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Scotch-Tape and Graphene-Oxide Photomobile Polymer Film

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Abstract: In this work, we report on the fabrication and photonic activation of a novel kind of photomobile polymer (PMP) film based mainly on a double layered asymmetric configuration. The PMP is cheap and extremely easy to make. It is made of PVC/isoprene tape with a layer of graphene-oxide (GO) attached. Under illumination at different intensities, and with coherent and incoherent light sources, the bending of the PMP film changes considerably. In particular, we noticed a more efficient bending effect when the film is directly exposed to high light intensities or to NIR radiation in the case of incoherent light sources. For the exposure times used in our experiments, the process is completely reversible when the light source is switched off. Additionally, if we paint the side of the PVC tape exposed to light black, the film is not able to return to its starting position and the bending results are permanent. This suggests that the presence of the GO-layer is responsible for the restoration of the position of the PMP film.

Keywords: photomobile polymer films; bilayered films; graphene-oxide; metasurfaces

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1. Introduction

Nowadays, composite materials are used in many application fields spanning from optical-/photonic-materials, devices, and holographic sensors [1–16]. Materials responding to light-/photonic-stimuli are a novel emergent class of compounds that include azobenzene-based liquid crystal photomobile polymer films (azo-PMP) [17–27]. However, the most used and notable azo-PMPs are limited in their use and commercial diffusion due to two main factors: their cost and the dependence of the reversibility of their motion on two wavelengths. Regarding the first point, it is known that the synthesis of the most notable and commonly used azo-PMP [17] requires many reaction steps and has high fabrication costs [20]. Furthemore, the motion of azo-PMP is induced in one direction by one wavelength (e.g., UV), while its reverse requires a different wavelength (e.g., Vis). However, the high-frequency oscillation of azo-PMPs under visible wavelength irradiation is also reported in the literature [28,29]. At the present time, scientific and technological research is moving towards the optimization of the optical and mechanical characteristics of the PMPs. In particular, one of the main topics concerns the study of PMPs, the restoration of which is autonomously operated when the pumping energy source is switched off. These kinds of PMPs are usually based on double layered asymmetric configurations [24,27,29,30]. Very cheap and efficient bilayers are based, e.g., on single wall carbon nanotubes (SWCNTs) and polycarbonate (PC), or on reduced graphene-oxide carbon nanotubes (GRO-CNTs) and polydimethyl siloxane (PDMS). The results are very interesting and include the continuous motion of the PMP film under a fixed source of energy [29]. In this context, we report on a novel PMP film (alphred-1-PMP) based on the coupling between an electrically insulating

PVC Scotch tape and a graphene-oxide (GO) substrate. In addition, the light-induced response of the asymmetric film is investigated in the near-UV-/Vis-/NIR-range, with the aim of proposing a platform for cost-effective future applications in opto-electronics, sensors, energy harvesting, and optical metasurfaces [31–33].

2. Materials and Methods

2.1. Materials

Graphene-oxide (aqueous suspension, 4.5 mg/mL) was from NANESA s.r.l.; electrically insulating white Scotch tape with a thickness of 0.15 mm was from BM-group.

2.2. Alphred-1-Pmp Preparation

An aqueous suspension (2 mL) of GO 4.5 mg/mL is poured onto a 2 mm thick glass slide placed on a hot plate at 60 °C ovenight (12 h). After that, a ≈ 7 µm thick layer of GO is obtained and it is peeled off using the Scotch tape. At this stage, a 7 × 5 mm^2 GO film is attached to a 20 × 5 mm^2 PVC film, and it is ready to be used.

2.3. Experimental Set-Up

Two incoherent lamps are used to illuminate the alphred-1-PMP film, while a camera connected to an image acquisition system (IMAQ) detects each single frame up to a maximum resolution of 100 frames/s. The two lamps emit radiation in the NIR (incandescence traditional bulb) and white range (LED) of wavelengths, respectively; see Figure 1. Each single lamp impinges on the sample area with an intensity of ≈50 mW/cm^2. We also used three CW pumping coherent light sources at 405, 532, and 650 nm, having a power P = 60, 65 and 133 mW, respectively, and impinging on a circular spot area with a radius r of about 2.5 mm.

