Optical Phase Modulation Utilizing Magnetoelastic Properties of Metallic Glasses

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OPTICAL PHASE MODULATION UTILIZING
MAGNETOElastIC PROPERTIES OF
METALLIC GLASSES

BY

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B.S.E.E., University of Texas, 1971

RESEARCH REPORT

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Three different optical fiber phase modulators utilizing the magnetostrictive properties of the metallic glass alloy Fe$_{74}$Co$_{10}$B$_{16}$ were constructed. By binding the optical fiber to the magnetostrictive metallic glass, the strain imparted to the metallic glass from the magnetic field is transferred to the optical fiber. The strain on the optical fiber shifts the phase of the light, which can be controlled indirectly by varying the current producing the magnetic field permeating the metallic glass. The performance of the modulators on the basis of optical phase shift as a function of bias magnetic field and optical phase shift as a function of excitation frequency was measured. Speculations were made on the loss mechanism inherent in the various modulator designs in order to explain the deviation in performance of the three modulator designs.
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I wish to gratefully acknowledge the generous support and use of facilities of the Underwater Sound Reference Detachment, Transducer Branch, of the Naval Research Laboratory. This project would not have been possible without the help of Jeff Bush and his phase-swept, phase-locked interferometer system. His optimism and insight were a great help when problems were encountered. The help I received from Steve Meeks is also appreciated. His unselfish sharing of his outstanding technical knowledge in the area of magnetostrictive material and metallic glasses was invaluable in organizing this project and interpreting the resulting data.
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I. INTRODUCTION

The development of low loss single mode optical fiber has opened a new area of engineering opportunity with vast possibilities. Many of the tasks performed by electronics today may ultimately be performed more efficiently with integrated optics. One example is the optical sonar system being developed by Naval Research Laboratory in which acoustic pressure waves modulate the light in an optical fiber which is then processed to retrieve the acoustic signal. These new optical hydrophone systems offer a significant advantage over present systems. Conventional transducers have severe impedance matching problems. They are susceptible to large charge buildup due to environmental changes. The ceramic elements used in conventional sonar systems must be isolated from the seawater to prevent electrical shorting. They require high impedance cables and are susceptible to electric and magnetic interference.

Optical hydrophones offer a solution to the traditional problems and are being investigated by the Naval Research Laboratory for shipboard use. Bucaro and Dardy have demonstrated the feasibility of fiber optical hydrophones. Although the pressure induced refractive index variation of the optical fiber is small, the development of long, low loss optical fibers has made the fiber optical hydrophone compare well with the best conventional hydrophone. The principle of
operation of the optical hydrophone is illustrated in Figure 1. For this system the intensity at the detector will be

\[ I(t) = I_0 I_1 \cos(\phi_d) \]  \hspace{1cm} (1)

where

\[ \phi_d \] is the phase difference due to the optical path difference between \( L_1 \) and \( L_2 \).

The phase difference \( \phi_d \) can be separated into several terms

\[ \phi_d = \phi_s + \phi_t + \phi_a \]  \hspace{1cm} (2)

where

\[ \phi_s \] is the static phase difference due to the initial path length difference.

\[ \phi_t \] is the path length variation due to the thermal variation in the fiber lengths.

\[ \phi_a \] is the phase variation introduced by the acoustical wave in the signal to be detected.

The phase change due to the acoustical wave is due to two effects

\[ \phi_a = \left( \frac{dn}{dP} + \frac{n}{k} \frac{dP}{dP} \right) k \Lambda \sin(\omega_t) \]  \hspace{1cm} (3)

where

\( \ell \) is the length of the fiber exposed to the acoustical wave.

\( n \) is the effective index of refraction of the fiber.

\( k \) is the wave number.

\( \Lambda \) is the amplitude of the acoustical wave.
Fig. 1. Simple optical fiber interferometer system for acoustic detection. Pressure changes due to the acoustic signal surrounding the acoustic detector modulate the phase of the light in the optical fiber. When the light in this fiber is combined with the light in the reference path ($L_1$) interference fringes are produced whose intensity is modulated by the acoustical signal. The varying light intensity is converted to an electrical signal and amplified by the photo detector.
Due to the protective jacket coating on the fiber, the second term, $\frac{n}{L} \frac{dL}{dP}$, is dominant. This is due to the plastic coating stretching the silica fiber since the strain for the plastic coating alone would be 450 times that of the silica fiber. This has been verified experimentally and indicates the phase shift to pressure ratio is improved by an order of magnitude. This type of plastic coated fiber is used throughout this investigation.

In order to implement an optical sonar system in a working environment, integrated optics and semiconductor devices such as laser diode and solid state detectors will be used. An inherent disadvantage of using the semiconductor detectors is that a major source of noise, the 1/f noise, is centered about $0$ Hz. A method to enhance the optical fiber hydrophone is to modulate the light beam in one of the arms of the interferometer which shifts the detector signal to the modulation frequency. One approach was reported (Bucaro and T. R. Hickman, 1979) which modulated one of the beams with a Bragg cell and used a FM discriminator and differentiator to retrieve the signal information. Although such a system eliminates the 1/f noise problem, it is inherently inefficient since the acoustic signal phase modulates the light in the optical fiber while the detector is a frequency demodulator.

A solution to both the 1/f noise in the homodyne system, and the inefficiencies of using an fm demodulation of an inherently phase modulated signal is to use phase modulation and a phase detection optical system. Such a system is described in the Appendix and is
modified to measure the response of the metallic glass phase modulators
developed for the project.

