Design and Analysis of Femtosecond Laser-Generated Metasurface for Optical Filter Application

Yousuf Khan 1,2,*
Dua Noor 1
Naqeeb Ullah 1
Svetlana N. Khonina 3,4
Nikolay L. Kazanskiy 3,4
and Muhammad A. Butt 4,5

1 Nanophotonics Research Group, Department of Electronic Engineering, Balochistan University of Information Technology, Engineering and Management Sciences, Quetta 87300, Pakistan
2 Nanophotonics Research Group, Technological Electronics, Institute of Nanostructure Technologies and Analytics, University of Kassel, Heinrich-Plett-Str. 40, 34132 Kassel, Germany
3 IPSI RAS—Branch of the FSRC “Crystallography and Photonics” RAS, 443001 Samara, Russia
4 Technical Cybernetics Department, Samara National Research University, 443086 Samara, Russia
5 Institute of Microelectronics and Optoelectronics, Warsaw University of Technology, Koszykowa 75, 00-662 Warsaw, Poland
* Correspondence: yousuf.khan@buitms.edu.pk

Abstract: This work investigates a Fano filter design based on a nano-hole array, patterned in fused silica using high-energy ultrafast femtosecond laser pulses. After carefully observing the experimental results, the structural profile of the nano-holes is numerically modeled in a 3D finite-difference time-domain-based software platform. The metasurface design consists of conical shaped air holes structured in the substrate, and a later deposited waveguide layer which leaves craters on the surface as the material fills inside the nano-holes. The spectral properties of the device are studied against variations in the structural parameters, such as the depth of the nano-holes, its surface diameter, and the depth of the craters on the surface of the waveguide. The proposed Fano filter device is designed to operate in the near-infrared (NIR) wavelength range around a telecommunication window of 1550 nm. Multiple narrowband resonances are observed with a linewidth in the range of 1.4 to 24.2 nm and a quality factor of 66.51 to 1090.12. The device shows good spectral tunability over a wide range from 1380 to 1650 nm comprising multiple narrowband resonances and variations in the structural parameters. Since the device can be implemented using a cost-effective and rapid fabrication method, it can be proposed for use in various optical filtering and sensing applications.

Keywords: femtosecond laser structuring; photonic crystals; dielectric materials; metasurfaces; optical filter; structural properties

1. Introduction

1.1. Background

The continuous advancement in the miniaturization of technology in various application areas has increased the demand for rapid, cost-effective, and versatile material processing and fabrication techniques. Moreover, considering the materials being used for nanophotonic applications, dielectrics have been a favorite candidate due to their cost-effectiveness, low absorption over a wide spectral range, higher mechanical stability, and inert chemical properties. However, dielectric materials also come with a few disadvantages, for example, during fabrication they are hard to etch and undergo surface charging effects during SEM imaging, limiting their fabrication quality [1,2]. Many nanophotonic applications, such as optical filtering [2], sensing [3], and optical switching [4], involve periodic nanostructures in dielectric materials commonly known as photonic crystals (PhCs). The most commonly used techniques for the conventional fabrication of PhCs include electron-beam lithography [5], focused ion-beam milling lithography [6,7], reactive ion-etching (RIE) [8], and nanoimprint lithography [9,10]. All of these techniques are relatively
complex, requiring vacuum conditions, charge particle-based beams, and the usage of etchant chemicals. Moreover, they also involve multiple process steps and lengthy fabrication procedures. An emerging and alternate fabrication method is the usage of high-energy ultrafast laser pulses for material processing commonly known as a femtosecond (FS) laser [1,2,11,12]. Usage of the FS laser has already been proposed for various application areas including design of optical filters [1,2,12], refractive index sensing [13,14], fluid sensors [15], surgery [16], biomedical sensing [17], chemo-sensing [18], nanolithography [19], and nano-welding [20].

1.2. Motivation for the Study

The FS laser structuring can write the structures directly onto the surface of the specimen without requiring vacuum conditions, preprocessing, and photolithography steps. Additionally, the technique is fast and easy to operate. The FS laser material processing entails thermal ablation [12,21,22] of the target material using temporally shaped FS laser pulses [1,22,23]. The energy of the incident laser irradiation is absorbed in the material; thus, enabling the ablation process by the formation of plasma and its expansion into the material [21–23]. The ablation process consists primarily of two ionization processes: multiphoton ionization and avalanche ionization [21–25]. The pulse shape and energy can be engineered as per the bandgap of the subject material [24,25]. FS laser processing offers a generation of reproducible nanostructures with structural dimensions in the order of magnitude below the diffraction limit of incident laser pulse [22–26]. Moreover, the structural properties of the resulting nanostructures can be varied by tuning the properties of the incident laser pulse such as pulse energy, its shape, and the focal point on the targeted material.

