Microlaser Arrays for Optical Information Processing

RECENT ADVANCES IN VERTICAL-cavity surface-emitting microlaser arrays opened a variety of new possibilities in the field of optical information processing. This article describes some of the recent progress in compact, robust, and ultrafast optical information processors that can be used for image/signal processing, pattern recognition, and neural networks, as well as holographic storage, optical interconnects, and image transmission.

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SURFACE-EMITTING LASER DIODE ARRAY (SELDA)

About four years ago, AT&T Bell Laboratories and Bellcore jointly developed a vertical cavity surface emitting laser diode array (VC- SELDA)[1-4] that was originally proposed by K. Iga.[5,6] Figure 1 shows a scanning electron microscope picture of the SELDA. In the figure, a hair-like structure only a few microns in diameter is an independent laser.

The SELDAs have many features that make them highly desirable for use in optical information processing. The individual lasers can be as small as a few microns (often called "microlasers"). Also, the cavity of a VC-SELDA is formed along the direction vertical to a wafer surface, as the name "VC (vertical cavity)" implies. Therefore, a high density stacking of over one million microlasers on a 1 cm^2 chip in a two-dimensional arrangement is possible. In addition, the threshold current of the laser is low—near 1 mA for lasers less than 5 µm in diameter—due to the small active volume of a SEL (surface-emitting laser). This low threshold current allows operation of many lasers at the same time without significant power consumption. The wavelength of the light from the microlaser ranges discretely from 0.7 - 1.5 µm with a spectral linewidth of about 0.001 nm due to its small cavity length that supports only one laser mode. This gives a coherence length of about 1 meter (longer than that of a HeNe laser) and the spectral resolution of about one million. Therefore, a hologram of a high quality image can be recorded and reconstructed by using a microlaser. However, the microlasers are mutually incoherent, meaning that phases of the light from each of the microlasers are not locked with each other. The output light power from each microlaser is bright enough (typically, several mW, continuous) to reconstruct a hologram that can be easily detected by a normal 2-D image sensor. The switching speed of the lasers is very high(less than one billionth of a second). Finally, contrast is extremely high, since a laser generates no light when it is off. Some of the key promising applications of the SELDA will be described below.

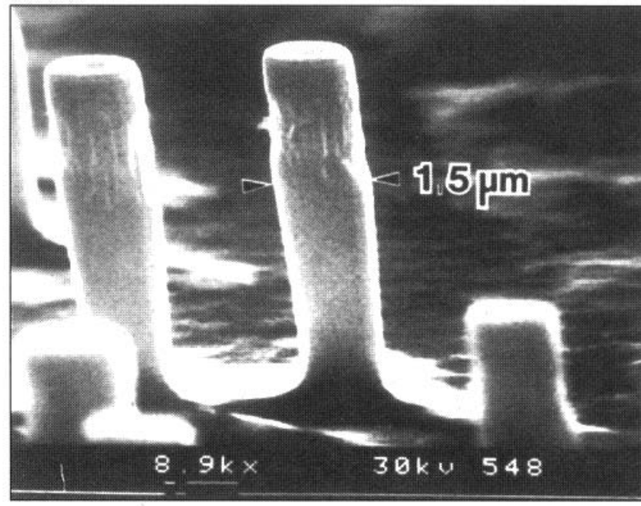

Figure 1. Scanning electron micrograph of a vertical cavity surface-emitting microlaser array. The human hair-like structure with the diameter of 1.5 µm is an independent laser. The laser light is emitted along the direction vertical to the wafer surface.

COMPACT, ULTRAFAST VOLUME HOLOGRAPHIC MEMORY

Volume holographic memory has been extensively investigated as a means of providing large storage capacity with the potential for fast random access to page-organized information. These qualities are highly desirable for applications such as multimedia. However, in most proposed architectures, holographic memories require bulk and complicated beam deflectors to steer the beam direction corresponding to the desired page. Such devices also limit the speed and resolution of the system.

The use of SELDAs, instead, can alleviate many of these problems.[7] A combination of a SELDA and a lens, as shown in Figure 2(a), can be used as a compact method of generating different collimated optical beams. The direction of each beam depends on the location of its microlaser. Hence, the beam direction can be switched within one billionth of a second. This scheme lends itself well to the reconstruction of angularly multiplexed holograms, where each image is recorded using a reference beam propagating along different angle.

