MODELLING, DESIGN AND FABRICATION OF DIELECTRIC PHOTONIC CRYSTAL STRUCTURES USING TEMPORALLY ASYMMETRIC SHAPED FEMTOSECOND LASER PULSES

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ABSTRACT

We present high aspect ratio Fano-resonance structures for optical filter application along with their fabrication technique, design and numerical simulation. The structuring of photonic crystal elements using temporally shaped femtosecond laser pulses is described. Performance considerations for the presented device due to angular spread of a real optical beam are discussed in addition.

Keywords- dielectric photonic crystals, guided-mode resonance, femtosecond laser, temporally asymmetric shaped pulses, TOD, FDTD, beam profile

INTRODUCTION

Guided-mode resonance (GMR) based devices are emerging in various application fields such as optical filters [1-3], micro-electro mechanical systems (MEMS) [2,4] and polarizers [4]. Due to their compactness, low cost and potential to be operated in a wide spectral range such as near infrared [1,2], ultraviolet and visible regions [2,3], dielectric photonic crystals (PhCs) have proven to be a suitable alternative to conventional optical filters. Besides being more stable and easy to fabricate, a main challenge considering all-solid dielectric slab devices is to achieve strong Fano-resonances due to their low refractive index contrast between the layers. Additionally, conventional fabrication techniques such as electron-beam lithography and focused ion beam (FIB) milling lithography suffer from surface charging problems and prolonged process durations due to hardness of dielectric materials, which limits the fabrication quality. The use of high energy femtosecond (fs) laser pulses for material processing [5-8] offers a good fabrication alternative with many different advantages including rapid structuring, high aspect ratio, no vacuum condition requirement, low cost and no surface charging. In general laser structuring is restricted by diffraction limit but in previous works we have shown that structure sizes of one order of magnitude below the diffraction limit [5,6,9] can be achieved by using temporally asymmetric shaped laser pulses obtained by introducing third order dispersion (TOD).

TECHNOLOGICAL FABRICATION

Our fabrication setup consists of a Ti:Sapphire femtosecond laser system which generates linearly polarized laser pulses with a full width at half maximum (FWHM) of 35 fs at a central wavelength of 790 nm along with pulse shaping and material processing mechanism [5-7,9]. The pulses pass through a custom built phase modulator [6,9] to reach a 50x objective with NA=0.5 to form a spot diameter of 1.4 µm. We use temporally asymmetric shaped pulses by introducing TOD of $\emptyset_3 = +6 \times 10^5 \mathrm{fs}^3$ to generate structures below the diffraction limit. TOD pulses consist of a high energy pulse followed by a sequence of sub-pulses. The high energy pulse provides enough photons to meet the band gap threshold, enabling the electrons to reach the conduction band (multiphoton ionization). The sequence of sub-pulses ignites further ionization (avalanche ionization) resulting in ablation process [8]. This ionization process is known as seed and heat mechanism. Cross-sectional view and schematic of melting rim (inset) of structure fabricated by a single shot laser pulse are shown in Fig. 1. The formation of a rim around the surface diameter of the hole, the hole-shape and depth are linked to the focus position of the laser to the substrate.

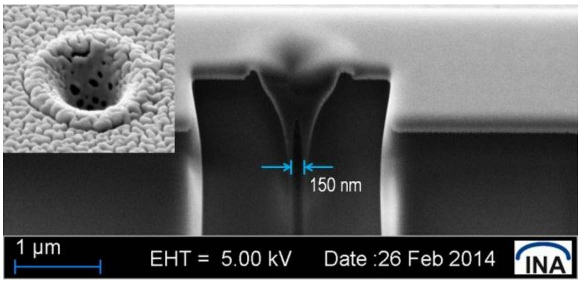

Fig. 1. Cross-sectional view (generated by focused ion-beam) of the structure in fused silica, fabricated by using a single shot fs TOD pulse. The hole has a surface diameter of 800 nm which decreases rapidly downwards to form a channel of 150 nm and a depth of a few micro-meters.

DESIGN & NUMERICAL SIMULATION

Design and simulation of the fabricated structures is performed by 3D Finite-difference Time Domain (FDTD) method using an open source software *meep*

[10]. The output spectra are obtained by Fourier transform of the time domain simulation. Since our current investigations involve only structuring bulk materials, the high refractive index layer is assumed to be deposited after the structuring of the PhC elements, which results in an irregular surface profile along with the hollow voids below it (Fig. 2). The simulation considers a unit cell containing all the required information of the original structure essential to compute effects such as influence of hole-shape, rim, layer deposition and resonances in a low-index contrast slab. It is repeated in lateral direction by periodic boundary conditions (PBC) and the domain is terminated in vertical directions by applying perfectly matched layers (PML). Full 3D models are simulated if investigation of a real device with limited dimensions and source problems is required. The device has a lattice constant of 1 µm, with surface diameter of holes 600 nm and depth of 2 µm. The waveguide layer is 330 nm thick with a refractive index of 2.2, deposited over a fused silica substrate having refractive index 1.5. The filter shows a sharp narrowband resonance at 1.78 µm with negligible effects of rim formation (Fig. 3). The whole device can be scaled down to tune to different wavelengths considering the material properties.

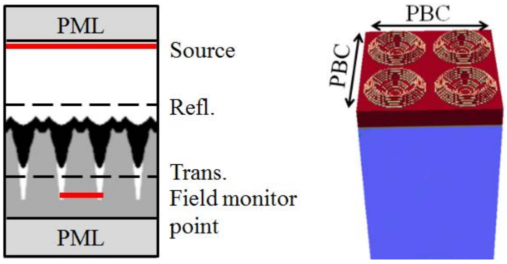

Fig. 2. Simulation domain composition and use of boundary conditions.

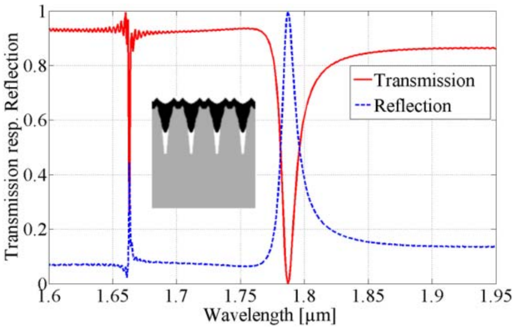

Fig. 3. Transmission and reflection spectra along with the cross-sectional view of simulated PhC structure.

PERFORMANCE CONSIDERATIONS

The performance of the presented device in potential applications is studied with a custom made characterization setup. The setup is a combination of optical fiber and free space optical elements [4]. The setup makes use of a spatial Gaussian beam profile focused to a small spot diameter, targeted to characterize small devices. From fundamental considerations it is known that Fano-resonances are sensitive to angular spread and polarization properties of the incident wave. The impact of this resonance behavior is currently under investigation by numerical simulations.

CONCLUSION & OUTLOOK

In this paper, a fabrication technique of high aspect ratio dielectric PhCs using temporally asymmetric shaped fs laser pulses along with its design and numerical simulation is presented. Effects of rim formation on output spectra and the challenges faced during characterization of dielectric PhC filters with a Gaussian beam profile are also discussed. Direct patterning using fs laser pulses proves to be a very efficient fabrication technique for nanophotonics and the numerical simulation of high aspect ratio PhC structures shows that it has a great potential towards narrow band Fano-filters. Furthermore, these periodic structures can be scaled down to operate in visible and UV regions.

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