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Light-induced deformation in a liquid crystal elastomer photonic crystal

D. Krishnan, H.T. Johnson *

Department of Mechanical Science and Engineering, University of Illinois, Urbana–Champaign, 1206 W. Green Street, Urbana, IL 61801, USA

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ABSTRACT

Elastomer materials can undergo large, reversible elastic deformation, and offer novel possibilities for coupled optomechanical behavior when light itself is used to induce that deformation. This phenomenology is especially interesting to consider when photonic bandstructure effects and mechanical instabilities are present over the same length scales. Here we investigate a novel, coupled optomechanical material behavior whereby complex deformation, with the potential to occur cyclically, occurs in a soft photonic crystal structure due to a mechanical instability, as a result of constant, uniform illumination by normally incident light. We suppose that the base material for the structure is a material that responds to light by undergoing a microstructural change. Such a behavior is observed, for example, in a liquid crystal elastomer containing azobenzene moieties attached to the liquid crystal main-chains (Finkelmann et al., 2001) transformational strain generated by the effect of localized light energy on the isomerization of the azobenzene moieties can be calculated from an order-parameter based model (Hogan et al., 2002). Under uniform exposure to constant illumination, the interaction between the light, the material, and the deforming structure lead to a complex, reversible deformation sequence. We analyze the electromagnetic energy distribution inside this photonic crystal structure by solving Maxwells equations for the electromagnetic problem of light transmittance using finite element analysis. First, upon contraction of the structure due to isomerization in the uniformly illuminated material, the photonic bandstructure shifts, thereby significantly reducing the average illumination of material within the structure. The locally reduced illumination allows for a relaxation of the strain in some parts of the structure, due to the reversible isomerization at room temperature. Then, as a result of this relaxation, the structure is subjected to uniaxial stress, leading to a mechanical instability that triggers a geometrical pattern transformation. This in turn produces a second contractile deformation, as a result of the buckling-like deformation in the structure. Finally, the highly nonuniform local strain field that results generates a dramatic change in the photonic bandstructure of the system, leading to a new localization of the light that tends to reverse the effect of pattern transformation. This completes the transformation sequence, demonstrating the potential for cyclical deformation induced simply by uniform illumination. The coupled optomechanical material/structure behavior observed here could lead to applications in optically sensors, energy harvesters, or other reversible optomechanically active structures.

* Corresponding author. Tel.: +1 217 265 5468; fax: +1 217 244 6534.
E-mail address: htj@illinois.edu (H.T. Johnson).

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1. Introduction

Structures consisting of soft materials such as elastomers and hydrogels can be made to undergo large, reversible deformation due to the effects of various external stimuli, and they have use in a variety of applications including bio-MEMS devices, electro-active polymer actuators, and chemical or optical sensors. Numerous recent studies have explored the mechanics of soft materials in periodic structures that undergo buckling-like instabilities leading to symmetry transformations. Mullin et al. (2007) showed using finite element analysis, for example, that periodic two-dimensional elastomeric structures can be forced into symmetry-breaking buckling-like deformation patterns. This work was followed by several studies by Bertoldi and Boyce (2008) and Bertoldi et al. (2008) on the compressive deformation response of such structures. Lee et al. (2006) and later Zhang et al. (2009) reported analogous 3D and 2D pattern transformations under large, reversible deformation conditions in hydrogel or elastomer materials.

Most of the recent work on large deformation of soft materials in periodic structures has focused on the effects of mechanical loads applied directly to the boundaries, or on chemical or thermal swelling of the base material (Zhu et al., 2012). Recent progress in theoretical and experimental studies of dielectric elastomers has demonstrated the possibility of electrostatic actuation of periodic structures with instabilities (Li et al., 2013; Bertoldi and Gei, 2011; Zhao and Suo, 2007; Suo, 2010; Li and Landis, 2012). The primary objective of these studies has been to accurately predict the deformation through appropriate constitutive modeling and robust finite deformation computational algorithms. In a few other recent studies, however, the focus has been to predict the effects of symmetry-breaking deformation modes on acoustic (phononic) or optical (photonic) wave propagation through the material (Robillard et al., 2009; Krishnan and Johnson, 2009). Our own study showed that photonic bandstructure can be significantly modified by buckling-like deformation modes.

