1

CONF-8909161--1

Received by OSTI

JUL 07 1989

LA-UR--89-2112

DE89 014226

TITLE: MULTIMODE FIBER INTERFEROMETRY AND SEVERAL-MODE FIBER
POLARIMETRY VIA PHASE CONJUGATION

AUTHOR(S): P.R. Forman, F.C. Jahoda, B.L. Mason, C.B. Netterfield

SUBMITTED TO: The Sixth International Conference on Optical Fiber Sersors
Paris, France
September 17-20, 1989

DISCLAIMER

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MULTIMODE FIBER INTERFEROMETRY AND SEVERAL-MODE FIBER POLARIMETRY VIA PHASE CONJUGATION

P. R. Forman, F. C. Jahoda, B. L. Mason, C. B. Netterfield

Los Alamos National Laboratory
P.O. Box 1663, CTR-8, MS K639, Los Alamos, NM 87545 USA
Telephone: 505-665-2999
Facsimile: 505-665-4027

INTRODUCTION

While the simplest fiber optics sensors are realized by transmission intensity modulations impressed on multimode fibers, great enhancements in sensitivity are achieved by interferometric or polarimetric methods with light propagated through single-mode fibers. In this paper we report preliminary experiments on retaining the sensitivity of interferometric and/or polarimetric measurements while using only multimode fiber components. The utility of success in this endeavor can be measured by greater experimental simplicity (light injection and alignment tolerances), by cost factors (cheaper fiber optics components), or by larger intensity transmission limits (which can be translated to higher time resolution for a given signal-to-noise ratio).

It is not an intrinsic requirement for interferometric/polarimetric measurements that a fiber be single mode, since all modes of a multimode fiber are affected by an externally applied stimulus. Single mode operation is, however, generally a practical necessity because of the averaging over the exit phase or polarization, significantly different for each mode, that occurs even in the quiescent state of a multimode fiber before the application of the stimulus.

We use phase conjugation for unscrambling of the spatially superposed modes at the exit of a multimode fiber, prior to deriving the common information carried by all the modes. The phase conjugation is achieved with self-aligning, self-pumped phase conjugation in $BaTiO_3$ [1], requiring no auxiliary beams. While the original phase conjugate, faithful to the transverse spatial distribution exiting the fiber in one polarization, forms only slowly (seconds) in the photorefractive crystal, the response to subsequent spatially uniform phase shifts along the direction of light propagation does not have a sign reversal [2]. It follows from the same argument that the response to both this kind of phase shift or to any change in the incident intensity is instantaneous. We consider interferometry and polarimetry in separate sections below.

MULTIMODE FIBER INTERFEROMETRY

A. Single Channel

It has been demonstrated by Fischer and Sternklar [3] that a spatially uniform interference pattern can be obtained with a multimode fiber and self-pumped phase conjugator in one arm of a Michelson interferometer configuration. Quite recently Kwong [4] has demonstrated time resolved interferometrically determined temperature changes impressed on the multimode fiber in such an

arrangement. He also demonstrated improved utilization of the available light with the polarization-preserving modification for self-pumped $BaTiO_3$ phase conjugation introduced by McMichael et al [5].

In [4] the data were obtained by fringe counting in the basic homodyne arrangement. This does not permit fractional fringe counts, accuracy better than integral fringe number count, nor unambiguous determination of maxima and minima in the measured stimulus, i.e. the true integer value of successive fringes if the time derivative of the measurand changes sign close to a fringe extremum. It also does not distinguish extraneous environmental phase shifts picked up differentially by the two interferometer arms from the desired signal.

In our first modification of this basic arrangement we used a heterodyne method, e.g. [6], by placing a 40 MHz acousto-optic Bragg cell in a Sagnac loop at the end of the reference path and measuring the beat signal between the interferometer output and the driver frequency of the Bragg cell.