In order to perfect such systems as the optical sonar which are
phase modulated systems, support devices such as optical phase modu-
lators will have to be developed. The objective of this paper is to
investigate a possible method to phase modulate light in an optical
fiber, taking advantage of the magnetoelastic properties of metallic
glass. Several metallic glass modulators are constructed, tested, and
compared to theoretical expectations.
II. MODULATOR MATERIAL

The material used to construct the optical phase modulators is Fe\textsubscript{74}Co\textsubscript{14}B\textsubscript{16} amorphous alloy which is a type of metallic glass. Metallic glass is the name given to a new group of materials with a wide variety of properties and great engineering promise.

The familiar glasses are compounds of silicon and oxygen and, as far as their structure is concerned, are almost identical to the liquid state. This means that there is no discernible order to the molecules within the material. Until recently, it was believed that other substances, notably the metals, would not solidify in the glassy state, but invariably assume a crystalline form. For any material there is always at least one crystalline form that is more stable than the amorphous state. This is true even for the silicate glasses except that the crystallization rate at room temperature is nil, and during the normal manufacturing process the crystallization rate is negligible as the material cools from the liquid to the solid state. The silicate glasses crystallize slowly because of the strong covalent bonds interconnecting the atoms. In order for the atoms to rearrange themselves from the amorphous liquid form to the crystalline form, many of these strong covalent bonds would have to be broken and then reestablished. Thus, although ultimately the free energy of the crystal would be less than that of the glass, there would still be a significant input of energy required.
Conversely, the chemical bonding between the metal atoms is much more diffuse and weaker than the covalent bonding in silicates and similar insulating material. As a result of the less directional bonding of a metal, a crystal can form from the amorphous form more rapidly and with less expenditure of energy. It was for this reason that the prospects of solidifying metals in an amorphous state was considered remote. For a glassy material to form, it must be cooled from above the melting temperature. The glass temperature varies from one substance to another and is always lower than the melting temperature. When a material is between its melting temperature and glass temperature, the atoms are free to make extensive translational movement and it is during passage through this region that crystallization occurs. When a liquid is cooled from the melting temperature to below the glass temperature, crystallization does not form immediately. Rather, a finite amount of time is required for the formation of nucleation sites on which the crystallization will occur. The principle method of formation of glassy solids therefore is to cool the material to below the glassy temperature before the nucleation sites have a chance to form. For silicates this maximum cooling time is on the order of hours or days, whereas for pure metals, such as iron it is on the order of microseconds. For the more common alloys used for formation of metallic glass, it is on the order of milliseconds which translates to a quenching rate of $10^5$-$10^6$ °C/sec. necessary to produce an amorphous state.

With the exception of their amorphous structure, metallic glasses exhibit few similarities with conventional glasses. They are
not brittle nor are they transparent. They are relatively good conductors of heat and electricity and on casual appearance seem to be similar to their crystalline form. On closer inspection, however, metallic glasses are found to have unique properties not available in any other substance. Properties also may vary widely from one metallic glass to another which makes them particularly versatile. For instance, Co$_{72}$Fe$_3$P$_{16}$B$_6$Al$_3$ has nearly zero magnetostriction, while annealed Fe$_{78}$Si$_{10}$B$_{12}$ has the largest magnetostriction known. Some metallic glasses exhibit much lower hysterisis loss and higher permeabilities than do their crystalline form which are properties ideal for transformer core material, while other types of metallic glass exhibit a square B-H loop which would be useful for magnetic memories and bistables.

Magnetostriction has been explained using various theories with mixed success for different materials. On the simplest level magnetostriction can be explained in terms of domain orientation. If the magnetic domains are modelled as ellipsoids, then as the magnetic domains are rotated by an applied magnetic field, the material will get longer along the axis of the applied magnetic field if the magnetization axis is along the long axis of the ellipsoid. Although this theory is not untrue it is very qualitative and does not begin to explain all of the differences encountered in magnetostrictive materials.

Another approach views the material in terms of minimum energy and draws together the strain and magnetic components. This minimum energy theory is really an analysis of the material and how the strain
and magnetic energy components interrelate, rather than an explanation of the actual origin of the magnetostrictive effect. The following development is taken from E. W. Lee:

Magnetostriiction occurs when there exists a contribution of magnetic origin, to the free energy of a system which is linear in strain. This strain-dependent free energy is equivalent to a set of constant forces which deform the crystal until the forces are exactly opposed by the elastic forces.15

Assuming for simplicity, an isotropic material with no external applied stresses and a uniform applied magnetic field, then the Helmholtz free energy $F$ is written,

$$ F = F_m + F_e $$

where

$F_m$ and $F_e$ are the magnetic and elastic parts of the free energy over the total volume of the material.

$F_m$ may be expanded in a Taylor series in terms of the strain $e$

$$ F_m = F_0 + V_0 B e + \frac{1}{2} V_0 B' e^2 + ... $$

where

$V_0$ is the unstrained volume

$B$ and $B'$ are the first and second strain derivatives of the free energy. Physically $B$ is the magnetoelastic constant and $B'$ is the magnetic contribution to the elastic stiffness constant.

