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Title	Tuning MEMS cantilever devices using photoresponsive polymers
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Publication date	2019-06-29
Original Citation	Jackson, N., Kumar, K., Olszewski, O., Schenning, A. P. H. J. and Debije, M. G. (2019) 'Tuning MEMS cantilever devices using photoresponsive polymers', Smart Materials and Structures, 28(8), 085024, (9 pp). doi: 10.1088/1361-665x/aad013
Type of publication	Article (peer-reviewed)
Link to publisher's version	https://iopscience.iop.org/article/10.1088/1361-665X/aad013 - 10.1088/1361-665x/aad013
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Download date	2026-11-15 03:45:49
Item downloaded from	https://hdl.handle.net/10468/9747

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Smart Materials and Structures

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To cite this article before publication: Nathan Jackson *et al* 2018 *Smart Mater. Struct.* in press https://doi.org/10.1088/1361-665X/aad013

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Tuning MEMS Cantilever Devices Using Photoresponsive Polymers

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Abstract. Microelectromechanical systems (MEMS) energy harvesting devices have had limited commercial success partly due to the frequency mismatch between the device and the vibration source. Tuning the cantilever device is one possible solution but developing a tuneable MEMS device is difficult. This paper demonstrates a novel method of tuning a MEMS cantilever device post-fabrication by using light responsive azobenzene liquid crystal polymers (LCP). Light exposure causes the photoresponsive polymers to change their elastic modulus, thus affecting the resonant frequency of the device. The photoresponsive polymer was integrated with three different MEMS cantilever substrates including: LCP, parylene, and silicon. The three cantilever beams all demonstrated changes in resonant frequency when exposed to UV light of 10.4%, 8.13%, and 4.86%, respectively. The change in resonant frequency is dependent on the stiffness of the substrate, the thickness of the azo-LCP, the intensity and duration of the light exposure, and the wavelength of the light. The results in this paper validate that light responsive polymers can be used to reduce the frequency of MEMS cantilevers post-fabrication, which could lead to developing devices that can be precisely tuned for specific applications.

Keywords: Frequency Tuning, MEMS, Cantilever, Energy Harvester, Photoresponsive liquid crystal polymer

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1. Introduction:

Microelectromechanical systems (MEMS) based vibrational energy harvesting devices have been extensively researched over the last decade. Significant advances have been made to enhance power density, in order to achieve levels capable of powering the Internet of Things (IoT). However, one of the biggest challenges ahead of MEMS energy harvesters is the mismatch between the resonant frequency of the MEMS device and the vibration source. Typically, MEMS devices are fabricated using silicon as the structure, which results in a high Q-factor (low bandwidth) device. A high Q-factor is desired to obtain a high-power density, but the low bandwidth creates a potential problem. If the resonant frequency of the device is not matched to the frequency of the vibration source the power harvested is significantly reduced. This problem occurs for both piezoelectric- and electromagnetic-based energy harvesting devices. This problem led researchers to investigate various methods of increasing the bandwidth by using nonlinear dynamics (1), bistable magnetics (2), mechanical stoppers (3, 4), sliding mass (5), creating arrays of devices (6), and numerous other methods (7). However, increasing the bandwidth typically results in lowering the Q-factor, which reduces the peak power density. Therefore, a preferred option would be to tune the resonant frequency of the device to match the vibration source, and thus maintaining the high Q-factor and power density.

Tuning the resonant frequency of a MEMS cantilever could be desirable when: 1) the frequency of the vibration source changes or is different than what was anticipated and/or 2) the MEMS device has a different frequency than was anticipated. The latter case is quite common as the frequency of fabricated devices usually has a 5-10% deviation from the expected frequency due to manufacturing issues (*i.e.* variation in layer thicknesses due to sputtering or etching) (5, 8). Therefore, a small 5-10% tuning capability is desired for MEMS energy harvesters. Within the last decade there have been numerous attempts at developing a tuneable MEMS energy harvesting device. Most of the attempts involve using an active component that requires power, which defeats the purpose as these active components often require more power than they can harvest. Passive tuning is preferred as it does not consume power during operation. Researchers have attempted to use magnetic repulsive and attractive forces to tune the frequency (9). Other attempts include stiffness tuning by applying electrical bias circuits (10). Still other techniques using lasers to etch small sections of the cantilever post-processing

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have also been proposed (11, 12). Various other techniques have been proposed with macroscale devices, but many of these are not compatible with MEMS fabrication techniques (7). Passive tuning can be accomplished by changing the dimensions, moving the center of gravity, straining the structure, or changing the spring stiffness of the cantilever. Most of these methods are not practical or difficult to accomplish for MEMS devices, with the exception of changing the spring stiffness. Recently it was reported that the stiffness of a liquid crystalline polymer film (13),(14) can be tuned by using light as a non-invasive, non-mechanical trigger (15, 16,17, 18). A liquid crystal polymer (LCP) hosts was doped with a photoresponsive azobenzene dye that responded to light. The light absorbed by the *trans* azo-molecule results in the formation of the *cis* azo isomer resulting in a change in elastic modulus (16).

