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Multi-physics field models of photostrictive unimorphs and heterogeneous bimorphs subjected to light illumination and mechanical loading

Quantian Luo, Liyong Tong *

School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, NSW 2006, Australia

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ABSTRACT

This paper presents novel constituent equations for photostrictive unimorphs and heterogeneous bimorphs by considering multi-physics fields. Although the formulation is conducted using the lead lanthanum zirconate titanate ceramics (PLZT) polarized in 0-3 direction subjected to light illumination and mechanical loading, the results may be extended to other photostrictive materials or degenerated to piezoelectric ceramics. In the present formulation, photo-induced electrical, thermal and mechanical fields in PLZT ceramics are studied first, and then one-dimensional opto-thermo-piezoelectric equations for 0-3 polarized PLZT and other photostrictive materials are discussed. On the basis of the photo-induced multi-physics equations, 0-3 polarized PLZT unimorphs and bimorphs are investigated and the associated constituent equations are derived. The numerical results calculated using the present formulations are then compared with those available in the literatures to validate the derived novel constituent equations.

1. Introduction

A cantilever in a form of piezoelectric (PZT) bimorphs has been widely used in micro-electro/opto-mechanical system (MEMS/MOMS) and intelligent systems. When it is used as an actuator, large deflection output is achievable. A PZT cantilever subjected to mechanical loading or structural vibration can be used as a sensor or an energy harvesting device (Sodano et al., 2003; Ajitsaria et al., 2007). Cantilever transducers have also been used as a platform of sensors in chemical and biological systems (Wachter et al., 1996; Lavrik et al., 2004).

Smits et al. (1991) reviewed the development of PZT bimorphs from 1930s, and then derived the constituent equations for PZT symmetric bimorphs (Smits et al., 1991) and heterogeneous bimorphs (Smits and Choi, 1991) under electrical and mechanical loadings. These formulations establish the relations between input and output responses in a PZT cantilever, and have been widely used in MEMS. PZT bimorph has received an increasing attention in the past two decades (DeVoe and Pisano, 1997; Wang and Cross, 1998; Brissaud et al., 2003; Fernandes and Pouget, 2003; Wang, 2004; Wood et al., 2005; Li et al., 2009) due to its superior electrical and mechanical performance, simple geometry and easy manufacturing.

Recently, a cantilever driven by light illumination attracted a considerable interest (Li et al., 2003; Corbett and Warner, 2007; Steinbock and Helm, 2008; Luo and Tong, 2009a) as a photocantilever can be used to potentially realize remote and wireless actuation and control. Because light intensity decreases with light penetration depth in transparent materials, the photo-induced strain in photostrictive materials can attenuate in a similar way. Variation of the photo-induced strain in through-thickness direction creates direct bending of a photocantilever (Corbett and Warner, 2007; Luo and Tong, 2009a) and thus photostrictive materials can be fabricated as a unimorph with simple geometry.

When PLZT ceramic is illuminated by ultraviolet light with wavelength of around 365 nm, an electrical field is generated along spontaneous polarization duo to the photovoltaic effect and mechanical strain is induced owing to the converse piezoelectric effect. A PLZT strip can be polarized either in 0-1 direction (along length) and 0-3 direction (along thickness direction), as shown in Fig. 1(a) and (b).

The 0-1 polarized PLZT ceramics have been investigated by a number of researchers (Uchino et al., 1985; Fukuda et al., 1995; Poosanaas-Burke et al., 1998; Shih et al., 2004). When the 0-1 polarized PLZT ceramic is illuminated by light, the induced electrical field E_1 can cause a PLZT strip to deform in extension or contraction. Two PLZT strips can be bonded to form a PLZT bimorph (Brody, 1983; Fukuda et al., 1995). Structural responses of this type of PLZT can be determined using the method similar to that of PZT bimorphs.

The 0-3 polarized PLZT ceramic with one transparent electrode appears more attractive due to low poling voltage and easy fabrication (Ichiki et al., 2005; Qin et al., 2007). When light illuminates on the transparent electrode of a 0-3 polarized PLZT strip, the light intensity, induced electrical field and the photo-strain decrease

* Corresponding author. Tel.: +61 2 93516949; fax: +61 2 93514841.
E-mail address: ltong@aeromech.usyd.edu.au (L. Tong).

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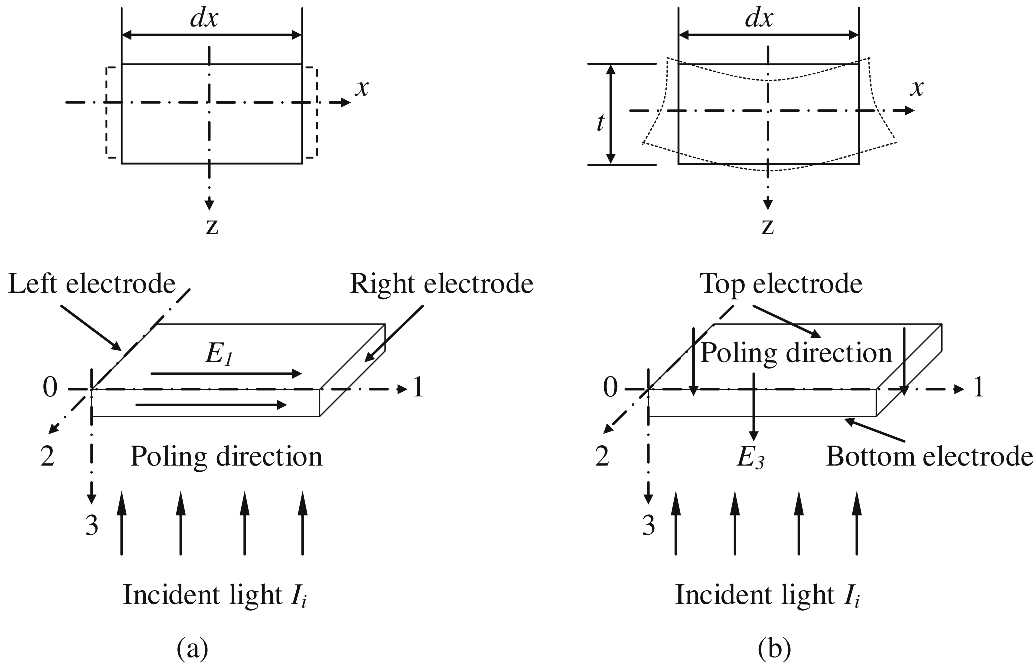

