Measurements of Magnetostriction of Metallic Glass Ribbons by Fiber-Optic Interferometry

Kyung-Shik Lee, Moo-Youn Park, Tae-Kyun Kim, Min-Hyoung Kim, and Hyun-Seo Kang

Abstract

Magnetostrictions of metallic glass ribbons were measured by fiber-optic Mach-Zehnder interferometry. The saturation magnetostrictions measured here are accurate to within 10%. For accurate measurements the fibers in the ribbons were uncoated, the ribbons were flattened before bonding, and two passes of fiber in the sensing arm were bonded to a single layer metallic glass ribbon at the ends only. Various factors affecting the accuracy of the measurements were also discussed.

I. Introduction

Metallic glass ribbons have so far been used for fiber-optic magnetometers. The performance and the properties of the magnetometers depend on the magnetostrictive response of the metallic glass ribbons. Thus to improve the performance of the fiber-optic magnetometers magnetostrictive properties of the metallic glass ribbons should be first characterized and best metallic glass materials should be selected. O'Handley et al.[1]. measured the magnetostriction of $Co_{80-x}T_xB_{20}$ metallic glasses using metal-foil strain gauges. Bulk-optic Michelson interferometers[2, 3] were used to measure the magnetostriction of metallic glass as a function of field. Measurements of magnetostriction in metallic glass ribbons were also made by fiber-optic dilatometers [4, 5]. Moreover, the magnetostrictive responses of the ribbons have been measured using fiber-optic Mach-Zehnder interferometers by many investigators[6-8].

Recently we have measured rather completely the magnetostrictive properties as well as the magnetostrictive responses of a number of magnetostriction materials using fiber-optic Mach-Zehnder interferometers[9, 10].

However, the measured results reported in [9, 10] can not be considered as those for a single ribbon because the magnetostrictive measurements[9, 10] were performed for a two-layer sandwich ribbon rather than for a single-layer ribbon.

In this work we attempted to accurately measure the magnetostrictions of single-layer metallic glass ribbons with the fiber-optic Mach-Zehnder interferometer by considering various factors affecting the measurements. Special care was taken in attaching a single ribbon to the sensing fiber arm of the fiber-optic Mach-Zehnder interferometer for the measurements, because the magnetostrictive strain energy transfer from the ribbon to the fiber depends on how the ribbon is attached. Bucholtz et al.[11] reported that 75 percent of the magnetostrictive strain energy in the ribbon was transferred by bonding the fiber only at the ends of the ribbon. In the same reference he mentioned that the value of less than 100 percent may be due to a combination of mechanical losses in the fiber jacket and the geometry of the bonding configuration in which only a portion of the fiber circumference was in contact with the ribbon. Nader-Rezvani et al.[12] also discussed about the problem of ribbon being curled inward, thus causing errors in measurement.

Taking the various factors causing errors into consideration we carefully measured the magnetostrictive responses of three metallic glass ribbons with the interferometer described in [9, 10]. The values of saturation magnetostrictions for three different samples were determined from the response curves and compared to the quoted saturation magnetostrictions[13]. Factors affecting the accuracy of the measurements were also discussed.

II. Measurement System

1. Measurement Principle

To measure the magnetostrictive properties of metallic glass ribbons the fiber-optic Mach-Zehnder interferometer[9, 10] shown in Fig. 1 was used. For the measurements the ribbon samples were first attached to the sensing fiber arm of the interferometer and placed inside a solenoid where dc and ac currents were

Manuscript received April 1, 1997; accepted November 12, 1997.
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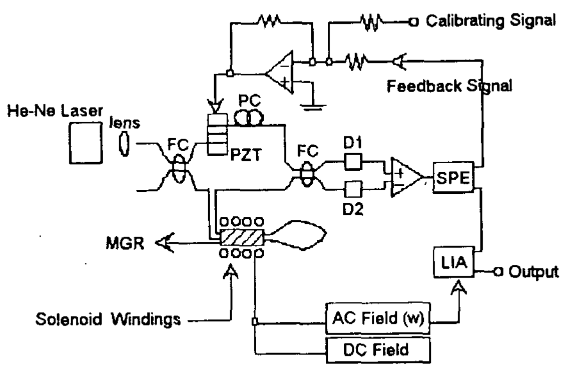

