Laser Interferometry and Complex Piezoelectric Constant of PZT Ceramics

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Abstract A modified Michelson laser interferometer was constructed to measure a complex piezoelectric constant of PZT ceramics with the composition of $0.95Pb(Zr,Ti)O_3$-$0.05Pb(Sb,Nb)O_3$. A small displacement (~0.1nm) could be detected up to 100kHz by this interferometer. The response of the interferometer was consistent with a theoretical expression including the effect of multiple reflections. The complex piezoelectric constant was also determined by least squares fitting of complex admittance to the theoretical expression. Complex piezoelectric constants ($-d_{31}$) of a PZT ceramic determined by an ordinal resonance technique, least squares fitting of complex admittance and the laser interferometer were 184, 173-4.5i and 187-6.0i pC/N, respectively.

Key Words Piezoelectricity, PZT, Laser interferometer, Ferroelectricity, Ceramics

1. Introduction

The piezoelectric d-constant is the most important and fundamental quantity to specify the property of piezoelectric materials. The piezoelectric constant is a complex number, and in piezoelectric ceramics, it may change with frequency and amplitude of electric field. Usually, the piezoelectric constant is determined as a real number by a resonance technique, where the frequency and amplitude of electric field are restricted in the ranges above 100kHz and below 10V/mm, respectively. In order to determine the piezoelectric constant at desired frequencies and amplitudes, it is necessary to measure electric-field-induced strains of piezoelectric materials. Laser interferometer has been frequently used to detect the electric-field-induced strains of piezoelectric materials. Zhang et al.[1,2] have developed both Michelson and Mach-Zehnder systems to measure piezoelectric strains. Vohra and Bucholtz[3] have developed Mach-Zehnder fiber optic interferometer and measured filed-induced electrostrictive strains of relaxor materials. Royer and Kmetik[4] have on the other hand employed a heterodyne interferometer to measure the frequency dispersion of piezoelectric constant of $LiNbO_3$. However, the determination of the complex piezoelectric constant by interferometer has been extremely limited so far except the studies of Li et al.[5] and Yamaguchi and Hamano.[6]

Li et al.[5] used an ordinal geometry of Michelson interferometer to measured the complex piezoelectric constants of quartz and PLZT from 10Hz to 100kHz. They pointed out that a short optical path was essential for accurate and stable measurements because noises due to thermal expansion and mechanical vibration increased with increasing optical path length. Yamaguchi and Hamano[6] made a modified and miniaturized Michelson interferometer whose optical path length between two mirrors was only a few mm, and measured complex piezoelectric constants of $AgNa(NO_2)_2$ up to 50kHz. However, to find the most sensitive position of interferometer, the so-called λ/4 condition, they had to adjust the optical path length by changing air pressure in a sample cell. Because of this adjusting process, measurements required a long time, which decreased the stability of the system.

In the present study, we propose a new set up of a modified Michelson interferometer in which the optical path length of a few mm is adjustable by an electric signal using a piezoelectric actuator. The complex piezoelectric constant of PZT ceramics is measured as functions of frequency and amplitude. The results are compared with those determined by both an ordinal resonance technique and a modified resonance technique using a least-squares fitting of complex admittance.

2. Experimental

The chemical composition of PZT ceramic used for the measurements was $0.95Pb(Zr,Ti)O_3$-$0.05Pb(Sb,Nb)O_3$. The detailed process of ceramic preparation was described in ref.7). The PZT ceramic had a rectangular shape of 10x3x1.5mm^3 where electrodes were made on the 10x3mm^2 surfaces with a silver paste. The poling condition was 3kV/mm at 110 ℃ in silicon oil. The piezoelectric d_{31} tensor was determined by an ordinal resonance technique or a modified

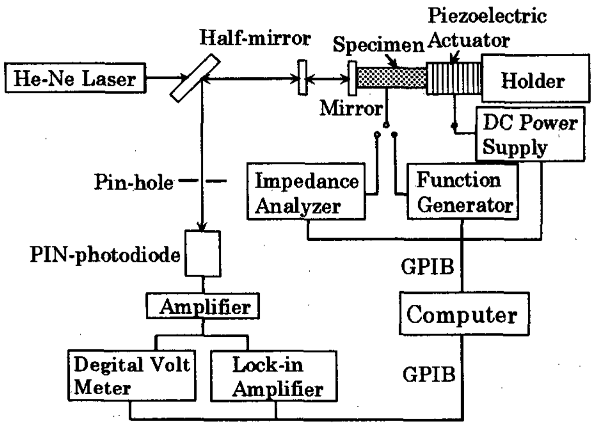

Fig.1 Schematic diagram of laser interferometer.

resonance technique where a least-squares fitting of complex admittance to a theoretical expression was carried out.