1.3. Contribution of the Study

This article focuses on investigating the spectral properties of a Fano filter, based on different structural parameters of nanostructures produced by asymmetric temporally shaped FS laser pulses. Following a careful study of the experimental results presented in [1,26,27], a numerical model of the nanostructure is designed featuring the structural profile. The investigated structural parameters include the depth of the nano-hole, its surface diameter, and the depth of the crater on the surface, due to the deep filling of material in the nano-holes. The designed device works on the principle of guided-mode resonances (GMR), also known as Fano resonances [28,29]. The studied spectral properties include shifting of the resonant wavelength $\lambda_{res}$, variation in the linewidth ($\Gamma$), and the quality factor ($Q_F$) of the resonant modes. The optimum filter design of the Fano filter is chosen based on the quality of the resonant modes. The designed filter operates in the NIR range around the telecommunication window of 1550 nm, which is well proposed for usage in optical fiber communication, sensor design, and numerical devices for optical computing.

2. Related Works

Thus far, optical filters have been demonstrated using different basic techniques such as ring resonators [30,31], optical pump-rejection filters [32,33], and waveguide coupled resonators [34]. Moreover, periodic structures such as PhCs have been demonstrated in various application areas, such as optical filters [2,6], optical switching [4], sensors [5], dielectric metasurfaces [35], and several other nanophotonic applications [26,36]. PhCs are implemented in semiconductors, metals, and dielectrics. Dielectric PhCs have been demonstrated in several spectral ranges including ultraviolet (UV), visible, and near-infrared (NIR) wavelengths [1,2]. Structuring of fused silica to design optical filters in the NIR range using temporally shaped FS laser pulses have been reported in [1,2,26]. The ablation and ionization processes of femtosecond laser pulses in dielectric materials is well explained in [21–25]. Moreover, pulse shaping of the FS laser using bandwidth-limited ultrashort pulse (BWL) and chirping of laser pulses by introducing group delay dispersion (GDD) and third-order dispersion (TOD) is discussed in [23]. The design of optical filters in
the NIR range using different depths and shapes of the FS laser-generated nanostructures in a silica substrate is reported in [1,2,26,27]. Additionally, the authors of [14,15] investigate a design of fluid sensors based on FS laser-generated nano-holes introduced in fiber optics. The application of the FS laser in biomedical sensing in the NIR range for the detection of biological refractive indices is discussed in [17,18].

3. Materials and Methods

3.1. Experimental Work

The nano-holes were structured using a Ti: Sapphire femtosecond laser, setup with a laser source operating at 790 nm wavelength, and generating linearly polarized laser pulses with full-width at half-maximum of 35 femtoseconds and an energy of 250 nJ [22–25]. The laser pulses were passed through a custom-built phase modulator setup [23,25] and a 50× objective with numerical aperture NA = 0.5 and formed a spot diameter of 1400 nm. The pulses were shaped by introducing a third-order dispersion (TOD) of $\phi_3 = +6 \times 10^5$ fs$^3$ to produce temporally asymmetric pulses which were capable of generating structures with a feature size below the diffraction limit [1,2,27]. The TOD pulses consisted of a sequence of pulses with a first high-energy pulse followed by sub-pulses. The high-energy pulse was tuned to provide enough energy to meet the bandgap of the targeted material, enabling the electron to reach the conduction band. Adding to that, the sequence of sub-pulses triggered further ionization, resulting in an ablation process within the material [1]. A detailed explanation of the experimental setup and pulse shaping is given in [22–25]. A Scanning Electron Microscopy (SEM) image showing a cross-sectional and top view of the experimental results are depicted in Figure 1a,b. The images were prepared on a dual platform Focused Ion-beam (FIB) machine [31]. To make a periodic PhC structure, the laser setup was programmed to move in steps of 1000 nm in both lateral directions with a fixed vertical focal distance, as depicted in Figure 1b. The nanostructures used in this work were taken as a reference for numerical designs from previous works of the research group [1,26,27]. It can be observed that the fabricated structure (Figure 1a) had a marginally conical shape with a depth of around 1500 nm and a surface diameter in the range of 600 nm. Moreover, the SEM image also showed a secondary material (light grey shade) filled into the air holes which it adopted to fill deep inside the hole leaving a crater on the surface (dark grey shade). All of these observations are carefully noted and mimicked in the numerical design shown in Figure 2.

