Coherent Optical Information Systems

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Coherent optical beams are used to communicate, store, and process information in a growing number of applications. The availability of coherent laser sources is of critical importance for the realization of such optical information systems. An incoherent source randomly populates the available temporal and spatial channels of the optical system, making it difficult to represent information. Coherent laser sources provide a stable carrier on which to encode information, making it possible to realize powerful information-processing techniques such as wavelength division multiplexing in fiber networks, gated holographic imaging, and three-dimensional optical data storage.

Introduction

In computers, communication networks, sensors, and other information systems, information is encoded in the various properties of electromagnetic fields. The optical portion of the electromagnetic spectrum has been used for information applications relatively recently, notably in fiber optics and optical disks. The primary motivation for the use of optics is the high temporal frequency of optical waves and the corresponding short wavelength. The high frequency leads to information channels with large temporal bandwidth, whereas the short wavelength implies that these channels can be compact. The emergence of laser sources with a high degree of coherence (*1*) has been essential for the practical development of such systems. We will explore the relation between the coherence of the light and its ability to represent information efficiently with the help of the block diagram shown in Fig. 1. In this abstracted optical information system, a light source is temporally modulated with information in each of several spatial channels. The modulated light propagates through the optical system and is detected at the output. Imaging systems, fiber optic links, and optical memory disks are examples of information systems that can be described by the system in Fig. 1. If an incoherent source [such as a light-emitting diode (LED)] is used in each of the channels in Fig. 1, then the optical waveform that the modulator has to work with is a random, broadband signal. The modulator enters the information into the system by modifying this unknown LED signal. From an information theory standpoint, the random wavefront of the incoherent light source is equivalent to information that an intruder might be transmitting over the same information channel, and this must be subtracted from the information capacity of the optical channel to obtain the capacity available for the transmission of useful information. In practice, LED emission is modulated by turning the emission on and off at a rate much slower than that of its temporal bandwidth. As a result, utilization of the bandwidth of the optical channel is dominated by the LED instead of by the information. When light from a coherent laser is used instead, the carrier signal is approximately sinusoidal, and an arbitrary broadband modulation can be deterministically applied to claim the full temporal bandwidth available in the optical channel.

On the basis of the above discussion, we can conclude that temporal coherence is preferable for utilizing the full information capacity of an optical channel. Spatial coherence, on the other hand, is required for efficiently using multiple channels simultaneously. Suppose that there is little crosstalk between the spatial channels in Fig. 1. For example, this is true for an imaging system. In this case each channel operates almost independently, and the advantage of using coherent radiation discussed above applies equally well to each channel. If a light source with the same temporal wavefront is used in each channel, then the system is said to be spatially coherent. A spatially coherent system can be either temporally coherent or incoherent, and systems in which all spatial channels are illuminated with the same coherent laser are automatically spatially coherent. Spatial coherence is particularly useful in systems where the outputs in Fig. 1 are linear combinations of the inputs. An unfocused image or a multimode fiber are examples of such a system. In an incoherent system, where the illuminating light is random, it becomes difficult to retrieve information from the combined detected signals because at each channel the information has been scrambled by a different, random wavefront. In a coherent system it is generally possible to retrieve information at the output by undoing, as far as possible, the linear transformation. Phase conjugation is an illustrative example. Suppose that the inputs to the channels in Fig. 1 are pixels of an image. The light from the entire image is then coupled into a multimode fiber, and the outputs are spatially resolved light measurements at the other end of the fiber. The measured output is unrecognizable because the different spatial modes of the multimode fiber scramble the information. However, in principle, we can recover the original image from the output measurement using phase conjugation if the illumination is coherent (*2*). If, however, the input illumination is completely incoherent, then the information about the input image is lost.

In free space, most of the light from a coherent laser beam can be focused to the classical resolution limit (about one wavelength or about a micrometer at optical wavelengths), making it possible to generate high light intensities by focusing a laser beam. For instance, high-intensity illumination is used to record information in commercially rewritable optical disks. Light emanating from a diffraction-limited spot can be collimated with a lens into a beam propagating in a well-defined direction. Consider, as an example, the wireless optical interconnection between different nodes in a communication network. The nodes can be buildings in an urban area or optical ports on a semiconductor chip inside a computer. In either case, the advantage of optical wireless communications over radio frequencies is the ability to implement point-to-point connections with good pointing accuracy and minimum crosstalk between the channels.