Similarly,

$$ F_e = \frac{1}{2} V_0 C' e^2 $$
where

\[ C' \text{ is the elastic stiffness constant and is related to Young's Modulus for the material. If } B' \text{ and } C' \text{ are grouped together: } C = C' + B', \text{ the Helmholtz free energy becomes} \]

\[ F = F_0 + V_0 Be + \frac{1}{2}V_0 Ce^2 \]

To find the minimum free energy with no external stress,

\[ \frac{\partial F}{\partial e} = 0 = \frac{\partial}{\partial e}(F_0 + V_0 Be + \frac{1}{2}V_0 Ce^2) \]

\[ = V_0 B + V_0 Ce_{\text{min}} \]

Then

\[ C_{\text{min}} = -B/C \]

\[ F_{\text{min}} = F_0 + V_0 B_{\text{min}} + \frac{1}{2}V_0 C_{\text{min}} \]

\[ = F_0 - V_0 B^2 / C + (\frac{1}{2})V_0 B^2 / C \]

\[ = F_0 - V_0 B^2 / C \]

\[ = F_0 - V_0 B_{\text{min}} \]

This shows that the free energy of the system is lowered by allowing the strain to occur. To calculate magnetoelastic effects, a knowledge of the magnetic and elastic constants for the material which are best determined experimentally is required. For the three dimensional anisotropic material (which include most magnetostrictive materials, including metallic glasses) these constants become tensors of the fourth rank. 16.
In a study by R. C. O'Handley, several magnetostriction theories were compared with experimental results for various metallic glass compounds. It was found that the dense random packed model of the material structure combined with the pseudodipolar model of the magnetostriction closely follows the experimental findings for the iron-cobalt-metalloids metallic glass compounds. Using the pseudodipolar model and various computer generated random packed structures for the iron-cobalt metalloid, a structure of 45 atoms (9 of them metalloids) was found to most nearly fit the observed experimental magnetostrictive behavior. If this is the correct model of the metallic iron-cobalt-metalloid, then the simple amorphous model is an oversimplification, and the actual structure has a short range structural order similar to the crystalline alloys (both are close packed with 12-fold coordination) and that this short range order has a nonuniform distribution of orientations throughout the material. Although this structure has not been directly verified, it is consistent with observed macroscopic anisotropic behavior of ferromagnetic glasses and their field annealing properties.17

In addition to their unique magnetostrictive and other properties, metallic glasses are attractive from an engineering and economic standpoint. They are inexpensive in that they are primarily composed of iron, the least expensive of all metallic materials.18 In terms of manufacturing cost, metallic glasses are attractive in that they may be produced in a single step. In the planar-flow-casting method, a stream of molten metal is sprayed on a cold rotating metal disc, thereby producing a flat ribbon of metallic glass (Figure 2).
Fig. 2. Diagram illustrating the planar-flow-casting process. Slotted nozzle is brought close to a cold, rapidly rotating copper drum. The results are a rapid quenching of the liquid metal to form a continuous ribbon of metallic glass. Source: Gilman, "Metallic Glasses," *Science*, p. 857.
Such a method requires less than one-fourth the energy than would be required by conventional metallurgical process. Also, planar-flow-casting and other splat quenching methods are fast and would lend themselves to automatic production methods. 19

The material used in this investigation is Fe₇₄Co₁₀B₁₆ and is available commercially from Allied Chemical under the trade name Metglass® Alloy #2655 Co. This particular alloy was chosen because of its commercial availability and similarity to Fe₇₁Co₉B₂₀ which was shown by Mitchell et al. to have the highest magnetomechanical coupling coefficient. Studies by R. C. O'Handley have also reported on the excellent magnetostrictive behavior of the iron-cobalt-boron metallic glass alloys. 20
III. MODULATOR CONFIGURATIONS

Various metallic glass optical modulators were constructed. The goal was to find a practical geometric configuration which would efficiently transfer the magnetic induced strain of the metallic glass to the optical fiber, and thereby phase modulate the light within the optical fiber.

Three basic designs were investigated. The first two were constructed in a toroid similar to the piezoelectric phase modulator reported by Jackson et al. The first toroid modulator was constructed by insulating a strip of metallic glass 95 inches long by one-half inch with Krylon #1320 insulating dielectric spray coating to reduce eddy current losses. This was then wrapped tightly on a spindle forming a rigid ring by applying a thin coating of Aron Alpha #201 bonding adhesive. The completed ring is shown in Figures 3 and 4. Around the circumference of the metallic glass ring, sixteen turns of single mode optical fiber, ITT-T110, was wrapped tightly and attached with bonding adhesive. Perpendicular to the fiber and the metallic glass ring, #32 insulated copper wire was wrapped to produce the magnetic field.

The second ring modulator was constructed in a similar fashion, except that the ring was insulated and bonded into a ring by applying a layer of thin double sided adhesive tape to the strip of metallic glass prior to winding into the ring configuration. This resulted in a
Fig. 3. Unfinished ring modulator showing the metallic glass core constructed of many layers of the metallic glass ribbon with insulating and bonding material between layers. The optical fiber is shown wrapped cylindrically around the ring.

Fig. 4. Completed ring modulator with copper winding wrapped around the ring and perpendicular to the optical fiber and the length of metallic glass ribbon.
flexible ring modulator, but in all other respects was similar to the first rigid ring modulator.

The third modulator design was chosen for geometric simplicity and diversity from the first two modulators. The third modulator was constructed by sandwiching a portion of the optical fiber between two strips of metallic glass and bonding with adhesive cement. The modulator was magnetically excited by placing a coil loosely around the modulator. The modulator and coil are shown in Figures 5 and 6.