A schematic diagram of a laser interferometer constructed in the present study is shown in Fig.1. The geometry of the system was based on the interferometer reported by Yamaguchi and Hamano.[6] A standard cw He-Ne laser (λ=633nm, P=10mW) was used as a source of coherent radiation. A small mirror, made by sputtering platinum on thin glass plate (0.2mm thick), was adhered with epoxy glue to the surface of PZT ceramic plate which was fixed on a piezoelectric actuator. A half mirror which transmits half of incident beam was fixed parallel to the small mirror on the sample. Interference occurred among light beams reflected by the mirror on the sample and the half-mirror.

A piezoelectric strain of the PZT ceramics slightly changes the optical path length between the two mirrors. A small change in the optical path length causes a change in light intensity, which was detected with a pin-photodiode (Electro-Optics Tech. Inc., ET-2000). In the measurement of small displacements, it should be necessary to adjust and keep the optical path length of interferometer at the most sensitive position, the so-called $\lambda/4$ condition. To solve this problem, we detected light intensity continuously with changing optical path length using a piezoelectric actuator. The detected light intensity I is composed of two components, I_{dc} and I_{ac}. The change of *dc* component (I_{dc}) is caused by the change in optical path due to the displacement of piezoelectric actuator, while that of *ac* component (I_{ac}) is caused by the piezoelectric strain of PZT ceramics. In the present system, the signal from the photodiode was amplified by a preamplifier (Atago Bussan Co.LTD,AM-100), and the *dc* component (V_{dc}) in the output signal was detected with a digital voltmeter (hp,34401A) while the *ac* component (V_{ac}) in the output signal was detected by a two phase lock-in amplifier (NF,5610B). The lock-in amplifier also measured the phase difference (phase lag) between the applied signal to the sample with a function generator (hp,8116A) and the *ac* component of the output signal. The complex piezoelectric constant was calculated from the phase lag δ by

$$d^* = d' - id'' = |d|\exp(-i\delta) \qquad (1)$$

The complex admittance of the mounted sample was also measured by an impedance analyzer (hp,4192A). The measurement sequence was perfectly computer automated.

3. Results and Discussion

3.1 Performance of laser interferometer

Figure 2 shows the change in V_{dc} and V_{ac} with the driving voltage of piezoelectric actuator. The amplitude and frequency of *ac* signal on the sample was 1V/mm and 6kHz, respectively. Clear periodic signals were observed in both V_{dc} and V_{ac}. The change of V_{dc} is approximately sinusoidal. However, a pair of asymmetric peaks with different heights repeats in the curve of V_{ac}.

By considering multiple reflections between the mirror and the half-mirror, we represented the *dc* component of the light intensity I_{dc} as follows;

$$I_{dc} = \left[AJ_h \cos\left(\frac{2\pi}{\lambda}L\right) + \sum_{k=1}^{n} AG_k J_t^2 J_h^{k-1} J_f^k \cos\left(\frac{2\pi}{\lambda}(L+2kr)\right)\right]^2 \qquad (2)$$

where A is amplitude of laser beam, λ is wavelength of Ne-Ne laser (633nm), J_h, J_t are reflectance and transmission factor of half mirror, J_f is reflectance of mirror on the sample, G_k is extinction parameter of multiple reflection which may represent the slightly inclined effect of the two mirrors, L is a characteristic length which determines the phase of incident laser beam at the surface of the half mirror, r is optical path length between the two mirrors. The *ac* component of light intensity (I_{ac}) was calculated from the change

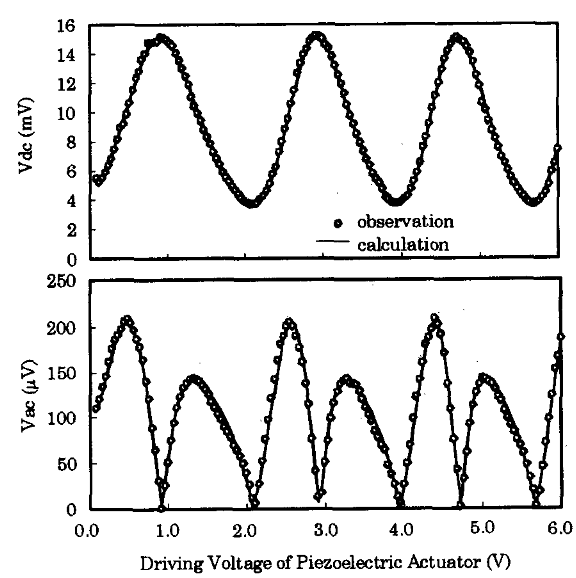

Fig.2 Changes in V_{dc} and V_{ac} with driving voltage of piezoelectric actuator measured at the *ac* field of 1V/mm, 6kHz and those calculated from eq.(2).