This paper investigates a novel method of tuning the resonant frequency of a MEMS cantilever device using photoresponsive liquid crystalline polymers. Previous work has demonstrated the damping of cantilever vibration using UV-responsive photo-rheological fluids (19). Other work has measured the changes in stress in a cantilever coated by a monolayer of photoresponsive spiropyran dyes (20). The combination of a photoisomerizable azobenzene molecule with a LCP matrix placed on top of a cantilever in order to modulate the frequency of the cantilever via illumination appears to be untested. Integrating the photoresponsive LCP material with a MEMS will allow the combined device to change its effective bulk modulus, thus tuning the resonant frequency. Using light to tune the resonant frequency is preferred over other stiffening methods, such as electrical bias, as it does not require direct contact with the cantilever or constant stimulation. Therefore, the device can be tuned post-fabrication to match the frequency of the vibration source for a particular application. The paper investigates various methods of integrating the azobenzene LCP material with MEMS cantilevers to experimentally determine if the material can be used to tune the resonant frequency of the cantilever structure. First, the concept of using the azobenzene LCP material directly as a cantilever was tested using different UV light intensities. Then the material was integrated with two different types of cantilever beam substrates (polymer and silicon), in order to validate that the change in elastic modulus of the azo-LCP would affect the bulk modulus of the device.

2. Materials and Methods:

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2.1 Concept

A general device concept for tuning the resonant frequency of a MEMS energy harvesting cantilever using photoresponsive LCP is described schematically in Figure 1. The first resonant frequency mode of a rectangular cantilever can be numerically represented by the following equation:

$$f = \frac{1}{2\pi} * \sqrt{\frac{3E}{m}} * \sqrt{\frac{wt^3}{L^3}} \qquad (1)$$

where E is the elastic modulus of the beam, m is the mass, w is the width, t is the thickness, and L is the length. The physical dimensions of the cantilever beam have the most significant influence on the frequency, (12) but altering the dimensions of the cantilever after fabrication is not practical for commercial devices. The other two parameters that influence the frequency are the mass and elastic modulus. The mass may be altered by adding weights to the fabricated device, but this is also undesired as it includes an additional additive manufacturing process, which is not desired for large scale production. Thus, the simplest solution for adjustable cantilever frequencies would be the capability of adjusting the modulus on demand. The device concept shown in Figure 1 of a typical MEMS energy harvesting device is comprised of a beam substrate, a mass, and a photoresponsive LCP that changes its elastic modules via light exposure. Selection of the photosensitive azobenzene moiety of the LCP can allow response to different wavelengths of light: modulus changes to UV, blue, green or normal sunlight has previously been demonstrated (15, 16).

---------- Figure 1----------

The beam substrate is likely to dominate if it has a high elastic modulus like silicon. However, by creating a hybrid beam material that consists of the substrate material and the LCP, a change in the elastic modulus of one material will affect the overall modulus of the device. The goal is not to create large changes in resonant frequency, but to allow small, tuneable changes that can compensate for the 5- 10% error in resonant frequency stemming from variations during the manufacturing process (5, 8). Figure 1(b) demonstrates the concept: the fabricated device has a different resonant frequency compared to the vibration source, and since the Q-factor is typically high for MEMS cantilever beams, the power

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harvested would be significantly affected. If the vibration source frequency is known, one could expose the device to light with known wavelength and intensity, changing the bulk modulus of the cantilever and tuning the resonant frequency.

The photoresponsive material used in this paper is reversible, meaning that the modulus will change when the cantilever is exposed to specific light wavelengths. Removing the light will allow the modulus to eventually return to its original value. In real-life energy harvesting application, a non-reversible material would be desired so that continuous light exposure would not be required; however, the reversible material allows us to validate the concept.

