.	1991	Demonstration of 2P-induced memory with a single-beam approach	--
Glezer et al.	1996	2P-induced 3-D voids recording in silica	17 Gbits/cm^3
Kawata et al.	1998	Rewritable 2P recording in a photorefractive crystal	33 Gbits/cm^3
Gu et al.	1999	Realization 2P recording using a CW laser	3 Gbits/cm^3
Day et al.	1999	Rewritable 2P recording in a photorefractive polymer	5 Gbits/cm^3
Kawata et al.	2000	2P recording in photochromic materials by a confocal reflection microscope	--
McPhail et al.	2002	Polarization-sensitive 2P recording in polymer dispersed liquid crystal materials	205 Gbits/cm^3
Day et al.	2002	2P-induced voids recording in polymers	2 Gbits/cm^3
Walker et al.	2007	2P-induced photochromic recording in a multilayer disc	250 GB/disc
Walker et al.	2008	2P-induced photochromic recording in a 200-layer disc	1,000 GB/disc

[5-D optical data storage]



Information bits are polarization- and spectra-multiplexed in multiple layers inside the medium. (Center) One recorded layer indicated by the red dashed line is addressed using a randomly polarized broad band source. (Right) The multiplexed information can be individually addressed with corresponding polarization (indicated by the arrow) and wavelength, as illustrated in the right column.

optical properties of nanoparticles emerge, such as a large 2P sensitivity, wavelength-tunable absorption and emission over their sizes, and a sharp polarization sensitivity, depending on their shapes. With the significantly enhanced 2P sensitivity, 2P-induced 3-D recording can be efficiently implemented using quantum dots as the energy transfer donors.

To this end, rod-shape semiconductor nanoparticles have been incorporated into photopolymers to introduce a polarization-sensitive energy transfer, therefore enabling the world's first nanoparticle-enabled polarization-sensitive 4-D optical data storage device. On the other hand, when the sizes of metallic nanoparticles shrink, their absorption and scattering cross-sections can be significantly enhanced at the surface plasmon resonance wavelength. These appealing properties make nanoparticles suitable to fulfill the application in both spectral and polarization encoding techniques with higher 2P sensitivity and less cross-talking.

When photoexcited at the surface plasmon resonance wavelength, the nanorods can raise the temperature above the melting point and re-shape into spheres. As a consequence of the shape change, surface plasmon bands are blue-shifted. This phenomenon can be used as a permanent recording mechanism, and it contributes a key technique for spectral encoding that uses nanorods of different sizes. In a 2009 *Nature* article, Zijlstra and colleagues demonstrated that gold nanorods, combined with the sharp 2P-induded polarization sensitivity, enable information to be recorded in five dimensions.

Future exploration

According to the global data storage market projection by the International Data Corporation, the amount of information that can be captured has been increasing explosively—six-fold within every four years. In the near future, the information generated each year will much overwhelm available storage capacity.

The urgent demand for more capacity compels the development of ultra-high-density storage devices. The major achievement of 5-D optical data storage marks the beginning a journey to the new era of multi-dimensional petabyte optical memory systems (1 exabyte = 1,000 petabytes; 1 petabyte = 1,000 terabytes)—which are equivalent to 10,000 times the current DVD capacity.

These multi-dimensional optical data storage devices are called multi-dimensional CD (MD CDs). They should emerge within the next 5-10 years. If successful, this new technology will underpin every sector of our modern life, with roles in remote education, portable banking, global e-security and telemedicine. It will also lead to enormous economic benefits.

