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Abstract. We propose and demonstrate a technique for monitoring the recovery deformation of the shape-memory polymers (SMP) using a surface-attached fiber Bragg grating (FBG) as a vector-bending sensor. The proposed sensing scheme could monitor the pure bending deformation for the SMP sample. When the SMP sample undergoes concave or convex bending, the resonance wavelength of the FBG will have red-shift or blue-shift according to the tensile or compressive stress gradient along the FBG. As the results show, the bending sensitivity is around 4.07 nm/cm^{-1}. The experimental results clearly indicate that the deformation of such an SMP sample can be effectively monitored by the attached FBG not just for the bending curvature but also the bending direction. [DOI: 10.1117/1.OE.52.1.014401]

Subject terms: shape memory polymer; fiber Bragg grating; vector-bending sensor.

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1 Introduction

Shape memory polymers (SMP) are stimuli-responsive smart materials which have remarkable shape recovery function on the application of an external stimulus (such as heat, electricity, light, magnetism, moisture, and even a change in PH value).[1] Compared with the conventional resin-based composite materials, SMP could not only be used for structural materials but also for functional materials. Even compared with the shape memory alloys (SMA),[2] SMP have a number of advantages, such as the large recoverable strain, multi-stimulus approaches, low density, programmability, controllability of recovery behavior, and low cost. Based on these properties, they have been widely applied in biomaterials, actuators, sensors, and textiles.[3] In smart structures operation in space applications, the SMP are expected to further promote the development of active monitoring and controlling of the structures, such as morphing wing aircrafts. To meet the requirements for different applications, the current research works have investigated various aspects of SMP, including the fundamental mechanism, fabrication, modeling and characterization, stimulus method, and potential applications across a wide range of fields.[4] However, among them few researches have been carried out on monitoring and controlling the SMP shape recovery deformation process.

As a novel kind of smart materials, understanding the SMP recovery deformation process is important for real applications. In some special applications, the recovery process and the final recovery situation could not be directly observed in vision. If structural deformation of the SMP can be directly or indirectly measured during operation without affecting the recovery property of SMP, structural safety and performance control can be more clearly validated. Some typical shape sensors have been developed by using optical noncontact methods, such as the CCD array measuring system on a curved surface,[5] the laser scanning measurement system,[6] and laser profiling from photographs.[7] However, these methods cannot detect the change inside the structure and are not suited for real-time shape recovery deformation monitoring. Recently, Rapp et al. have investigated the reconstruction method of structural deformation of two dimensional structures by using a displacement-strain-transformation matrix and Bragg grating sensors[8,9] which offer an alternative method to monitor SMP. FBG sensors are optical-fiber-based sensors which show excellent performance in sensing temperature, strain, loading, and bending for structural health monitoring.[10] The FBG sensors have many advantages, such as compact in size, robust, chemically inert, nonconductive, immunity to electromagnetic interference (EMI), and the capability for multiplexing.[11] So, FBG sensors may be used to measure the SMP shape recovery deformation process under different conditions. In this paper, we report, for the first time to our knowledge, using an FBG as a vector sensor to monitor the deformation process of an SMP sample, showing not just the bending curvature but also the direction.

2 Theory Model

The SMP samples used in our experiment are thermo responsive, whose shape memory effect is triggered by heat. The SMP could be deformed to any desired shape above its glass transition temperature (T_g). This shape can be maintained by a cooling process below the T_g or recovered back to original position by heating it above T_g again. For an epoxy-based polymer to possess shape memory properties, it should show two states: a frozen and reversible phase. The former is responsible for memorizing the original shape and is usually achieved via chemical or physical cross-linking (e.g., chain entanglement and crystallization), and the latter corresponds to shape change under stimulus. Shape memory behavior can be observed in several polymers, including polyurethane-based,[12] styrene-based,[13] and epoxy-based[14] polymers. Among these SMP, the epoxy-based is a high-performance thermosetting polymer with a unique thermo-mechanical property, excellent shape memory effect, and short response time.[15] The SMP sample we used to measure the deformation by an FBG is epoxy-based polymer.