![Figure 1](image-url)
The design and simulations were performed on a software platform called MIT Electromagnetic Equation Propagation (MEEP) [37,38]. MEEP is an open source software package used for EM wave simulations which allows python scripting of the code. MEEP is a Finite-Difference Time-Domain (FDTD)-based package that computes the EM field by solving Maxwell’s equation in space and time by converting the simulation domain into a Yee grid [39,40]. The mesh size of the simulation domain was defined with a resolution of 30, with a central wavelength of the excitation source at 1400 nm, with the number of frequencies to compute flux as $nf = 1000$. Figure 2a shows the 3D view of the numerical design with a waveguide layer (red color) deposited on top of the already structured silica substrate (blue color). The substrate had a refractive index of $n_s = 1.5$ and the waveguide layer was designed with a refractive index of $n_w = 2.2$. The refractive indices of the materials were taken as a reference from published works by the group in [6,27]. The holes were placed with a lattice constant of $a = 1000$ nm, with the purpose of enabling the operation of the Fano filter in the NIR range. In Figure 2b, a unit cell simulation model of the designed device is shown with the termination of the simulation cell with Perfectly Matched Boundary Conditions (PML) in upper and lower z-directions. The unit cell is repeated in both lateral directions ($x$ and $y$), using Periodic Boundary Conditions (PBCs) to simulate a perfect crystal structure. A plane wave excitation source (indicated by a red line) is placed above the structure and the field is calculated using a transmission flux monitoring layer (dotted red line) below the waveguide layer. A field decay monitor point placed below the transmission layer helps the software decide when to stop the simulation as per user-defined conditions. The investigated structural parameters, i.e., depth of the nano-hole $d$, radius of the nano-hole $r$, and depth of the crater $c$ on the surface are also indicated in Figure 2b.

4. Results and Discussion

The structural morphology and physical properties of the FS-generated structures may vary following the incident laser-pulse parameters. These parameters include the shape of the pulse, its energy, and the focus point on the substrate. The transmission spectrum of a PhC structure with conical holes, with structural parameters of $d = 900$ nm, the radius of holes as $r = 250$ nm, and the depth of the crater as $c = 300$ nm is shown in Figure 3. The
transmission spectrum appears with three different narrowband Fano resonances. The spectral parameters of these resonances are evaluated by curve fitting of Fano resonance lineshape function represented in Equation (1), whereas, the QF of these resonances is given by Equation (2):

\[ F(\omega) = A_o + F_o \frac{q + 2(\lambda - \lambda_{res})/\Gamma)^2}{1 + [2(\lambda - \lambda_{res})/\Gamma]^2} \]  

\[ QF = \frac{\lambda_{res}}{\Gamma} \]

where \( q \) is the Fano factor; \( \lambda_{res} \) is the central wavelength of the resonant mode; \( \Gamma \) represents the linewidth; and \( A_o \) and \( F_o \) are constants. In Figure 3, the values of the Fano factor \( q \) are varied to obtain the appropriate shape of the Fano function, and the linewidth \( \Gamma \) for the resonant modes appearing at \( \lambda_{res} = 1381.398 \), \( \lambda_{res} = 1573.103 \) and \( \lambda_{res} = 1645.347 \) are listed in Table 1. The device shows good potential for multi-purpose optical filtering and sensing applications. However, to make the study simple, the resonant mode that appears at \( \lambda_{res} = 1573.103 \) is considered for the investigation of an optical filter design, as it has the narrowest linewidth of 7.391 nm with a considerably symmetric shape, and is located near a telecommunication window of 1550 nm. The following sections from Section 4.1 to Section 4.3 are dedicated to the investigation of the above-mentioned structural parameters, i.e., radius, depth, and crater size.