Fig. 1. Fiber-optic Interferometric system for the measurement of measuring the magnetostriction of Metallic glass ribbons (FC, fused coupler ; D1 and D2, detectors; SPE, signal processing electronics ; MGR, metallic glass ribbon ; PC, polarization controller).

applied. Then the optical phase shift ϕ occurs because of the magnetostrictive strain produced by the magnetic field $H_t(= H + H_\omega \cos\omega t)$. According to the Coherent Rotation Model, the magnetostrictive strain induced in the metallic glasses, e,is given by $e = CH_t^2$, where C is the magnetostrictive constant which equals to $3\lambda_s/2H_A^2$, λ_s is the saturation magnetostriction, H_A is the anisotropy field and H is a dc magnetic field. As a result for low fields, the magnetostrictive strain component and the phase shift component at frequency ω are, respectively, given by

$$e_\omega = 2C\eta(H-H_c)H_\omega, \quad (1)$$

$$\phi_\omega = 2k_{eff}LC\eta(H-H_c)H_\omega, \quad (2)$$

where $k_{eff} = 1.56\,\pi n/\lambda$, n is the refractive index of fiber core, λ is the optical wavelength in a vacuum, L is the active length of the fiber transducer, $\eta(= C_{eff}/C)$ is the efficiency of the magnetostrictive strain transfer between the metallic glass and the fiber, C_{eff} is the effective magnetostrictive constant and H_c is the coercive field. The phase shift ϕ_ω is proportional to the magnitude of the fields H-H_c, H_ω, and the magnetostrictive constant C. Thus, C and e_ω are obtained under the assumption of $\eta \simeq 1$ when the phase shift ϕ_ω is measured.

The fiber-optic interferometer used in this work consists of a He-Ne laser(632.8 nm), two 50/50 fused couplers(FC), a polarization controller(PC), two photodiodes (D1, D2), signal processing electronics (SPE) and a lock-in amplifier(LIA). Here, to stabilize the interferometer at its quadrature point under any circumstances the output signals from the electronics(SPE) were fed to a piezoelectric (PZT) cylinder attached to the reference fiber arm. In addition, the polarization controller was adjusted in every measurement so that maximum visibility was achieved. The amplitude of the phase shift ϕ_ω induced by the applied ac field in the interferometer can be computed from the output of the lock-in amplifier tuned to the frequency ω because the LIA output is linearly proportional to small ϕ_ω. However, to improve the accuracy calibrating the system before the measurement is required. Calibration was done by appling a small known voltage signal to the PZT and by reading the LIA output.

2. Source of Errors in Measurement

There are a number of factors affecting the accuracy: 1) magnetostrictive strain transfer efficiency η defined here as the ratio of maximum strain in the fiber after bonding to maximum strain in the ribbon before bonding, 2) nonlinear phase response of interferometer to signal H_ω, 3) PZT conversion coefficient (degrees/volt) defined as the phase shift induced in the fiber due to an 1-volt signal applied to the PZT.

The error resulting from the nonideal transfer efficiency η becomes negligible as η approaches to 1. Bucholtz et al.[11] reported that the magnetostrictive strain transfer efficiency η of 0.75 was achieved by bonding the fiber only at the ends of the ribbon. He also mentioned that values of less than 1 may be due to a combination of mechanical losses in the fiber jacket and the geometry of the bonding configuration. Nader-Rezvani et al.[12] discussed that a single layer of metallic glass ribbon is very likely to curl inward, causing the longitudinal axis of the metallic glass layer to deviate from the axis of the applied magnetic field. To reduce the errors by maximizing η, therefore, the fibers in the ribbons should be uncoated and the metallic glass ribbons need to be flattened before bonding. When the measurement is performed at low frequency, uncoating the fibers is not necessary.

The nonlinear phase response of the interferometer increases as the phase ϕ_ω to be measured gets bigger, because the Bessel function $J_1(\phi_\omega)$ deviates more severely from ϕ_ω as ϕ_ω increases. The errors expected in the measurement of phase ϕ_ω of 0.3 radian, 0.5 radian and 1 radian are 1.1%, 3% and 12%, respectively. Thus, small signal H_ω should be applied for the accurate measurements of e_ω, C and λ_s.