A 15-cm section of the multimode fiber in the signal arm was passed through an electrically heated oven on its way to the phase conjugator. The results over a three minute time span with a changing temperature in the oven gave about 100 fringes for a 20° temperature change. The average sensitivity, obtained by normalizing to conventional thermocouple readings, is 0.4 fringes/cm/°K. This value is consistent with published values for the thermal expansion of glass. However the ambient noise drift over three minutes with no temperature change in the oven was separately determined to be about 1 to 2 fringes.

The ambient noise was reduced to about 0.2 fringes over a three-minute interval by routing two multimode fibers closely together along their entire length. The fibers had a length difference of 10 cm within the oven, but were made approximately equal total length by increasing the path length of the other fiber outside the oven. Both fiber outputs are phase conjugated on the same crystal, vertically displaced to avoid beam overlap within the crystal, and the return beam of each is recombined with the reference beam. The two approximately 40MHz beat patterns are then electronically processed and computer analyzed for their relative differences. The results during changing oven temperature were consistent with the one fiber measurement and are displayed in Fig. 1.

The drift noise decreases nearly an order of magnitude further if the total time duration examined is reduced to only several seconds. Fig. 2 shows the ambient noise (when the oven temperature is held constant) for three different time intervals. This residual value is not much more than the 0.02 fringes obtained independent of time duration when two identical fibers are intertwined along their entire length. The latter is not a useful configuration for an interferometric measurement, but gives an approximation of our electronic noise limit.

An extension of this phase of our work, deferred for that reported below, would also incorporate a fiber in the reference arm with the acousto-optic cell and use self-aligning phase conjugation on the same or a second self-pumped crystal. A by-product of this approach would be a doubled heterodyne frequency due to the forth and back transit of the Bragg cell.

When the very high frequency response of the Bragg cell heterodyne arrangement is not needed (e.g. temperature measurements) it is simpler and more economical to eliminate the separate reference path altogether and to put a piezo-electric stretcher modulation on one of the two multimode fiber phase conjugator inputs. This reverts to a conventional Michelson two arm interferometer except that both

arms terminate in the same phase conjugator crystal. The piezo-electric modulation in one arm achieves the same non-integer fringe count capability and unambiguous determination of sign reversal in time of the signal as described in the beginning of this section.

This type of signal processing has been described before, e.g. [7]. A sinusoidal length modulation gives an equivalent sinusoidal modulation to the phase factor in the exponential of the electric field of the light propagating through the fiber. After recombining the coherent light in the two arms on a square-law intensity detector, a mathematical identity permits the transmitted intensity to be written as an infinite series of Bessel functions in integer harmonics of the modulation frequency. The odd and even terms are amplitude modulated respectively with the sine and cosine of other slowly varying phase factors (i.e. desired signal) in either interferometer arm. Processing the detected intensity electronically to determine separately the first and second harmonic terms for the modulation frequency impressed by the stretcher then gives the sine and the cosine and hence the unambiguous value itself of the signal induced phase shift. If the amplitude of the modulation frequency is reasonably near 2.4 radians phase shift the intensity of the zero order Bessel term is suppressed, and both the 1st and 2nd harmonics have suitably large intensities.

Using a 20 kHz piezo-driver modulation frequency results similar to Fig. 1 were obtained.

B. Multiple Channels

One of the motivations for this work is the replacement of numerous thermocouples in the electromagnetically hostile environment of a magnetic confinement fusion experiment. This would gain the the well-known fiber optic EMI advantages and some finite length averaging instead of individual spatial point temperatures.

To make this anywhere near cost competitive it is desirable to use the same $BaTiO_3$ phase conjugator crystal for as many separate interferometer pair inputs as possible. (One 5mm x 5mm x 5mm crystal from Sanders, Inc. costs about $3.4K). The c-axis is in the horizontal plane and all the beam fanning and four-wave mixing is also in the horizontal plane.

With GRIN lenses terminating the fibers, which limits the vertical spread of the light in the conjugator crystal, it has been possible to separate the two single channel inputs by only 0.8 mm vertically without cross-talk. This should permit six beams or three interferometer pairs in a vertical column on the 5 mm high crystal. At the time of writing only two pairs have been successfully demonstrated; three pairs have not yet been tried for extraneous reasons. A 15 mm vertical height crystal for $6.0K is on order.