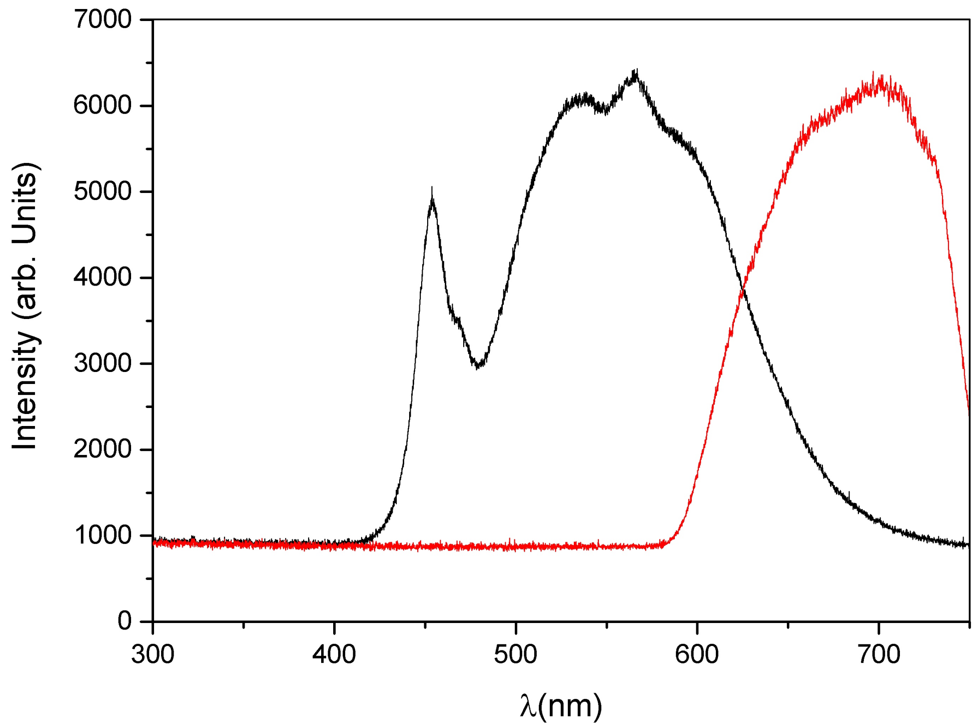

Figure 1. Absorption spectra of the incoherent lamps used in our experiments (black line = white LED lamp; red line = NIR lamp). The intensity impinging on the sample is ≈50 mW/cm^2.

3. Results and Discussion

Light-/photonically or thermally driven actuators that are able to restore their initial position by switching off the energy source at the basis of their motion are an important focus of the scientific research in PMPs [19,30] Recently, we have exploited the properties of multi-acrylate and the oxidated version of 4-amino-phenol-doped-N-Vinyl-Pirrolidinone (ox-4AP-NVP) to obtain an asymmetric PMP that is also suitable for holography [34–36]. This approach opened the door to the use of PMPs in the field of light-induced dynamic holography. Here, we focus on a new photomobile polymer (alphred-1-PMP) that is able to bend under coherent or incoherent irradiation in the VIS-NIR range, and to restore its initial position when the energy source is switched off. As shown in the left part of Figure 2, there are three steps for alphred-1-PMP fabrication: (a) making the 4.5 mg/mL aqueous solution of GO and its deposition on a glass placed on a hot plate at T = 60 °C overnight (12 h); (b) placing the white PVC/isoprene tape in contact with the GO dried film; and (c) peeling off the GO-film using the white Scotch tape, resulting in one layer as the final film configuration. Reported in Figure 2d is a picture of the final alphred-1-PMP film.

