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# Tunable frequency band structure in photo-responsive elastic metamaterials

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***Abstract*** – An important issue in the field of elastic metamaterials is that their dynamic properties, such as the band gap frequencies, are typically fixed once the structure has been designed and fabricated. To overcome this limitation, many efforts have been made to conceive materials with adaptive elastic properties based on piezoelectric materials, temperature and magneto-based techniques, actuated polymers via electromagnetic waves, as well as the application of an external mechanical load. In the present research we present an alternative approach based on light-responsive polymers. We show the possibility to reversibly change the material parameters in specific regions of the unit cells of these structures through external light stimuli, leading to the tunability of their transmission spectrum.

## I. INTRODUCTION

The paradigm of elastic metamaterials has opened new opportunities for achieving unprecedented dynamic properties, such as frequency band gaps, negative refraction, unidirectional propagation, etc. Although a variety of metamaterial arrangements and designs have been proposed so far, one important problem in practical applications is that their dynamic properties, such as the band gap frequencies, are typically fixed once the structure has been designed and fabricated, since their geometrical and mechanical properties are constant with respect to time [1, 2]. To overcome this limitation, periodic systems with adaptive elastic properties have received great attention in the recent years. Indeed, introducing an additional degree of freedom, enables the reversible tailoring of the dispersive diagram of the structure, considerably enhancing their functionality and technological applications. To achieve this goal, several approaches have been proposed and explored so far, including active systems, such as piezoelectric materials, temperature and magneto-based techniques, actuated polymers via electromagnetic waves, as well as the application of external mechanical loads [3 - 6].

In the present research we present an alternative approach based on light-responsive polymers fabricated via UV-polymerization of Bisphenol A Ethoxylate Diacrylate and a BAPO photoinitiator in a DLP system. We show the possibility to reversibly change the material parameters in specific regions of the unit cells of these structures through external light stimuli, leading to the tunability of their transmission spectrum [7].

## II. MODELS AND METHODS

The proposed Light-Responsive MetaMaterial (LRMM) consists of a patterned slab waveguide fabricated by means of a 3D printing process on a photocurable acrylic resin containing azo-functional groups. The waveguide height is  $h = 500$  micrometers and spans a total length of  $L = 60$  mm. Along the waveguide, a periodic linear array of eight square pillars is disposed over a length of 40mm, as shown in Fig. 1. The crystal unit cell includes a single pillar fabricated on top of the slab waveguide. The transverse cross section of the cell is square, with a side length of  $a = 4.5$ mm. The square pillars have a height  $H = a$  and lateral size  $b = 0.7a$ .

Our approach is based on the fact that upon illumination with a 405 nm wavelength laser (see Fig. 1), a photosoftening effect is induced on the material, resulting a change of its elastic properties (Young's modulus and

attenuation coefficient). Through a scanning laser Doppler vibrometer (OFV-505, Sensor Head by Polytec) (Fig. 1), we show that it is possible to achieve a controlled widening and / or shift of the band gap frequencies of the non irradiated structure.

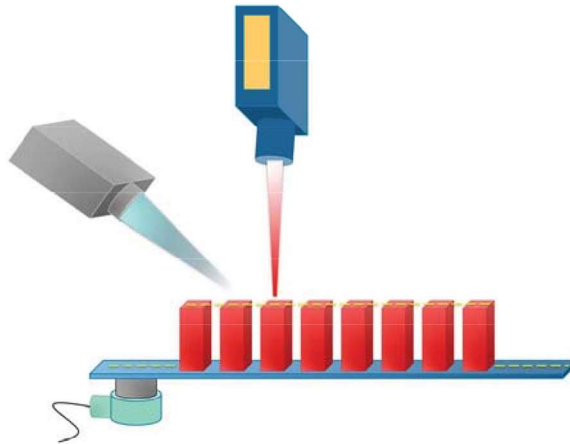


Fig. 1. Schematic representation of the specimen and of the experimental approach. The waveguide, 500 micrometers thick and 60 mm long, presents a periodic arrangement of pillars (represented in red). The experimental set-up is made of an irradiating laser (blue light) inducing a selective photo-softening effect in specific portions of the specimen, and a scanning laser Doppler vibrometer (red light), which is used to detect the out-of-plane displacement once the elastic waves are generated by a piezoelectric transducer glued to the bottom part of the waveguide.