![Figure 3. Transmission spectrum of the 3D-FDTD unit cell model of the nano-hole with \( d = 900 \) nm, \( r = 250 \) nm, and \( c = 300 \) nm. The transmission spectrum shows three narrow-band resonances appearing at 1381.398, 1573.103, and 1645.347 nm wavelength ranges.](image)

### Table 1. The values of the parameters used in the Fano function to obtain the curve fitting for the three resonant modes are shown in Figure 3.

| Central Wavelength (\( \lambda_{res} \)) (nm) | Fano Factor (\( q \)) | Linewidth (\( \Gamma \)) (nm) |
|--------------------------------------------|----------------------|-------------------------------|
| 1381.398                                   | 0.44                 | 8.191                         |
| 1573.103                                   | 0.15                 | 7.391                         |
| 1645.347                                   | -0.41                | 12.791                        |

### 4.1. Surface-Radius of Nano-Holes

The diameter of the FS laser-generated nano-holes can vary following the shape of the laser pulse, its energy, and the focal point. Moreover, different kinds of laser pulses can...
create nano-holes with different structural profiles where the surface radius can also be changed. This section investigates the $r$ of the conical shape nano-hole shown in Figure 1b. The value of $r$ is varied from $r = 200$ to $300$ nm with a step size of $20$ nm keeping all the structural parameters constant. The resultant transmission spectra are shown in Figure 4, where a redshift of resonant modes can be observed, along with an increase in the linewidth of the resonances. The effect can be interpreted in terms of an increase in the effective refractive index $n_{\text{eff}}$ of the waveguide layer where the material is also filled in the nano-holes. The rise in $n_{\text{eff}}$ corresponds with the increase in thickness of a slab waveguide, where a thickness waveguide can accommodate higher order modes and a wider spectral range. In Figure 4, some peaks in the transmission spectra exceed unity which is due to the unresolved field components caused by sharp structural features of the nano-holes. It can be avoided by decreasing the value of field decay check even further.

Figure 4. Transmission spectra of PhC-structure with hole-radii varied from 200 to 300 nm. A redshift along with an increase in the linewidth of the resonant modes can be seen.

The structural and spectral characteristics of the device for variation in $r$ of the nano-holes are summarized in Figure 5 in terms of plots representing the shifting of $\lambda_{\text{res}}$, linewidth, and $QF$. Figure 5a depicts different shapes of the nano-holes as a result of variation in the value of $r$. Since the lattice of the device is designed as $a = 1000$ nm, it is kept in mind that the value of the upper diameter ($2r$) must not exceed the value of $a$. It can be observed in Figure 5b that the $\lambda_{\text{res}}$ follows an almost linear trend from $1525$ nm to $1610$ nm as the value of $r$ varies from $200$ nm to $300$ nm, which can be promising in the spectral tuning of the Fano filter device; meanwhile, considering the linewidth of the resonant modes, a non-linear trend is observed where a minimum linewidth in order of $1.40$ nm is observed for $r = 200$. The linewidth increases exponentially as the $r$ increases until it reaches a maximum value of $24.20$ nm when $r = 300$ nm. Similarly, the $QF$ of the modes follows an exponential trend where it has its highest value of $QF = 1090.12$ for the sharp resonance appearing for $r = 200$ nm and a minimum value of $QF = 66.51$ for $r = 300$ nm. Therefore, a nano-hole with $r$ in the range of $200$ to $250$ nm can be recommended for an optimum design of a Fano filter.
The transmission spectra shown in Figure 6 depict the shifting of resonant modes with a redshift along with an increase in the linewidth of the resonant modes can be observed. Figure 6, a wide spectral range starting from 1535 nm to 1572 nm. It can also be observed that transmission peaks appearing at lower values of $d$ are shallower and they start reaching zero value as the depth increases. The redshift of the resonant modes can again be interpreted by the phenomenon of a rise in $n_{eff}$ of the waveguide.

4.2. Depth of Nano-Holes

Depending on the FS laser-pulse shape and the focus of the laser on the substrate, the depth of the damage can be decided. During experimentation, if the focus of the laser is kept above the surface, the resultant damage will be less deep, and if the focus is on the surface or moved below the surface, the depth of the nano-holes will increase. Considering the high aspect ratio of the fabricated structures, the depth of the holes is numerically investigated over a wide range of values starting from $d = 400$ nm to 1300 nm with a step size of 100 nm. The transmission spectra shown in Figure 6 depict the shifting of $\lambda_{res}$ over a wide spectral range starting from 1535 nm to 1572 nm. It can also be observed that transmission peaks appearing at lower values of $d$ are shallower and they start reaching zero value as the depth increases. The redshift of the resonant modes can again be interpreted by the phenomenon of a rise in $n_{eff}$ of the waveguide.

![Figure 5](image1.png)

**Figure 5.** (a) Cross-sectional view of the simulation model with hole-radius values of $r = 200$, 240 and 300 nm. (b) $\lambda_{res}$ vs. hole-radius. (c) Linewidth vs. hole-radius. (d) $Q_F$ vs. hole-radius.