When the two interferometer pairs (each consisting of two vertically displaced inputs) were separated horizontally on the crystal there was invariably cross-talk, until the equal length fibers of interferometer B differed from the equal length fibers of interferometer A by more than the argon-ion laser source coherence length. Cross-talk is defined here as any response above background in interferometer B when one arm of interferometer A experiences a significant change due to the oven. For the case of incoherent lengths the alignment was still quite critical to avoid cross-talk. This is not surprising in view of the considerable current literature reporting perfect cross-coupling for incoherent beams, [8] and references therein, and the on-going effort to elucidate the mechanism. This literature has been focussed on steady-state images and does not deal with the rapid phase-only changes of interest here. Note that perfect cross-coupling, i.e. everything from the signal arm of A returns on the signal arm of B

and vice versa, would work for us with half the signal level (one transit through the phase disturbance instead of two) for a time period until the changing signal appreciably re-writes the internal gratings. Even so this is not of value for us because complete cross-coupling cannot be extended beyond two channels.

We summarize the above by stating that at the present time the prospects for 6 simultaneous independent interferometer pairs on a 5 mm height crystal and 18 pairs on a 15 mm height crystal appear reasonable. We use an argon-ion laser input furnishing light through a multimode 1xN star coupler, each output arm spliced to one arm of a 2x2 multimode coupler that is the input to each of N interferometers. It requires about 2 mw of light incident on the phase conjugator through each interferometer arm to get good conjugation.

There are two directions for future research which might increase the number of inputs in a horizontal plane possible on a single phase conjugator crystal. The first is using different incommensurate piezo-stretcher frequencies for each vertical column of interferometer pairs and electrically filtering out the cross-talk. The second is using different wavelength light inputs (multiple laser diodes replacing the argon-ion laser source). No cross-talk between incohernt beams differing by more than 1 nm has been reported. However self-pumped phase conjugation in $BaTiO_3$ becomes more difficult and less efficient at the longer wavelengths characteristic of laser diodes [9].

SEVERAL-MODE FIBER POLARIMETRY

The circular birefringence imposed on the two degenerate orthogonal polarization modes of a "single mode" fiber by a longitudinal magnetic field is the basis of Faraday rotation. Via Ampere's law the polarization rotation through single mode fiber loops measures the total current enclosed by the loops. The present status of this type of measurement is reviewed in these proceedings [10].

The biggest problem in Faraday rotation measurements with fibers is the suppression of intrinsic or externally induced linear birefringence. Intrinsic birefringence results from departures trom perfect cylindrical symmetry introduced in the manufacturing process, and externally induced birefringence is most commonly the result of the bending radii and asymmetric pressure introduced in the fiber deployment. The fiber leadsto and from the sensor section can be a further source of problems, e.g.[11]. The effects of linear and circular birefringence are not simply additive, and the magnitude of the linear birefringence relative to the circular birefringence can either distort or completely obliterate the Faraday rotation. Solutions to suppressing the deleterious effect of linear birefringence include a) twisting the fiber along its axis to induce a large bias circular birefringence b) annealing in situ to relieve stress, and c) Spun- HIBI fiber (nearly circularly polarized eigenmodes) [12].

The Faraday effect is non-reciprocal, i.e. simple reflection at the exit point and re-traversal of the incoming path to the entrance point doubles the rotation angle of linearly polarized light. This occurs because both the magnetic field and the sense of rotation (clockwise or counter-clockwise viewed into the light direction) change sign. A perfect phase conjugator with instaneous response acts exactly like a reflector as far as rotation sense is concerned.

We report below our initial results on making Faraday rotation measurements with the $BaTiO_3$ self-pumped phase conjugator at the 514 mm argon-ion laser wavelength using a Corning fiber that is single mode at 1.3 μm. Based on the V-number there are 10 (doubly degenerate) modes at 514 μm

[13]. Linearly polarized light entering the approximately 5 meter long fiber section emerges almost completely unpolarized. The fiber is loosely wound in X turns of 4 cm diameter around a damped, oscillatory capacitor discharge current. As expected, a two-polarization analyzer measurement (45 $^\circ$ extinction separation) at the fiber exit yielded nothing.