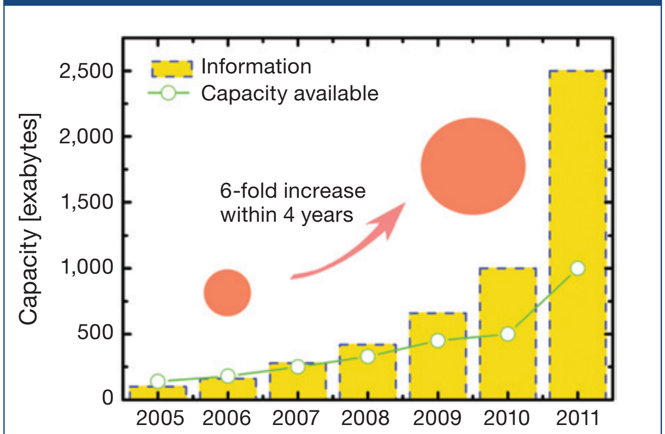
Multi-dimensional optical drives

In the future, we hope to see the development of a multi-dimensional optical drive that is not only compatible with the current DVD and Blu-ray discs, but also able to record and read polarization and spectral information. The signal noise ratio and bit error rates of multiplexed data decoding should be tested. The writing and reading speeds can be optimized to make large-scale petabyte capacity feasible, provided that parallel binary optics can be adopted.

Engineering of multi-dimensional point spread function

In a 3-D optical system, the point spread function is considered only in the *x-y-z* spatial dimensions. However, for a 5-D optical system, the point spread function must be engineered

[Global data storage market projection]



Source: Extracted from International Data Corp.

to incorporate not only the spatial dimensions but also spectral and polarization distribution. To realize spectral encoding in the volume of a recording medium, researchers must use a broadband source such as a supercontinuum source as the excitation source.

Due to the nature of dispersion, the focus of a broadband source will split when it propagates through the dispersive medium. To maintain the intensity distribution of the focus in the whole volume of the recording medium and remove the aberration effect, one must engineer the point spread function of a broadband source by providing spectroscopic compensation.

For a 5-D optical system, the point spread function must be engineered to incorporate not only the spatial dimensions but also spectral and polarization distribution.

In addition, owing to their vectorial properties, the electric field will depolarize into three components—Ex, Ey and Ez—in the tight focus of an objective with a large NA. The three electric-field components of the point-spread function can be engineered individually with a 3-D polarizer. This will enable information to be encoded in the polarization states of the writing beam; it will be added three-dimensionally inside the focus instead of only being multiplexed in the *x-y* plane. Therefore, this effort can significantly expand the number of multiplexed channels.

Further, the point spread function can also be engineered to split the single focus into multiple ones using phase modulation technology to engineer the input phase. This effort can lead to an efficient solution to address the recording and reading speed associated with the bit-by-bit data storage.

Breaking the diffraction-limited barrier

Although the capacity of 5-D optical data storage is potentially much larger than that of 3-D systems, the focus spot size is still confined in the *x-y-z* spatial region by the diffractive nature of light. For a given number of multiplexed channels, the storage capacity is mainly restricted by the spatial resolution of the optical system. Therefore, breaking the diffraction limitation to achieve a superresolution focus spot size is of significance to petabyte 5-D optical data storage. There have been several approaches to break the diffraction-limited barrier of a light beam, including far-field stimulated emission depletion (STED) and superlens methods.

In a typical STED system, one beam can be used to activate the recording, while another deactivates the recording. By spatially shaping the overlapping of the two beams, one can achieve a superresolution focus spot size of Lamda/20. Combining the STED method with spectral and polarization encoding techniques can significantly expand the current storage capacity.

An alternative approach to achieving a focus spot size below the diffraction-limited barrier is to collect the evanescent waves and propagate into a far-field region. This idea has led to the superresolution achieved in materials of negative refractive-index, which is called the superlens effect. With metamaterials, researchers have realized far-field superlenses for imaging sub-diffraction objects. Designing and developing such a far-field superlens for applications in 5-D optical data storage will be one of many promising future explorations. The lens would be capable of focusing a superresolution spot in the far field.

Beyond five dimensions

Apart from the physical dimensions in the spectral and polarization domains, an optical beam also possesses orbital angular momentum. This physical dimension can be adopted to encode information. When successful, it can provide the sixth dimension for optical data storage, thereby resulting in a further expansion that will help fill our insatiable need for data storage.

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