![Figure 6](image2.png)

**Figure 6.** Transmission spectra of PhC-structure with hole-depth varied from 400 to 1300 nm. A redshift along with an increase in the linewidth of the resonant modes can be observed.
a non-linear trend while undergoing a redshift as the depth of the nano-holes increases. The linewidth of the resonant modes (Figure 7c) observes its maximum values of 6.36 nm for $d = 1200$ nm, whereas it has minimum values of 1.43 nm for $d = 400$ nm. Following the inverse trend, the $Q_F$ of the modes has maximum values of 1073.16 and 1002.52 for $d = 400$ and 500 nm. However, the resonant peaks do not reach a near-to-zero transmission value for such shallow holes. Therefore, a minimum depth of 600 nm can be recommended for the FS-generated holes considered in this work.

![Cross-sectional view of the filled nano-holes with different depths](image)

**Figure 7.** (a) Cross-sectional view of the simulation model with hole-depth values of $d = 400, 800,$ and $1300$ nm. (b) $\lambda_{res}$ vs. hole-depth. (c) Linewidth vs. hole-depth. (d) $Q_F$ vs. hole-depth.

### 4.3. Depth of the Crater

Following the creation of the structures, the waveguide material is deposited on the substrate, which also fills inside the nano-holes, leaving craters on the surface as observed in the experimental result shown in Figure 1b. The variation in the size and depth of the crater will contribute to the spectral characteristics of the designed Fano filter. In this study, the diameter of the crater is kept the same as the diameter of the nano-holes, where the depth is varied. To investigate the contribution of the crater depth to Fano resonances, its value is changed from $c = 60$ nm to 380 nm with a step size of 40 nm. The transmission spectra in Figure 8 show that the Fano resonances undergo a blueshift from 1559 to 1579 nm as the depth of the crater increases. The blueshift of the resonances is due to the drop in the $n_{eff}$ of the periodic waveguide. Moreover, the shape of the Fano resonances also become more asymmetric with an increase in the depth of the crater.
The depth of the crater increases. Similarly, the linewidth of the modes continues increasing from 2.4 to 5.27 nm as the \( c \) increases from \( c = 60 \) to 400 nm. Moreover, the \( QF \) has a maximum value in the range of \( QF = 657.94 \) for \( c = 60 \) nm, and it gradually moves up to \( QF = 295.84 \) for \( c = 400 \) nm. From the graphical trends, a less deep crater can be recommended, however the creation of a crater cannot be controlled by the user as it depends on the depth of the nano-holes.

Figure 8. Transmission spectra of PhC-structure with crater-depth varied from 60 to 380 nm. A blueshift along with an increase in the linewidth of the resonant modes can be observed.

Figure 9a shows simulation models with no crater present on the surface to a very deep crater reaching beyond the upper diameter of the nano-hole. The \( \lambda_{res} \) trend shown in Figure 9b implies that resonant modes undergo a blueshift in an almost linear way as the depth of the crater increases. Similarly, the linewidth of the modes continues increasing from 2.4 to 5.27 nm as the \( c \) increases from \( c = 60 \) to 400 nm. Moreover, the \( QF \) has a maximum value in the range of \( QF = 657.94 \) for \( c = 60 \) nm, and it gradually moves up to \( QF = 295.84 \) for \( c = 400 \) nm. From the graphical trends, a less deep crater can be recommended, however the creation of a crater cannot be controlled by the user as it depends on the depth of the nano-holes.

Figure 9. (a) Cross-sectional view of the simulation model with crater-depth values of \( c = 0, 200 \) and 400 nm. (b) \( \lambda_{res} \) vs. hole-depth. (c) Linewidth vs. crater-depth. (d) \( QF \) vs. crater-depth.
5. Comparative Analysis

In the literature, most of the reported works on FS laser-based material processing are experimental, with the principal investigations on FS laser generation, pulse shaping, and properties of targeted materials. Moreover, the published works also include the study of laser-pulse parameters concerning the structural parameters of the generated patterns. Different kinds of structures are reported, including nano-gratings, periodic patterns of nano-holes, pillars, and other 3D shapes. The kind of optical filters fabricated by FS laser pulses include laser-pulse shapers, phase filters, waveguides, wavelength filters, and oil–water separators. Very selective work has been reported in which the spectral properties of the narrow band resonances resulting from FS laser-generated structures have been discussed. After a careful study of the literature, Table 2 lists some related works in which the spectral properties of the FS laser pulses, the kind of target materials, the nature of the generated structures, and spectral characteristics of the output spectra are mentioned, where $\lambda_c$ represents the central wavelength of the FS laser.