To calibrate the phase detection system the PZT conversion coefficient ought to be first measured. Applying a ramping signal to the PZT and counting the number of fringes N per cycle we can determine the conversion coefficient. In this case the error in measurement of the conversion coefficient is about 100/2N%. Considering typical fringe number of ~12 per cycle we expect the error in phase measurement less than 5%.

III. Results and Discussion

The samples (5 cm long, 25 μm thick, Nilaco product) used in these measurements were METGLAS 2605S3 ($Fe_{79}B_{16}Si_5$), METGLAS 2605SC ($Fe_{81}B_{13.5}Si_{3.5}C_2$) and METGLAS 2826MB ($Fe_{40}Ni_{38}Mo_4B_{18}$). They were in the as-received unannealed state and were cut into 5 mm wide. Two passes of fiber in the sensing arm were bonded to each metallic glass ribbon (~5 cm long) at

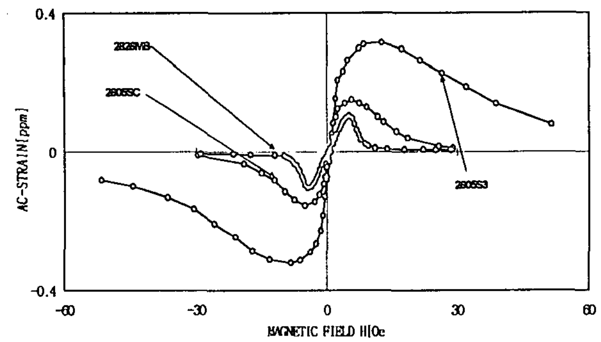

Fig. 2. Ac magnetostrictive responses as a function of dc bias field for METGLAS 2605SC (H_ω = 0.7 mOe, f = 2.3 kHz), METGLAS 2826MB (H_ω = 1 mOe, f = 2.5 kHz) and METGLAS 2605S3 (H_ω = 2.9 mOe, f = 2.7 kHz).

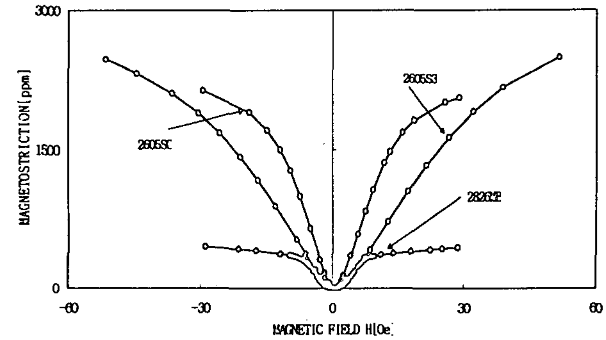

Fig. 3. Magnetostrictive responses as a function of dc bias field for METGLAS 2605SC (H_ω = 0.7 mOe, f = 2.3 kHz), METGLAS 2826MB (H_ω = 1mOe, f = 2.5 kHz) and METGLAS 2605S3 (H_ω = 2.9 mOe, f = 2.7 kHz).

Table 1. Various parameters measured by the Fiber-optic interferometer for three different metallic glass ribbons.

Sample	Metglas 2826MB	Metglas 2605SC	Metglas 2605S3
λ_s(at f_p)	3.4×10^{-4}	20.2×10^{-4}	26.5×10^{-4}
λ_s(at 15Hz)	9.7×10^{-6}	25.2×10^{-6}	24.5×10^{-6}
λ_s' (at 15Hz)	12.3×10^{-6}	26.8×10^{-6}	25×10^{-6}
λ_s[13]	12×10^{-6}	30×10^{-6}	27×10^{-6}
C[Oe^{-2}]	7.6×10^{-6}	2.0×10^{-5}	1.1×10^{-5}
H_p[Oe]	5.2	5.8	12.6
H_s[Oe]	11.7	26	79.2

