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ORIGINAL PAPER

On the Attenuation of Light by a Polydimethylsiloxane (PDMS) Foam and Its Implementation as a Weight Sensor

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Abstract: We report a Polydimethylsiloxane (PDMS) foam based sensor for measuring weight. The transmission spectrum of PDMS foam is studied by subjecting it to compression in the direction of the incident light. The attenuation of transmitted light through the PDMS foam is discussed. An apparatus is fabricated which compresses or uncompresses the PDMS foam by loading or unloading weights which varies the intensity of the transmitted light. Observations show no hysteresis and good repeatability over a range of weights from 500 to 2800 g.

Keywords: PDMS; Sponge; Foam; Weight sensor; Light attenuation

1. Introduction

SOLID foams are a three dimensional form of cellular solids [1]. The random dispersion of gas within a solid matrix gives rise to structural/mechanical properties which have several engineering applications [2]. Research on such foam structures have resulted in several novel applications in biosensing and biomedicine [3, 4]. Investigations have been carried out on various foam based materials like polyurethane, polyethylene and polystyrene foams for their mechanical and thermal properties [5, 6]. The open-cellular structures of polymer foams are reported to be advantageous in fabricating capacitive sensors [7, 8]. Optical properties of solid foams depend on the phenomenon of absorption and scattering of light. While absorption is affected directly by the solid phase of the cellular solids, scattering is most effective when the cell wall thickness is of the order of 0.5 µm [9]. The effect of cellularity of a solid on the light transmitted through has been extensively studied [10]. With the change in the thickness of such a cellular solid, there is a corresponding attenuation in the intensity of the transmitted light. Thickness measurement and the amount of light attenuation observed have been reported for polyethylene and polystyrene foams [11, 12]. Recently there have been developments in the types of porous solid foam structure forming materials.

A Polydimethylsiloxane (PDMS) foam is one such material used to form a foam structure. Sugar or salt leaching [13] and precursor emulsions processes [14] are generally used to prepare a porous PDMS foam. The PDMS foam is reported to be applied in creating scaffolds [15] and as a pressure pump in microfluidics [16]. In both these applications, mechanical properties, i.e. stress–strain characteristics of PDMS foam have been studied. Optical pressure sensors based on using the PDMS elastomer in bulk form as a waveguide have been fabricated by [17] in a pressure regime of (0–40) kPa with a sensitivity of 0.2 kPa, by [18] in pressure regime of (0–160) kPa with a sensitivity of 1.93 kPa and [19], in a pressure regime of (0–478) kPa with a sensitivity of 1 kPa. Microstructured PDMS is used as a dielectric layer to fabricate highly sensitive capacitive sensors by [20] in pressure range of (0–20) kPa.

But to the best of our knowledge PDMS foam structure is not used for any sensor application. We have fabricated PDMS foam via the sugar leaching technique [13] using the commercially available sugar cubes and characterized the foam using UV–Vis-Near IR spectroscopy. Light attenuation in this PDMS foam is studied by subjecting it to compression. This characteristic of the PDMS foam of attenuating light intensity has allowed us to further develop it as a weight sensor. Such a sensor may find applications in

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dead weight machines [21, 22] and pressure balances [23, 24].

2. Experimental

2.1. Preparation of PDMS Foam

The PDMS foam is prepared using the sugar template method [13]. This provides us with a sponge size of the order of 1.5 cm × 1.5 cm × 1.5 cm as dictated by the commercially available sugar cubes. Sylgard's Silicone 184 elastomer kit [Dow Corning] which consists of a base and curing agent is mixed together in 10:1 ratio and left for open air degassing. The degassed mixture is then slowly poured over sugar cube till saturation. These saturated sugar cubes are cured at 80 °C for 1 h in a hot air oven which results in the formation of PDMS cubes with embedded sugar. Tap water, heated at 40 °C is used to wash the PDMS cubes embedded with sugar. As the sugar dissolves, PDMS cube floats up to the surface of water. The dissolution of sugar results in the formation of the open foam structure. Washing is repeated 4 times to ensure removal of sugar within the foam structure.