In order to produce the magnetic field to drive the modulators, a current source was needed that could supply both the dc bias field as well as an ac excitation field. Since most signal generators are ac voltage sources, a buffer amplifier was constructed (see Figure 7). A 2N176 power transistor was connected in the emitter follower mode using the modulator coil as the load. The dc bias current was controlled by varying the source voltage or the bias resistor ($R_B$). The ac signal was superimposed on the bias current by capacitor coupling the output from a signal generator into the base of the power transistor. Both the ac excitation and dc bias current levels were monitored by an ammeter in series with the modulator coil.
Fig. 5. Coil used to excite the strip metallic glass modulator which fits loosely in the cavity in the center of the coil.

Fig. 6. Metallic glass strip modulator. The optical fiber is sandwiched between two layers of metallic glass and glued to the metallic glass ribbon at the two edges.
Fig. 7. Common emitter circuit used to provide the necessary signal and bias current for the modulator coils. Bias level (dc current) was controlled with variable resistor $R_B$. Bias and signal current were monitored with an ammeter in series with the coil.
IV. DEMODULATION SYSTEM

In order to measure the actual phase modulation of the metallic glass modulator, a fiber interferometer system was used. In a simple fiber-optic Mach-Zhinder interferometer, the output varies constantly due to the interferometer's inherent sensitivity to random variation of temperature, air currents, and local acoustical noise, all of which modulate either optical path in the interferometer. In order to measure extremely small phase shift, a modification to a more sophisticated interferometer system was used (see Appendix). By replacing the acoustic coupler and associated fiber with the metallic glass modulator, the system will measure the phase change imparted by the metallic glass modulator (see Figure 8). The signal was further improved by sending the system output to a spectrum analyzer in order to observe the time average of the frequency of interest. In the phase locked system used, the detector signal was amplified and fed back to a calibrated piezoelectric modulator which tracks the phase shift caused by the metallic glass modulator. Thus, the phase shift caused by the metallic glass modulator can be found by knowing the fed back voltage to the piezoelectric modulator, and the voltage-to-phase conversion factor for the calibrated piezoelectric modulator.
Fig. 8. Modified phase-swept phase locked interferometer. The signal generator excites the metallic glass modulator which phase modulates the light in path $L_1$. The carrier modulator phase modulates the light in path $L_2$ with a 70 Khz carrier to shift the interference intensity variation up in frequency. The carrier is removed by the multiplying circuit and the low pass filter. By closing the loop back to the comparator modulator the phase error between the different paths is kept small and the phase modulation in path $L_1$ is duplicated by the comparator modulator in path $L_2$. Since the characteristics of the comparator modulator are known, the strain imparted to the fiber in path $L_1$ can be found by measuring the input voltage to the comparator modulator.
V. RESULTS AND CONCLUSIONS

Data was taken on all three modulators to determine their frequency response and the effect of varying the bias magnetic field. Results were compared between modulator configurations and with an ideal performance derived from typical values for an Fe-B-Si metallic glass under bias conditions similar to the experimental modulators.

In order to compare the performance of the modulators on an equal basis, the raw data was converted to a normalized strain parameter \( (G) \), which factored in the effect of fiber length, and the rms value of the excitation field.

Thus for the rigid ring modulator (see Figure 9) using standard toroid approximation for Ampere's Law, the excitation magnetic intensity will be

\[
H = \frac{NI}{2\pi R} = \frac{515(0.01)}{(2\pi)(0.0115)} = 71.274 \text{ A/m} = 0.8957 \text{ Oe}
\]  

(10)

In order to put the strain on a comparative basis, define the parameter \( G \) such that \( G \) is the strain per unit length per magnetic intensity. Then the units will be milliradians/cm-Oe. Since the raw data measured is the feedback voltage to the calibrated piezoelectric modulator, the amount of strain measured in terms of phase change of
Fig. 9. Physical parameters for the rigid ring modulator. $R$ is the mean radius of the ring.
He-Ne laser light (6328 Å) can be found knowing the voltage-to-strain constant for the piezoelectric modulator which is

$$K_p = 7.07 \frac{\text{rad}}{\text{volt}}.$$  \hspace{1cm} (11)

Therefore, for the rigid ring modulator the raw data (that is the feedback voltage to the piezoelectric modulator) can be converted to the normalized strain parameter $G$ by multiplying by the following constant,

$$G = K_S V$$  \hspace{1cm} (12)

where

$$K_S = \frac{K_p}{LH} = \frac{7.07}{118.737(.8957)} = .0665 \frac{\text{mrad}}{\text{mV-Cm-Oe}}$$  \hspace{1cm} (13)

where

$L$ is the length of fiber that is being stretched.

In this case:

$$L = (16) \pi D = 16 \pi 2.362 = 118.737 \text{cm}$$  \hspace{1cm} (14)

$H$ and $K_p$ are as previously defined.

