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Mechanical tunability in one-dimensional photonic crystals fabricated by direct laser writing

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ABSTRACT

Recently, two-photon polymerization has been successfully employed to fabricate high-contrast one-dimensional photonic crystals. Using this approach, photonic bandgap reflectivities over 90% have been demonstrated in the infrared spectral range. As a result of this success, modifications to the design are being explored which allow additional tunability of the photonic bandgap. In this paper, a one-dimensional photonic crystal fabricated by two-photon polymerization which has been modified to include mechanical flexures is evaluated. Experimental findings suggest these structures allow mechanically induced spectral shifting of the entire photonic bandgap. These results support the use of one-dimensional photonic crystals fabricated by two-photon polymerization for opto-mechanical applications.

Keywords: photonic crystal, two-photon polymerization, photonic bandgap, mechanical flexure, opto-mechanics

1. INTRODUCTION

Photonic crystals have been used in bandgap filtering applications for several decades.[1–6] These structures are ideal due to their ability to induce highly reflective optical photonic bandgaps. The position of these photonic bandgaps can be tuned over a broad spectral range depending on the structure's geometrical constituents. Conventionally, a photonic crystal is categorized as being one-, two-, or three-dimensional.[5] In this study we will focus on the one-dimensional structure where a dielectric periodicity is created along a single axis.[1,2,7–15]

The ability to cause an optical shift in the bandgaps of photonic crystals by mechanical means has been explored in the past.[6,12,16,17] Thanks to the one-dimensional photonic crystals extreme sensitivity to changes in layer thickness, shifting of the photonic bandgap may be realized by straining the structure. This effect has been demonstrated in the THz spectral range using low-density layers composed of cantilever arrays.[18]

Recently, the first demonstration of this concept in the infrared spectral range has been explored by our research team.[13] In this study we aim to further verify the mechanical functionality of the fabricated one-dimensional photonic crystal by studying bandgap edge effects. Previously, only the changes in the bandgap's peak center was observed during mechanical testing. By carefully studying the changes of the bandgap edge reported here, the mechanically induced optical shifting can be more accurately characterized. The results presented here corroborate previous experimental findings, which concluded that photonic crystals incorporating mechanical flexures can be used to dynamically tune the optical response of the crystal using mechanical stimuli.[13]

2. DESIGN, FABRICATION, AND CHARACTERIZATION

Before fabrication of the one-dimensional photonic crystal, the geometry of the photonic crystal was determined using numerical simulations in order to ensure that the photonic bandgap is located in the infrared spectral range. In this study, the optical response was calculated using a simple stratified-layer optical model (WVASE32, J.A. Woollam, Co., Lincoln, NE, USA). This model consists of 13 plane parallel layers which alternate in high- and low-density. This variation in density provides the necessary dielectric contrast to induce photonic bandgaps (see

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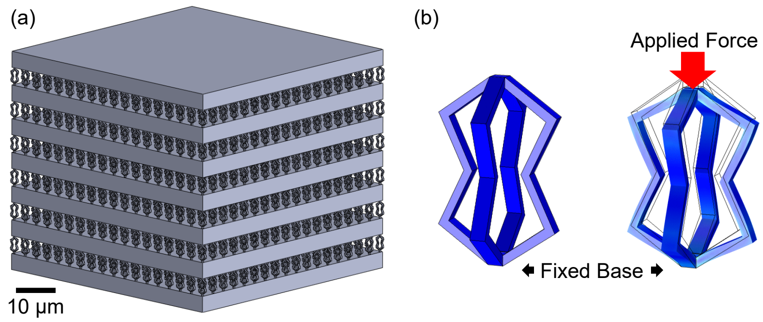

Figure 1. (a) CAD model of the one-dimensional photonic crystal design consisting of 13 alternating high-density compact and low-density layers. The nominal thickness of the high-density layers is 3.35 µm. The low-density layers with a nominal thickness of 3.40 µm are composed of an array of bow tie flexures which are arranged in a square-lattice pattern on the surface with a lattice constant of 2.85 µm. The corresponding nominal volumetric fill factor f_i of the low-density layer is $f_i = 0.04$. (b) Set-up for finite element modeling testing of the flexure geometry used in this study. The left shows the flexure before and the right after some compressive force has been exerted. All portions are free moving with the exception of the bottom surface which remains fixed during simulation.

Refs. [7, 13–15]). For visualization, a CAD model of the structure is given in Figure 1 (a). The structure was fabricated from a single photosensitive polymer (IP-Dip). The optical properties of IP-Dip used in this study can be found in reference [19].

After determining appropriate layer thicknesses and volumetric fill fractions for the photonic crystal structure (see Figure 1 (a)), an appropriate flexure geometry was selected. The flexure geometry used here is a bow tie design adapted from reference [20]. Finite-element modeling (COMSOL, Multiphysics) was used to determine the potential mechanical response of this flexure geometry. The general setup for these simulations is given in Figure 1 (b). The mechanical properties of the photosensitive polymer used here (IP-Dip) vary significantly depending on fabrication parameters. For the model calculations reported in this study, the mechanical properties for IP-Dip reported in Refs. [21, 22] were used.

The one-dimensional photonic crystal is fabricated by two-photon polymerization using a commercially available system (Photonic Professional GT, Nanoscribe, GmBH). The 63x objective was selected for the fabrication of this structure. The settings used during printing were obtained based on a dose matrix testing where laser power and scan speed were varied. The settings which provided a geometry nearest to the nominal design were determined to be at a laser power of 20% (max output 25 kW) and a scan speed of 500 mm/s.

