Chapter 3
Material Processing of Dielectrics via Temporally Shaped Femtosecond Laser Pulses as Direct Patterning Method for Nanophotonic Applications

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Abstract Dielectric materials are of great interest for optical applications since they are transparent in the UV, visible and IR spectral range. That makes them very suitable for optical filters, polarizer, waveguides or even reflectors. When dielectrics are processed with conventional techniques based on electron or ion bombardments, they suffer from severe charging effects. For this reason, we present temporally shaped femtosecond laser pulses as a novel direct patterning method of wide band gap materials with very high precision to create photonic crystal structures in dielectrics. Material processing with temporally shaped femtosecond laser pulses overcomes the charging problems. Fabrication of structures well below the diffraction limit is feasible with temporally shaped asymmetric pulse trains due to nonlinear ionisation effects like multiphoton ionisation and avalanche ionisation. For the implementation as optical filters, a thin-film waveguide with a 2D periodic pattern of photonic crystals with circular base elements is investigated. The wave guiding layer consists of a material with a higher refractive index than the surrounding materials, in our case SiO_2. Although the refractive index contrast is low, numerical design results prove that light with normal incidence to the plane of

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periodicity couples to waveguide modes and Fano resonances are excited. This makes the device extremely interesting as a compact narrow-band optical filter.

Keywords Photonic crystal • Fano resonance filter • Low refractive index contrast • Dielectrics • Shaped femtosecond laser pulse

3.1 Introduction

Dielectric materials offer great potential for applications in photonic devices since they are transparent in the UV, visible and near infrared spectral range. A vast variety of dielectric materials is available with good chemical and mechanical stability and processing properties, especially oxide and nitride compounds. The implementation of nanophotonic structures like photonic crystals with dimensions smaller than the targeted wavelength enables the utilization of strong interaction or other specific effects.

On the one hand, dielectrics offer low-cost fabrication when compared to semiconductors, but in contrast to them they underlie severe charging effects when processed with conventional techniques based on electron beam lithography or focused ion beams as already presented in a previous work [1]. Material processing with temporally shaped femtosecond laser pulses avoids these charging effects. Additionally, it provides very fast processing times, while no additional sample treatments and no vacuum conditions are required.

The interaction between laser irradiation and transparent materials is mainly based on the deposition of energy into the medium. This enables the ablation of the material by plasma formation and the expansion of the plasma into the material [2–4]. The free electron density is controlled in this case by temporally shaped femtosecond laser pulses. The two main ionization processes involved are multiphoton ionization and avalanche ionization [5, 6]. The utilization of these effects allows the generation of reproducible structures with dimensions being an order of magnitude below the diffraction limit [5, 7, 8].

Our design consists of a photonic crystal (PhC) array and a wave guiding layer with dimensions smaller than the target wavelength. We utilize the guided-mode resonance effect from light with normal incidence to the surface, which is based on the interference between the resonant waveguide modes and free space modes. Thus, externally propagating fields from direct transmission or reflection, respectively, couple to modes of the waveguide [9]. Hessel and Oliner [10] gave the first model in 1965 to describe these resonance types. Since then, different approaches using this effect as well as possible photonic applications have been reported [1, 9, 11–14].

3.2 Design and Fabrication

We generate a periodic grating of photonic crystal structures with circular base elements via shaped femtosecond laser pulses into a silicon oxide (SiO_2) substrate with a refractive index of $n_{\mathrm{Low}} = 1.5$. The deposition of a thin Nb_2O_5 layer with a