in I_{dc} according to the change in optical path length from $r_1=r+d_{31}El$ to $r_2=r-d_{31}El$, where r is an initial optical path length, d_{31} is piezoelectric constant, E is electric field and l is a length of sample. It was assumed that V_{dc} and V_{ac} were proportional to I_{dc} and I_{ac}, respectively. Parameters in eq.(2) including piezoelectric constant (d_{31}) were determined to fit the calculated results to the observed results by a least squares method.

The calculated V_{dc} and V_{ac} were shown in Fig.2 with the observed results. It is seen that the calculation well explains the observed results, indicating that the performance of the interferometer constructed in this study was consistent with the theoretical expression in eq.(2). The difference in the peak height observed in V_{ac} was attributed to the effect of multiple reflections between the two mirrors.

Figure 3 shows V_{ac} curves measured at the *ac* fields of 0.01V/mm(A) and 0.1V/mm(B). The displacements of the sample surface at 0.01V/mm and 0.1V/mm were about 0.01nm and 0.1nm, respectively. The V_{ac} signal was clear and periodic when the displacement was above 0.1nm but the signal began to scatter below this value. From the specification of instruments, theoretical accuracy was estimated to be less than 10^{-3} nm but in fact the accuracy was decreased about two orders of magnitude by some noises and instability of the system.

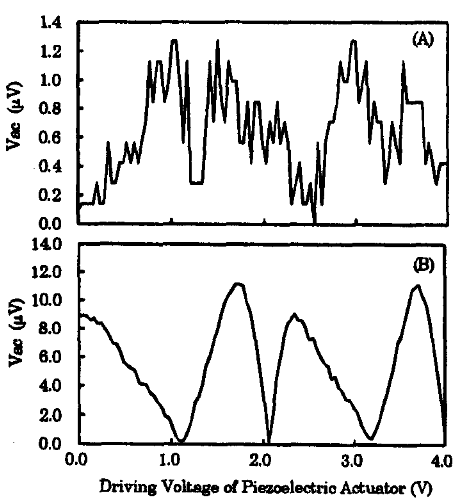

Fig.3 Changes in V_{ac} measured at the field of 0.01V/mm (A) and 0.1V/m (B).

3.2 Admittance fitting in resonance technique

The equation for the admittance of a bar resonator is represented by

$$Y = \frac{i\omega lW}{t}\left(\varepsilon^T_{33} - \frac{d^2_{31}}{s^E_{11}}\right) + \frac{i2Wd^2_{31}}{\left(\rho s^E_{11}\right)^{1/2} s^E_{11} t}\tan\frac{1}{2}\omega l\left(\rho s^E_{11}\right)^{1/2} \quad (3)$$

where Y is admittance, ω is angular frequency, W is width, l is length, t is thickness, ρ is density, ε is dielectric constant, d is piezoelectric constant, and s is elastic compliance of specimen. Complex nature of d, s, ε constants is introduced as follows,

$$d_{31}=d'_{31}-id''_{31}\,,\quad s^E_{11}=s'^E_{11}-is''^E_{11}\,,\quad \varepsilon^T_{33}=\varepsilon'^T_{33}-i\varepsilon''^T_{33} \quad (4)$$

Each parameter in eq.(4) was determined by Simplex calculation method[8] which is a kind of a non-linear least squares method. Similar efforts using iterative calculations have been done to determine the complex constants in eq.(3) by Smits[9], Alberta et al.[10] and Tsurumi et al.[11]

Figure 4 shows the frequency dependence of complex admittance observed for the PZT ceramic plate and calculated from eq.(3). We have achieved a very good agreement between observed and calculated results. This agreement was not obtained when the piezoelectric constant was treated as a real number. In Table 1 the physical constants determined in this process were compared with those determined by an ordinal resonance technique. A fairly large difference was observed in dielectric constant, because in ordinary method dielectric constant is measured at much lower frequency (1kHz) than the resonant frequency, giving rise to a considerable error due to frequency dependence of dielectric constant.