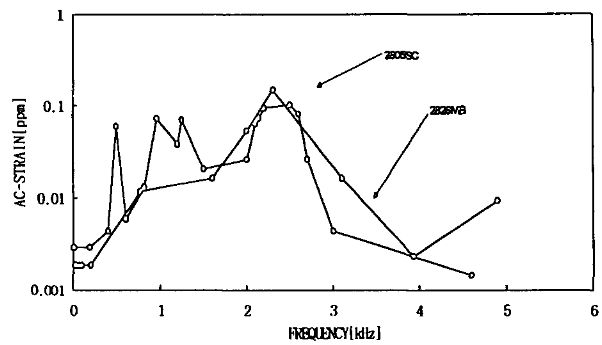

Fig. 4. Frequency responses of Fiber-optic magnetostrictive transducers for METGLAS 2605SC (H_ω = 0.7 mOe, H = 5.8 Oe) and METGLAS 2826MB (H_ω = 1 mOe, H = 4.4 Oe).

the ends only for measurement. The fibers in the ribbons were uncoated and the ribbons were flattened before bonding.

With the fiber-optic interferometric system the ac magnetostrictive responses of various metallic glass ribbons were measured. Fig. 2 shows the measured ac magnetostrictive responses for three different materials. The applied signal H_ω was typically smaller than 2.9 mOe, which corresponds to $\phi_\omega < 0.36$ radian. And the conversion coefficient measured near 2.5 kHz for the PZT(EC-70, EDO Co.) used here was ~280 (degrees/volt). It can be noted that the response curves contain information on the coercive field H_c, the saturation field H_s and the dc bias field for the maximum response H_p. Here, H_s is defined as the field where the ac magnetostriction drops to 10% of its maximum. The values of fields H_p and H_s for different materials were listed in Table 1. The solid dots in Fig. 3 are the magnetostriction values corresponding to those in Fig. 2. Saturation magnetostriction λ_s corresponding to the magnetostriction value at H_s and the magnetostrictive constant C (or C_{eff}) were obtained from Fig. 3 assuming $\eta \simeq 1$, and are listed in Table 1. The magnetostrictive constant C was determined by fitting the magnetostriction values at different bias fields up to H_p to the equation CH_t^2. The magnetostrictive response curves in Fig. 2 and 3 were measured at frequency f_p of maximum response, that is, at the mechanical resonance frequency. The frequency f_p and the Q at resonance are dependent on the sample geometry and mounting conditions.

The frequency responses of metallic glass ribbons are also shown in Fig. 4. From Fig. 2, 3 and 4 the saturation magnetostrictions λ_s at low frequency (~15 Hz) for different materials were obtained and listed in Table 1. Note that the values λ_s measured at low frequency are matched within 19% to the quoted saturation magnetostrictions[13]. When the saturation magnetostriction λ_s' is redefined as the value corresponding to the field where the ac magnetostriction drops to 5% of its maximum, the deviation reduces to within 10%. Thus the saturation magnetostrictions λ_s' measured by the fiber-optic Mach-Zehnder interferometer are said to be reasonably accurate to within ~10%.

IV. Conclusion

Magnetostrictive responses of metallic glass ribbons were measured with a fiber-optic Mach-Zehnder interferometer. We were able to obtain magnetostrictive parameters from the magnetostrictive response curves. The saturation magnetostrictions at low frequency defined as the value corresponding to the field where the ac magnetostriction drops to 5% of its maximum, measured by the fiber interferometer are accurate to within 10%. To know the accuracy more precisely of the magnetostriction measurement method, further measurements should be made on annealed ribbons. Magnetostriction measurement of metallic glass ribbons with higher accuracy using the fiber-optic interferometer would be possible when the measurement is performed under the consideration of various factors affecting errors.

Acknowledgement

This work was supported by the Korea Research Foundation under grant No. 94-01-E0796(94' NON DIRECTED RESEARCH FUND) and the 63 Research Fund, Sung Kyun Kwan University, 1996.

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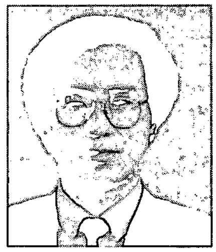

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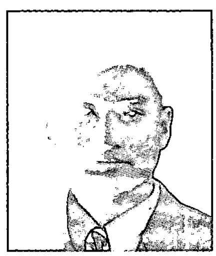

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