2.1 *Pure Bending Deformation*

In this paper, we mainly focus on the simple bending deformation of the thermo-responsive SMP which could be deformed to any desired shape above its glass transition temperature, cooled and maintained the shape below the glass transition temperature. We consider first the simple deformation and displacement of an SMP beam in pure bending condition, which can be regarded taking place over a finite portion of a span when the bending moment is a constant over that portion. The steps involved during a thermo-mechanical cycle consisting of 1. deformation at T_g, 2. the shape fixing, and 3. recovery, as illustrated in Fig. 1(a). The bending applied to the SMP sample was implemented by rolling it on a cylinder when it was heated above the transition temperature, as shown in Fig. 1(a).

Based on the pure bending assumption, the deformation shape of an SMP beam is shown in Fig. 1(b). Here, we see the cross section of the beam remains perpendicular to the longitudinal axis. From Fig. 1(b), we see the top side beam (B_1B_2) above its neutral axis (dot-dash line O_1O_2) is in compression and the bottom side (A_1A_2) below the neutral axis is in tension. Based on the mechanics of materials theory, the strain ε of the longitude of the beam under the bending can then be determined as:

$$\begin{aligned}\varepsilon_{\text{elongation}} &= \frac{\bar{A_1A_2}-\bar{O_1O_2}}{\bar{O_1O_2}} = \frac{(R+y/2)\Delta\theta - R\Delta\theta}{R\Delta\theta} = \frac{y}{2R} = \frac{yC}{2}\\ \varepsilon_{\text{reduction}} &= \frac{\bar{O_1O_2}-\bar{B_1B_2}}{\bar{O_1O_2}} = \frac{(R-y/2)\Delta\theta - R\Delta\theta}{R\Delta\theta} = \frac{-y}{2R} = \frac{-yC}{2},\end{aligned} \tag{1}$$

where y is the thickness of the SMP sample and R (or C) is the radius (curvature) of bending for the SMP sample. From Eq. (1), it is clearly seen that the stress strain induced by the elongation and the compress strain induced by the reduction of surface of the SMP sample only depend on the thickness and curvature of the sample. The FBG sensor is attached to the surface of the SMP sample and its Bragg resonance will shift with different radius and direction of the bending.

2.2 *Sensing Principle*

The principle of an FBG as a sensor is to monitor the wavelength shift of Bragg resonance under changes of the physical condition (e.g., strain, temperature). The strain response arises due to both the physical elongation of the sensor for corresponding fractional change in grating pitch and the change in fiber index due to photo-elastic effects. The shift in Bragg wavelength $\Delta\lambda_B$ with strain ε_m can be expressed using:[16]

$$\Delta\lambda_B = (1 - p_e)\lambda_B \varepsilon_{m\text{FBG}}, \tag{2}$$

where p_e is the photo-elastic constant of an optical fiber, λ_B is the Bragg wavelength of the FBG, and $\varepsilon_{m\text{FBG}}$ is the strain acted on the FBG.

Actually, the strain acted on the FBG is transferred from the strain that is induced by the elongation and reduction of the SMP sample. When the SMP sample is bent, the FBG endures a stressed-strain or compressed-strain depending on whether it is attached to the outer or inner surface of the SMP sample. However, since the FBG is attached to the SMP sample by epoxy glue, the measured strain on FBG, $\varepsilon_{m\text{FBG}}$, is not the same as the strain, ε, experienced