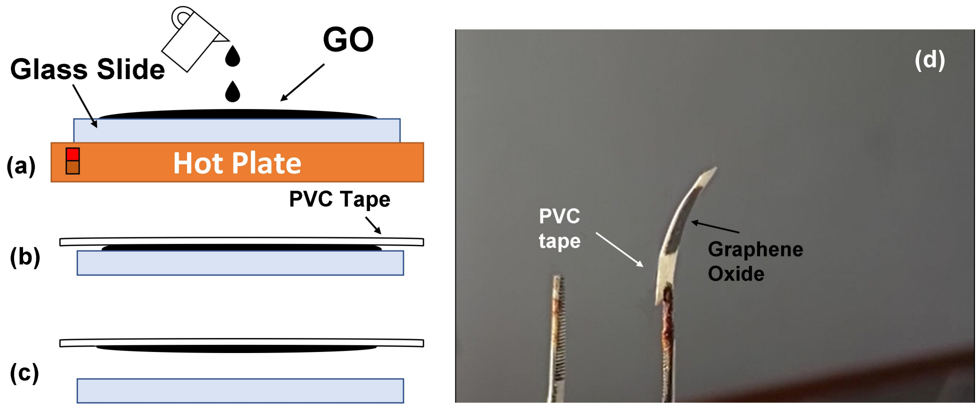

Figure 2. On the left side is a sketch of the preparation process. In (**a**), GO is deposited on a glass substrate placed on a hot plate at 60 °C. In (**b**), the PVC tape is placed in contact with the dried GO film, and in (**c**), the bilayered structure is detached from the substrate. On the right side (**d**) is the final result.

By illuminating the film with an incoherent (red) NIR lamp, a clear bending of the PMP structure is observed, as shown in Figure 3. It is known that GO shows a slowly decreasing absorption from visible to NIR [37]. However, it shows an excellent photothermal conversion efficiency in the NIR region [38]. This property explains the behavior of the PMP film reported in Figure 4. When the light is switched off, the PMP film goes back to its starting position. The entire process is reversible for the few seconds of exposure time used in our experiments. For longer exposure times, the film collapses to a stable irreversible final position. A measurement of the angular displacement as a function of time is shown in Figure 4. As we can see in ≈30 s, the film bends by about 34°, and when the light is switched off, it slowly goes back to its starting position. When we use a LED white lamp to perform the same measurements, alphred-1-PMP bends by only 2.5° in about 70s. This is a clear indication that the effect we observe is mainly a light-induced thermal effect. The first derivative of the measured data is reported in the inset of the same figure: the angular velocity increases up to 6 Degs/s; after that, it goes to zero and almost symmetrically reverts its behavior. A similar type of behavior is observed by using different coherent light sources (the advantage of using a laser is the possibility of controlling the device remotely). The results are reported in Figure 5 when three different lasers impinge on the black GO part of the PMP film. The wavelengths and powers used are specified in the experimental set-up section. The curve relative to the red wavelength in Figure 5 shows a different behavior during the raising time, due to the higher power of the laser used. Since the absorbance of the GO is almost flat in the visible range [37], the change in the slope can be attributed to the light-induced thermal effect in the GO [38]. Under these conditions, the angle of rotation reaches 19° in less than 7 s. The restoration of the film is warranted by the consistency of the GO-layer that absorbs the incident radiation and releases the heating just when the energy source is switched off. It is the presence of the GO-layer that allows the restoration of the initial position of the film when the light is switched off. This fact is evidenced in Figure 6. It reports the angular displacement as a function of time of a white Scotch tape painted black, namely the alphred-1-PMP, where the GO-layer is replaced by a black painted area. We used a black marker to paint the Scotch tape. In this case, the film is illuminated by the same λ = 650 nm red laser used in the previous configuration. It is clear that after switching off the laser, the film is not able to restore its initial position. The maximum rotation angle is ≈20° and remains unaltered in time, making this a very simple system that can be considered as a sort of a light-controlled shape-memory film [39].

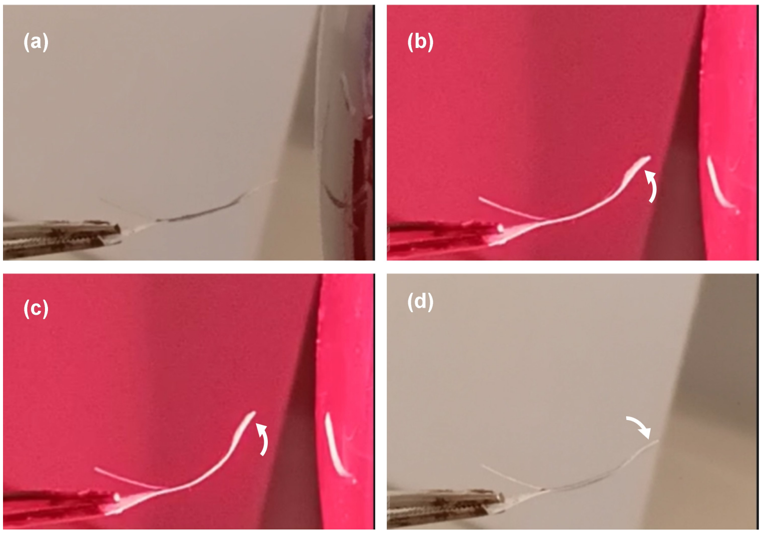

Figure 3. Frames taken at (**a**) 0, (**b**) 5 s, (**c**), 10 s, and (**d**) 180 s during the irradiation with an incoherent NIR red light. Arrows indicate the direction of bending.

