

using different crystal orientations, if results of chemical etching of different low index planes⁴ are also observed for photoelectrochemical etching. It is important to note that the very mild electrolytes used in photoelectrochemical etching of GaAs are compatible with virtually all resist or mask materials.

Commercial availability of 10-cm (4-in.) GaAs wafers suggests that this material could be used for practical spectroscopic gratings. In addition, gratings with a variety of groove structures are used in integrated electrooptics which are mostly based on compound semiconductors.¹² An understanding of crystallographic effects in controlling groove geometry during photoetching will permit the fabrication of new structures with a high degree of process control.

This work was supported in part by the Office of Naval Research and the National Aeronautics and Space Administration.

References

1. M. Hutley, *Diffraction Gratings* (Academic, New York, 1982).
2. P. Philippe, S. Valette, O. Mata Mendez, and D. Maystre, "Wavelength Demultiplexer: Using Eschelette Gratings on Silicon Substrate," *Appl. Opt.* **24**, 1006 (1985).
3. S. Sriram and E. P. Supertzi, "Novel V Grooves in Silicon," *Appl. Opt.* **24**, 1784 (1985).
4. R. E. Williams, *Gallium Arsenide Processing Techniques* (Artech House, Dedham, MA, 1984), Chap. 5.
5. L. Comerford and P. Zory, "Selectively Etched Diffraction Gratings in GaAs," *Appl. Phys. Lett.* **25**, 208 (1974).
6. W. Tsang and S. Wang, "Profile and Groove-Depth Control in GaAs Diffraction Gratings Fabricated by Preferential Chemical Etching in H₂SO₄-H₂O₂-H₂O System," *Appl. Phys. Lett.* **28**, 44 (1976).
7. H. Gerischer, "On the Stability of Semiconductor Electrodes Against Photodecomposition," *J. Electroanal. Chem.* **82**, 133 (1977).
8. Y. Y. Gurevich and Y. V. Pleskov, "Photoelectrochemistry of Semiconductors," in *Semiconductors and Semimetals, Vol. 19*, R. K. Willardson and A. C. Beers, Eds. (Academic, New York, 1983).
9. R. Lum, A. Glass, F. Ostermayer, Jr., P. Kohl, A. Ballman, and R. Logan, "Holographic Photoelectrochemical Etching of Diffraction Gratings in *n*-InP and *n*-GaInAsP for Distributed Feedback Lasers," *J. Appl. Phys.* **57**, 39 (1985).
10. M. M. Faktor and J. L. Stevenson, "The Detection of Structural Defects in GaAs by Electrochemical Etching," *J. Electrochem. Soc.* **125**, 621 (1978).
11. H. Gerischer, "On the Mechanism of Anodic Dissolution of Gallium Arsenide," *Ber. Bunsenges.* **69**, 578 (1965).
12. T. Suhara and H. Nishihara, "Integrated Optics Components and Devices Using Periodic Structures," *IEEE J. Quantum Electron.* **QE-22**, 845 (1986).

For information regarding the length of a Letter, number of illustrations and tables, and general preparation of manuscript, see Information for Contributors on the second page of any issue.

Mach-Zehnder interferometer with multimode fibers using the double phase-conjugate mirror

Shmuel Sternklar, Shimon Weiss, Mordechai Segev, and Baruch Fischer

Technion—Israel Institute of Technology, Department of Electrical Engineering, Haifa 32000, Israel.

Received 28 May 1986.

0003-6935/86/244518-03\$02.00/0.

© 1986 Optical Society of America.

Phase-conjugate mirrors (PCMs) have been shown to be useful as distortion correction devices in configurations where the light beam retraces its path, such as a laser cavity¹ or a Michelson interferometer arm.^{2,3} On the other hand, one-way transmission of 3-D images through multimode fibers has not yet been demonstrated using phase conjugation. One-way transmission of uniform phase, or length information, useful for fiber optic sensors based on the Mach-Zehnder interferometer, is generally done with single-mode fibers.⁴ Given their relative versatility and ease of alignment, compatibility with other systems, and multichannel carrying capacity, multimode fiber interferometers have a certain advantage over their single-mode counterpart.⁵

We have recently^{6,7} demonstrated the operation of a unique device based on photorefractive four-wave mixing, the double phase-conjugate mirror (DPCM). Among its many applications, we discussed and demonstrated its ability to clean up spatially a distorted beam and its usefulness in constructing a Sagnac interferometer incorporating multimode fibers. Here we show that this device can be used to convert a modally dispersed light beam due to a single pass through a multimode fiber into an aberration-free beam which carries, however, the uniform phase information of the multimode fiber. Thus it allows for the construction of a Mach-Zehnder interferometer using multimode fibers.

