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The primary objective of this research has been to investigate optical logic operations using nonlinear optical techniques in bulk media as well as in waveguide structures such as fibers and/or laser diodes. We have been exploring, in general, optical logic gates that can be implemented utilizing spectral parallelism. This spectral parallelism has been demonstrated for various optical computing components. While most of these components demonstrated were implemented in photorefractive media, the possibility to perform optical logic in optical fibers as well as laser diodes has also been explored.

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AUGMENTATION TO PROPOSAL FOR STUDIES OF NONLINEAR OPTICAL LOGIC GATES FOR DIGITAL OPTICAL COMPUTING

(AASERT Contract No. F49620-92-J-0368)

Final Report

(June 15, 1992 through June 14, 1995)

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1.0. Research Description:

The primary objective of this research has been to investigate optical logic operations using nonlinear optical techniques in bulk media as well as in waveguide structures such as fibers and/or laser diodes. We have been exploring, in general, optical logic gates that can be implemented utilizing spectral parallelism. This spectral parallelism has been demonstrated for various optical computing components. While most of these components demonstrated were implemented in photorefractive media, the possibility to perform optical logic in optical fibers as well as laser diodes has also been explored.

1.1. Scientific Problem:

It is well known that spatial parallelism can be utilized in optical information processing and optical computing to increase the calculation speed, such as 2-D Fourior transform using a thin spherical lens. However, for a long time, spectral parallelism for optical computing has not been fully utilized. For example, four-wave mixing can be realized in photorefractive crystals over a large spectrum range. It is desirable that the broad spectrum of photorefractive media and optics can also be explored to increase the capacity and processing speed of optical computing components. This can be achieved by exploring the spectral parallelism of four-wave mixing within the whole spectrum range the photorefractive crystal can respond. In other words, we can perform multiwavelength optical wave-mixing to achieve parallelism. This wavelength domain parallelism is especially important for photorefractive materials whose response time is relatively slow. In addition to spectral parallelism, we have also explored the possibility to implement nonlinear optical logic gates in materials other than photorefractive materials. Specifically, four-wave mixing in optical fibers and laser diodes has been theoretically investigated as alternative means to implement optical logic. Although the nonlinearity of fibers is relatively small, its large interaction length and large intensity due to waveguiding effect makes it a promising candidate to perform optical logic operations. This program therefore addresses issues of design and functionality of such spectrally parallel and/or waveguide enhanced components for optical logic gates.

1.2. Scientific and Technical Approach

In an effort to increase the capacity and processing speed of optical information processors, we have investigated the wavelength domain parallelism in photorefractive crystals. Specifically, wavelength is employed as an additional dimension to encode, transfer, and process optical information. In this way, the broad bandwidth of optics can be utilized to increase the capacity and processing speed. We have proposed and demonstrated several multiwavelength optical computing components such as a polarization encoded full adder, an arithmetic logic unit, and a fuzzy logic processor. As well, wavelength conversion and phase conjugation using four-wave mixing in optical fibers has also been investigated as a possible way to achieve wavelength encoded logic operations. In this way, four-wave mixing can be realized with a relatively small power (as low as those delivered by laser diodes) and a fast response time. In addition, a primary study on cavity-enhanced highly-nondegenerate four-wave mixing in semiconductor lasers has also been carried out.

During the period of this program, we have carried out a comprehensive study in the area of optical logic operations and spectrally parallel optical computing elements. Many of the results of these investigations (both theoretical and experimental) are documented in the following list of publications. Publications listed in previous reports are not included.

1.3. Publications:

1.3.1. Papers Published

Shaomin Zhou, Weishu Wu, Scott Campbell, Pochi Yeh, and H.-K. Liu, "Optical implementation of fuzzy-set reasoning," Appl. Opt., 33, 5335-5347 (1994).

Weishu Wu, Pochi Yeh, and Sien Chi, "Phase conjugation by four-wave mixing in single-mode fibers," IEEE Photonics Tech. Lett., 6, 1448-1450 (1994).

Scott Campbell, Pochi Yeh, Claire Gu, and Q. Byron He, "Fidelity of image restoration by partial phase conjugation through multi-mode fibers," Opt. Communications., 114, 50-56 (1995).

Weishu Wu, Scott Campbell and Pochi Yeh, "Implementation of an optical multiwavelength full adder using a polarization encoding scheme," Opt. Lett., 20, 79-81 (1995).

Weishu Wu, Changxi Yang, Scott Campbell, and Pochi Yeh, "Photorefractive optical fuzzy logic processor based on grating degeneracy," Opt. Lett., 20, 922-924 (1995).

Weishu Wu and Pochi Yeh, "Energy coupling by partially degenerate four-wave mixing in multichannel lightwave systems," IEEE Photonics Tech. Lett. 7, 585-587 (1995).

1.3.2. Conference Papers Published

Weishu Wu, Pochi Yeh, and Sien Chi, "Frequency conversion by four-wave mixing in single-mode fibers," Technical Digest of Nonlinear Optics Topical Meeting'94 (Hawaii, USA) .