$G$ is derived in a similar fashion for the soft ring modulator (Figure 10). Similarly, the rms value of the excitation magnetizing intensity

$$H = \frac{NI}{2\pi R} = \frac{198(10^{-2})}{(2\pi R).012256} = 25.712 \text{A/m}$$

$$H = .3231 \text{ Oe}$$  \hspace{1cm} (15)

The length of fiber under stress will be:
Fig. 10. Physical parameters for the soft ring modulator.
\[ L = \pi DN = \pi (2.667)11 = 92.165 \text{ Cm} \] (16)

Which results in the normalization strain-to-voltage constant \( K_s \):

\[
K_s = \frac{7.07}{(92.165)(.3231)} = .2374 \frac{\text{mrad}}{\text{mV-Oe-Cm}}
\] (17)

For the strip modulator \( K_s \) can be found with slight modification (Figure 11). The magnetizing intensity is calculated using the long coil approximation of Ampere's Law:

\[
H = \frac{NI}{L}
\] (18)

Then the strain to voltage constant \( K_s \) for the strip modulation becomes

\[
K_s = \frac{Kp}{\ell H} = \frac{7.07}{(6.985)(1.5304)} = .6614 \frac{\text{mrad}}{\text{mV-Oe-Cm}}
\] (19)

Due to the geometrical constraints, the magnetizing intensity could be measured directly only in the coil for the strip modulator. This was done using a Gauss meter (Electrodyne Model 725). The results are plotted for various values and compared with the simplifying approximation in Figure 12.

Since the magnetoelastic constants were unknown, but known to vary widely with changing bias levels, plots were recorded for modulator response as a function of dc bias level. Results are shown in Figures 13 and 14. No attempt is made to correlate the observed data with the calculated value due to the unavailability of the required magnetoelastic parameters for the metallic glass. However, the shape of the strain versus bias curve is similar to the curves developed by A. Clark (1973) for rare earth metallic glasses. 21
Fig. 11. Strip modulator physical parameters. $L_1$ is the distance between the points where the fiber is attached to the metallic glass and is also the length of the fiber under stress. $L_2$ is the total length of the metallic glass strips and the length of the excitation coil.
Fig. 12. Magnetic field intensity as a function of current for the strip modulator. Solid line is the calculated value based on the long coil approximation of Ampere's Law \( H = \frac{NI}{L} \). Δ points are the measured magnetic field intensity as a function of the measured current.
Fig. 13. Soft ring modulator dynamic strain as a function of bias magnetizing intensity. Data points (△) are derived from the rms value of the voltage fed back to the comparator modulator. Data points were further enhanced by a spectrum analyser which measured the frequency of interest (1 KHz) and time averaged over 32 sample increments. The smooth curve is drawn through the data points to indicate the function's trend.
Fig. 14. Rigid ring modulator dynamic strain as a function of bias magnetizing intensity. Data points are derived from the rms value of the voltage fed back to the comparitor modulator. Data points were further enhanced by a spectrum analyser which measured the frequency of interest and time averaged over 32 sample increments. The smooth curve is drawn through the data points to indicate the function's trend.
It was initially believed that an optimum bias level could be found at which the maximum strain on the optical fiber would occur, since the magnetoelastic coupling coefficient \( k \), typically reaches a maximum at 2 to 5 Oe, depending on the particular metallic glass. However, the strain is not simply proportional to \( k \), but for simple one dimensional geometry is related by the following equations:

\[
\frac{d}{\sqrt{B \mu T}} \]

Where

\( d \) is the magnetostrain coefficient and is related to more fundamental constant by the equations

\[
B = dT + \mu^T H \quad (21)
\]

\[
S = s^H T + dH \quad (22)
\]

where

- \( B \) is the resulting magnetic field
- \( T \) is the stress and in the modulators investigated will be the results of the restraining forces from the optical fiber and due to the geometry of the modulator
- \( \mu^T \) is the permeability of the material with constant stress
- \( H \) is the magnetizing intensity
- \( S \) is the resulting strain
- \( s^H \) is the elastic compliance and is the reciprocal of Young's Modulus
d is the magnetostrictive coefficient relating strain to magnetic field

For real, anisotropic materials such as the metallic glasses and for the geometrics used, all of the above parameters become tensors. For example, equation 21 becomes:

\[
B_n = 6 \sum_{p=1}^{6} s_{pq} H_q + \sum_{p=1}^{3} \sum_{m=1}^{3} d_{mp} H_m 
\]

(23)

In addition, these parameters are functions of the heat treatments and bias level. For the one dimensional case for a typical metallic glass, Fe_{80}B_{15}Si_{5} several of these parameters were measured by Brouha et al. and are shown in Figure 15. In conclusion, the observed modulator efficiency increased as the bias level increased and is consistent with the results from magnetostrictive investigation using rare earth metallic glass alloys.

Since all modulators are constructed from the same material and the response is compared on a normalized basis, then difference in performance can be attributed to losses due to the construction or the geometric configuration.

As would be expected, the frequency response of the two ring modulators are similar except the efficiency of the rigid ring modulator is approximately four times that of the soft ring modulator (see Figures 16, 17). The drop in efficiency with increased frequency for the ring configuration and the overall poor performance of the soft ring modulator indicates an inherent loss mechanism, which dominates any internal losses associated with the material. The suspected loss
Fig. 15. Coupling factor, incremental permeability and piezomagnetic strain constant of Fe₈₀B₁₅Si₂ as a function of bias field. Samples are either as-quenched (a.q.) or annealed for 30 minutes at 300°C in a transverse field (H, 150 kA/m). Source: Brouha and van der Borst.
Fig. 16. Soft ring modulator dynamic strain as a function of frequency. Data points (Δ) are derived from the rms value of the voltage fed back to the comparator modulator. Data points were further enhanced by a spectrum analyzer which measured the frequency of interest and time averaged over 32 sample increments. The smooth curve is drawn through the data points to indicate the function's trend. Bias magnetic field was 6.46 Oe.
Fig. 17. Rigid ring modulator dynamic strain as a function of frequency. Data points (Δ) are derived from the rms value of the voltage fed back to the comparator modulator. Data points were further enhanced by a spectrum analyzer which measured the frequency of interest and time averaged over 32 sample increments. The smooth curve is drawn through the data points to indicate the function's trend. Bias magnetic field was 17.9 Oe.
mechanism is simply frictional losses within the ring, especially between the layers of metallic glass in the bonding material in the ring. For a coil around an infinitely thin ring, the magnetic intensity can be expressed:

\[ H = \frac{NI}{2\pi R} \]  

(24)

Where

- \( N \) is the number of turns of wire
- \( I \) is the current
- \( R \) is the radius of the ring.