2.2 LCP Development

The chemical structures of the materials used in this study are shown in Figure 2. Nematic liquid crystal films were obtained from mixtures of the reactive monomers (RM82/ RM105/ RM23, Merck) in a 2:3:1 weight ratio, 10 wt% azobenzene derivative (A3MA, Syncom) or 10% of the fluorinated azobenzene (f-Azo) (15), and 2 wt% photoinitiator (Irgacure 819, Ciba). The compounds were dissolved in dichloromethane, mixed, and subsequently dried at 50 °C. The dried mixture was used to fill 20 µm or 50 µm planar rubbed polyimide cells (Optmer AL 1051, JSR Corporation) at 75 °C. The photopolymerization of films were carried out using a mercury lamp (Exfo Omnicure S2000) with a > 400 nm cutoff filter (Newport FSQ-GG400) at 35 °C for 30 min, to ensure well-aligned nematic phases. A post heating exposure at 120 °C for 5 min followed to improve conversion of the acrylate groups into polymer chains. After opening the cells, yellow colored polymer films were obtained.

---------- Figure 2----------

2.3 Cantilever fabrication

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Multiple types of MEMS cantilevers were developed in order to investigate the potential frequency modulation effects from altering the modulus of the LCP on the cantilever devices. Four types of beam substrates were developed as demonstrated in Table 1. All of the cantilever devices were bonded to a custom fabricated PCB, which was used as a frame for handling the devices and for experimental testing. After the photoresponsive material was fabricated they were bonded to a glass substrate, and then diced using a standard wafer dicer with 25 μm wide blade. This allowed the LCP to be cut into precise rectangular dimensions of 8 x 5 mm^2.

Two of the cantilever devices did not contain a separate substrate, but instead used the LCP as the cantilever beam material. The LCP films of thickness (20 and 50 μm) were bonded to a rigid PCB to create the cantilever structure and a silicon mass was attached to the LCP. A 500 μm thick silicon piece was diced into dimensions of 5 mm by 2 mm and bonded to the LCP cantilever. The silicon piece served two purposes 1) it acted as a mass for the cantilever and 2) it was required to perform experimental measurements using a Laser Doppler Vibrometer (LDV). The silicon created a reflective surface that allowed the LDV system to be used to measure tip displacement and frequency. The LCP cantilevers were then bonded to the PCB, which allowed the cantilever to move freely.

---------- Table 1----------

2.3.1 Parylene Cantilevers. In order to validate the tuning concept, the azo-LCP was bonded to two other cantilever devices which consisted of 1) a Parylene-C based cantilever substrate and 2) a silicon-based cantilever substrate. Polymer based MEMS cantilever structures are becoming more common due to their biocompatibility and potential low resonant frequency (21, 22), and it is important to determine how the change in modulus of the LCP will affect a lower modulus substrate compared to silicon. The Parylene-C MEMS cantilever devices were fabricated similar to methods previously described (23), where a silicon wafer was used as the substrate. An oxide layer was deposited on the wafer using thermal oxidation methods. Parylene-C was then deposited (20μm) using the Gorham process (SCS Labcoater) as previously described (24). Then the Parylene-C was patterned using RIE (O_2 Plasma) to define the

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dimensions of the cantilever beam (8 x 5 mm^2). Then DRIE was used to etch the silicon wafer in order to release the cantilever. A silicon mass remained on the parylene cantilever with same dimensions as for the LCP cantilever in order to have a reflective surface for the LDV measurements. A thin azobenzene LCP layer was cut (8 x 5 mm^2) and bonded onto the parylene cantilever using a thin film adhesive layer and a bonding machine for alignment.

2.3.2 Silicon Cantilevers. Silicon based MEMS cantilever devices were fabricated to determine the frequency modulation effects of the LCP on a high modulus substrate, and silicon based MEMS cantilevers are the most common substrate for vibration energy harvesters (6, 25-27). The silicon-based cantilever was developed from an SOI wafer with a 20 μm device layer and a 500 μm handle wafer. A thick 3μm thermal oxide was grown and patterned on both sides of the wafer. DRIE was used on the device layer to define the dimensions of the cantilever (8 x 5 mm^2). Then DRIE was performed on the handle wafer and BOX layer to create a free-standing cantilever. The silicon mass was developed from patterning the handle wafer. The mass dimensions were larger than in the parylene or LCP cantilever devices in order to reduce the resonant frequency. The resonant frequency of each device was kept below 250 Hz, as this is common frequency range for IoT energy harvesters. The thin film (20 μm) azo-LCP film was then bonded to the silicon cantilever as previously described for the parylene cantilever.

2.4 Characterization

The characterization consisted of experimentally testing both the material effects due to various light exposures as well as the effects on the MEMS cantilever device containing the substrate material and the photoresponsive material. The methods for characterizing the materials and the devices is described in detail below.