An important feature of monochromatic

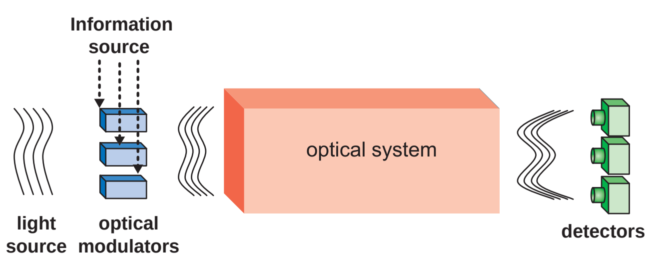

Fig. 1. Coherent optical information system. Schematic diagram of a generalized optical information system, showing an input illumination and multiple channels, each consisting of an input modulation stage in which information is entered, and a detector. Each of the channels represents a spatial mode of the optical system.

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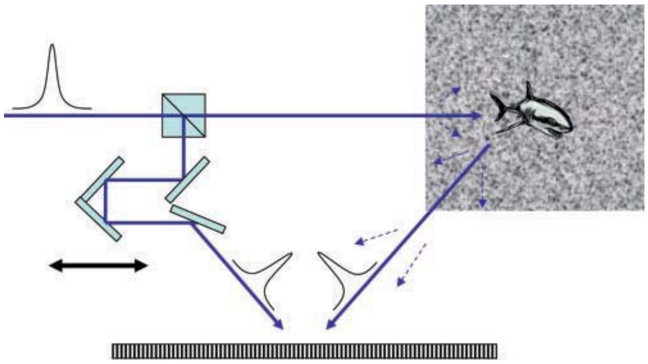

Fig. 2. Imaging through scattering media. Holographic system for producing a 3D image of an object buried in a turbid scattering medium. The coherence requirement for hologram formation separates the light reflected by the object from the scattered light.

light is that it makes phase measurements through interferometric detection possible. Because detectors at optical frequencies respond to light intensity and not to the field amplitude, the phase information is lost. Consider the system shown in Fig. 1, with incoherent illumination at the input and an optical system with a broad point-spread function (i.e., a nonimaging system). In this case, the detected intensity at the output is approximately uniform, independent of the information that was inserted at the input. Such a system is not useful for information processing. If a source with sufficient coherence is used, then the information about the input information and/or the properties of the optical medium can be inferred through interferometric detection.

In what follows, we will discuss the three major categories of optical information systems: imaging and sensors, communication, and memories. In each case, we will highlight examples in which the coherence of the light source has played a critical role.

Imaging

Conventional imaging provides an important example of an optical system in which incoherent light is the preferred source of illumination. We can think of the imaging performed by our eyes as a simple but powerful information-processing system. Visual information to be communicated to the brain spatially and temporally modulates the light field (for instance, through a liquid crystal device in a projector); this light field reaches the entrance pupil of our eye, and the lens performs the proper transformation to undo the blurring that was done to the image as it propagates through space to the eye. Each of the spatial and temporal modes that make up the incoherent illumination produces its own image independently. The averaging that happens when the image is detected smoothes out noise artifacts (*3*) (speckle) produced by individual, coherent modes. This is an important, but rather unique, example of an optical information system in which the lack of coherence is decidedly advantageous.

Imaging with coherent light can have certain advantages. Holography (*4*, *5*) is the best-known coherent-imaging technique. The intensity pattern recorded in a hologram is the interference produced between the field scattered from an object and that from a known reference. When the hologram is reconstructed with the reference, an exact replica of the object field amplitude and phase is produced, exhibiting all the properties of the original coherent field. For example, holograms appear three-dimensional (3D) because of the parallax that can be seen through the window of the hologram. Most holograms are recorded with coherent light, although some of the most commonly displayed holograms work in reflection (for instance, holograms on credit cards) and can be read out with incoherent, white light (*6*, *7*). The hologram in this case performs two functions. It spatially modulates the light reflected from the hologram with the image that we see and at the same time it selects only one color, thereby converting the incident light to a more coherent field. Holography as a practical 3D display method has not yet had a broad impact, and the idea of a holographic 3D television for the home remains a challenge for the future.