Fig. 1. A PLZT wafer: (a) electrically poled in 0-1 direction and (b) electrically poled in 0-3 direction.

with light penetration depth (Luo and Tong, 2009b). The photo-strain variation across the thickness enables bending directly.

Brody (1983) studied 0-1 polarized PLZT bimorphs, and Wachter et al. (1996) discussed remote optical detection using semiconductor bimorphs. In the semiconductor unimorph investigated by Steinbock and Helm (2008), only the photo-strain is induced in the surface layer. In studying performance of polymeric unimorphs, Corbett and Warner (2007) derived formulas for describing light intensity and photo-strain variations with light penetration depth. Luo and Tong (2009a) discussed the non-linear deformations and optimization for photocantilevers. In these investigations, only the photo-induced actuation was considered.

This paper aims to consider the coupling of electrical, thermal and mechanical fields in PLZT ceramics illuminated by light and to derive constituent equations for 0-3 polarized PLZT unimorphs and bimorphs subjected to light illumination and mechanical loading. The photo-induced multi-physics fields in the 0-3 polarized PLZT materials are generally coupled and non-linearly dependent on incident light intensity. This type of PLZT ceramics can be readily fabricated into a unimorph and bimorph used as an actuator or sensor. A new set of constituent equations with coupled multi-physics fields is presented in a closed form for a 0-3 polarized PLZT unimorph and bimorph. Numerical results are then presented to validate the present formulations and to demonstrate actuating and sensing performance of a 0-3 polarized PLZT unimorph and bimorph.

2. Photo-induced electrical, thermal and mechanical fields in a 0-3 PLZT unimorph

Owing to photovoltaic, pyroelectric and piezoelectric effects, electro-thermo-mechanical fields can be generated in PLZT ceramic when it is subjected to light illumination. Due to the photo-induced strain attenuation with light penetration depth, the 0-3 polarized PLZT ceramic can be fabricated as a unimorph or deposited on a substrate to form a heterogeneous bimorph.

The phenomenon of the photo-induced strain variation across thickness in PLZT is similar to that of other photostrictive materials such as semiconductor and polymer to some extent (Luo and Tong, 2009a), and thus the obtained formulations in the following sections are relevant and may be used for these materials when they are fabricated into actuators. The uniform electrical field and strain along thickness direction may also be deemed as a special case of the present formulations. Therefore, the derived formulations can degenerate to those for 0-1 polarized PLZT and PZT ceramics.

2.1. The photo-induced electrical field in 0-3 polarized PLZT ceramic

When a 0-3 polarized PLZT wafer is illuminated with ultraviolet light, it absorbs photons and generates free charge carriers (Piprek, 2003). The charge carrier current satisfies continuity equation and the electrical conductivity is equal to the sum of dark and photo conductivities (Fridkin, 1979; Poosanaas-Burke et al., 1998). As the photocurrent density is equal to conductivity multiplied by field strength (Saslow, 2002), the photo-induced electrical field strength E_3 at light penetration depth z_d (measured from the light irradiating surface) of a 0-3 polarized PLZT wafer is given by (Luo and Tong, 2009b):

$$E_3 = \frac{k_3\alpha\alpha_s I_i e^{-\alpha z_d}}{\kappa_d + \kappa_{ph} I_o e^{-\alpha z_d}} = \frac{k_3\alpha I_o e^{-\alpha z_d}}{\kappa_d + \kappa_{ph} I_o e^{-\alpha z_d}} = \left(\frac{k_3\alpha I_o}{\kappa_d}\right)\frac{e^{-\alpha z_d}}{1+Ke^{-\alpha z_d}} = E_{3o} f(z_d) \tag{1}$$

where

$$I_o = \alpha_s I_i; \quad f(z_d) = \frac{e^{-\alpha z_d}}{1+Ke^{-\alpha z_d}}; \quad K = \frac{\kappa_{ph} I_o}{\kappa_d};$$
$$E_{3o} = \left(\frac{k_3\alpha}{\kappa_d}\right) I_o = \left(\frac{k_3\alpha}{\kappa_{ph}}\right) K \tag{2}$$

In Eqs. (1) and (2), I_i is the incident light intensity; α_s is the surface transmittance and I_o is light intensity after surface absorption; k_3 is the photocurrent density coefficient; κ_d and κ_{ph} are dark and photo conductivities, respectively; α is the light absorption coefficient. It worth noting that light intensity decreasing exponentially with light penetration depth (Beer's law) is used in Eq. (1).

The photovoltaic electrical potential difference in an infinitesimal layer with thickness of (dz_d) at z_d is given by the gradient equation of photovoltaic potential and strength. The photovoltaic