2.4.1 Liquid Crystalline Polymer.

The LC phases of the mixture were characterized using a Leica polarized optical microscope equipped with a Linkam hot-stage. A Shimadzu UV-3102 spectrophotometer was used to obtain UV-vis spectra of the LCP samples to ensure good alignment.

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2.4.2 Resonant Frequency. The first resonance frequency of the various cantilever beam devices were measured using a LDV (Polytech MSA-400). The LDV used a dual laser system with reference laser positioned on the frame of the device and the measurement laser was positioned at the tip of the cantilever beams. The devices were excited into vibration by applying a mechanical shock pulse to the holding apparatus. The LDV measured tip displacement as a function of frequency, which allowed us to determine the resonant frequency of the cantilevers. During testing all room conditions were kept the same, and temperature at the beam surface was monitored to make sure there was no rise in temperature due to the light exposure. The overhead lights were turned off to try and reduce errors caused from normal light. Blinds were used to try and reduce effects of sunlight as well.

Three light sources were used to stimulate the azobenzene LCP substrates. Two of the light sources consisted of UV light (365 nm) with two different intensities (high- 90 mW cm^{-2} and low- 0.7 mW cm^{-2}). The f-Azo doped LCP film was exposed to green light (530 nm) (Thorlabs M530L3) with intensity of 150 mW cm^{-2}. The lights were positioned at the same distance and angle to ensure that the entire LCP film was exposed for each type of cantilever. The light was applied for a specific amount of time and then removed, while the modulus returned back to its initial value, allowing the cantilever resonant frequency to return to its original value.

3. Results and Discussion

Previous work showed exposure of LCP films containing the A3MA azobenzene to 365 nm resulted in significant moduli drops (approximately 1.8 GPa to 1.1 GPa with 200 mW cm^{-2} UV intense light) (16). The first experiment on the cantilever devices was to validate the concept that altering the modulus of the LCP would result in a frequency modulation. The thin film UV responsive A3MA LCP cantilever device was used in this experiment. The tip displacement as a function of frequency was measured using the LDV, and the results are demonstrated in Figure 3. The peak to the right in the figure was for the initial value, which had a peak amplitude of 105 μm at a resonant frequency of 130.5 Hz due to the applied shock impulse. The same shock was then applied after the device had

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been exposed to UV light (90 mW cm^{-2}) for 2 minutes, and the results demonstrate a significant frequency shift. The resonant frequency after UV exposure was 113.5 Hz, which represents a 13.03% change in resonant frequency. The amplitude and bandwidth did not show any significant changes. This validated the concept of using photoresponsive materials to alter the resonant frequency of a MEMS cantilever beam.

---------- Figure 3----------

Following the initial proof of concept, the thin film (20μm) LCP beam was exposed with two different UV light intensities at separate times (0.7 mW cm^{-2} and 90 mW cm^{-2}) in order to determine the effects of varying UV intensity. Due to the reversible nature of the azobenzene LCP, the material returned to its initial state between exposures, which allowed the researchers to use the same cantilever beam for both experiments to eliminate possible material effects between different samples. The cantilever beam was exposed to the UV light for 1 minute in both cases and the results are demonstrated in Figure 4, which shows the resonant frequency as measured by the LDV as a function of time. The LDV measurements were limited to one data point every 4 s. The results show a frequency reduction from 158.25 Hz to 154 Hz (2.69%) for the 0.7 mW cm^{-2} UV intensity light exposure. The higher intensity UV light (90 mW cm^{-2}) demonstrated a frequency reduction from 158.25 Hz to 141.8 Hz (10.4%). After the UV light was turned off, the cantilever frequency began to increase, and eventually returned to their original frequency in about 5 minutes, as demonstrated in Figure 4. Reversible photoresponsive materials were used to better demonstrate the responsive behaviour of the material. However, the concept of using a photoresponsive film to tune a cantilever's frequency would require a non-reversible photoresponsive material. This preliminary result demonstrates that tuning the resonant frequency can be accomplished by i) controlling the intensity of the light and ii) controlling the duration of the light stimulation. By controlling these two parameters the cantilever beams frequency could be tuned by at least 10.4%. Higher intensity of light is likely to result in a greater modulus reduction as previously demonstrated (16), which would lead to a larger frequency reduction. Numerical estimations on the frequency change were calculated based on Eqn. (1) and previously reported data on the change of

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modulus of the A3MA azobenzene material (16). The previously reported data used a higher intensity UV light, but based on interpolating the data, an estimated frequency reduction of 9.9% was calculated. This value is slightly lower than the experimental value of 10.4% but within 0.5% of the value. The reduced prediction is likely caused from the difference in UV intensity effects of the elastic modulus. A higher UV intensity light (200 mW cm^{-2}) similar to what was used in (16) should result in a frequency reduction of 24.6%. Therefore, higher frequency reduction should be possible if a higher UV intensity light was used.