The experimental setup is shown in Fig. 1. Light beam *A* from an argon-ion laser operating at 488 nm without an etalon is split into a signal beam 4 and reference beam 5. The signal beam passes through an electrooptic SBN crystal to which a variable dc voltage is applied and is then directed into a step-index multimode fiber (1000 μm in diameter, 50 cm long). The fiber output, shown in Fig. 2(a), enters the *z* = 0 face of a photorefractive BaTiO₃ crystal where it is loosely focused to an intensity of ~20 mW/mm². The SBN crystal, through the electrooptic effect, changes the uniform phase of beam 4 relative to beam 5, simulating a length changing perturbation of the fiber arm. Beam *B* from the same laser source is directed into the *z* = *l* face of the BaTiO₃ crystal as beam 2. Beams 2 and 4 interact with the crystal and mutually pump a single four-wave mixing process, as described elsewhere.⁶ This interaction causes the self-bending of beam 2 into beam 4 and vice versa, resulting in the buildup of beams 1 and 3. We point out that beam 1, although derived from beam 4, is the phase conjugate of beam 2. Similarly, beam 3 is derived from beam 2 but is the phase conjugate of beam 4. In this fashion, the crystal transmits photons and the uniform (or dc) spatial phase information but acts as a PCM for the nonuniform (or ac) spatial information of input beams 2 and 4. A portion of beam 1 was combined with reference beam 5 on screen *S*, resulting in the interference fringes shown in Fig. 2(b). Varying the voltage on the SBN crystal caused an instantaneous corresponding shift of the interference fringes. There is no time delay associated with this effect, since the grating structure in the BaTiO₃ crystal is invariant to an identical change in the uniform phase of

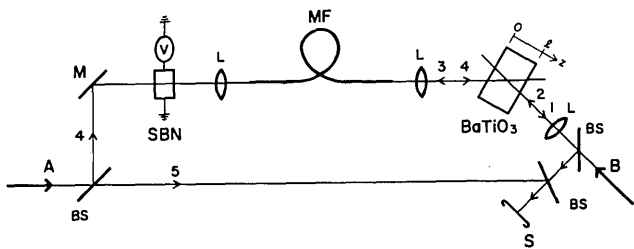
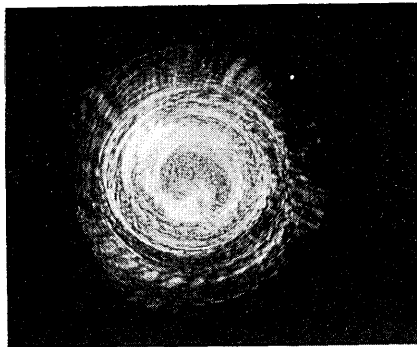
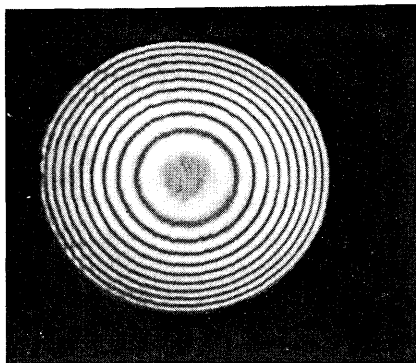


Fig. 1. Experimental configuration of the Mach-Zehnder interferometer with multimode fibers: BS, beam splitter; L, lens; M, mirror; MF, multimode fiber; S, screen; V, variable dc voltage supply. The electrooptic SBN crystal introduces a variable phase shift by changing the dc voltage supply. Four-wave mixing and phase conjugation are done with the photorefractive BaTiO₃ crystal shown here in the DPCM configuration. A and B are two inputs to the interferometer and can be derived from separate lasers.



(a)



(b)

Fig. 2. (a) Output of the multimode fiber (beam 4). (b) Interference fringes seen at screen S where beams 1 and 5 are combined.

beams 4 and 1 and thus is not disturbed by these phase changes.³

A check of the spatial structure of beam 3 revealed that it incorporated virtually all the modal information of beam 4 shown in Fig. 2(a). This implies that most, if not all, the modes in beam 4 exiting from the fiber donated energy to the single clean oscillation beam 1. This is in contrast to other more tedious methods suggested for multimode fiber interferometry.^{8,9}

We have shown that the DPCM works best when input beams 2 and 4 are not in coherence and can even be taken from separate lasers.^{6,7} Thus beam A can be derived from a