2.2. Structural Properties of PDMS Foam

The PDMS foam thus formed has an average pore size of 314 μm and cell wall thickness of 75 μm. The average pore size is equivalent to the average size of the sugar crystals, which is 287 μm that make up the sugar cube template. SEM image of the surface of PDMS foam is shown in the Fig. 1a and the optical micrograph of the sugar crystals in the sugar cube is shown in the Fig. 1b. The relative density [1] of the PDMS foam, which is defined as ρ^*/ρ_s (where ρ^* is the foam density and ρ_s is the density of bulk PDMS [25]) is 0.363. And hence the porosity, defined as $(1 - \rho^*/\rho_s)$ is 0.637. The Young's Modulus of the PDMS foam is measured (Fig. 2) to be 21,168 Pa which is significantly lesser than that of bulk PDMS [26] and is comparable to the PDMS foams prepared using the sugar leaching technique [13].

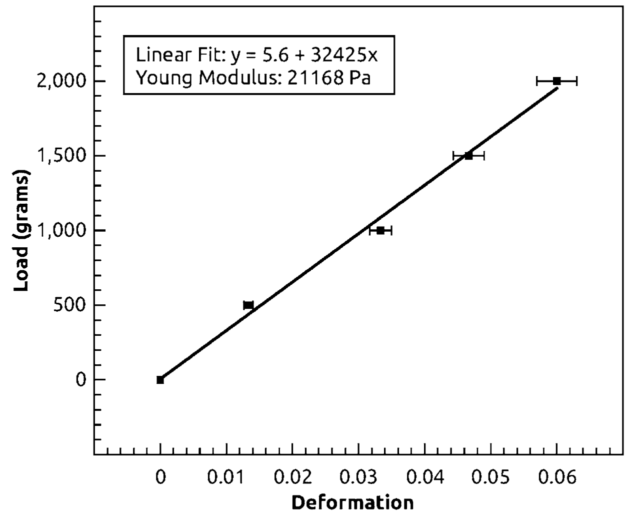

Fig. 2 Young's modulus of the PDMS foam is 21,168 Pa

2.3. Spectroscopic Study of PDMS Foam

Transparent acrylic glass plates of 5 mm thickness are coupled with 3 mm screws to hold the sponge and compress it. This configuration is tested under UV–Visible spectrometer (JASCO UV–VIS–NIR Spectrophotometer) for the wavelength range from 300 to 800 nm. The screwing and unscrewing of the attached screws enables the control of the compression length of the PDMS sponge.

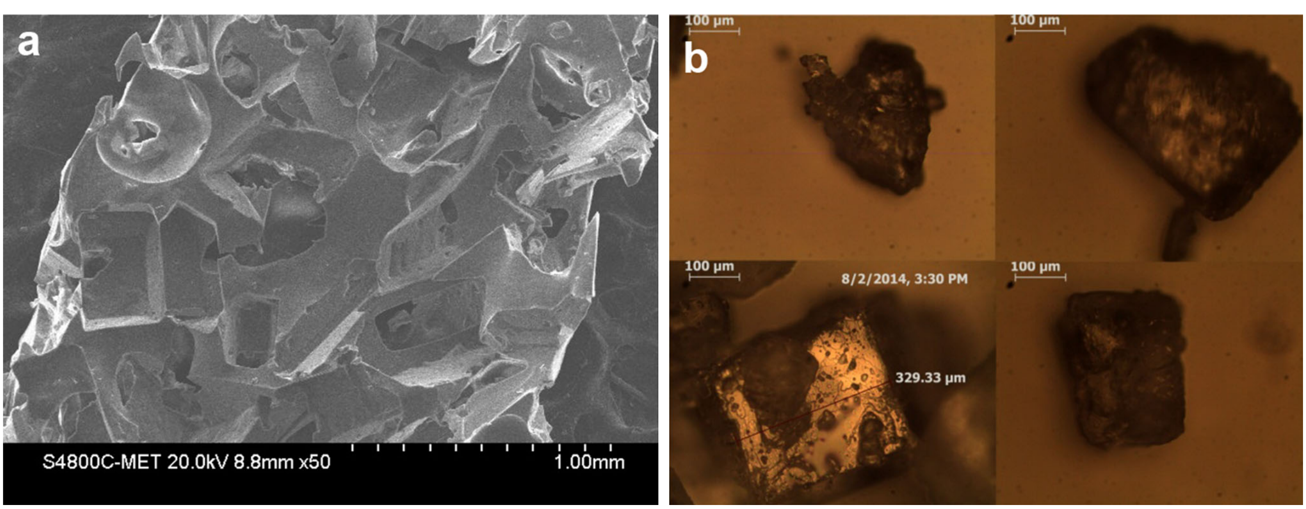

Fig. 1 **a** Micrograph of PDMS foam's surface. **b** Micrograph of Sugar crystals in the sugar cube template