---------- Figure 4----------

The next experiment investigated the use of using a thicker azobenzene LCP cantilever (50 μm) along with altering the duration of the light exposure. The high intensity UV light (90 mW cm^{-2}) was used in this case as it demonstrated a higher change in the resonant frequency of the thin beam. Light exposure was set at 10s, 20s, and 40 s. After light exposure, the LCP modulus was allowed to recover, thus returning the cantilever to its original resonant frequency. The recovery of the LCP modulus directly followed removal of the UV light, as the LCP material used in this study was reversible. However, for practical applications a non-reversible photoresponsive material would be ideal. Figure 5 shows the results from the experiment. It was demonstrated that the frequency decreased as the exposure duration increased, resulting in reduction of 0.89%, 2.24%, and 5.52% for the 10s, 20s, and 40s exposure times respectively. Likewise, the recovery time increased as the frequency decreased. The thickness of the material also affected the resonant frequency change. Figure 4 demonstrated a reduction of 10.4% with a 20 μm cantilever, and the results in Figure 5 demonstrated a frequency reduction of 5.52% for a 50 μm thick material with the same intensity and similar exposure duration. This demonstrates that a higher intensity UV light or increasing the duration of exposure is necessary for thicker films to produce similar reductions in resonant frequency.

---------- Figure 5----------

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After validating that the azobenzene LCP cantilevers showed reduce frequency upon UV light exposure, the next step was to determine if a reduction in resonant frequency was possible with the azobenzene LCP directly bonded to a cantilever substrate. The first experimentation was to use a polymer-based cantilever beam, because the polymer cantilever would have a similar elastic modulus as the LCP material. The polymer cantilever used for this experiment was based on Parylene-C. The thickness of the parylene beam and the LCP were 20 μm each. The UV stimulation was applied for 3 minutes to ensure maximum reduction in resonant frequency. The results are shown in Figure 6, which demonstrates a reduction of 1.19% and 8.13% in resonant frequency for low intensity and high intensity UV light, respectively. The results demonstrate that elastic modulus changes in the LCP due to the UV light was capable of altering the bulk elastic modulus of the hybrid device, thus reducing the resonant frequency of the cantilever. This validates the concept that using a photoresponsive material can be used to tune an all-polymer-based cantilever device by creating a hybrid material. The degree of reduction was less than the change from the LCP cantilever shown in Figure 4, which was expected since the bulk modulus in hybrid materials will not be affected as significantly due to the combination of the two materials. Numerical estimations using the rule of mixtures to predict the modulus of the hybrid and Eqn. (1) were used to predict a frequency reduction of 7.5% for the LCP/Parylene cantilever, which is lower than the experimental value of 8.13%. This is likely due to a lower than expected estimation of the modulus change due to lower UV intensity, or the thickness measurements of the two films.

---------- Figure 6----------

After validating that a hybrid bilayer polymer cantilever MEMS device demonstrated reduced frequency, the next stage involved investigating the effects of and LCP on a silicon-based cantilever. Silicon-based MEMS cantilevers are the most common substrate material used in MEMS. Silicon is a stiff material with an elastic modulus of around 120-200 GPa, depending on the type of silicon used. The MEMS device fabricated in this paper used (100) silicon, as it is the most commonly used silicon in MEMS fabrication. The 10% A3MA azobenzene LCP film was bonded to the silicon MEMS

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cantilever as described above. The results shown in Figure 7 demonstrate that the silicon cantilever beam with azobenzene LCP had a significant reduction of frequency when a higher intensity UV light was used. The cantilever resulted in a frequency reduction of 0.4% and 4.86% for the low and high intensity UV light exposure, respectively. The reduction of frequency required a longer duration of UV light stimulation due to the stiffness of the silicon. The numerically predicted frequency reduction, based on the rule of mixture and estimation of the modulus change due to UV intensity for the material on a silicon cantilever was 1.17%, which is lower than the experimental value. In all three devices the predicted frequency reduction was lower than the experimental reduction, which means that the estimation of the modulus due to lower UV intense light was lower than expected. The change in frequency of the silicon beam was lower (4.86%) than that of the parylene (8.13%) and LCP (10.4%) cantilevers at similar doses, which was expected due to the higher stiffness of silicon. The results validate that a photoresponsive material can be used to alter the resonant frequency of a variety of beam substrates with high or low elastic modulus.