Holographic, or more generally interferometric, techniques have found interesting applications in imaging other than 3D displays (*8*, *9*). Because interferometric detection preserves the phase of the field, it is possible to extract more information about the object being imaged than can be done with conventional techniques. Gated holography for imaging objects that are obscured by scattering media is an interesting example. When a scattering medium is placed between the object and the detector (a shower door, for example), the spatial modes of the object field are scrambled, and an image produced with conventional incoherent techniques becomes blurry. Although it is virtually impossible to form a sharp image with incoherent light, a variety of techniques have been demonstrated to address this problem with coherent light (*10*). We will discuss as an example the imaging system shown in Fig. 2 (*11*). A short laser pulse (typically 50 to 100 fs) illuminates the object that is embedded in a scattering medium. Imaging of biological samples is a typical example. Some of the photons that are reflected from the object propagate right through the scattering medium, avoiding any collisions in the medium (these are called ballistic photons), and they exit carrying a clean image free of the blurring that the scattering medium normally produces. The rest of the photons undergo one or more collisions in the scattering medium. If the scattering medium is turbid (the scatterers move around), then the radiation that results from the nonballistic photons loses its coherence. Therefore, if we make a hologram of the light passing through the scattering medium, only the ballistic photons will form an interference pattern and record a hologram, and the reconstruction of the hologram is no longer blurred. What we have described so far would work equally well with a continuous coherent source. The pulsed laser is used to provide depth resolution. A pulse that is 50 fs long has a spatial extent of 15 μm. Therefore, the coherence length of such a pulsed laser is at most 2 × 15 μm. If we introduce a delay in the path of the reference pulse in the holographic recording arrangement of Fig. 2, then the recorded hologram captures a new depth slice of the object. In this imaging method, the coherence properties of the laser source are used ingeniously in multiple ways. The temporal coherence during the pulse is critical in order to separate the ballistic photons. The spatial coherence is necessary to spatially filter the scattered light. Finally, the limited temporal coherence due to the pulse is used to extract depth information. This is only one of many possible ways in which an interferometric measurement of the partial coherence of an object field can provide information about the properties of the object. A particularly advanced method of this type is a variation of the system in Fig. 2 (*12*), in which the object is probed with a focused beam and the image is formed one pixel at a time by scanning in two dimensions. An example of an image produced with this technique (generally referred to as optical coherence tomography) (*13*) is shown in Fig. 3.

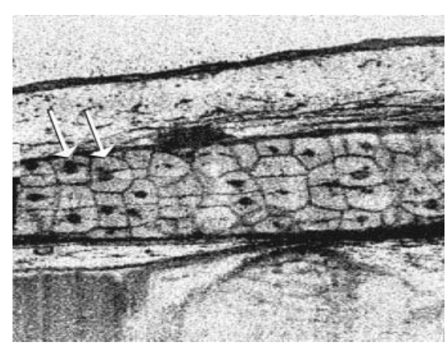

Fig. 3. Optical coherence tomography. The partial coherence of the light source (pulsed laser or incoherent source) is used to measure 3D structure with high accuracy. The image shows the cellular structure in an African frog tadpole. (http://rleweb.mit.edu/Publications/currents/cur11-2/11-2oct.htm)