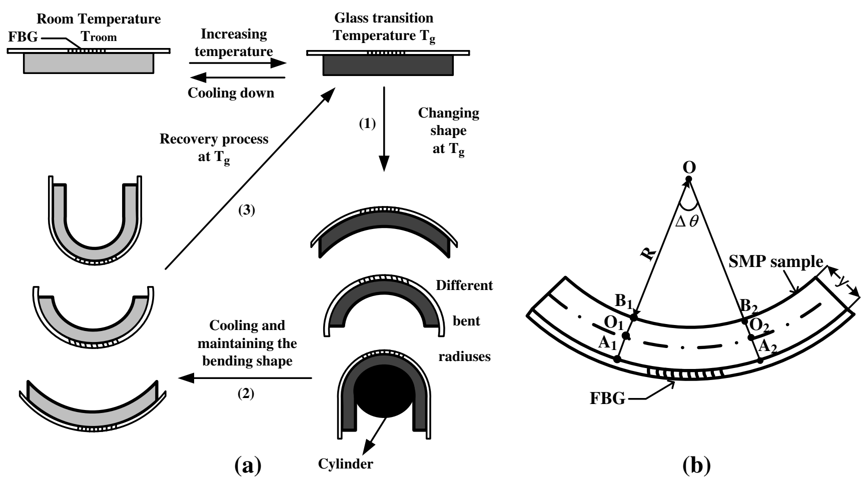

Fig. 1 (a) The schematic diagram of the formation and deformation process of an SMP sample. (b) Illustration of the cross-section of the SMP sample attached to a surface FBG with pure bending deformation.

by the SMP sample. The relation between them may be expressed as:

$$\varepsilon_m = \kappa\varepsilon. \tag{3}$$

The strain transfer coefficient κ is dominated by various parameters, such as geometric parameters of the coating material, adhesive thickness between the FBG and the SMP sample, bond length of the fiber, and the modulus of elasticity of the materials.

Substituting Eqs. (1) and (3) into Eq. (2), the measurable Bragg wavelength shift can be then reduced to a more simple form:

$$\Delta\lambda_B = (1 - p^e)\lambda_B\varepsilon_m = \frac{(1 - p^e)\lambda_B\kappa y}{2R} = \frac{K_\varepsilon\kappa yC}{2}, \tag{4}$$

where $C = 1/R$ is the curvature and $K_\varepsilon = (1 - p^e)\lambda_B$ and κ are approaching constant values. The wavelength shift is directly proportional to the curvature C of the SMP sample, thus the deformation of the sample can be monitored by examining the Bragg resonance of the bonded FBG.

3 Experimental Results and Discussion

The SMP used is a new type of epoxy SMP designed for outer space structure applications. The initial SMP samples of different sizes were synthesized in the authors' laboratory. For the deformation monitoring experiment, a rectangular sample of such an SMP was chosen with dimensions of $100 \times 30 \times 1$ mm^3 and its glass transition temperature is about 120°C. The FBG sensor was UV inscribed in hydrogen loaded standard fiber (SM-28) using a frequency doubled Ar ion laser with the standard phase mask scanning technique. The scanned length was 1 cm. After UV inscription, the FBG was annealed at 150°C for 24 h to stabilize its property. The FBG has a central wavelength of 1545 nm with a reflectivity of 15 dB. The setup to measure the response of the SMP sample is shown in Fig. 2(a).

The stripped and UV-exposed section of the fiber was then recoated using acrylic resin in order to maintain the durability. The FBG was then attached on to the SMP sample surface using UV-curable epoxy which has a high Young's modulus. Before the deformation, the reflection spectrum of the surface-attached FBG was measured by illuminating the device using a broadband light source and an optical spectrum analyzer with a resolution of 0.05 nm. Its spectrum is shown in Fig. 2(b) as label (1). Before heating the sample, the FBG sensor was bonded to the middle position of the flat sample to ensure all the points bear stress evenly, avoiding chirp effect. After the temperature rose to the glass transition temperature, the SMP sample was bent through rolling on the cylinders with different radiuses (2, 3, 4, 4.5, 5, and 6 cm,