By using the two-orthogonal polarization input method on the $BaTiO_3$ phase conjugator of [5], (subsidiary optics put both polarizations into the plane required by the crystal), we made the two-analyzer-at-45° measurements following a non-polarizing beam splitting at the entrance end of the fiber. The conventional processing gave the result presented in Fig. 3a. While this is far from an accurate representation of the true current time history measured with a Rogowski loop and given in Fig. 3b, the qualitative resemblance is extremely encouraging to pursue further improvement. (Note that in conventional single-mode one-way transits we have previously achieved excellent agreement with Rogowski coils [6]).

A definitive result of this experiment based on the known Verdet constant of glass is that the magnitude of the rotation is that to be expected for a one-way and not a two-way transit. We relate this to the time lag factor in forming a phase conjugate in photorefractive crystals as follows. The initial phase conjugate gratings are written prior to the application of the magnetic field *midway* along the fiber path. For subsequent polarization rotations the individual gratings do not change fast enough to keep up, but instead respond to a changing intensity level as the rotation decreases the intensity levels in the original polarization direction. The return light at the crystal therefore has the same spatial structure as before rotation set in (reduced intensity), and in the absence of rotation would "unscramble" to the original spatial pattern and polarization direction at the fiber entrance. Polarization rotation on the return path is superposed on this pattern and gives the one-way transit information.

The reasons for the distortions in the current waveform are not clear at present. Either or both of two distinct problems may be involved. The first is that we have no knowledge of the amount of residual linear birefringence in our ten mode fiber. As stated above linear birefringence is known to cause distortions. If this is the dominant problem any of the methods used with single mode (twisting, annealing, or spun HiBi fiber) should improve the results and open the way for truly multimode (large core) fiber to be used.

The other open question is more fundamental and troubling. We do not know how well the exquisitely precise unscrambling of modes in a fiber by phase conjugation works when the polarization of the return wave, due to polarization rotation away from the conjugator, creates different polarization directions everywhere along the fiber path for the forward and return beams. There is, for instance, the Goos-Hanchen Effect [14], a differential shift along the propagation direction for ordinary and extra-ordinary rays undergoing total internal reflection. (This will be suitable for experimental test when we bring together a non-birefringent single mode fiber at a wavelength amenable to phase conjugation and of more than 2 mm intensity exiting the fiber.) If the distortion problem is indeed inherent to phase conjugation we also do not know if increasing the number of modes to true multimode will increase the distortions or decrease them by further averaging.