However, for a non-ideal ring, the magnetic intensity is inversely proportional to the radius. Thus, the material on the inner side will be under compressive stress due to the higher magnetic intensity while the outer part of the ring will be under tensile stress due to less magnetic intensity (see Figure 18).

A nonuniform stress across the radius of the ring would not in itself be a cause of excessive losses. However, the primary loss mechanism of the ring is in the adhesive layer between the metallic glass. Thus, most of the elastic energy is dissipated in the bonding layer as heat, and less is transferred to the optical fiber. The frequency response of the ring modulators is also consistent with this theory, since the losses for damped lossy system would be proportional to frequency.

The strip modulator had the best performance which could be explained due to the lack of restraints on the movement of the metallic glass (Figures 19, 20). Also, many of the losses proportional to the volume
Fig. 18. Internal stress in the non-ideal ring modulator as a function of radius. Since the magnetic field is inversely proportional to the radius within the ring the metallic glass nearest the center will exhibit greater magnetostriction than the metallic glass near the outer edge of the ring. The results will be an equilibrium in which the metallic glass near the center will be under compressive stress and the metallic glass near the outer edge will be under tensile stress.
Fig. 19. Strip modulator dynamic strain as a function of frequency. In spite of enhancing data by time averaging and monitoring only the frequency of interest with a spectrum analyzer, data points were more scattered than with the two previous modulators. This can be attributed to limitation of the detection system in that the strip modulator was overdriving the system to the point that the system would occasionally lose lock. Bias magnetic field was 30.6 Oe.
Fig. 20. Strip modulator dynamic strain as a function of bias magnetizing intensity. Data points were derived from the rms value of the voltage fed back to the comparator modulator. Data points were enhanced by a spectrum analyzer which measured the frequency of interest (1 KHz) and time averaged over 32 sample increments. The smooth curve is drawn through the data points to indicate the function's trend.
of magnetic material, such as hysteresis losses, would be minimized in the strip configuration since it contains the least volume. In addition the performance of the strip modulator is unaffected by $\lambda_1$ and operates entirely on $\lambda_2$ due to the geometry of the modulator, where $\lambda_1$ is the magnetostriction constant relating strain to magnetic intensity with strain measured perpendicular to the magnetic field and $\lambda_2$ is the magnetostriction strain constant parallel to the magnetic field.

Bozorth observed that $\lambda_1$ and $\lambda_2$ are of opposite signs and for a magnetostrictive material under an applied magnetic field, the change in volume is several orders of magnitude less than the change in linear dimension. Therefore, although the strip modulator is unaffected by $\lambda_1$, the performance of the ring modulator is detracted by the opposing effect of $\lambda_1$ and $\lambda_2$. In a worst case, the ring configuration could result in no strain on the optical fiber if the ring thickness-to-radius were improperly chosen.

In order to evaluate the performance of the experimental metallic glass modulator, typical values for the material parameters were used to calculate the ideal strain for a given excitation magnetic field. This ideal strain neglects losses both due to the material and intrinsic to the particular design, and is meant to give a rough comparison between ideal and actual modulator. Using typical values for the material and starting with the basic equations:

$$S = s^{HT} + dH$$  \hspace{1cm} (25)
where:

\( s^H \) is the compliance of the material

\( T \) is the applied stress

\( d \) is the magnetostrictive coefficient that relates strain to magnetizing intensity

\( H \) is the applied magnetic field. \(^{25}\)

Assuming that the as quenched permeability for a bias level of .2 kA/m from Figure 15 is typical:

\[
\mu T = 700 
\]

\[
s^H = 7.143 \times 10^{-13} \text{ cm}^2/\text{dyne} \quad (27)
\]

Assuming that the value for \( k \) for Fe\(_{80}\)B\(_{15}\)Si\(_5\) shown in Figure 15 for a bias level of .2 kA/m is typical:

\[
k = .45 \quad (28)
\]

Then the governing equation \(^{26}\) relating \( k \) to \( d \), \( \mu T \) and \( s^H \) for the one dimensional case becomes:

\[
d = k \sqrt{\mu T s^H}
\]

\[
= .45 \sqrt{(700)7.143(10^{-13})}
\]

\[
= 1.006 \times 10^{-5} \text{ Oe}^{-1} \quad (29)
\]

If the restraining stress of the optical fiber on the modulator and the stresses due to the modulator's shape and bonding material are neglected then the previous equation for strain becomes:
when \( H = 1 \text{Oe} \) then the resulting strain, \( S \), may be compared with the actual modulator performance. Taking the maximum value of \( G \) for each of the modulators from Figures 16, 17, 18 and converting to units of \( \frac{\text{Cm}}{\text{Cm-Oe}} \), and since the wavelength, \( \lambda \), for the He-Ne laser is 6328 \( \text{Å} \), then 1 rad of phase shift corresponds to \( 1.007(10^{-8}) \text{Cm} \). Then for the soft ring modulator:

\[
G_{\text{max}} = 1.007(10^{-8}) \times 8.5 = 8.56(10^{-8})
\]  

(31)

For the rigid ring modulator:

\[
G_{\text{max}} = 1.007(10^{-8}) \times 22.5 = 2.27(10^{-7})
\]  

(32)

For the strip modulator:

\[
G_{\text{max}} = 1.007(10^{-8}) \times 96 = 9.67(10^{-7})
\]  

(33)

Thus, the observed performance varied from about 1% to 10% of the ideal modulator performance.