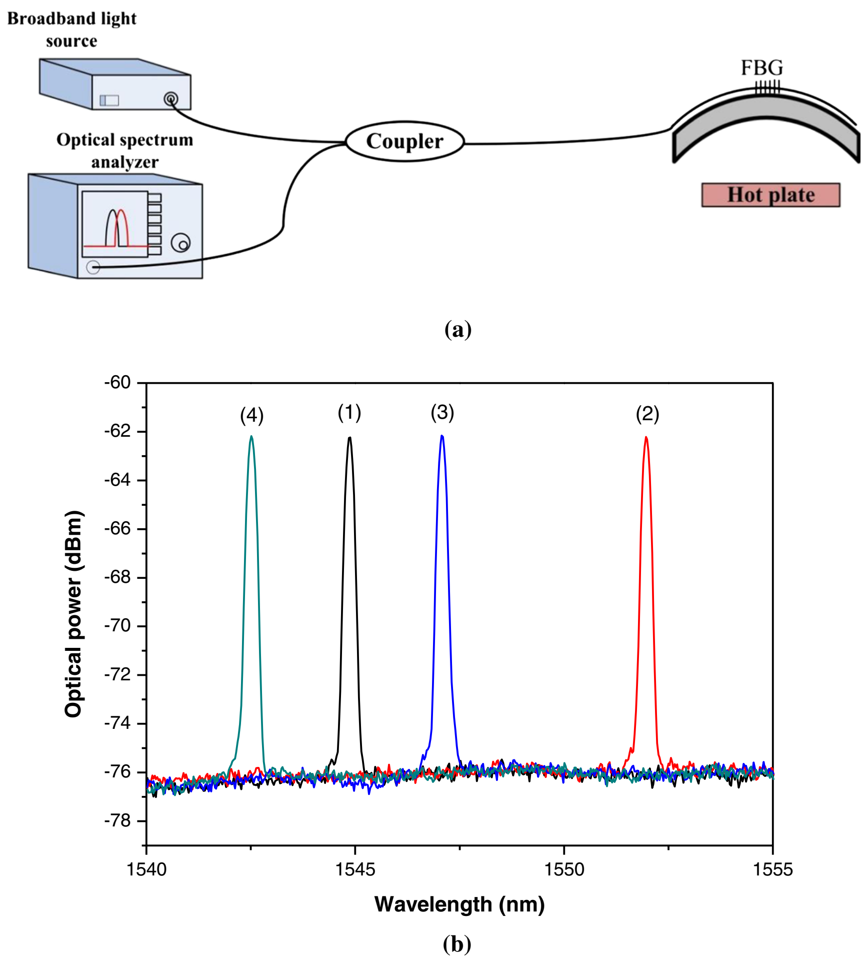

Fig. 2 (a) Experiment setup for measuring SMP-FBG response. (b) The reflection spectra of FBG when the SMP sample in flat shape at (1) room and (2) glass transition temperature, and under (3) convex and (4) concave bending at room temperature.

respectively) corresponding to different levels of shape deformation. The shape of the deformation was fixed when the sample cooled down to room temperature. Figure 2(b) shows the reflection spectra of the FBG bonded to the SMP sample at various conditions. The second and forth peaks in the figure correspond to the SMP sample in flat position at room temperature ~23°C and glass transition temperature at 120°C. It can be seen at 120°C, the Bragg resonance red-shifted ~7 nm. In the experiment, when the SMP sample was heated to its glass transition temperature, we bent the sample in convex (the FBG on the outer surface of the bending) and concave (the FBG on the inner surface of the bending) directions. The Bragg resonance shifted near-symmetrically in the opposite direction. The first and third peaks shown in Fig. 2(b) indicate around 2.5 nm blue- and red-shift for convex and concave bending when the SMP sample was rolled on a cylinder with a 2 cm radius. Clearly the direction of the shift of the Bragg resonance could be used as a marker for the direction of the SMP deformation.

In order to quantitatively analyze the bending-induced deformation on SMP at its glass transition temperature, the FBG responses were monitored for each cases. Figure 3(a) and 3(b) show the reflection spectra and the shifts of the Bragg wavelength, respectively, against the SMP samples bent in concave and convex directions with a bent radius at 2, 3, 4, 4.5, 5, and 6 cm. It can be clearly seen from the figure that the Bragg wavelength has a blue-shift with increasing curvature (deceasing radius) for concave bending, whereas it shows a red-shift for convex bending. If plot the shifts for the concave and convex bending against curvature as shown in Fig. 4, we see the bending-induced Bragg wavelength shifts distributed bilaterally around the original position with a linear fit of gradient at 4.07 $\mathrm{nm/cm^{-1}}$. We should also point out that the experimental data is not a perfect linear behavior as we have described in the theoretical analysis. That is because the curvature of SMP is not accurately controlled in this experiment.