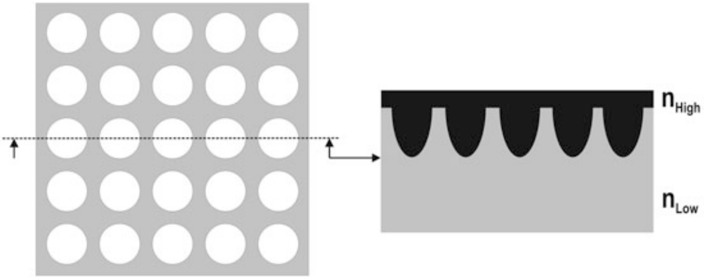

Fig. 3.1 *Left*: A photonic crystal structure array generated into a fused silica substrate (n_{Low}). *Right*: Sectional view with added waveguide layer (n_{High})

higher refractive index $n_{High} = 2.2$ completes this guided-mode resonance filter device. A schematic of this design is depicted in Fig. 3.1. The Nb_2O_5 layer acts as slab waveguide and enables the coupling of incident light to discrete slab modes. Although the refractive index contrast is low, we prove this device to be suitable as narrowband filter. We achieved asymmetric Fano resonances in the near infrared spectral region for base element structure sizes of typically a couple hundred nanometers. By simple scaling down, this kind of devices are also applicable in the visible or UV spectral range.

The laser setup for material processing consists of an amplified Ti:Sapphire laser system which provides linearly polarized laser pulses with a full width at half maximum (FWHM) duration of 35 fs at the central wavelength of 800 nm. Laser pulses are temporally shaped with a self-built pulse shaper [15] and focused onto the substrate with a microscope setup. The lateral spot diameter is 1.4 μm ($1/e^2$ value of the intensity profile). During the experiment, the energy of the pulses is controlled and monitored with a neutral density gradient filter and a photodiode, respectively. The sample is moved via a 3-axis piezo stage which provides an accuracy of 10 nm.

PhC profiles were produced by means of bandwidth-limited and modulated femtosecond laser pulses by introducing a third order dispersion (TOD) of $\varphi_3 = +6 \times 10^5$ fs^3. TOD shaped pulses with positive φ_3 were applied which show a temporally asymmetric profile. This specific pulse profile consists of a high energy sub-pulse followed by a long pulse train of lower energies with a constant instantaneous frequency throughout the entire pulse. Different focal positions of the laser beam relative to the substrate surface are investigated. They vary in vertical direction from a few micrometers below the substrate surface to a few micrometers above in steps of $\Delta z = 1$ μm, with the total energy of the pulses remaining constant.

The characterization of the inner profiles of the generated PhC structure was carried out after focused ion beam (FIB) preparation. Cross-sections were performed at the center of the elements to evaluate specifically the diameter D and depth h. A thin platinum layer was sputtered onto the entire substrate as conductive layer to avoid charging of the dielectric material while operating with FIB and SEM. Additionally, a platinum layer was deposited locally on the

PhC elements to protect the structure during the milling process. After cross-sectioning, the PhC profile parameters were measured in the SEM mode.

3.3 Results

The numerical simulation in Fig. 3.2 demonstrates a suitable conical PhC shape for implementation as narrowband optical filter. The parameters for the calculation are diameter $D = 500$ nm, depth $h = 900$ nm, lattice constant $a = 1$ μm and waveguide layer thickness $d_{\mathrm{wgl}} = 330$ nm. Two sharp narrowband resonances are observed at wavelengths around $\lambda = 1.52$ μm and $\lambda = 1.82$ μm.

As first experimental result,[1] shown in Fig. 3.3, we compare the PhC profiles fabricated with a bandwidth-limited pulse and a TOD shaped pulse with the same focal position (on the substrate surface) and same energies (2.5 times above the damage threshold). In comparison, the diameter at the surface is similar for both types of pulses: for bandwidth-limited pulses $D = 956$ nm and for TOD pulses $D = 985$ nm. The profile created by the bandwidth-limited pulse is restricted in depth to around 340 nm, while the result created by the TOD pulse shows a