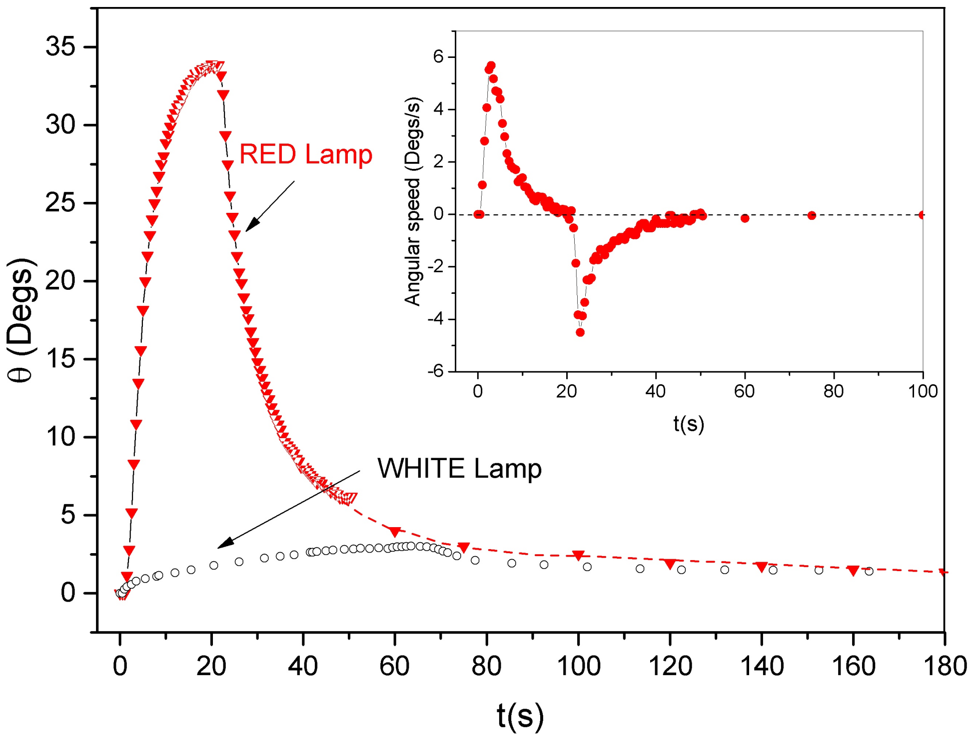

Figure 4. Angular displacement of the film as function of time when incoherent illumination is used. Different sources give completely different results. In the inset is the angular velocity corresponding to the NIR red lamp.