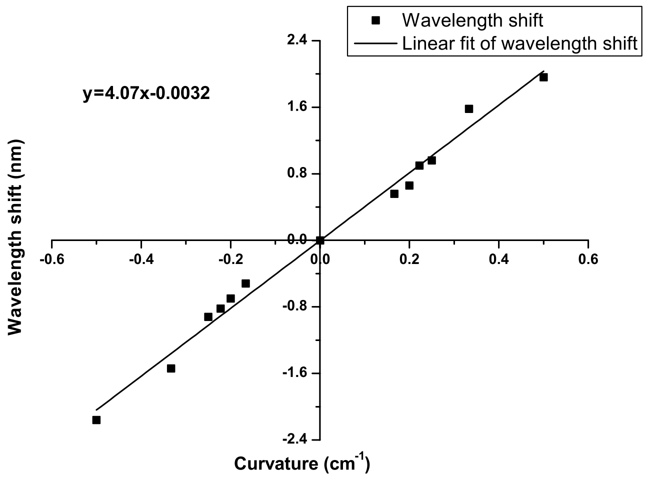

Fig. 4 The relation between Bragg wavelength shift and curvature for the FBG bonded to the SMP sample under concave and convex bending.

From the distinctive experimental results we can see the direction and degree of the deformation of the SMP sample can be measured easily by simply monitoring the spectral response of the FBG bonded (embedded) to the SMP sample.

4 Discussion and Conclusion

We experimentally demonstrated a simple and practical scheme for shape recovery deformation monitoring of an SMP sample using a surface-attached FBG as a vector-bending sensor. We have investigated the SMP sample under various bends with curvature up to 2 $\mathrm{cm^{-1}}$ for both concave and convex directions. For implemented SMP sample, we have demonstrated a bending sensitivity of 4.07 $\mathrm{nm/cm^{-1}}$. The experimental results clearly show that the deformation of such an SMP structure can be effectively monitored by the attached FBG, both for the degree of shape recovery

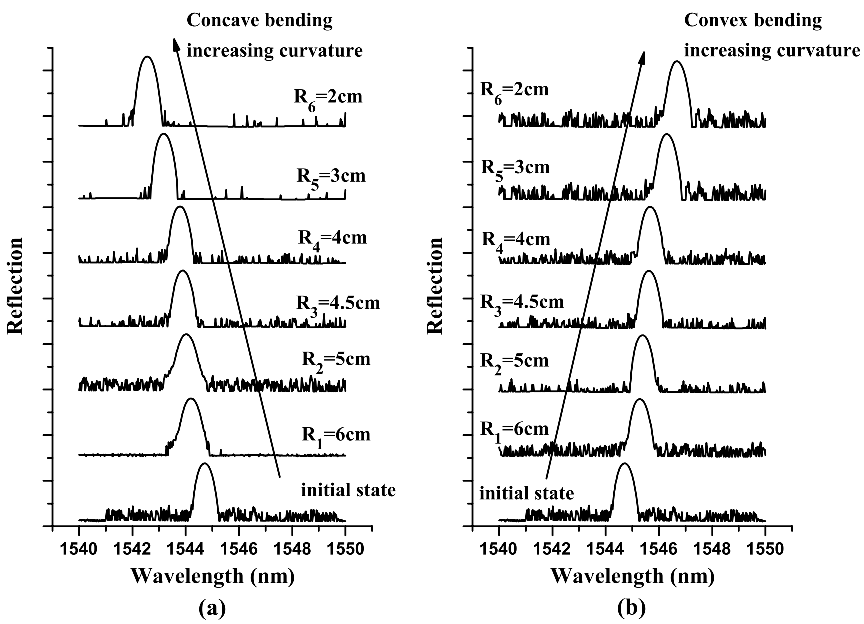

Fig. 3 Reflection spectra of the FBG bonded to the SMP under (a) concave and (b) convex bending with radius at 2, 3, 4, 4.5, 5, and 6 cm.

deformation and the recognition of the direction. Although this very first experiment has only used one FBG for proof-of-concept, it should be possible to embed FBG arrays in two dimensions to measure/monitor arbitrary deformation of SMP structures in static and/or dynamic conditions, which will be the future work for the authors.

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Biographies and photographs of the authors are not available.