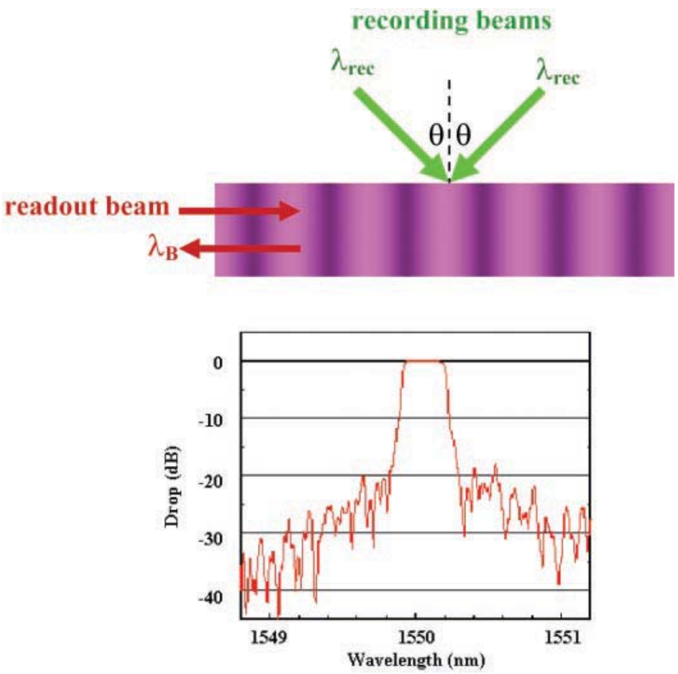

Fig. 4. Holographic filters. A grating is recorded in an iron-doped lithium niobate crystal by the interference pattern produced with two green beams ($\lambda = 514$ nm). The grating is illuminated from a different angle with infrared light (wavelength $\lambda \sim 1.55$ μm). The reflectivity of the infrared beam at the center of the filter is better than 99.89%, and the bandwidth at the 0.5 dB is 25 GHz.

Communications

Unlike imaging, which is the oldest application of optics, optical communications (*14*) have been adopted relatively recently. The availability of coherent light sources has been the key innovation enabling the rapid rise of this field. The basic fiber optics system is the same as that shown in Fig. 1, but with only one spatial channel. The light source is modulated by the information to be transmitted and then focused at the edge of the fiber. The light propagates in the fiber toward its destination, where it is coupled out and converted to an electronic signal by a detector. Such systems can be implemented with either coherent (laser) or incoherent (LED) sources. The performance obtained with coherent sources is vastly superior to that obtained with incoherent sources, and LED systems are used only for short, low-bandwidth links. One reason is that single-mode fibers are needed for long-range transmission to avoid mode dispersion (*14*) due to the different propagation velocities of the different spatial modes. Typically, the diameter of the core of a single-mode fiber at wavelength $\lambda = 1.5$ μm is ~ 8 μm. The theoretical limit for the spot size of a focused laser is about one wavelength, and therefore it is relatively easy to couple essentially all the light from a laser to the fiber by transforming the single spatial mode of the laser to approximately the shape of the single spatial mode of the fiber. The radiation from an LED, on the other hand, consists of a very large number of free space spatial modes, and it is impossible to efficiently couple all of them simultaneously into the single mode of the fiber.

The temporal coherence of lasers is also of importance in several ways. The emission bandwidth of an LED is typically 11 THz (*15*). At first glance, this does not appear to be a problem because the data only turn on and off the average intensity of the source, and the detector senses the average intensity. In other words, the underlying temporal variation due to the incoherence of the source does not seem to matter. In fact, it matters a great deal because of the fiber's chromatic dispersion. With an LED source the information is spread uniformly over the entire 11-THz spectrum of the LED. Severe distortion of the signal occurs as different portions of this broad spectrum reach the destination with different delays. When a laser is used, the bandwidth of the modulated waveform is essentially equal to the signal bandwidth (2.5 or 10 GHz in current systems), and the chromatic dispersion can be managed over this relatively small bandwidth.

The narrow bandwidth of the modulated signal compared to the available bandwidth of the fiber makes it possible to launch multiple signals centered at different optical wavelengths. This powerful technique [known as wavelength division multiplexing (WDM) (*14*)] was made possible by the availability of narrowband lasers whose center wavelength can be accurately specified (within a few GHz). A wide range of devices have been developed in the past decade to manage the wavelength channels in WDM systems. Filtering is a basic WDM function that permits any one of the wavelength channels to be separated from the rest and diverted to a detector or another fiber. Thin-film filters (*16*) (multilayer dielectric films similar to antireflection coatings) are most commonly used, but a wide range of other devices have recently emerged that promise improved functionality, e.g., grating filters recorded in fibers (*17*) or bulk materials (*18*). A grating filter (Fig. 4) is recorded as the interference between two coherent beams. The WDM signal to be filtered propagates parallel to the direction of the grating. Each grating period acts as a partial mirror. When the period of the grating is such that the round-trip distance between two grating elements is equal to the illuminating wavelength, then the signals reflected from all the elements interfere constructively, and strong reflection occurs at that wavelength. As the input wavelength is tuned away from this Bragg wavelength, the reflectivity of the filter rapidly drops. Figure 4 shows the filter shape produced by a grating holographically recorded in lithium niobate at $\lambda = 514$ nm (*19*). The maximum reflectivity is at the Bragg wavelength $\lambda = 1550$ nm (Fig. 4). Notice that the filter has a flat top. In other words, the filter continues to reflect almost 100% of the light for a range of wavelengths around the Bragg condition. This is an example of a 1D photonic bandgap medium (*20*) in which the periodic structure prevents photons