In the present work we consider a novel extension to this concept that introduces a new aspect to the mechanics of periodic soft structures: that of optical actuation of the buckling-like deformation modes, in the presence of photonic bandgaps. Such a configuration presents the possibility of a complex deformation behavior mediated by both structural characteristics (e.g. manufactured periodicity) and material characteristics (e.g. light-induced strain), in a regime with two-way optical–mechanical coupling. The potential applications of such soft structures include sensors, actuators, and even energy harvesters. Building on the recent work on deformation modes of soft structures, the challenges in designing such new configurations lie in appropriately selecting and accurately modeling the material, and in coupling the material and structural models.

One particularly interesting soft material to consider for use in large-deformation applications is a liquid crystal elastomer (LCE) that can be functionalized with azobenzene, a widely used compound that photoisomerizes from a *trans*- to *cis*-configuration under optical irradiation, producing macroscopic strains and deformation (Blair et al., 1980). This forward reaction from a stable configuration can be reversed either optically or thermally, as the *cis*-configuration is considered metastable. The behavior of liquid crystal polymers with azobenzene side-chain moieties depends on several factors including the light intensity incident on the material (Wu et al., 1998), the dynamics of the alignment process of the azobenzene moieties (Wu et al., 1999a) and the azobenzene chemistry itself (Wu et al., 1999b). Moreover the material is sensitive to the polarization of the incident light as observed by Harvey and Terentjev (2007) in their study on nematic elastomers. It is also known that the direction of contraction of a sheet of an azobenzene liquid crystal elastomer is parallel to the polarization of incident light (Yu et al., 2003), which may be useful in numerous applications such as actuators (van Oosten et al., 2008; White et al., 2008, 2009), artificial muscles and shape memory materials (Ikeda et al., 2007; Barrett et al., 2007), heterojunctions (Hwang et al., 2005), diffraction gratings (Bai and Zhao, 2002) and as optically stimulated mechanical devices (Koerner et al., 2008; Tajbakhsh and Terentjev, 2001; Dunn and Maute, 2009).

Finkelmann et al. (2001) report on the first LCE that displays a large macroscopic contraction of 22% due to the incident light. To predict the compressive strain, they map the optically induced change in the nematic order as an effective shift in the nematic–isotropic transition temperature of the system. The temperature-strain effect is studied to validate the use of order transition theories in the mapping process (Tajbakhsh and Terentjev, 2001). Detailed investigations on the coupling of liquid crystals to the main chain of the elastomer with the orientational behavior indicate that the properties depend on the type of the liquid crystal mesogens and Young's modulus of the elastomer (Krause et al., 2009). The micromechanics and kinetics of liquid crystal elastomers are well understood; the notion of soft elasticity is used to represent orientation change of liquid crystal mesogens due to bulk deformation (Warner and Terentjev, 2003). Speeding up the dynamics of the isomerization process, however, is difficult because of two competing effects that must be tuned with respect to the kinetics of the problem: higher elastic stiffness of the elastomer increases the coupling constant but slows the orientation dynamics, while reducing the material stiffness increases the dynamics but reduces the coupling (Cviklinski et al., 2002).

In the present work we first develop a coupled rigorous model based on large deformation finite element methods (FEM) and analytical models of phase transition in liquid crystalline materials to model the optomechanical response of structures made from an optically sensitive material. Using such a material as a basis for a photonic crystal, which undergoes a mechanical phase transformation at the appropriate level of macroscopic strain, we demonstrate the possibility for a unique and highly sensitive structure that can be made to deform cyclically under constant intensity, uniform incident light. In Section 2 the constitutive model for the LCE material is presented, followed by the simulation method for the optomechanical FE analysis of the photonic crystal in Section 3. Then, through the use of a simple computational example, we discuss the design and analysis of this unique optomechanically coupled structure in Section 4.