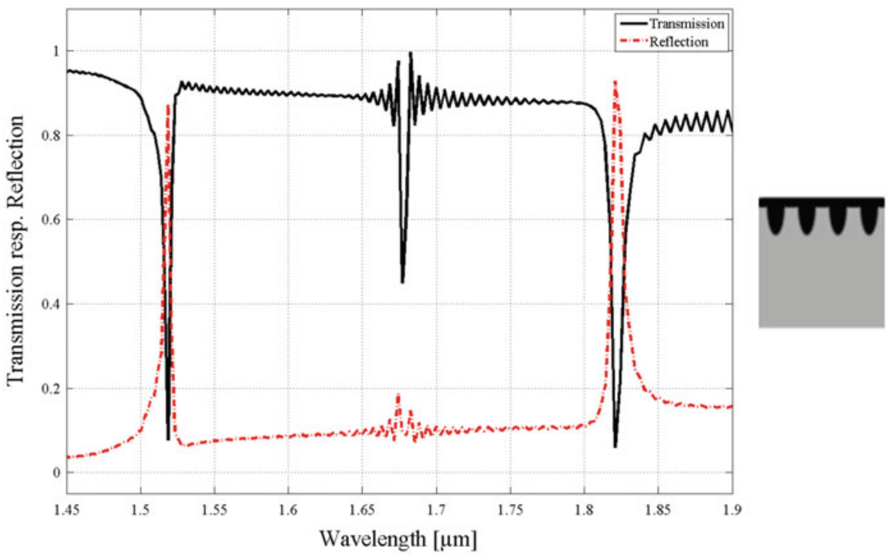

Fig. 3.2 Numerical simulation performed with the parameters: diameter $D = 500$ nm, depth $h = 900$ nm, lattice constant $a = 1$ μm and waveguide layer thickness $d_{\mathrm{wgl}} = 330$ nm. Two sharp narrowband resonances appear at wavelengths around $\lambda = 1.52$ μm and $\lambda = 1.82$ μm

[1] All measured values underlie an error of ±20 nm due to analyzing software.

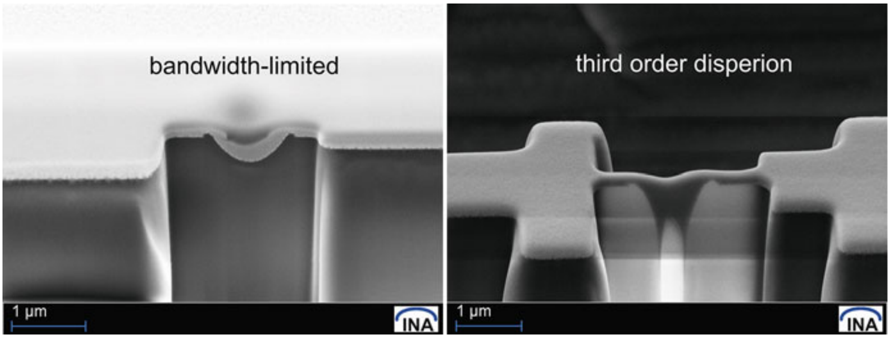

Fig. 3.3 Resulting hole profiles from a bandwidth-limited pulse (*left*) and a TOD shaped pulse with $\varphi_3 = +6 \times 10^5$ fs^3 (*right*) at the same focal position $z = 0$ µm with energies 2.5 times above damage threshold. The difference in penetration depth is clearly observable

funnel-shaped hole with an increased depth of more than 2 µm. Hence, the aspect ratio of PhC elements created by bandwidth-limited pulses is not sufficient to achieve strong guided-mode resonances, whereas the PhC structures created by TOD show a promising profile. Additionally, for the same energy values less than 250 nm of the inner diameter were achieved, which is well below the diffraction limit (1.4 µm).

3.4 Conclusions

We demonstrated numerically that our PhC designed structures show great potential for application as narrowband optical filters due to guided-mode resonances. The characterization of the PhC profiles confirms that direct material processing via temporally shaped femtosecond laser pulses is a very promising tool for nanophotonic device fabrication in dielectric materials. We compared PhC profiles fabricated with bandwidth-limited laser pulses and TOD shaped laser pulses. TOD shaped pulses provide a very promising aspect ratio.

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