### Table 2. Comparative analysis of the presented work with the literature for optical filtering properties.

| FS Laser Parameters | Target Material | Type of Generated Structures | Spectral Properties of the Structure | References |
|---------------------|-----------------|-----------------------------|-------------------------------------|------------|
| $\lambda_c$: 775 nm Width: 150 fs | Si-on-SiO$_2$ | Nano-holes based waveguide | $\lambda_{res}$: 1575 nm Linewidth: 22 nm QF: 70 | [41] |
| $\lambda_c$: 800 nm Width: 50 fs | TiO$_2$ | Periodic nano-holes | Oil–water separation with 99% efficiency | [42] |
| $\lambda_c$: 800 nm Width: 30 fs | BG18 glassBG36 glass | Periodic nano-holes | $\lambda_{res}$: 775 nm and 835 nm Linewidth: 50 nm | [43] |
| $\lambda_c$: 1030 nm Width: 300 fs | Bulk glass | Chirped periodic nano-grating | 50% filtering efficiency for reflection peaks at 0° degree incidence | [44] |
| Two cross-polarized FS laser pulses $\lambda_c$: 800 nm Width: 50 fs | Tungsten | Periodic nano-holes | Optical filter to reduce optical reflectivity of the targeted surface below wavelength range of 2000 nm | [45] |
| Ti: Sapphire FS laser system $\lambda_c$: 790 nm Width: 35 fs | Fused silica | Periodic nano-holes | Optical filter in communication wavelength range with $\lambda_{res}$: 1550 nm Linewidth: 1.4 to 24.2 nm QF: 66.51 to 1090.12 | This work |

6. Conclusions

In this research work, the feasibility of implementing optical filters from FS laser processing of dielectric materials is investigated for NIR spectral range. After carefully analyzing the PhC structures generated by FS laser high-energy pulses, their numerical models were created in 3D-FDTD, replicating similar structural morphologies. Moreover, the structural characteristics of the waveguide layer deposited on the top of the nano-hole array on the SiO$_2$ substrate were considered. The studied structural features include the depth of the filled nano-holes, the upper diameter of the nano-holes, and the depth of the crater on the surface. It was found that the periodic nanostructures created by FS laser pulses can be successfully converted into optical filters with good spectral characteristics. The highest value of QF was found in the range of QF = 1090.12, with the lowest value observed as QF = 66.51. Moreover, the linewidth of the studied device ranges between 1.40 to 24.2 nm, which is very promising for the design of a narrowband Fano filter. The device shows a spectral tuning capability in a wide spectrum with three different narrowband
resonant modes located around 1380, 1550, and 1650 nm. The studied modes showed spectral tuning from 1520 to 1610 nm as different structural parameters were varied. Considering the experimental results studied in this work, the optimum depth of the filled nano-holes was found to be in the range of \( d = 600 \) to 800 nm, whereas to achieve good Fano filtering characteristics, the radius of nano-holes has to be \( r = 200 \) to 250 nm. The studied device shows a great potential for optical filtering, sensing, and various other applications where an easy-to-implement and cost-effective solution is required.

**Author Contributions:** Conceptualization, Y.K. and D.N.; methodology, Y.K., D.N. and N.U.; software, Y.K., D.N. and N.U.; validation, Y.K. and N.U.; formal analysis, Y.K., N.U. and N.L.K.; investigation, Y.K., D.N. and N.L.K.; resources, M.A.B., S.N.K. and N.L.K.; data curation, M.A.B., S.N.K. and N.L.K.; writing—original draft preparation, Y.K., M.A.B., S.N.K. and N.L.K.; writing—review and editing, Y.K. and M.A.B.; visualization, M.A.B., S.N.K. and N.L.K.; supervision, M.A.B., S.N.K. and N.L.K.; project administration, Y.K., M.A.B., S.N.K. and N.L.K.; funding acquisition, M.A.B., S.N.K. and N.L.K. All authors have read and agreed to the published version of the manuscript.

**Funding:** The project was financially supported by the German Research Organization (DFG) under priority program SPP1327 to achieve sub-100 nm structures.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The authors would like to thank the Nanophotonics group members at the Institute of Nanostructure Technologies and Analytics (INA), University of Kassel, Germany for providing the experimental data, based on which this research work was conducted. Moreover, the authors are grateful to the Nanophotonics group members at the Balochistan University of Information Technology, Engineering and Management Sciences, Quetta for their efforts in making this project’s work possible.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**

1. Götte, N.; Kusserow, T.; Winkler, T.; Sarpe, C.; Engliert, L.; Otto, D.; Meinl, T.; Khan, Y.; Zielinski, B.; Senftleben, A.; et al. Temporally shaped femtosecond laser pulses for creation of functional sub-100 nm structures in dielectrics. *Opt. Induc. Nanostruct.* 2015, 23, 47–72.