In any case it seems likely that smaller rotation angles than the Z degrees maximum involved in Fig. 3a, either due to smaller currents or fewer fiber loops, will improve the fidelity of the measurement.
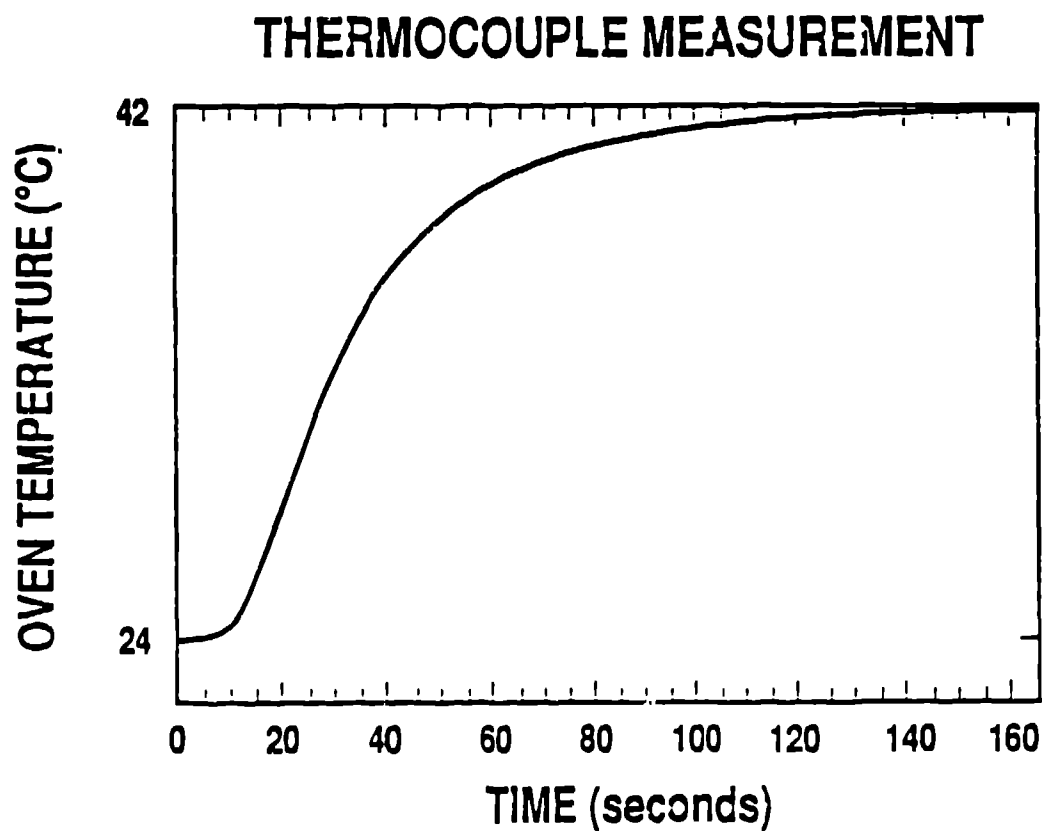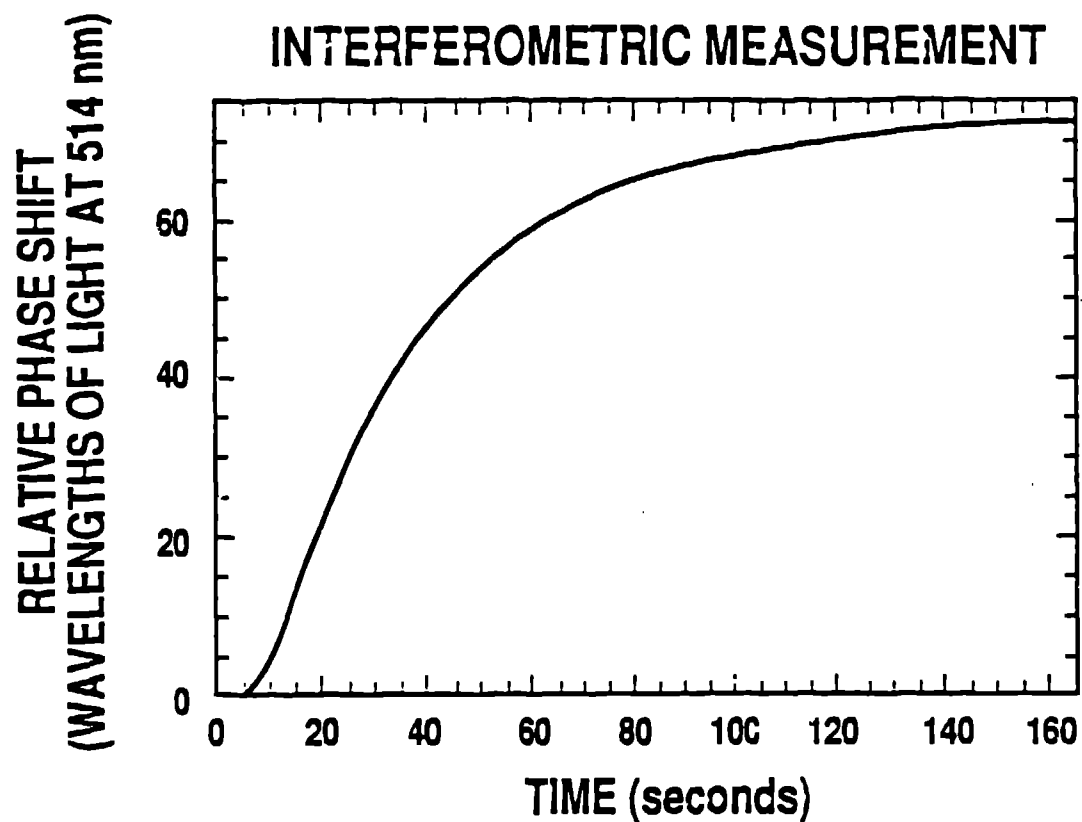
REFERENCES