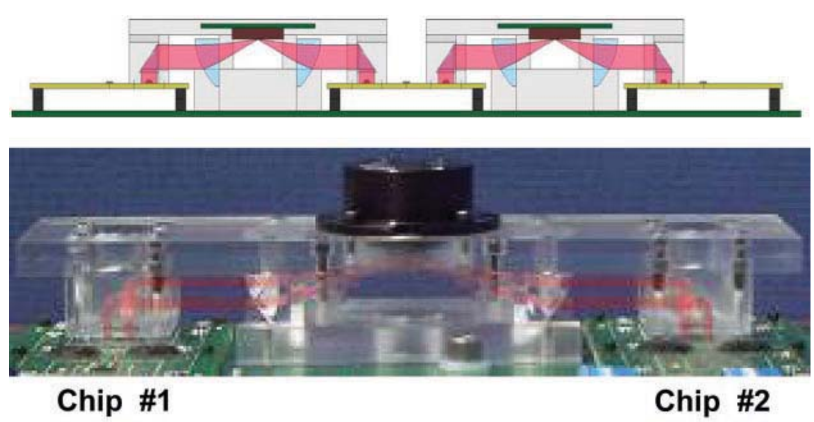

Fig. 5. Chip-to-chip interconnection. Four free-space optical interconnect modules are used to interconnect five daughter boards to accelerate fast Fourier transform calculations on a board. Light from an array of 4 by 4 vertical cavity surface-emitting lasers on each daughterboard exit vertically, are collimated by a lenslet array, and are reflected 90°. The light is then focused by a lens on an adjustable mirror that relaxes the alignment tolerances. A second lens and a lenslet array are used to image the optical signals on a detector array. Use of these modules with 4 by 4 channels operating at 1 Gb/s has been demonstrated with only passive alignment (*22*).

from propagating for a range of frequencies. The width of the bandgap is typically controlled by the strength of the grating. Obtaining this flat-top response is important for fiber optic networks because it allows the data bandwidth to be filtered without distortion. For example, the size of the photonic bandgap in Fig. 4 is 40 GHz, which allows the 10-GHz signals to pass readily and allows margins for laser drifts of the center frequency of the WDM channel. The reflectivity of the filter in Fig. 4 decreases by a factor of 100 at 50 GHz away from the peak value. This rapid drop, which is important to avoid crosstalk from the next channel (only 50 GHz away), is controlled during the holographic exposure by nonuniform illumination (apodization) by the recording laser.

Optical communication through free space optics (FSO) does not have the same strict requirement for temporal coherence as does fiber optics because propagation in free space does not have chromatic dispersion. Spatial coherence, however, is essential to accurately point laser beams from one point in space to another. The system shown in Fig. 5 is a prototype of a FSO chip-to-chip communication system (*21*, *22*). A silicon chip is electronically interfaced to a GaAs chip through a technique called flip-chip bonding. The GaAs chip contains an array of vertically emitting lasers, each of which can be modulated with data from the Si circuit with up to 1 GHz per laser. The light from each laser is guided though free space to detectors on other chips.

Memories

Optical memory disks have found widespread application in audio, video, and data storage. As with imaging and communications devices, the availability of coherent light sources has been essential for the development of optical disks. The main advantage of optical disks as compared with other recording media (magnetic, semiconductor) is that they can be easily removed from the recording device and can be cheaply replicated and distributed. In addition, optical technology offers good storage density. In a conventional optical disk, a laser is focused onto a single spot on the disk, and the reflectivity of each spot is measured on an optical detector. The number of bits per unit area that can be stored on the disk is roughly equal to 1 divided by the area of the focused spot [spot size = λ/NA, where NA is the numerical aperture of the focusing lens; NA ~ 0.6 for current digital video disks (DVDs)]. The position of this small spot is accurately tracked on the surface of a spinning disk through optical feedback. The recent development of blue semiconductor lasers (λ = 405 nm) has been motivated by the need for improved memory disk density. The spot size with a blue laser and the NA = 0.75 is only 540 nm, and it is expected that future generations of DVD systems that use blue lasers will have more than twice the density of current devices.

