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Investigation of fast and sizeable photostriction effect in tellurium thin films using fiber Bragg grating sensors

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ABSTRACT

We report a sizeable photoinduced strain in 90 nm tellurium (Te) thin film, coated on a fiber Bragg grating (FBG) sensor. The Bragg wavelength shift of the FBG sensor is used as the probe, to understand the photostrictive properties of Te thin film under illumination with laser light of visible wavelengths (405, 532 and 633 nm), at varying optical power density (5–161 mW/mm^2), and also during cyclic exposure. An induced elastic strain of the order of 10^{-5} to 10^{-4} has been observed which is found to increase with increasing wavelength of laser illumination. The high (1 pm) resolution of the FBG interrogator used facilitates the accurate detection of the elastic strain induced in Te thin films even at a short exposure time of 0.1 s.

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1. Introduction

The photostriction is an athermal process, in which the illuminated light energy is directly converted into a mechanical motion [1], building up a non-thermal strain in the material. The phenomenon of photostricition finds a wide variety of applications, in the fabrication of photonic switches, plastic motors, Micro-Opto Mechanical systems (MOMs), nano-positioning systems, robotics, etc [2–4]. These applications have led to the discovery of novel photostrictive materials which include ferroelectrics (e.g., SbSI single crystal, PLZT, $BiFeO_3$ single crystal and films) [1,5–7], polymers [8–10], carbon nanotubes (CNT) [1,11,12], and chalcogenides [1,13,14].

The photostriction effect in different materials have different origins depending on the material characteristics [1,12]. For instance, the lattice deformation correlated with a change in the internal electric field is responsible for the photostriction in ferroelectric materials [1]; the transformation from cis (contraction) to trans (expansion) isomeric states due to photoinduced deformation, gives rise to photostriction in organic polymeric materials [1,9,10]; the photoinduced bond bending and stretching cause the photostriction effect in CNTs [1,11,12]. In chalcogenide films, the photomechanical actuation induces a reversible contraction and dilation under light illumination [13,14].

In our previous communication, the direct demonstration using FBG sensors, of the photostriction effect in GeS chalcogenide films, has been reported [15]. The photostriction effect reported in different materials so far, including GeS films, is generally limited either by a slow response (of the order of few seconds) or by a small magnitude (0.001% to 0.01%). Hence, there is an interest in finding a suitable photostricitve material which exhibits fast photoresponse and high elastic strain.

The unique optical, electronic and mechanical properties of tellurium (Te) [16] such as photoinduced alteration of electron transfer [17], photoconductivity, photoelectricity, thermoelectricity and piezoelectricity [18,19] make it a suitable candidate for examining the photostriction effect. Though Te thin films made of nanocrystals, nanotubes, nanoribbons, and nanowires have long been known, photoinduced effects of Te thin films have been barely explored [20,21]. This paper reports the in-situ monitoring of tunable photostriction characteristics of Te thin films upon exposure to visible laser illumination. The wavelength- and time-dependent photoinduced strain responses have been measured at different laser power densities. Efforts have also been made to improve the response speed on photoinduced deformation in Te film and to identify the faster switching regime for photostrictive actuation applications.

A relative photostriction of the order of 10^{-5} to 10^{-4}, with a response speed of <1 s to reach the saturated state, and initial response time of less than 0.1 s have been observed in the present study. The FBG sensors [15,22–24], provide an ideal platform for direct quantitative measurement of photoinduced strain in Te thin films with a strain sensitivity of 1.2 pm/$\mu\varepsilon$. A FBG

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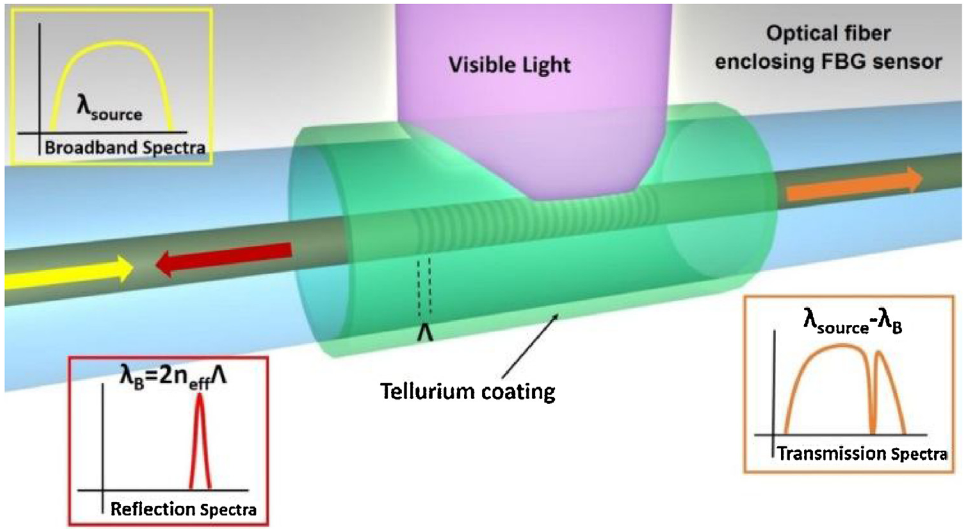

Fig. 1. Schematic of the experimental set-up used for monitoring reversible photoinduced strain in Te thin film, coated on the FBG.

interrogator with 1 pm resolution, used in this investigation, facilitates the detection of the induced elastic strain of small magnitudes of the order of 1 $\mu\varepsilon$. The results obtained demonstrate the suitability of Te thin films for Photo-Mechanical Optical Devices (PODs), photo-nano-actuators, and as a switch in optical communication. It is noteworthy that the photostriction effect in Te thin films in this work is faster with smaller rise and fall times of 0.76 s and 0.85 s for 633 nm excitation at 34 mW/mm^2 power density, in comparison to CNT, polymers and $BiFeO_3$ materials [6,10,11].