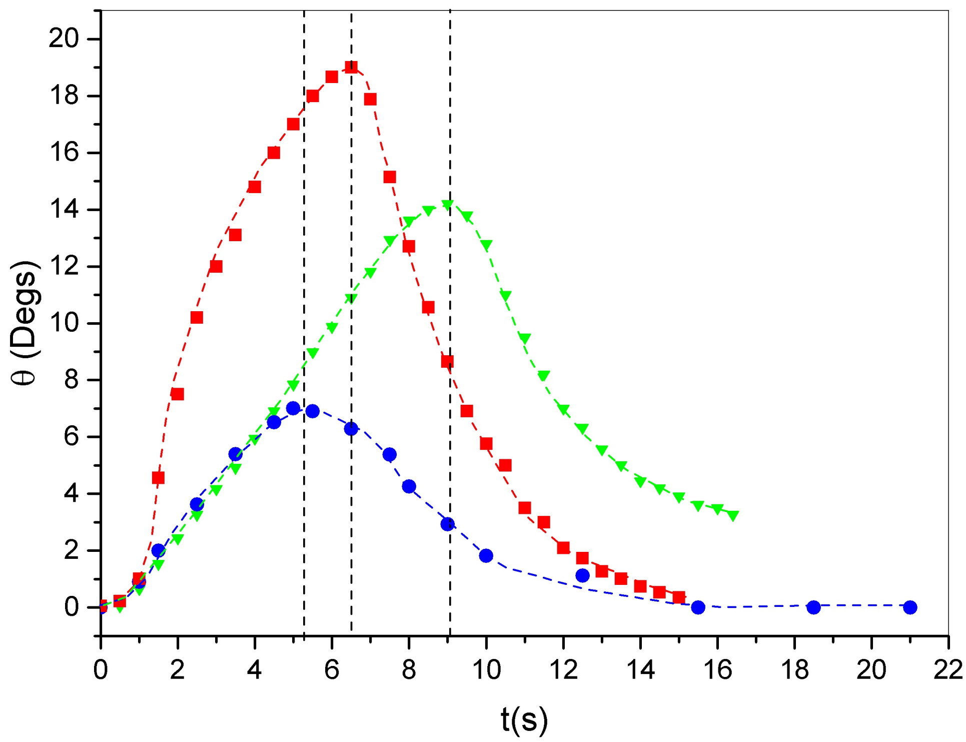

Figure 5. Angular displacement (Degs) as a function of time (s) for three different wavelengths, λ = 405 (blue filled circles), 532 (green filled triangles), and 650 (red filled squares) nm. The dashed lines represents the points where the laser lights are switched off.

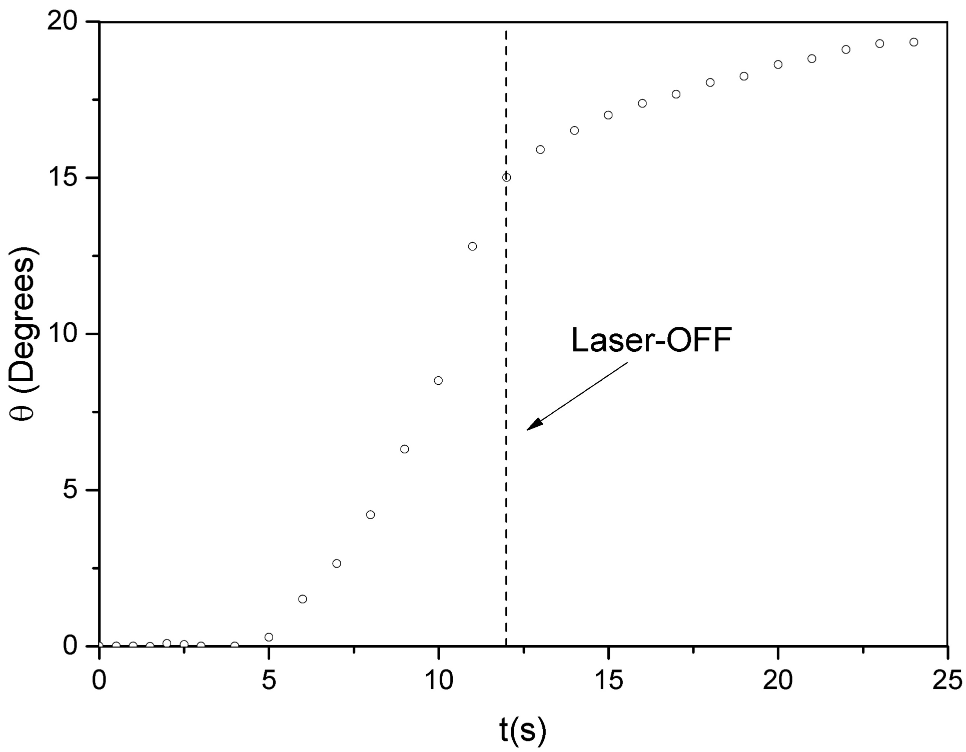

Figure 6. Angular displacement (Degs) as a function of time (s) for the black colored PVC tape when illuminated by the red laser at λ = 650 nm. The dashed line indicates the point at which the red laser is switched off.

4. Conclusions

A novel photomobile configuration is shown and analyzed. It involves the use of a layer of graphene-oxide and PVC/isoprene-based tape. The film is very easy to make and at extremely low cost. By following the proposed approach, researchers could access the PMP technology in a very simple and cost-effective way. In spite of the ease of manufacturing and low cost, the PMP film works over a wide range of wavelengths from near-UV/Vis to NIR, offering the best performances in the NIR region. These findings pave the way for the use of this technology in different research fields, including optical communications. Furthermore, the use of an insulating tape allows alphred-1-PMP to be used in many different experimental conditions.

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