---------- Figure 7----------

Recently, green light (530 nm) was used to expose LCPs doped with f-Azo, which also demonstrated a change in elastic modulus (15). An identical silicon-based cantilever beam as was used in the study of the A3MA films was employed, but this time using the f-Azo LCP (10 wt%). A green LED light of 150 mW cm^{-2} intensity was used to expose the cantilever to the appropriate wavelength of light. The material was exposed for 2, 4, and 8 s. The results are shown in Figure 8. This cantilever demonstrates a reduction of resonant frequency of 3.5%, 5.9%, and 8.33% for the different exposure durations, and a recovery time constant of 40, 78, and 150 s. This demonstrates that using different photoresponsive materials can be used to create unique tuning affects at different wavelengths of light, and that optimization of the photoresponsive material is necessary for future applications.

---------- Figure 8----------

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Conclusion

In this study we have demonstrated that using light responsive materials which change their mechanical properties when exposed to specific wavelengths of light can be used to tune the frequency of various MEMS cantilever substrates. This affect was experimentally demonstrated by using three different types of cantilever substrate materials (LCP, parylene, and silicon) and two different LCP topping materials, one using a standard azobenzene A3MA that responded to UV illumination and one using a fluorinated azobenzene that responded to green light. In this study we used reversible photoresponsive materials to validate the concept, but in eventual, real applications a non-reversible material will be developed. This study demonstrated that the photoresponsive material can decrease its elastic modulus upon light exposure, thereby tuning the resonant frequency of the MEMS device. This study also demonstrated that different photoresponsive materials could be used that require different wavelengths of light or combination of wavelengths. The intensity, duration, and wavelength of light all have a significant role in determining the change in the elastic modulus. The photoresponsive materials used in this study demonstrated up to a 10.4% change in resonant frequency; however, optimization of the parameters of the material can be investigated further in order to increase the changes in the elastic modulus. Numerical simulations demonstrated a similar reduction in resonant frequency, but in all cases the numerical prediction was lower than the experimental, which means the estimation of the materials modulus due to lower intense UV light was lower than predicted. Applying higher intense UV light should decrease the modulus even more, which will result in further reduction of resonant frequency. The use of these materials can be applied to various MEMS devices that require frequency tuning.

Acknowledgements

The authors would like to thank the MANpower consortium for their contribution. MD would like to thank Nicky Meertens for her help in measuring the LCPs. The research leading to these results was funded from the European Union Seventh Framework Program under grant agreement no. 604360.

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Figure Captions:

Figure 1- Schematic diagram representing the MEMS tuning concept: (a) demonstrates the experimental setup and concept that the photoresponsive LCP is bonded to a MEMS cantilever structure, with UV light used to alter the modulus of the LCP, thus altering the frequency of the cantilever; (b and c) are schematics that demonstrates the concept of tuning as the initial frequency of the cantilever differs from the vibration source, so changing the modulus of the cantilever will allow frequency tuning to match the frequency of the vibration source to maximize power.

Figure 2- Chemical structures of components used to prepare the nematic liquid crystalline network.

Figure 3- Experimental results demonstrating the frequency shift of a azobenzene LCP cantilever before and after UV light exposure for 120 s with 90 mW cm^{-2} intensity.

Figure 4- Resonant Frequency of the thin film LCP cantilever as a function of time for low intensity (0.7 mW cm^{-2}) and high intensity (90 mW cm^{-2}) UV light exposure for 1 min. The purple box indicates the “On” and “off” states of the UV light exposure.

Figure 5- Resonant frequency of a thick film LCP cantilever as a function of time for high intensity UV exposure for different durations (10, 20 and 40 s).

Figure 6- Resonant frequency of a Parylene-C based cantilever with an azobenzene LCP thin film as a function of time for high and low intensity UV light exposure.

Figure 7- Resonant frequency of a silicon beam cantilever with an azobenzene LCP thin film as a function of time for high and low intensity UV light exposure.

Figure 8- Resonant frequency of a thin f-Azo LCP cantilever as a function of time for Green light (530 nm, 150 mW cm^{-2}) exposure. The duration of the green light exposure is shown in the figure to be 2, 4, and 8s.