2. Khan, Y.; Götte, N.; Kusserow, T.; Senftleben, A.; Baumert, T.; Hillmer, H. Modelling, design and fabrication of dielectric photonic crystal structures using temporally asymmetric shaped femtosecond laser pulses. In Proceedings of the 2014 International Conference on Optical MEMS and Nanophotonics, Glasgow, UK, 17–21 August 2014; pp. 207–208.

3. Paul, A.K.; Habib, S.; Hai, N.H.; Razzaq, S.A. An air-core photonic crystal fiber based plasmonic sensor for high refractive index sensing. *Opt. Commun.* 2020, 464, 125556. [CrossRef]

4. Rehman, A.U.; Khan, Y.; Irfan, M.; Butt, M.A.; Khonina, S.N.; Kazanskiy, N.L. A Novel Design of Optical Switch Based on Guided Mode Resonances in Dielectric Photonic Crystal Structures. *Photonics* 2022, 9, 580. [CrossRef]

5. Yu, H.; Yu, J.; Sun, F.; Li, Z.; Chen, S. Systematic considerations for the patterning of photonic crystal devices by electron beam lithography. *Opt. Commun.* 2007, 271, 241–247. [CrossRef]

6. Khan, Y.; Rehman, A.U.; Batool, B.A.; Noor, M.; Butt, M.A.; Kazanskiy, N.L.; Khonina, S.N. Fabrication and Investigation of Spectral Properties of a Dielectric Slab Waveguide Photonic Crystal Based Fano-Filter. *Crystals* 2022, 12, 226. [CrossRef]

7. Steve, R.; Robert, P. A Review of Focused Ion Beam Applications in Microsystem Technology. *J. Micromech. Microeng.* 2001, 11, 287–300.

8. Hadzialic, S.; Kim, S.; Sudbo, A.S.; Solgaard, O. Two-Dimensional Photonic Crystals Fabricated in Monolithic Single-Crystal Silicon. *IEEE Photonics Technol. Lett.* 2009, 22, 67–69. [CrossRef]

9. Huang, H.W.; Lin, C.H.; Huang, J.K.; Lee, K.Y.; Lin, C.F.; Yu, C.C.; Tsai, J.Y.; Hsueh, R.; Kuo, H.C.; Wang, S.C. Investigation of GaN-based Light Emitting Diodes with Nano-Hole Patterned Sapphire Substrate (NHPSS) by Nano-Imprint Lithography. *Mater. Sci. Eng., B* 2009, 164, 76–79. [CrossRef]

10. Chen, A.; Chua, S.-J.; Fonstad, C.G., Jr.; Wang, B.; Wilhelm, O. Two-Dimensional Photonic Crystals Fabricated by Nanoimprint Lithography: Advanced Materials for Micro- and Nano-Systems; Massachusetts Institute of Technology: Cambridge, MA, USA, 2015.

11. Amoako, G. Femtosecond laser structuring of materials: A review. *Appl. Phys. Res.* 2019, 11, 1–11. [CrossRef]

12. Simon, P.; Islemann, J.; Bonse, J. Special Issue “Laser-Generated Periodic Nanostructures”. *Nanomaterials* 2021, 11, 2054. [CrossRef]
13. Abou Khalil, A.; Lalanne, P.; Bérubé, J.P.; Petit, Y.; Vallée, R.; Canioni, L. Femtosecond laser writing of near-surface waveguides for refractive-index sensing. Opt. Express 2019, 27, 31130–31143. [CrossRef] [PubMed]

14. Li, B.; Jiang, L.; Wang, S.; Tsai, H.L.; Xiao, H. Femtosecond laser fabrication of long period fiber gratings and applications in refractive index sensing. Opt. Laser Technol. 2011, 43, 1420–1423. [CrossRef]

15. Wang, Y.; Wang, D.N.; Yang, M.; Hong, W.; Lu, P. Refractive index sensor based on a microhole in single-mode fiber created by the use of femtosecond laser micromachining. Opt. Lett. 2009, 34, 3328–3330. [CrossRef] [PubMed]