2. Experimental methods

In the present work, FBG sensors are fabricated in a photosensitive optical fiber (Fibercore SM1500 (4.2/125)) using the phase mask technique as described elsewhere [11,15]. The grating length is about 3 mm and the baseline Bragg wavelength is around 1566.45 nm. The FBG inscribed optical fibers, are coated on the cladding layer, with 90 nm Te thin films by the thermal evaporation technique; high-purity (99.999%) tellurium powder is placed in a molybdenum boat and thermally evaporated in a vacuum chamber maintained at 10^{-5} Torr pressure. The distance between the evaporation boat and the optical glass fiber substrate has been maintained constant at 17 cm.

The morphological characterization of Te-coated FBG sensor is carried out using Scanning Electron Microscopy (SEM, FESEM-Ultra 55), for measuring the thickness and uniformity of the film. Energy Dispersive X-ray Spectroscopy (EDS) and Raman spectroscopy (HORIBA JobinYvon, LabRAM HR) are used to confirm the compositional information of the coating. The Raman spectra are recorded in the range of 50–400 cm^{-1} at ambient temperature with an excitation wavelength of 532 nm at a low laser power of 1 mW and focal volume of ~1 μm.

Fig. 1 shows the schematic of experimental setup used to measure the photo-response in Te-coated FBG sensors. When a broadband light (1510–1590 nm) is passed through the core of the Te-coated FBG sensor, a particular wavelength (λ_B) which satisfies Bragg's condition is reflected back from the gratings [23,24], which is given by $\lambda_B = 2n_{eff}\Lambda$; here n_{eff} is the effective refractive index of the FBG and Λ, the grating period. The photoexcitation with visible pump laser and subsequent photo-striction of the Te film coated over the cladding layer of the FBG modifies the Λ and creates a shift in the Bragg wavelength ($\Delta\lambda_B$); this shift in λ_B is used to monitor the photostriction in the Te film.

The choice of wavelength for photoexcitation is based on the above–band gap energy. The laser light of 405 (20–95 mW), 532 (3–20 mW) and 633 (20 mW) nm center wavelengths values and a spot size of 3 mm are used for excitation. All the light excitation experiments have been carried out at room temperature under ambient conditions and by directing the light beam normal to the axis of Te-coated FBG sensor. The surface of the Te-coated FBG sample (0.589 mm^2) had been covered by light uniformly and photostriction has been measured. Neutral density filters have been used to change the power of the incident light. An uncoated bare FBG is also exposed to same visible laser, using the same conditions under which the Te-coated FBG sensor is exposed to estimate the temperature induced shift in Bragg wavelength ($\Delta\lambda_{Bare}$). The shifts in the Bragg wavelength of both coated and uncoated FBGs are recorded using the FBG interrogator (Micron optics, SM130), while illuminating them with visible light.

3. Results and discussion

Fig. 2a shows the SEM image of the Te-coated FBG sensor in the cross-sectional view. It is found that the coated Te film have a continuous and smooth distribution on the cladding of the optical fiber. Fig. 2b shows the zoomed SEM image of the red square area in Fig. 2a. From Fig. 2b, the film uniformity is confirmed and its thickness is determined to be 90 nm. The Raman spectrum of a Te film deposited on the optical fiber, with a thickness of 90 nm is shown in Fig. 2c. The spectrum shows peaks at 122, 142, and 274 cm^{-1} which correspond to elemental Te [25]. The EDS analysis (Inset of Fig. 2c) reveals that Te peaks exist in the sample apart from the peaks of Si and O owing to the substrate (SiO_2 cladding of the optical fiber).

3.1. 405nm light illumination

The Te-coated FBG sensor is exposed to 405 nm light with different power density (34–161 mW/mm^2) and during the illumination process, the Bragg wavelength shift ($\Delta\lambda_B$) has been recorded and plotted as shown in Fig. 3a. An increase in $\Delta\lambda_B$ with an increase in 405 nm light power has been observed, which corresponds to an increase in strain (ε) in Te film given by $\Delta\lambda_B/\lambda_B$= (1-$P_{eff}$)$\varepsilon$ $\Delta\lambda_B/\lambda_B = (1 - P_{eff})\,\varepsilon$; here, P_{eff} is the effective strain-optic coefficient and λ_B, the baseline Bragg wavelength of the Te-coated FBG sensor. A maximum shift of 128($\pm$5) pm is observed at a light power density of 161 mW/mm^2. The highest rise of <1.5 °C (~$\Delta\lambda_{Bare}$ = 16 p.m.) has been seen in bare FBG sensor under

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