The spectral behavior of the one-dimensional photonic crystal as a function of compressive strain was determined using infrared reflection measurements. Measurements were taken in the spectral range from 1500 cm^{-1} (6.7 µm) to 5000 cm^{-1} (2.0 µm) with 2 cm^{-1} resolution. An IR microscope (HYPERION 3000, Bruker, Inc.) in combination with an FTIR spectrometer (VERTEX 70, Bruker, Inc.) was used for these reflection measurements. A window (Fused Silica) was used to apply compressive force to the photonic crystals while allowing access for reflection for measurements as a function of compressive strain. Note, the window functioned as the first iteration of compressive force. For additional force, weight was added to the edges of the window so as to not obstruct the view for the measurements area.

3. RESULTS AND CONCLUSION

The photonic bandgaps induced by the fabricated one-dimensional photonic crystal within the measurement window is given in Figure 2 (a). Here, four main bandgaps can be seen. The photonic bandgap centered around 4000 cm^{-1} was isolated and observed during the compressive cycle. The change in peak center as a function of compressive force is plotted in Figure 2 (b). A hysteresis behavior can be seen as the photonic crystal is loaded and unloaded. During loading the photonic crystal experiences larger peak shifts than during unloading. This effect is common in elastic materials as energy is lost in the system during the compressive cycle.[23] Figure 2 (c) provides a reflection amplitude colormap of the cycle depicted in Figure 2 (b). In this colormap, the edge of

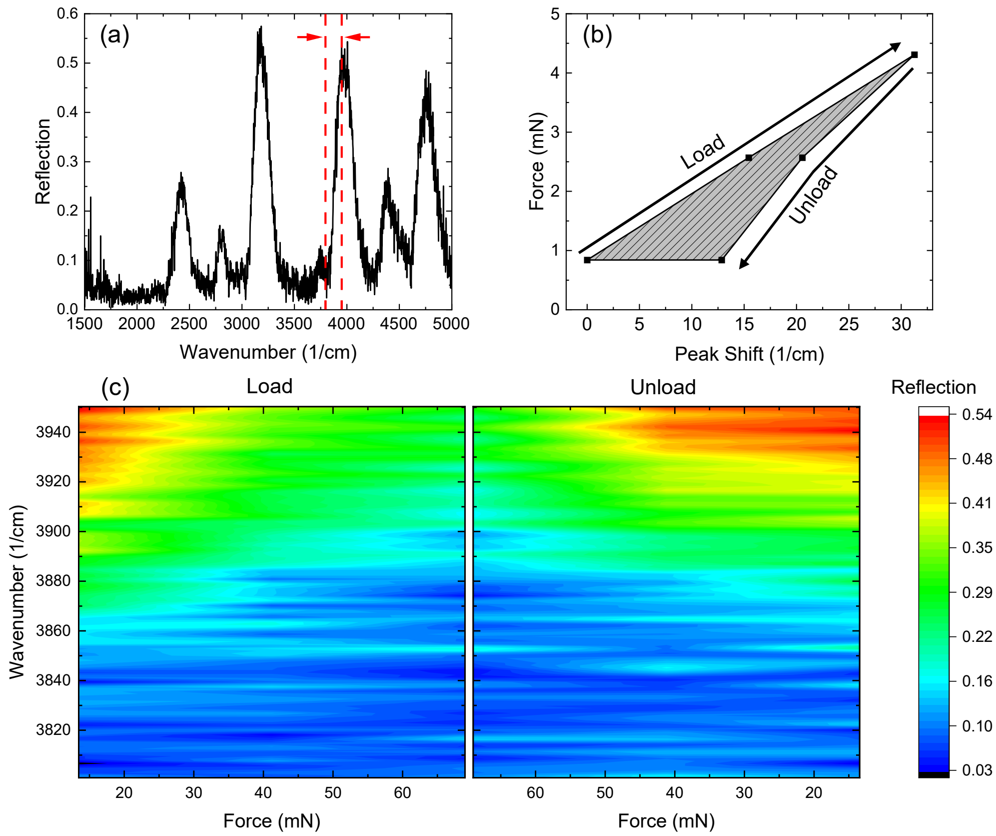

Figure 2. (a) Infrared reflection spectra showing the induced photonic bandgaps for the fabricated one-dimensional photonic crystal. (b) Peak shift as a function of compressive force on the photonic crystal. The bandgap which is isolated for this cycle is located at 4000 cm^{-1} as shown in (a). (c) Colormap of the reflection amplitude as a function of wavenumber and applied compressive force for the compressive cycle plotted in (b) for the spectral region indicated in (a).

the photonic bandgap (red dashed region of Figure 2 (a)) is observed in order to visualize changes in reflectivity during loading and unloading. From this data a clear shift in the edge of the photonic bandgap can be observed.

Mechanical testing of the fabricated one-dimensional photonic crystal under study demonstrates elastic functionality. The spectral shifts which were observed during compressive testing align with the effects of decreasing and increasing low-density layer thickness. Thus, shifting towards the initial bandgap location during unloading indicates the flexures are behaving elastically. Figure 2 (c) illustrates the shifts of the photonic bandgap for the loading and unloading cycle by selectively plotting the edge of the photonic bandgap. Elastic effects are present at the edges of the photonic bandgap and not only at the peak center. These results suggest one-dimensional photonic crystals which include mechanical flexures have opto-mechanical functionality. Such a functionality may be useful in applications such as micro-robotics and MOEMS.[24]

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