Optical storage in 3D is one of the methods used to obtain increased storage density. The basic difficulty in 3D optical storage is the need to control and access the properties of the recording material throughout its 3D volume while having access only to the surface. Holography and nonlinear optics are the two principal methods for obtaining access to the 3D volume. Both methods rely on the coherence properties of laser beams to accomplish the task. Localized recording (*23–25*) is achieved by using nonlinear optical recording materials. In this case, the optical properties at a particular point in 3D space (voxel) are altered only if the point is illuminated with light above a certain intensity threshold or with two beams simultaneously. In this way, the nonlinearity of the material allows us to alter only one voxel at a time even though the optical beams travel throughout a large portion of the optical material. The ability to generate strong light intensity within a small volume is characteristic of a spatially coherent light source.

In holographic storage (*26*), an information bit is stored by producing an interference pattern throughout the volume of the material of a known reference wave and a signal beam that is either on or off, depending on whether it represents a binary state of 1 or a 0. The stored bit is retrieved by illuminating the hologram with the reference to reconstruct the signal. The upper limit on the storage density (bits per unit volume) that can be achieved with holography is λ^{-3}, which is roughly the same for localized recording. Interestingly, although temporal coherence of the source is required for holographic 3D storage so that an interference pattern can be produced over the entire storage volume, the spatial coherence of the source is critical for the localized recording scheme.

An entire page of data typically of 1 million bits can be holographically recorded simultaneously (Fig. 6). A spatial light modulator (SLM) was used to imprint the page of data on the signal beam. Upon read-out, the reference illuminates the re-

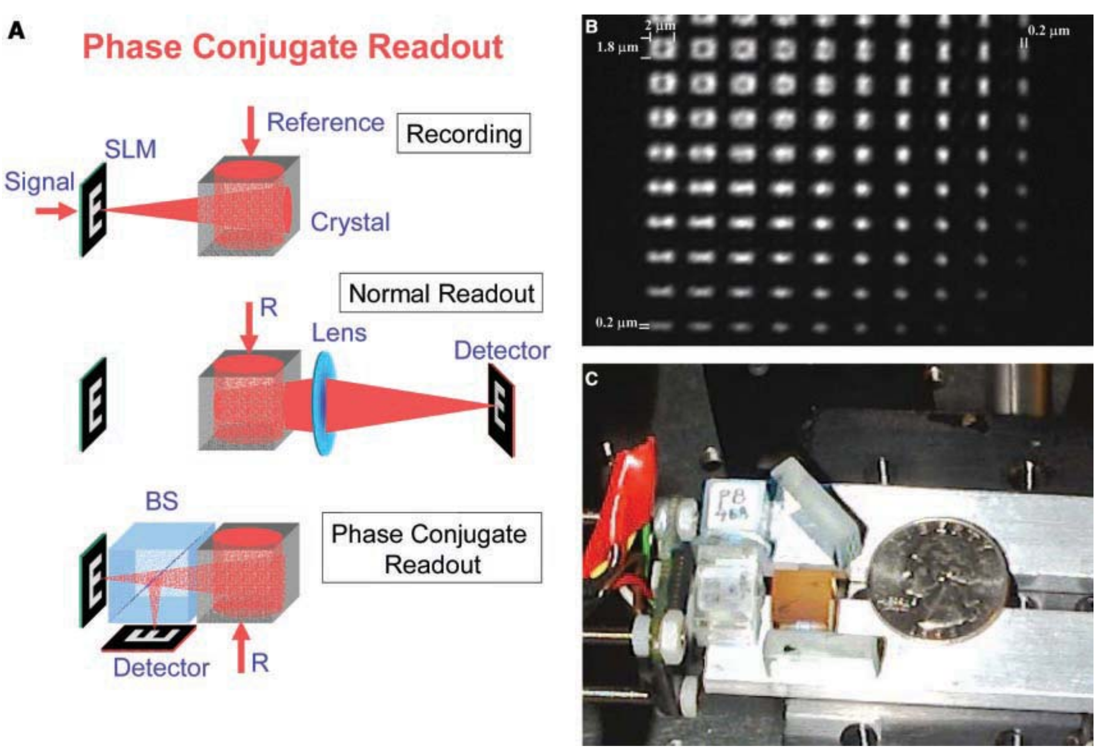

Fig. 6. Holographic memory. (**A**) Recording is achieved by interfering data recorded on a spatial light modulator and a reference wave. Conventional reconstruction uses the recording reference beam and a lens. Phase-conjugate readout with a counter-propagating reference beam allows lens-less readout. (**B**) Phase-conjugate readout allows high-density storage. Feature sizes well below 1 μm are visible in the reconstruction shown in (B). One hundred such holograms were superimposed in this experiment, yielding a surface storage density in excess of 100 bits/μm. (**C**) Photograph of the experimental apparatus.