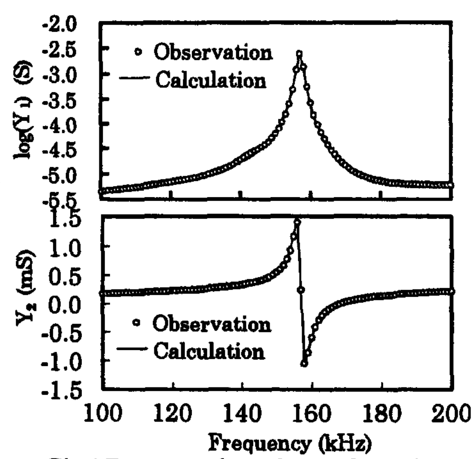

Fig.4 Frequency dependence of complex admittance observed and calculated.

Table 1 Physical constants determined by each method

Physical constants	Resonance technique	LSF* method	Inter-ferometer
$-d'_{31}$ (pC/N)	184	173	187
$-d''_{31}$ (pC/N)	-------	4.5	6.0
$\varepsilon'^T_{33}/\varepsilon_0$	1646	1504	---------
$\varepsilon''^T_{33}/\varepsilon_0$	31.1	36.8	---------
tan δ	0.0189	0.0245	---------
s'^E_{11} (pm²/N)	14.0	13.7	---------
s''^E_{11} (pm²/N)	0.194	0.178	---------
Q_m	72.2	77.0	---------

* Least squares fitting

3.2 Complex piezoelectric constant of PZT ceramics

The displacement of the sample surface was shown in Fig.5 as a function of *ac* filed on the sample. The frequency of the field was fixed at 6kHz. A strait line in the figure indicates that the displacement is caused by a piezoelectric effect. The complex piezoelectric constant measured at 1V/mm and 6kHz was listed in Table 1. The obtained values well agreed with those determined by resonance techniques.

Figure 6 (A,B) shows frequency dependence of complex piezoelectric constant of PZT ceramics. The interferometer constructed here was capable of measuring the piezoelectric constant as a function of frequency up to 100kHz. It should be noted that the piezoelectric constant in this figure is an apparent value rather than the intrinsic physical constant because the frequency range involves a resonant frequency at 77kHz. This

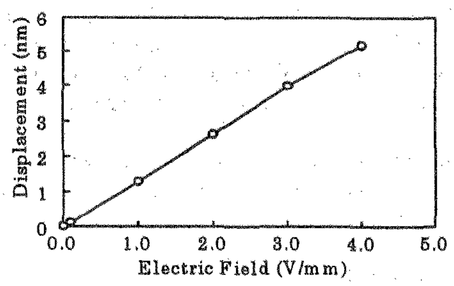

Fig.5 Displacement of sample surface as a function of electric field.

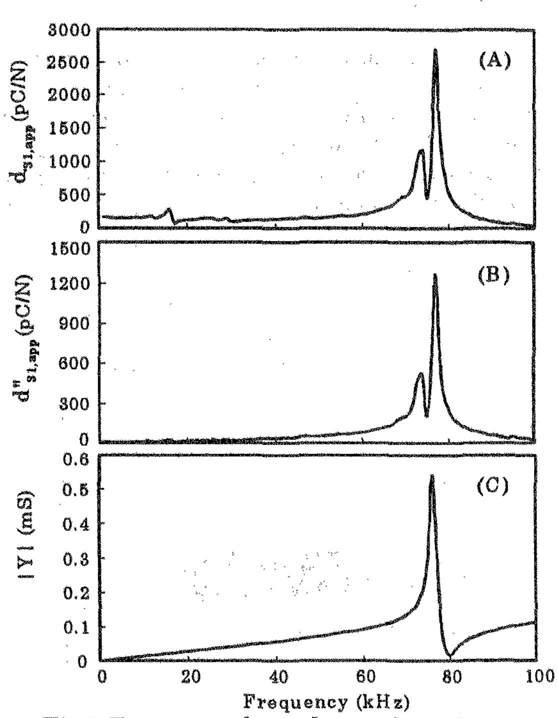

Fig.6 Frequency dependence of complex piezoelectric constant and admittance.
(A) real part of piezoelectric constant,
(B) imaginary part of piezoelectric constant
(C) admittance of the sample on the interferometer

resonant frequency is half of the frequency shown in Fig.4 because one end of the bar resonator was fixed, which reduces the specific frequency of fundamental vibration to half. This is evident form the admittance curve of the sample on the interferometer as shown in Fig.6(C).

The real part of piezoelectric constant d' was almost independent of frequency at low frequencies but it steeply increased about 20 times around the resonant frequency. Similarly, the imaginary part d'' was small at low frequencies but it steeply increased around the resonant frequency to show two peaks. These behaviors seem to be important for the design of piezoelectric devices driven at resonant frequencies like piezoelectric transformers or piezoelectric motors.

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