In conclusion, the modulators constructed in this study are far from optimum and it is a tribute to the excellent magnetostrictive qualities of metallic glasses that they performed as well as they did. Much could be done to improve the efficiency by modifying physical configuration and matching the stress-strain coefficient of the optical fiber with the magnetostrictive parameters of the metallic glass. Much improvement could be realized by more efficient coil design. Since the coils used to excite the modulators were made up of relatively few
turns of fine wire by increasing the number of turns on the coil less current would be required for the same magnetic field. This would result in a net decrease in Joule heating loss in the coil since for the same magnetic field the current and the coil resistance are inversely proportional and Joule heating loss is proportional to the coil resistance and the current squared. For the modulators used the Joule heating loss is significant. For example for the rigid ring modulator the ac input power at 1 Khz and 10 ma was found to be 2 mw. Since the dc coil resistance for this modulator was 6 Ω, then the Joule heating loss was .6 mw or 30% of the input power at 1 Khz.

Another method to enhance the performance of the metallic glasses by reducing residual stresses is by annealing the material in a magnetic field. This method has increased the magnetomechanical coupling coefficient as high as .82 for certain metallic glasses. Since the magnetomechanical coupling coefficient for the unannealed unbiased material used in this investigation was found to be .22, a several fold improvement in performance could be expected by annealing the metallic glass ribbon prior to modulator construction.

In addition to reducing the losses external to the metallic glass, there is as yet very little information in the literature concerning the magnetomechanical losses in metallic glasses. In a study by Berry and Prichet, losses are divided into macroscopic, microscopic, and hysteretic effect and were found to be strongly dependent on external bias. In addition, internal losses for metallic glasses were found experimentally which were much greater than could be explained by
present theory. Thus, more study is needed into the structure and behavior of metallic glasses before practical magnetoelastic devices can be fully optimized.

Although there is much to be learned about the magnetoelastic behavior of metallic glasses before the metallic glass phase modulators can be fully optimized, they already exhibit promising characteristics and have certain advantages over piezoelectric phase modulators. Metallic glass modulators are fundamentally current devices and have low impedance while the piezoelectric modulators are voltage devices and have high impedance. Low impedance would be an advantage in system noise reduction. The strip modulator configuration was especially promising in that in terms of size it occupied the least volume even compared to the piezoelectric modulators. Also, its planar shape would be an advantage in designing a miniaturized system. Finally, the strip modulator utilized far less optical fiber than any other modulator including the piezoelectrics. For example, the comparitor piezoelectric modulator described in the Appendix was wrapped with over a meter of optical fiber while the strip modulator achieved significant phase modulation with less than 7 cm of optical fiber. This would result in a significant reduction in system noise due to thermal and unwanted acoustic interaction with the optical fiber by reducing the total length of fiber in the system.
APPENDIX

DESCRIPTION AND OPERATION OF THE FIBER OPTIC PHASE-SWEP'T PHASE-LOCKED LOOP

The system is a standard fiber interferometer with one leg being exposed to an acoustic field and the other leg serving as a phase reference. In Figure 20, (A) represents the sensing fiber, (B) represents the phase shifter/sweeper. This device stretches the fiber a length that is proportional to the applied voltage. This device is currently being implemented with a piezoelectric ceramic (PZT) cylinder with a length of fiber wrapped around it.

The oscillator (J) drives the phase shifter (B) at a frequency with sufficient modulation depth to alter the phase at the detector (C) so that the fringe displacement on the interference pattern will shift at least $\pi$ radians which guarantees maximum signal contrast.

To understand the operation of the system (circuit), it is advantageous to break the feedback circuit and consider the output of the photodetector (C). The output of the detector is proportional to the absolute value of the square of the sum of the signals from both legs of the interferometer. It will be assumed (for simplicity) that the intensity levels from each of the legs of the interferometer are equal and the output is ac coupled.
Fig. 21. Fiber optic phase swept phase locked loop. Source: I. J. Bush.
The output of the detector can be described by

\[ s(t) = C \cos [(B \sin \omega_m t - A \sin \omega_a t - \phi(t) - \theta(t))] \]

where

- \( B \) is the phase excursion of the modulator (at \( \omega_m \)).
- \( A \) is the phase excursion of the acoustic signal.
- \( \omega_a \) is the acoustic frequency.
- \( \omega_m \) is the frequency of the oscillator. It is also the frequency of the shifter when the feedback loop is opened up.
- \( \phi(t) \) is the contribution of the thermal-induced phase shift.
- \( \theta(t) \) is the phase shift that results from the voltage applied to the fiber stretcher from the feedback loop and any static phase terms.
- \( C \) is the peak value of the signal (amplitude).