Weishu Wu, Changxi Yang, Scott Campbell, and Pochi Yeh, "Photorefractive optical fuzzy logic processor," in Optical Computing Technical Digest, 1995 (Optical Society of America, Washington, D.C. 1995), Vol. 9, paper OTuE10.

Weishu Wu, Scott Campbell, and Pochi Yeh, "Implementation of a multiwavelength photorefractive arithmetic logic unit," *Photorefractive Materials, Effects, and Devices* Technical Digest, Aspen Lodge Ranch Resort, Estes Park, CO (June 1995), pp. 532-535.

Weishu Wu and Pochi Yeh, "Power coupling by four-wave mixing in single-mode fibers," in CLEO'95, Baltimore, USA (1995).

2.0. Progress:

2.1. Progress Summary

The following is a list of the significant progresses we have made under the support of this program:

We are the first to propose, analyze, and experimentally demonstrate the following:

- A multiwavelength carry lookahead device for an optical full adder,
- A multiwavelength optical arithmetic logic unit in photorefractive crystals,
- A fuzzy logic processor based on grating degeneracy in photorefractive crystals.

We are also the first to

- quantitatively analyze the efficiency of four-wave mixing in optical single-mode fibers
- experimentally investigate the fidelity of image restoration by partial phase conjugation through optical fibers.

2.2. Progress Details

During this program period we have studied different schemes for nonlinear optical logic gates. Wavelength domain parallelism has been extensively studied and many components have been proposed, analyzed, and demonstrated in photorefractive crystals. Other schemes based on nonlinear interaction in optical fibers and laser diode cavities have also been studied.

In an effort to explore wavelength domain parallelism in photorefractive crystals, we have proposed and demonstrated an optical multiwavelength full adder that uses polarization encoding and four-wave mixing in photorefractive crystals. Optical wavelengths are employed to encode the different bits of binary numbers. In this way, we can perform multibit operation simultaneously in a single photorefractive crystal. The idea of multiwavelength four wave mixing and polarization encoding has been generalized to design a novel optical computing component--an optical arithmetic logic unit.

In addition to binary logic gates, we have also investigated the possibility of performing fuzzy logic in photorefractive crystals. Fuzzy logic can be in general regarded as an extension of binary logic. The major difference between binary logic and fuzzy logic is that the value of a fuzzy variable can be anywhere between 0 and 1, in contrast to two discrete values (0 or 1) for binary logic. When imprecision and vagueness are inevitable, fuzzy logic is a better way to describe some processes such as human reasoning. Therefore, fuzzy logic has many applications in fields such as process control, decision making, and pattern recognition. It is well known that max-min operation plays a key role in fuzzy logic operations. [1] Based on grating degeneracy in photorefractive crystals, we have proposed, analyzed, and demonstrated an optical fuzzy logic processor. Max-min operations, which are used to process fuzzy functions in disjunctive normal forms as well as fuzzy-set reasoning, can be easily realized in parallel. The fuzzy processor has advantages such as a simple data encoding scheme, high accuracy, immunity from intensity fluctuations, and shift invariance of input patterns.

In addition to the effort of making use of wavelength domain parallelism to increase the processing speed limited by the slow response time of photorefractive crystals, other efforts have been made to achieve a faster speed. One possibility is to use optical fibers as the nonlinear medium for optical four-wave mixing. Wave mixing in optical fibers has advantages such as long interaction length and small operating optical power. Therefore, wave mixing can be performed using optical laser diodes instead of gas lasers. The efficiency of wave mixing, however, is still of fundamental importance because of the relatively small nonlinearity of the optical fibers. Therefore, a thorough study on the efficiency of four-wave mixing in optical single-mode fibers has been carried out. An exact solution to the coupled-mode equation has been obtained, taking into account of pump depletion, fiber dispersion and fiber absorption. Using this analytical solution for four-wave mixing in single-mode fibers, optimum length of fiber is derived for most efficient fur-wave mixing. The calculated results are in good agreement with the reported experimental results and they are useful in designing new logic gates using wavelength encoding scheme in optical fibers.

Another effort to achieve fast optical wave mixing using optical cavities is also being investigated. We have carried a theoretical analysis on the efficiency of cavity-enhanced highly nondegenerate four-wave mixing in semiconductor lasers. We have established a general approach to analyze the highly nondegenerate four-wave mixing in a semiconductor laser. The interaction between the signal (probe) field and the conjugate field are described by a set of coupled-mode equations. The analytical solutions for the probe and conjugate reflectivities has been obtained in the weak-coupling and pump nondepletion regime. We have obtained an enhancement factor due to cavity resonance. The analysis provides a tool for designing frequency-domain logic operations based on highly nondegenerate four-wave mixing with insights for optimizing the performance and utilizing some special mechanisms for desired characteristics.

In addition, the quality an optical signal maintains as it travels down an optical fiber has also been systematically studied. The quality of signal is important for those systems utilizing multimode fibers as interconnection transmission lines between computing elements. An experimental investigation on the fidelity of image restoration by partial phase conjugation through multimode fibers has been conducted. For the first time, the conjugated image-to-background ratio is experimentally measured as an evaluation of the phase conjugate mirror's fidelity.

Detail discussion on the technical progress developed in this program can be found in Section 3 which contains reprints of the paper published.