One-Dimensional Photonic Crystals with Narrow-Band Defect Modes Fabricated by Direct Laser Writing

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Abstract

One-dimensional photonic crystals incorporating a defect layer were fabricated using two-photon polymerization. The introduction of a defect layer induced a narrow transmission band within the photonic bandgap. Fabrication, characterization, as well as potential applications of these photonic crystals are presented and discussed.

Index Terms

photonic crystal, two-photon polymerization, defect mode, layer thickness non-uniformity

I. Introduction

The ability of two-photon polymerization to fabricate high contrast one-dimensional photonic crystals for the infrared spectral range has been demonstrated [1]. In general, photonic crystals induce a reflective photonic bandgap where transmission is forbidden. This is achieved by creating a dielectric periodicity in one-, two-, or three-dimensions [2]. One-dimensional photonic crystals create a dielectric periodicity in a single direction. These photonic crystals can be easily tuned to the desired spectral range by altering the geometrical structure.

The introduction of defects which disrupt the dielectric periodicity of these one-dimensional photonic crystals can induce narrow band transparencies within the photonic bandgap. This spectral effect has recently been demonstrated in one-dimensional photonic crystals fabricated by two-photon polymerization [3]. Photonic crystals with defects show an increased sensitivity to layer thickness non-uniformity. In this paper we will further analyze the sensitivity these photonic crystals have to this important fabrication parameter and discuss potential applications.

II. Design, Fabrication, and Characterization

The one-dimensional photonic crystals which are characterized here were fabricated by a commercially available two-photon polymerization system (Photonic Professional GT, Nanoscribe, GmbH). This direct laser writing system allows the fabrication of nearly arbitrary structures from a single monomer with resolutions on the scale of a few hundred nanometers. This allows for the fabrication of sub-wavelength features in the design of one-dimensional photonic crystals for the infrared spectral range. In this case, a dielectric periodicity is created by altering layers of high- and low-density. The high-density layers consist of the solid monomer (IP-Dip). The low-density layers consist of a combination of pillars (IP-Dip) and the air between the pillars as shown in 1. The Bruggeman effective medium approximation is employed here to describe the dielectric properties of these low-density layers, this is described in detail in reference [4]. The dielectric properties of the monomer used in this study have been previously characterized for infrared spectral range and can be found in reference [5].

Using a simple stratified-layer optical model (WVASE32, J.A. Woollam, Co.) the spectral position of the photonic bandgap was designed such that it fell within a range where the monomer (IP-Dip) was transparent. A compact defect layer is introduced to the center of the layer stack which induced a defect mode in the center of this photonic bandgap. A design which supports these constraints can be seen in figure 1. Reflection measurements of these photonic crystals were conducted using an IR Microscope (HYPERION 3000 Bruker, Inc.) from 2000 cm^{-1} to 3000 cm^{-1} with a resolution of 2 cm^{-1}. Characterization of the spectral response of these photonic crystals was performed using the same simple stratified-layer optical software (WVASE32) which was employed for the design.

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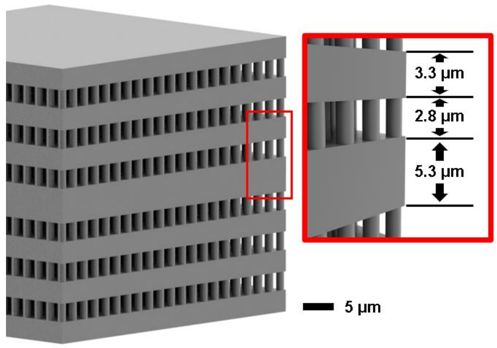

Fig. 1. CAD model of the designed one-dimensional photonic crystal investigated here. The photonic crystal consist of 6 alternating high- and low- density layers with a central high-density defect layer. The pillars have a diameter of 1.2 µm with a square lattice periodicity of 2.4 µm. The layer thicknesses of the low-density, high-density, and defect layer are given in the inset.

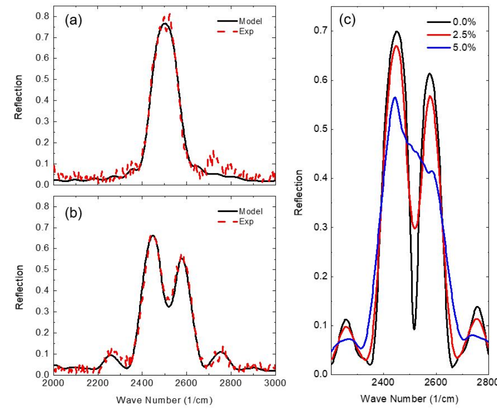

Fig. 2. Plots (a) and (b) compare the best-model calculated (solid) and experimental (dashed) reflection data for a photonic crystal without and with a defect layer respectively. Plot (c) illustrates the modeled effect of increasing layer thickness non-uniformity on defect mode amplitude for 0.0%, 2.5%, and 5.0% non-uniformity.

III. Results and Discussion

Initial fabrication attempts in photonic crystals without defects showed consistent variation in the layer thicknesses of the high- and low-density layers from that of the nominal design. Upon performing a Levenberg-Marquardt-based algorithm to fit the experimental spectral response it was found that, on average, the high-density layers were 8% thicker than designed and the low-density layers 30% thinner than designed. Conventionally, to correct for these density dependent effects, fabrication parameters would have have to be adjusted independently for each layer including laser power, scan speed, and hatching and slicing distances for example. This independent correction process would be complex and time consuming. As an alternative, a scaling factor was introduced to compensate which considers these density-dependant variations simultaneously.

The introduction of a scaling factor resulted in the fabrication of true-to-design photonic crystals both without and with defects. Best-model calculated layer thicknesses described variations of less than 2% in all layers from the nominal designed given in figure 1. The best-model calculated and experimental bandgaps for both a photonic crystal with and without a defect are shown in figure 2 (a) and (b), respectively. A significant amplitude reduction was observed in the defect mode from what was originally modeled by half. This reduction is an effect of layer thickness non-uniformities within the layers of the photonic crystal. The amplitude effects of this non-uniformity was observed in photonic crystals without defects but were minimal in comparison to the observed effect in photonic crystals with defects. In figure 2 (c) the effect of increasing layer thickness non-uniformity on defect mode amplitude can be visualized.

IV. Conclusion

The fabrication of one-dimensional photonic crystals by two-photon polymerization can produce high-contrast photonic bandgaps which are tunable for the spectral range of interest. The spectral response of these photonic crystals can be further manipulated by introducing defects which disrupt the dielectric periodicity. Since true-to-design layer thicknesses are crucial in the photonic bandgap and defect mode spectral position, implementation of a scaling factor is a necessary and effective corrective method. It is also noted that photonic crystals with defects show an increased sensitivity to layer thickness non-uniformity when compared with their defect-free counterpart. This sensitivity could be used to quantify this otherwise difficult to measure fabrication non-ideality for more accurate and rapid prototyping.

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