A simple way of looking at this signal is to group the last three terms in the brackets into one phase term as a function of time.

\[ \alpha(t) = A \sin \omega_a t + \phi(t) + \theta(t), \]

resulting in

\[ s(t) = C \cos [B \sin \omega_m t - \alpha(t)], \]

the signal can be broken up to reveal
\[ s(t) = \frac{C}{2} \left[ \cos(B\sin\omega_m t) \cos\alpha(t) + \sin(B\sin\omega_m t) \sin\alpha(t) \right] \]

\[ = \frac{C}{S} \left[ J_0(B) + 2 \sum_{k=1}^{\infty} J_{2k}(B) \cos(2k\omega_m t) \right] \cos\alpha(t) \]

\[ + 2 \sum_{k=0}^{\infty} J_{2k+1}(B) \sin[(2k + 1)\omega_m t] \sin\alpha(t) , \]

where \( J_k \) refers to an integer order Bessel function.

If the loop is now closed, it is seen that the signal is amplified (E) and clipped (F) and then mixed (G) with \( \sin\omega_m t \). The bandwidth cutoff frequency of the low pass filter (I) is very small compared to \( \omega_m \) and the output is the signal passed by the low pass filter (I) which is

\[ f(t) = A_2 C' J_1(B) \sin \alpha(t), \]

where \( C' \) is the level of the clipped signal.

That is, of course, the steady state result. It is the result of the feedback system duplicating the phase of the signal \( s(t) \) to insure quadrature components at the input of the mixer phase comparator. The open loop gain given for the system can be described as \( A_1'A_2'J_1(B) \) where \( A_1' \) is the clipped \( A_1 \) gain. If these terms are sufficiently large, it is seen, as in all phase-lock systems, that \( \alpha(t) \) will become small and the approximation can be made that

\[ \sin\alpha(t) = \alpha(t). \]

This being the case, it is seen that
\[ f(t) = A_2 \mathcal{C}'J_1(B) \alpha(t) = A_2 \mathcal{C}'J_1(B)[\text{Asin} \omega_a t + \phi(t) + \theta(t)]. \]

In the earlier discussion with the feedback circuit open, \( \phi(t) \) and \( \theta(t) \) could take on any arbitrary value between 0 and \( 2\pi \). When the system acquires lock (phase lock), it forces \( \theta(t) \) (the phase produced by the fiber stretcher) to duplicate \( \text{Asin} \omega_a t + \phi(t) \) (the signal produced by the interferometer) with an opposite sign. In other words, \( \theta(t) \) is trying to cancel out \( \text{Asin} \omega_a t + \phi(t) \). \( \theta(t) \) will never completely cancel \( \text{Asin} \omega_a t + \phi(t) \) and the result will be a phase error \( \alpha(t) \). As discussed earlier, the magnitude of \( \alpha(t) \) is determined by the system open loop gain. It can be shown, with much mathematical rigor, that the signal when in phase lock is equal to:

\[ \text{Asin} \omega_a t + \phi(t) + \theta(t) = \gamma [\text{Asin} \omega_a (t) + \phi(t)] = \alpha(t), \]

where \( \gamma \) is generally a small value \( (|\gamma| << 1) \). The output can now be written as:

\[ f(t) = A_2 \mathcal{C}'J_1(B)\gamma[\text{Asin} \omega_a t + \phi(t)]. \]

Where \( A_2 \mathcal{C}'J_1(b)\gamma \) are constants. It is now evident that the demodulated output replicates the acoustic information; it also replicates the thermal phase noise. The thermal phase noise poses no problem in that it is limited in bandwidth to very low frequencies, typically 5 Hz and lower.

The key to the entire invention lies in the phase sweeping.

The phase sweeping shifts the acoustical information up in frequency.
with a carrier frequency $\omega_m$ (the frequency of the oscillator). This enables ac coupling behind the optical detector and hence eliminates the unwanted dc component. The fact that the information is shifted up in frequency also allows the signal to be clipped (clipping will not effect the information, for all the information in a phase-modulated signal is contained in the zero crossings). The clipping of the signal renders the system insensitive to peak intensity fluctuations at the input of the optical detector.

A fiber optic phase-swept phase-locked loop was set up in the optics laboratory of the Naval Research Laboratory's Underwater Sound Reference Detachment. No special care was taken to optimize parameters such as thermal noise, 60-cycle interference, path lengths of the legs of the interferometer, or gain constants for the amplifiers. The system was set up just to demonstrate the concept of phase-swept phase locking. The system was set up as in Figure 20 with standard laboratory equipment. The source was a Spectra Physics Model 124 helium neon laser. The fiber used was ITT-T110 single-mode fiber.

The system even with no optimization exhibited a minimum detectable phase shift of $2 \times 10^{-4}$ radians for a signal-to-noise ratio of 1 in 1 Hz band. If the system is optimized, detection in the range of $1 \times 10^{-6}$ radians should easily be realized.


4 Ibid.

5 Bucaro and Hickman, p. 938.

6 Ibid., p. 939.


10 Ibid.


16 Ibid., p. 231.


19 Ibid., p. 857.

20 O'Handley, p. 379.


24 Bozorth, p. 632.

25 Technical Committee on Transducers and Resonators of the IEEE Group on Sonics and Ultrasonics, p. 72.

26 Ibid.

27 Mitchell et al., p. 1169.

28 Interview with Steve Meeks, Naval Research Laboratory, Orlando, Florida, 14 August 1980.


30 Ibid., p. 3300.

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