[1]   J. Feinberg, "Self-pumped, continuous-wave phase conjugator using internal reflection," *Opt. Lett.* **7**, 486 (1982).

[2]   J. Feinberg, "Interferometer with a self-pumped phase-conjugation mirror," *Opt. Lett.* **8**, 569 (1983).

[3]   B. Fischer and S. Sternklar, "Image transmission and interferometer with multimode fibers using self-pumped phase conjugation," *Appl. Phys. Lett.* **46**, 113 (1985).

[4]   N. S. K. Kwong, "Fiber-optic sensor using a tandem combination of a multimode fiber and a self-pumped phase conjugator," *Opt. Lett.* **14**, 590 (1989).

[5]   I. McMichael, M. Khoshnevisan, and P. Yeh, "Polarization-preserving phase conjugator," *Opt. Lett.* **11**, 525 (1986).

[6]   G. I. Chandler, P. R. Forman, F. C. Jahoda, and K. A. Klare "Fiber-optic heterodyne phase-shift measurement of plasma current," *Appl. Opt.* **25**, 1770 (1986).

[7]   D. A. Jackson, A. Dandridge, and S. K. Sheem, "Measurement of small phase shifts using a single-mode optical-fiber interferometer," *Opt. Lett.* **5**, 139 (1980)

[8]   P. Yeh, "Coupled-mode theory of hologram sharing in mutually pumped phase conjugators," *Appl. Opt.* **28**, 1961 (1989).

[9]   B. T. Anderson, P. R. Forman, and F. C. Jahoda "Self-pumped phase conjugation in $BaTiO_3$ at $1.06 \mu m$," *Opt. Lett.* **10**, 627 (1985).

[10]   G. W. Day, "Recent advances in Faraday effect sensors," *OFS-6 '89*, these proceedings.

[11]   P. R. Forman and F. C. Jahoda, "Linear birefringence effects on fiber-optic current sensors," *Appl. Opt.* **27**, 3088 (1988).

[12]   Experimental product of York Ventures and Special Optical Products, Ltd.

[13]   S. E. Miller, E. J. Marcatilli, and T. Li, "Research toward optical fiber transmission systems. Part I: The transmission medium," *Proc. IEEE* **61**, 1703 (1973).

[14]   A. W. Snyder and J. D. Love, in *Optical Waveguide Theory* (Chapman and Hall, 1983).