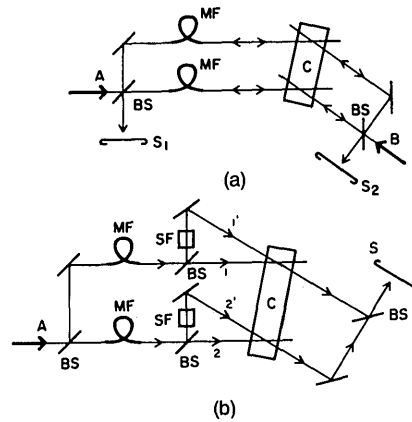


Fig. 3. (a) Schematic of the Mach-Zehnder interferometer with multimode fibers in both the signal and reference arms. C can be one common photorefractive crystal or two separate crystals. Note the two outputs at screens S₁ and S₂. (b) Schematic of the Mach-Zehnder interferometer with multimode fibers using two-wave mixing in a photorefractive crystal C. Portions of beams 1 and 2 are spatially filtered (SF) and then amplified via two-wave mixing resulting in clean output beams 1' and 2'.

remote laser source and beam B from a different local laser. We also point out that, as required in most applications, the reference arm can contain a multimode fiber as well. Reference beam 5 would then be processed in an identical fashion as the signal beam by using either a different region of the same BaTiO₃ crystal or another BaTiO₃ crystal. This is shown schematically in Fig. 3(a). Here the desired fringe output appears at both sides of the interferometer at screens S₁ and S₂.

Photorefractive two-wave mixing can also be used to clean up a distorted beam¹⁰ and in principle will allow interferometry with multimode fibers, as shown in Fig. 3(b). Here a small amount (beams 1' and 2') of the distorted signal and reference beams emerging from multimode fibers (beams 1 and 2, respectively) are spatially filtered (SF) and then amplified through two-wave mixing energy transfer from the rest of their respective beams. This will result in the emergence of clean signal and reference beams which contain the uniform phase information of their respective arms. Here, as opposed to the DPCM design, only one laser input to the interferometer is needed. However, it requires spatial filtering as well as coherence between beam pairs (1,1') and (2,2').

In earlier works we described the operation of a Michelson interferometer using the semilinear passive PCM (PPCM)³ and two types of Sagnac interferometer using either the ring PPCM¹¹ or DPCM,⁶ all with multimode fibers. This work supplements our description of these devices with a realization of a multimode fiber Mach-Zehnder interferometer.

References

1. T. R. O'Meara, D. M. Pepper, and J. O. White, "Applications of Nonlinear Optical Phase Conjugation," in *Optical Phase Conjugation*, R. A. Fischer, Ed. (Academic, New York, 1983).
2. J. Feinberg, "Interferometer with a Self-Pumped Phase-Conjugating Mirror," *Opt. Lett.* 8, 569 (1983).
3. B. Fischer and S. Sternklar, "Image Transmission and Interferometry with Multimode Fibers using Self-Pumped Phase Conjugation," *Appl. Phys. Lett.* 46, 113 (1985).

4. T. G. Giallorenzi, J. A. Bucaro, A. Dandridge, G. H. Sigel, Jr., J. H. Cole, S. C. Rashleigh, and R. C. Priest, "Optical Fiber Sensor Technology," *IEEE J. Quantum Electron.* **QE-18**, 626 (1982).
5. A. E. Bazarov and A. T. Semenov, "Nonreciprocal Effects in a Ring Interferometer with a Multimode Fiber Waveguide," *Sov. J. Quantum Electron.* **14**, 522 (1984).
6. S. Weiss, S. Sternklar, and B. Fischer, "The Double Phase Conjugate Mirror: Analysis, Demonstration and Applications," to be published in *Opt. Lett.*
7. S. Sternklar, S. Weiss, M. Segev, and B. Fischer, "Beam Coupling and Locking of Lasers using Photorefractive Four Wave Mixing," *Opt. Lett.* **11**, 528 (1986).
8. M. R. Layton and J. A. Bucaro, "Optical Fiber Acoustic Sensor Utilizing Mode-Mode Interference," *Appl. Opt.* **18**, 666 (1979).
9. M. Imai, T. Ohashi, and Y. Ohtsuka, "Multimode-Optical-Fiber Michelson Interferometer," *IEEE/OSA J. Lightwave Technol.* **LT-1**, 75 (1983).
10. A. E. T. Chiou and P. Yeh, "Beam Cleanup using Photorefractive Two-Wave Mixing," *Opt. Lett.* **10**, 621 (1985).
11. B. Fischer and S. Sternklar, "New Optical Gyroscope based on the Ring Passive Phase Conjugator," *Appl. Phys. Lett.* **47**, 1 (1985).

Multichannel Fabry-Perot spectrometer for infrared astronomy

Donald E. Jennings and R. J. Boyle

Donald Jennings is with NASA Goddard Space Flight Center, Planetary Systems Branch, Greenbelt, Maryland 20771, and R. J. Boyle is with Dickinson College, Department of Physics & Astronomy, Carlisle, Pennsylvania 17013.

Received 16 June 1986.