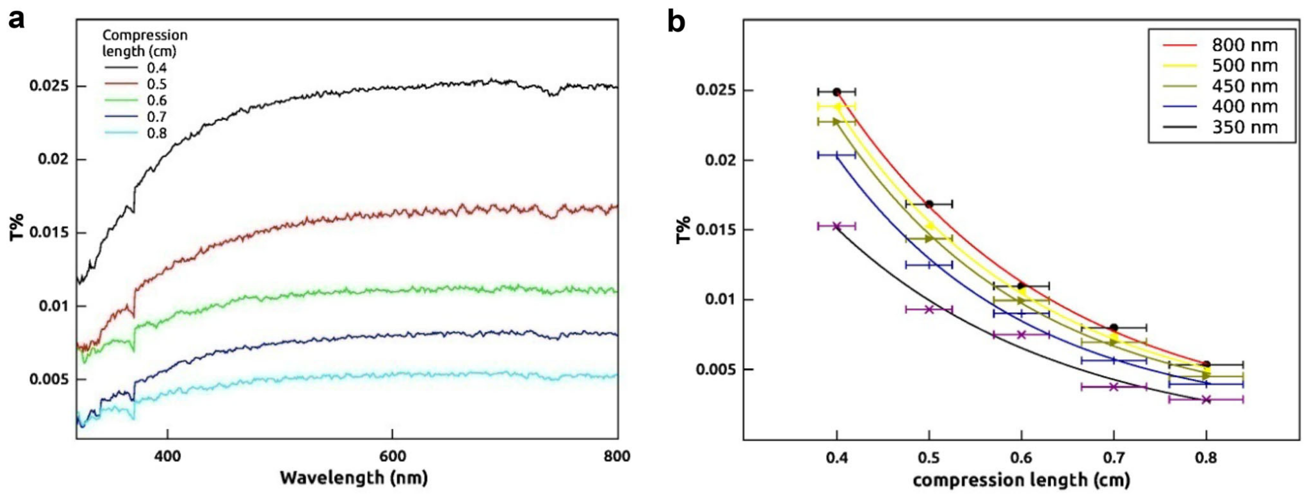

Fig. 3 **a** Transmittance of light over the visible range through the PDMS foam for various compression lengths. **b** Transmittance of light over the visible range through the PDMS foam for various wavelength. (Exponential fit: y = A $e^{-\alpha d} + c$, where A = 0.1, c = 0, d: compression length and $\alpha = 4.51$)

Transmittance of light through bulk PDMS and photo patternable PDMS has been studied by [27], which show the transmittance of PDMS in bulk form to be approximately 90 %, whereas the transmittance of a PDMS foam as shown in the Fig. 3, is in the range of 0.005–0.025 %.

2.4. Fabrication of the Weight Sensor

The phenomenon of attenuation of light associated with compression of the PDMS sponge can easily be observed as shown in Fig. 4. This effect was applied to fabricate a weight sensor. Sandwich mechanism consisting of two transparent acrylic glass plates with four guiding rails is used to compress the sponge. This mechanism is mounted on a configuration of aluminum frames which acts both as a support and a compression lever.