Figure 2(b) shows the above holographic readout technique schematically. Results of the experiments using a $LiNbO_3$ crystal (0.01 % iron doped) as the holographic recording medium and using a SELDA for readout are also shown in Figure 2(b). The microlasers in the array are separated by 70 µm, corresponding to an angular separation of about 0.04 degrees. From Figure 2(b), we see that adjacent lasers reconstruct independent images. Consequently, each microlaser can be assigned to read a separate page of information. Recently, successful recording and readout of 5,000 high resolution images in a 1 cm^3 $LiNbO_3$ crystal using beam steering devices have been reported.[8] One can foresee a scheme similar as that in Figure 2(b) used for reading such a high number of images.

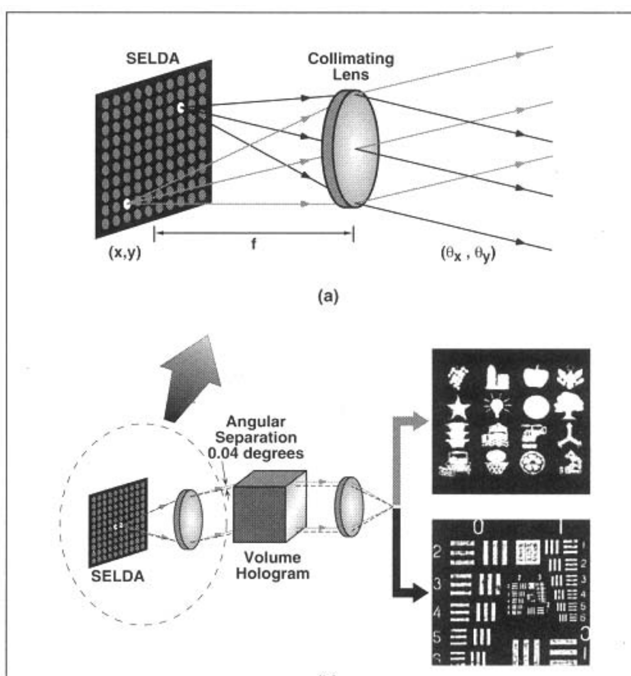

Figure 2. (a) Beam steering using a SELDA (surface-emitting laser diode array) and a collimating lens and (b) a compact and ultrafast volume holographic memory using a SELDA. The system is capable of retrieving two-dimensional images randomly within one billionth of a second from a three-dimensional volume holographic memory.

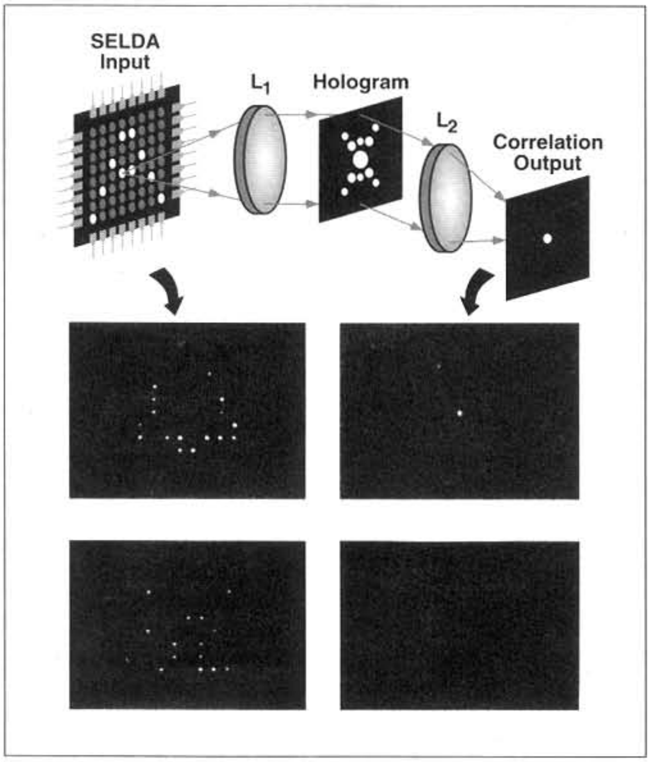

Figure 3. Compact and robust incoherent correlator using a SELDA: Schematic of the system (top), input patterns (left) and the corresponding correlation outputs (right) for the filter, the Bell logo. The bright spot at the center of the correlation output plane for the correct input (middle, right) indicates that the system is capable of recognizing patterns. The correlation output is almost insensitive to filter positioning due to incoherent summation.

COMPACT AND ROBUST PATTERN RECOGNITION

Parallelism of optics provides a powerful tool to conduct two-dimensional operations such as Fourier transform, correlation, and convolution. Pattern recognition is a major application that relies on the above operation. However, the conventional holographic pattern recognition system described by VanderLugt[9] has found limited application because of its bulkiness and sensitivity to misalignments.