#### IV. RESULTS

The aforementioned band gap tunability effects are experimentally demonstrated by measuring the transmission properties of the specimen before and after the blue light illumination. Elastic waves are injected into the waveguide by means of a piezoelectric transducer glued to the bottom side of the waveguide (see Fig. 1).

Results are presented in Fig. 2, as a three-dimensional contour plot, where the in-plane axes report the frequency and time evolution indicating if the blue light laser is turned ON or OFF, respectively. The z-axis reports the value of the transmission registered after the irradiation point. Initially, spectra are collected without illumination, and clearly show a 16 kHz wide band gap. After 30 s, the laser is switched on in correspondence of pillar #1. For this first position, the irradiation is kept constant for 100 s and the spectral evolution is recorded, until the steady state of the light-induced change of the elastic modulus is reached. The evolution of the transmission spectrum can be readily appreciated in terms of a progressive broadening of the band gap and changes in the relative spectral weights, as reported in Fig. 2a. Both band edges move further apart, leading to an increase of the band gap width when the blue light illumination is provided. The full reversible effect is also demonstrated by turning off the laser (see around 500 s). Figure 2b reports a cut at  $t = 0$  s and  $t = 100$  s, in order to better highlight the difference of the two spectra, i.e. with or without blue light laser illumination.

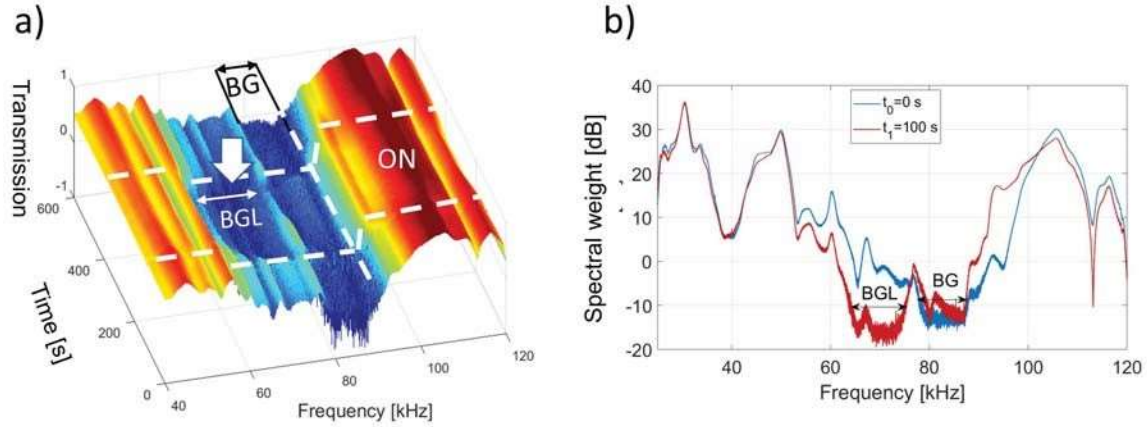


Fig. 2. Light induced effects on the band gap of the LRMM. (a) Three-dimensional contour plot, where the in-plane axes report the frequency and time evolution indicating if the blue light laser is turned ON or OFF, respectively. The z-axis reports the value of the transmission registered after the irradiation point. (b) Cut at  $t = 0$  s and  $t = 100$  s of Fig. 2a.

## VI. CONCLUSION

In conclusion, we have presented a one-dimensional tunable elastic metamaterial based on a 3D printed light-responsive patterned waveguide. Through numerical and experimental analysis, we have illustrated the potential of using light irradiation patterns to control the elastic response of the metamaterial, in particular, to tune the width of its frequency band gap. In perspective, our results open new opportunities for using light-responsive components in devices aimed at elastic wave control, such as elastic beam-splitters, switches, and filters.

## ACKNOWLEDGEMENT

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