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Tuning MEMS Cantilever devices using photoresponsive polymers

Figures:

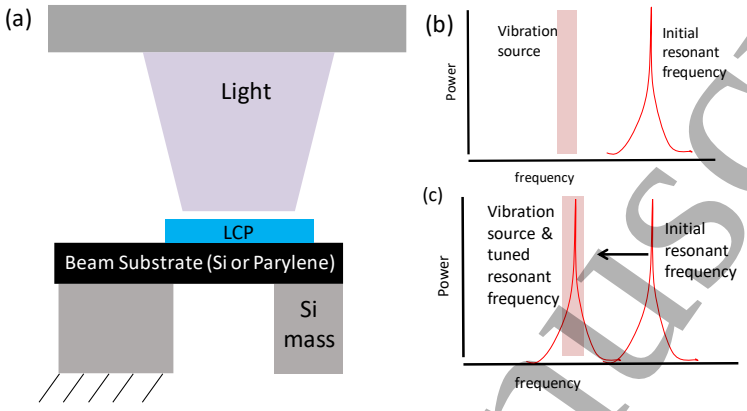


Figure 1

Cantilever Beam Substrate	LCP Thickness (µm)	Substrate beam thickness (µm)	Beam L & W (mm)
LCP	20	NA	8 x5
LCP	50	NA	8 x5
Parylene/LCP	20	20	8 x5
Silicon/LCP	20	20	8x 5

Table 1

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Tuning MEMS Cantilever devices using photoresponsive polymers

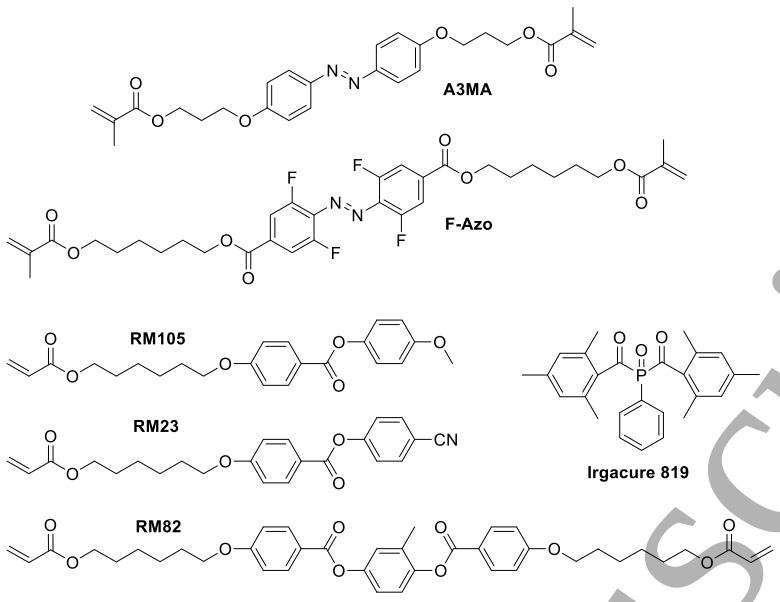


Figure 2

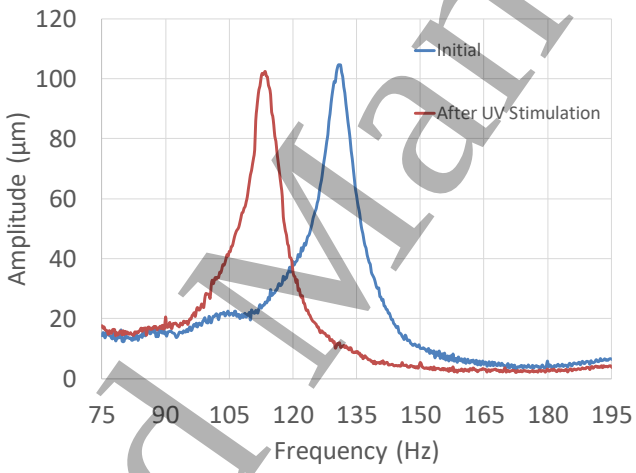


Figure 3

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Tuning MEMS Cantilever devices using photoresponsive polymers