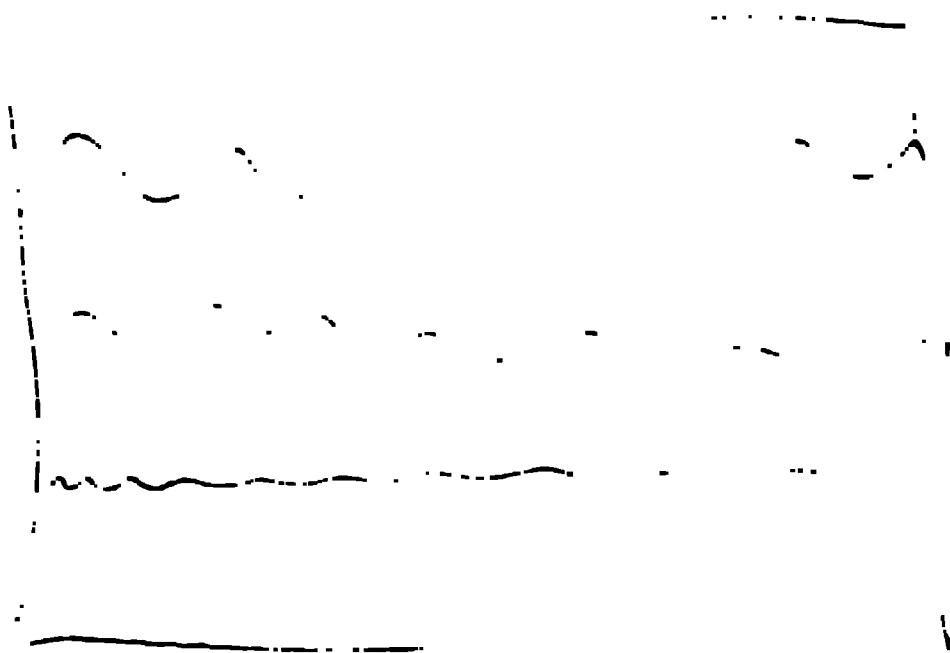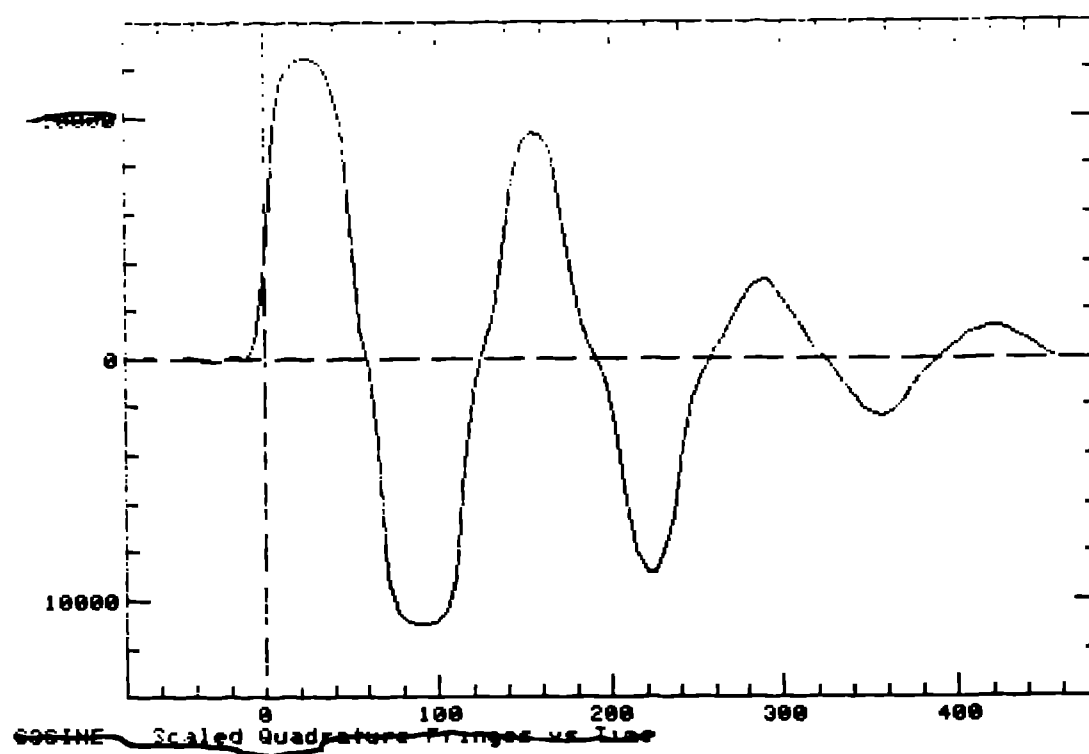# DIFFERENTIAL TEMPERATURE MEASUREMENT OF SMALL OVEN

INTERFEROMETRIC MEASUREMENT

THERMOCOUPLE MEASUREMENT

Fig 2

Fig 3a

COSINE   Scaled Quadrature Fringes vs Time

Fig 3b.

SHY   shot   787 19-Jun-89 1343 mode   0 type   0

3 CURRENT   AMP

microseconds