corded hologram, and the reconstruction of the entire signal beam is produced. This reconstruction can be brought to focus on a detector array [e.g., charge-coupled devide (CCD) camera]. What makes holographic memories an interesting technology is that changing the angle of the reference by as little as 0.007° during read-out (*27*) will cause the reconstruction to disappear. This makes it possible to superimpose many pages in the same volume (up to 10,000 pages has been demonstrated). Each page can be thought of as an additional layer in a holographic memory disk, leading to storage densities roughly two orders of magnitude better than are possible with DVDs (*28*). Because the recorded pages of data are holograms, it is possible to read them out using phase conjugation (*29*), in which case the hologram is illuminated with a beam that is the same as the reference used during recording except that it propagates backward. This results in the reconstruction of the signal beam that is also propagating backward, and in doing so it comes to focus back at the plane of the SLM. The focused page of data can be directed to a CCD by a beamsplitter (Fig. 6). The advantage of using phase-conjugate readout is that it allows us to be rid of the powerful lens that is required to focus the field of a 10^3 pixel by 10^3 pixel image with good resolution. In the experiment shown in Fig. 5, a page consisting of squares of varying sizes clearly shows that pixels with resolution well below a micrometer are well reconstructed (*30*). Several hundred pages were superimposed in the same crystal shown in Fig. 6. So far, systems like the one in Fig. 5 have not reached commercial success. The main practical success of 3D storage techniques has been the multilayer DVDs with as many as four layers (two-sided, two-layers per side). More ambitious 3D storage systems based on holography or nonlinear optics remain hindered by a lack of suitable materials.

Conclusion

The recent progress in optical information systems may be only the beginning of a long-lasting trend. For instance, optical communications are currently based on intensity detection, and the phase of the transmitted signal is not measured. Coherent communications have advantages of flexibility and signal-to-noise ratio. The emergence of inexpensive laser sources with high coherence and stability will allow their use as local oscillators similar to the way in which local oscillators are used in today's radio communication systems. One of the challenges for the future is the development of efficient methods for optical signals to directly interact with each other in nonlinear media. This is an emerging technology in fiber optics (for instance, semiconductor optical amplifiers used for wavelength conversion), but one that may lead to communication networks composed entirely of optical switching devices.

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REVIEW

Coherence with Atoms

Mark A. Kasevich

The past decade has seen dramatic progress in our ability to manipulate and coherently control the motion of atoms. This progress has both fundamental and applied importance. On the one hand, recent experiments are providing new perspectives for the study of quantum phase transitions and highly entangled quantum states. On the other hand, this exquisite control offers the prospect of a new generation of force sensors of unprecedented sensitivity and accuracy.

In 1991, the experimental analog to Young's double-slit experiment using helium atoms was realized (*1*). A beam of helium atoms first illuminated a microfabricated slit that was narrow enough to produce a wavefront capable of coherently illuminating a double-slit structure. A scannable detector recorded the number of atoms arriving at a given position in the far field of the double slit. The expected spatial oscillation in atom counts as the detector was moved across the atom distribution was observed, much as the intensity profile of a beam of light is spatially modulated as it is subjected to a similar series of slits. Nearly coincidentally with this work, three other groups observed atom de Broglie wave interference in interferometer geometries analogous to optical Mach-Zehnder interferometers (*2–4*).

Although it is a fundamental and well-tested tenet of quantum mechanics that wave-like properties are associated with particles, it is remarkable that a collection of particles as complicated as an entire atom can be coaxed to behave in this way. Since these initial experiments, the field of coherent atom optics has grown in many directions (*5*). The past several years have seen explosive growth. This review is meant to provide context for this recent work in terms of past accomplishments and future milestones.

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Deconstructing Decoherence

In the quantum mechanics paradigm, coherence between multiple propagation paths only manifests itself when there is no possibility of observing "which path" the particle follows. However, an interaction with the environment in some sense constitutes an observation of the system and suppresses possible interference. How well isolated does the interfering particle