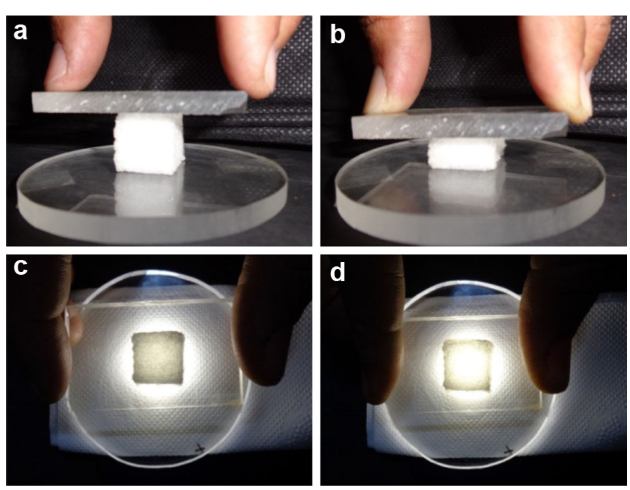

Fig. 4 In the image (**a**, **b**) (*side view*), shows the PDMS foam in uncompressed and compressed state in between two transparent acrylic plates. In the successive images (**c**, **d**) (*top view*), increased transmitted light intensity can be seen in (**d**) (*compressed*) as compared to (**c**) (*uncompressed*) state

Figure 5 shows the actual setup used for the weight sensor study. A 2 Volt, 4 cm × 4 cm photo-voltaic cell is fixed at the lower side of the acrylic glass on which the PDMS rests. The upper acrylic glass window is provided with a slit, to minimize the light incident on the PDMS foam refracted through the acrylic windows as shown in the schematic (Fig. 6). The apparatus is covered in an enclosure to reduce the noise level due to the ambient light. A polychromatic light source is adjusted at a distance of 10 cm over the first acrylic glass window and this distance is kept constant over the period of all measurements.

Measurements are made by loading or unloading of weights on the weight holder. As the weight is loaded (unloaded), the guiding rails slide the upper acrylic window downwards (upwards), thereby compressing (decompressing) the PDMS foam. The loading and unloading of weights is seen to cause no hysteresis in the detector output. The detector output is measured with the help of Agilent 34401A 6 1/2 digital multimeter. The measurements are repeated for 7 sets of readings.

3. Results and Discussion

The optical path length of light varies with the change in the configuration of the cell structure of the PDMS foam due to compression or decompression [11]. The solid foam scatters the incident light at random angles due to the presence of the gas–solid interface of its cellular structure. From the Fig. 3b, the output intensity of the transmitted light shows exponential decrease with respect to the compression in the PDMS foam. For the observed effect of

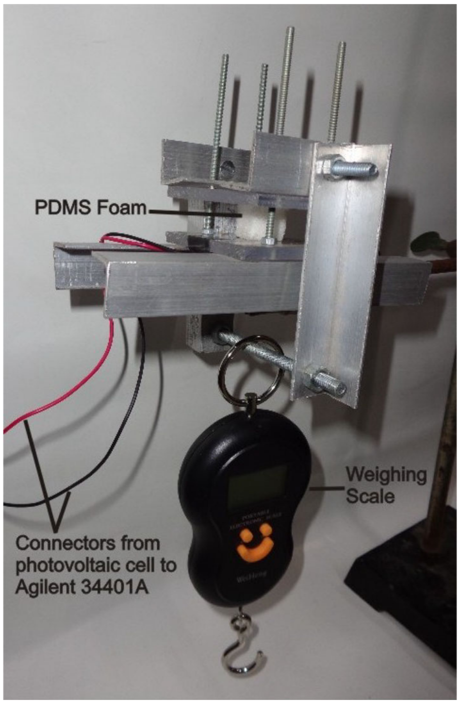

Fig. 5 Image of the actual setup used as the weight sensor

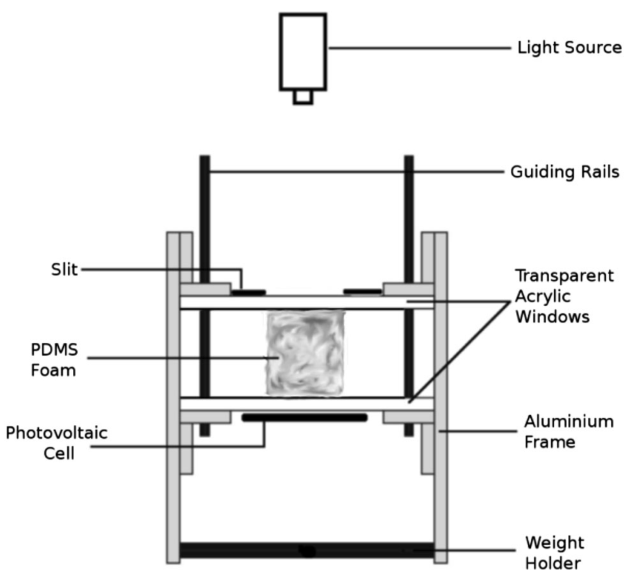

Fig. 6 Schematic showing the side view of the experimental set up of the weight sensor

light attenuation under various compressions in PDMS foam, the attenuated light intensity could be expressed in an exponential form [10].