Such problems can be greatly alleviated by using a SELDA. As explained before, the light from a SEL is highly monochromatic. However, the phase of the light from each of the SELs is not locked with each other. Using these two unique coherence properties (temporally highly coherent and spatially incoherent), a compact and robust incoherent correlator[10] has been demonstrated.[11] Figure 3 (top) shows the incoherent correlator using a SELDA. The light from each microlaser is collimated by the lens, L_1, which then illuminates the hologram. The reconstructed images are formed at the focal plane of the lens, L_2. The image generated by each SEL is shifted by the amount corresponding to the position of the SEL. The images reconstructed by different SELs are added up incoherently, averaging out the phase-sensitive interference terms. The eventual summation over all of the reconstructed images yields the correlation between the input and the reference image stored on the hologram. Since the system does not involve any moving parts (*e.g.*, rotating diffuser) or bulky optical components, it has the potential for integration and miniaturization.

Figure 3 (middle and bottom) shows the correlation output obtained from the SELDA correlator. A holographic filter was fabricated for the reference image pattern (the Bell logo) and was tested for the two input patterns—the Bell logo and a Chinese character meaning "light." For the correct input—Bell logo (middle left)—a bright auto-correlation peak appears at the center of the correlation output (middle right). On the other hand, for the incorrect input, Chinese character (bottom left), a cross-correlation is obtained (bottom right). As shown in the figure, the cross-correlation signal is much weaker than the autocorrelation peak, allowing a satisfactory discrimination between the two input patterns.

HOLOGRAPHIC NEURAL NETWORKS

Recent advances in neural networks opened up many new possibilities of optical information processing for broad application areas.[12,13] Coherent optics is highly suited for the implementation of neural networks requiring parallel and analog computing. Such a neural network system normally consists of three major parts: a recognition part to compare an input with all the stored information, nonlinear thresholding elements to make a decision, and a reconstruction part to retrieve the corresponding memory. By simply combining the recognition part and the reconstruction part explained previously, and by incorporating an array of nonlinear thresholding elements between the two, a compact, ultra-fast, and highly efficient neural network system may be implemented in the future.

Furthermore, even the bulk lenses shown in Figures 2 and 3 can be replaced by planar Fresnel lenses, making possible the integration of the whole system into a small scale on a GaAs substrate. A technique of integrating planar Fresnel microlenses with SELDAs by selectively ion-beam milling the substrate has been successfully demonstrated.[14] When these technologies are combined with future volume holographic recording materials with *in situ* read-write-erase capability and controllable sensitivity to allow both reconfiguration and storage, optical neural networks will play a major role in future information processing.

2-D IMAGE TRANSMISSION THROUGH A SINGLE-MODE FIBER (2-D WDM)

A two-dimensional coherent optical processor is capable of performing correlation and convolution at the speed of light. However, if such a processor is to be interfaced with other systems or cascaded, the operation speed is reduced. The reason for the slower operation speed is the requirement of electronics at the interfaces that operate serially.

As a means of alleviating this problem, an all optical 2-D image transmission through a single-mode fiber is presented.[15] The communication link is conducted in parallel between 2-D optical processors. To provide the necessary spatial information within a single-mode fiber, WDM (wavelength division multiplexing) is deployed. In Figure 4(a), the input image f(x,y) is encoded to spectral information, f(λ), and is transmitted through a single-mode fiber. In the decoding process, the spectral information is transformed back to spatial information, f(x,y). This 2-D WDM involves two difficult problems: how to efficiently couple all the light from an input image into a very small single mode fiber, and how to decode the spectral information to reconstruct the original 2-D images.

These problems can be tackled by combining a 2-D multi-color, surface-emitting laser diode array (MC-SELDA)[16] and a volume hologram as in Figure 4(b). The 2-D MC-SELDA is a 2-D array of microlasers, each with its own unique wavelength. In this system, efficient light coupling (middle) is achieved by an *in-situ* self-aligned light path provided by holography. In the decoding process (bottom), the spectrally transformed signal f(λ) from the single-mode fiber is diffracted by the same volume hologram and is redistributed to its original position to reconstruct the original image f(x,y). A volume grating responds to its own specific wavelength due to the phase matching selection property. Therefore, each wavelength of light can pass through a volume hologram as if there were only one grating created by itself, without being affected by other gratings. Moreover, diffraction efficiency of a volume grating is ideally close to 100%, and is independent of the number of gratings within the available index of the recording material. These advantages permit high coupling efficiency in encoding and a clear image reconstruction in decoding. Also, the system can cover a wide range of wavelengths, each of which does not need to be uniformly separated.

A monolithic 2-D MC-SELDA was recently demon-

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