Fabry-Perot interferometer spectrometers are among the most sensitive high spectral resolution instruments used in infrared astronomy today.^{1,2} They are used to study atomic and molecular lines in planetary atmospheres, interstellar clouds, and stars. Fabry-Perot spectrometers have the advantage that they achieve high resolution by producing a transmission fringe which is extremely narrow in spectral bandwidth. Radiation outside the transmission fringe is rejected and does not contribute noise to the spectrum. A cryogenically cooled Fabry-Perot spectrometer reduces the radiant background to the point where it is possible to operate near the sensitivity limits of the detector and preamplifier. Although the Fabry-Perot spectrometer covers only limited regions of the spectrum in a given observation, single molecular or atomic lines can be studied with maximum signal-to-noise. An additional advantage of the Fabry-Perot is that it is nondispersive, so that the source can be imaged in two dimensions in the focal plane. A detector array can therefore be used to produce spatial maps of all source points simultaneously.

Fabry-Perot spectrometers work by making use of the high finesse (ratio between fringe separation and fringe width) and high throughput efficiency available with etalons made from modern infrared materials and dielectric reflection coatings.³ A low resolution filter or grating selects one fringe of the etalon and radiation transmitted by this fringe is focused at the detector. To produce a spectrum, the spectrometer is scanned by either tilting the etalon or by changing the etalon plate separation. The time required to scan a region is $T = tN$, where t is the integration time per resolution element and N is the number of resolution elements (fringe widths) being scanned.

The primary disadvantages of Fabry-Perot spectrometers is that only one spectral element is accessed at a given time. Therefore a large fraction of the radiation from the telescope is rejected by the etalon, and flux containing useful information is wasted. A spectrometer scanning N resolution elements uses only a fraction of $1/N$ of the flux which could contribute to the spectrum. If a technique were devised which would allow the rejected radiation to be used the instrument sensitivity would be improved.⁴

We have developed a design which makes use of the radiation normally rejected in a Fabry-Perot spectrometer. Figure 1 is a schematic of a spectrometer which permits observation of multiple resolution elements simultaneously. A bandpass filter limits the spectral bandwidth of incoming radiation to one free-spectral-range (fringe separation) of the etalon. The radiation enters the spectrometer, after being limited by a field aperture, and is collimated by $M1$ and directed to the etalon. The etalon is oriented at an angle ϕ with respect to the incoming beam, and transmits a fringe pattern given by $m\lambda = 2d \cos\theta$, where m is the order (or fringe) number, λ is the wavelength of the radiation, d is the separation of the etalon surfaces, and the angle θ is equal to ϕ for the initial pass. The radiation is then focused at the detector element at one edge of a linear detector array. The radiation which is not transmitted by the etalon is reflected and focused at the surface of mirror $M2$ and directed to $M3$. The beam is then focused again by $M3$ at the edge of $M2$ near the entrance beam. The beam is returned to the etalon at an incident angle, i.e., $\phi - \delta$, which is slightly different from that of the initial beam. The angle is chosen to place the second-pass fringe at a spectral position adjacent to the first-pass fringe. The second-pass beam is focused at the second de-

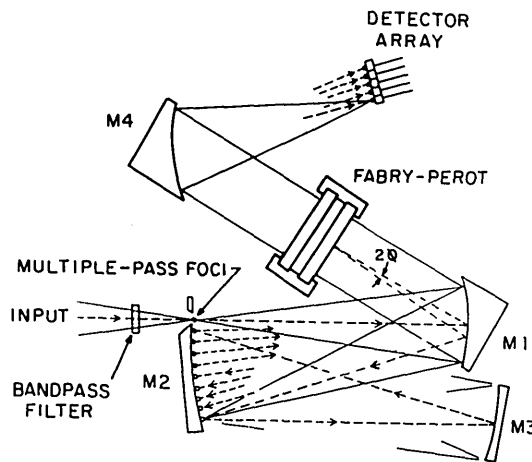


Fig. 1. Optical schematic of the multiple-pass Fabry-Perot etalon spectrometer. Mirrors $M1$ and $M4$ are off-axis parabolas, while $M2$ and $M3$ are spheres. The radiation path for the first cycle is shown with a dashed line. Radiation from the input focus and subsequent multiple-pass foci is collimated at mirror $M1$ and directed to the etalon, where one spectral element is transmitted. The etalon is tilted at a slight angle ϕ with respect to the first pass radiation beam. The radiation reflected from the etalon forms foci at $M2$ (open circles). Mirror $M3$ reimaging the foci back at $M2$, forming a series of evenly spaced foci (solid dots). Each shift in position at $M2$ corresponds to a change in incident angle at the etalon, so that the transmitted spectral element is shifted in wavelength. The pattern at $M2$ is imaged at the focal plane, where a detector array can be used to observe the multiple spectral elements simultaneously.