$$I_t = I_i e^{-\alpha d}$$

where I_t, I_i are the transmitted and incidence light intensities respectively, α is the absorption coefficient and

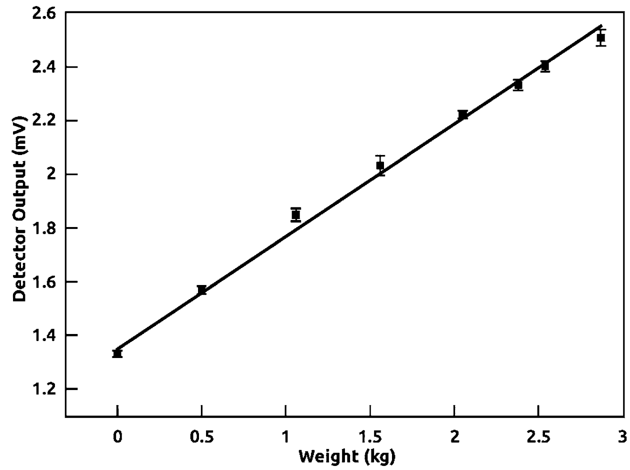

Fig. 7 Sensor response for detector output under applied weight

d is the thickness of the foam. As calculated from the Fig. 4b, the average value of α is 4.51 cm^{-1}.This can be restated in terms of transmittance as

$$I_t/I_i = e^{-\alpha d}$$

$$T_\lambda = e^{-\alpha d}$$

where T_λ is the transmissivity of the incident light of wavelength λ through the medium.

The deformation of PDMS foam results in the attenuation of light transmitted through it. Intensity change varies with the wavelength of incident light and is more prominent for higher wavelength range in the visible spectrum which is depicted in Fig. 3a. Intensity variation of the transmitted light is not just a function of the compression length but also of the wavelength of the incident light. This can be seen as the change in the slope of the percentage transmittance over the range of wavelengths. For the most part of visible spectrum, this slope is zero, but as the wavelength of the incident light approaches in the region of violet and near ultraviolet, the slope has a positive value for all deformations. The change in slope is gradual for deformation of 0.8 cm and steeper for deformation of 0.4 cm. Furthermore the transmission intensity decreases with the decreasing wavelength. An increase of about 400 % in the transmission intensity for minimum compression length (0.8 cm) to the maximum compression length (0.4 cm) is seen for the wavelength of 800 nm and this percentage increase is lower for the wavelengths less than 800 nm.

Using this phenomenon of attenuation in the transmission intensity of incident light, a PDMS foam based weight sensor is fabricated and calibrated by loading weights onto the apparatus as depicted in Figs. 5 and 6. The change in the detector output voltage as a response to the loading of weights is shown in Fig. 7. Sensitivity of 0.42 mV/kg is noted for this foam based sensor. The response of the weight sensor is linear within the range of 500–2800 g with $R^2 = 0.996$. The lower limit on the detector output voltage is due to the scattered light from the apparatus, whose value stays constant throughout the experiment.

4. Conclusion

The light attenuation property of Polydimethylsiloxane (PDMS) foam has been studied using a spectrophotometer. The intensity variation of transmitted light through the PDMS foam with compression showed exponential fit similar to that of Lambert's law for the visible range of light spectrum. This variation of intensity of transmitted light was applied to fabricate a PDMS foam based weight sensor for weight range from 500 to 2800 g with a precision of 50 g.

Cellular solids being less dense than their non-cellular counterparts can reduce the overall weight, size and cost of the sensor. Introducing an appropriate PDMS-composite solid phase could improve the weight sensing properties of the sensor. Repeatability and linearity of the sensor, with the absence of hysteresis, makes the PDMS foam an interesting candidate for sensing applications based on its light attenuation property.

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