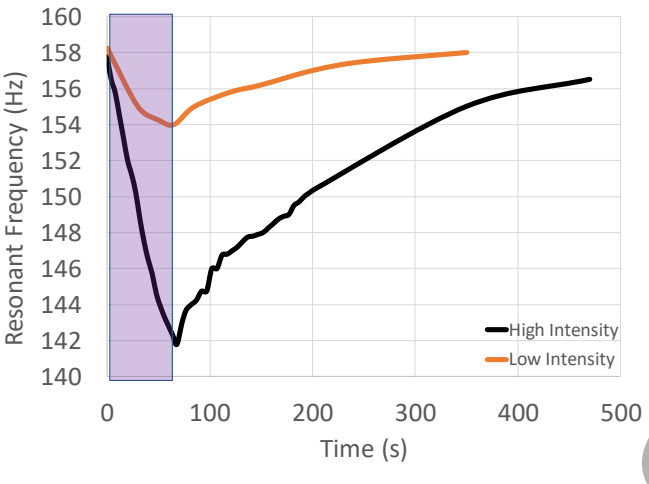


Figure 4

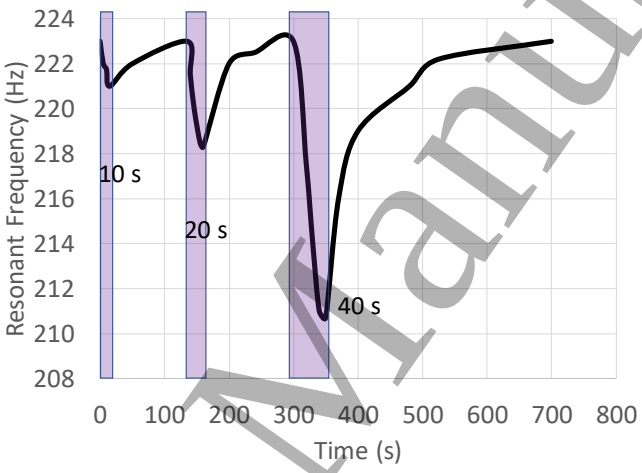


Figure 5

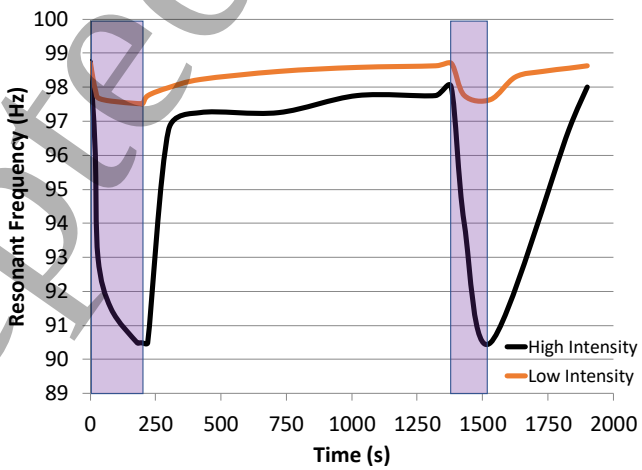


Figure 6

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Tuning MEMS Cantilever devices using photoresponsive polymers

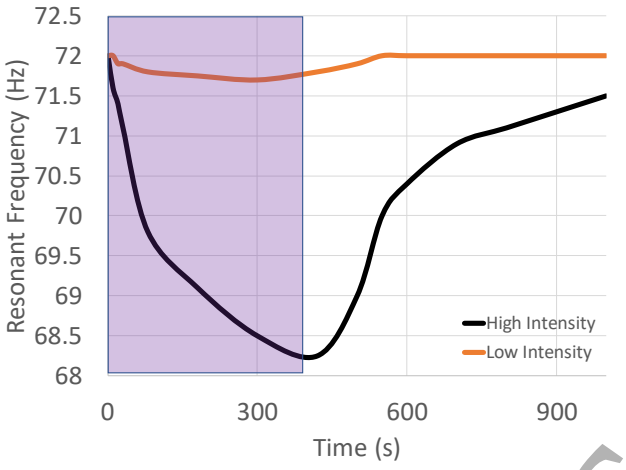


Figure 7

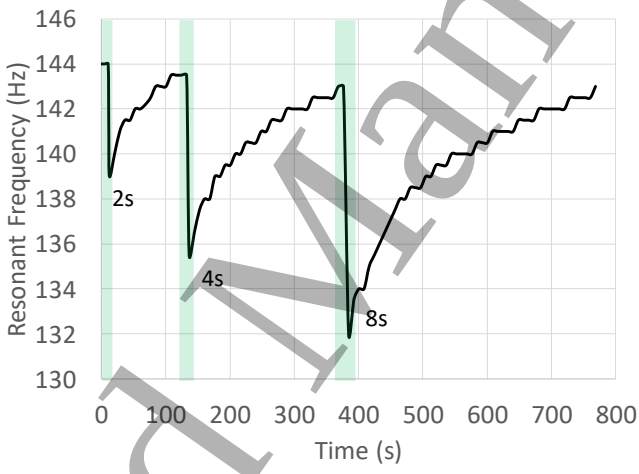


Figure 8

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