16. Chung, S.H.; Mazur, E. Surgical applications of femtosecond lasers. J. Biophotonics 2009, 2, 557–572. [CrossRef]

17. Kelemen, L.; Lepera, E.; Horváth, B.; Omros, P.; Osellame, R.; Vázquez, R.M. Direct writing of optical microresonators in a lab-on-a-chip for label-free biosensing. Lab Chip 2019, 19, 1985–1990. [CrossRef]

18. Kuchmizhak, A.; Pustovalov, E.; Syubaev, S.; Vitrik, O.; Khonina, S.; Kudryashov, S.; Danilov, P.; Ionin, A. On-fly femtosecond-laser fabrication of self-organized plasmonic nanotextures for chemo-and biosensing applications. ACS Appl. Mater. Interfaces 2016, 8, 24946–24955. [CrossRef]

19. Ródenas, A.; Gu, M.; Corrèli, G.; Paie, P.; John, S.; Kar, A.K.; Osellame, R. Three-dimensional femtosecond laser nanolithography of crystals. Nat. Photonics 2019, 13, 105–109. [CrossRef]

20. Ha, J.; Lee, B.J.; Hwang, D.J.; Kim, D. Femtosecond laser nanowelding of silver nanowires for transparent conductive electrodes. RSC Adv. 2016, 6, 86232–86239. [CrossRef]

21. Balling, P.; Schou, J. Femtosecond-laser ablation dynamics of dielectrics: Basics and applications for thin films. Rep. Prog. Phys. 2013, 76, 036502. [CrossRef]

22. Englert, L.; Wollenhaupt, M.; Sarpe, C.; Otto, D.; Baumert, T. Morphology of nanoscale structures on fused silica surfaces from interaction with temporally tailored femtosecond pulses. J. Laser Appl. 2012, 24, 042002. [CrossRef]

23. Köhler, J.; Wollenhaupt, M.; Bayer, T.; Sarpe, C.; Baumert, T. Zeptosecond precision pulse shaping. Opt. Express 2011, 19, 11638–11653. [CrossRef] [PubMed]

24. Englert, L.; Rethfeld, B.; Haag, L.; Wollenhaupt, M.; Sarpe-Tudoran, C.; Baumert, T. Control of ionization processes in high band gap materials via tailored femtosecond pulses. Opt. Express 2007, 15, 17855–17862. [CrossRef] [PubMed]

25. Wollenhaupt, M.; Englert, L.; Horn, A.; Baumert, T. Control of ionization processes in high band gap materials. J. Laser MicroNanoeng. 2009, 4, 144–151. [CrossRef]

26. Meinl, T.; Götte, N.; Khan, Y.; Kusserow, T.; Sarpe, C.; Köhler, J.; Wollenhaupt, M.; Sentftleben, A.; Baumert, T.; Hillmer, H. Material processing of dielectrics via temporally shaped femtosecond laser pulses as direct patterning method for nanophotonic applications. In Nanoscience Advances in CBRN Agents Detection, Information and Energy Security; Springer: Dordrecht, The Netherlands, 2015; pp. 29–34.

27. Khan, Y. Design and Numerical Simulation of Dielectric Photonic Crystal Devices and Investigation of an Optical Characterization Method. Ph.D. Thesis, University of Kassel, Kassel, Germany, 2017.

28. Limonov, M.F.; Rybin, M.; Poddubny, A.; Kivshar, Y.S. Fano resonances in photonics. Nat. Photonics 2017, 11, 543–554. [CrossRef]

29. Rybin, M.V.; Khasikaev, A.B.; Ionue, M.; Samusev, K.B.; Steel, M.J.; Yushin, G.; Limonov, M.F. Fano resonance between Mie and Bragg scattering in photonic crystals. Phys. Rev. Lett. 2009, 103, 023901. [CrossRef]

30. Ciminelli, C.; Dell’Olfo, F.; Brunetti, G.; Conteduca, D.; Armenise, M.N. New microwave photonic filter based on a ring resonator including a photonic crystal structure. In Proceedings of the 2017 19th International Conference on Transparent Optical Networks (ICTON), Girona, Spain, 2–6 July 2017; pp. 1–4.

31. Dong, P.; Feng, N.N.; Feng, D.; Qian, W.; Liang, H.; Lee, D.C.; Luff, B.J.; Banwell, T.; Agarwal, A.; Toliver, P.; et al. GHz-bandwidth optical filters based on high-order silicon ring resonators. Opt. Express 2010, 18, 23784–23789. [CrossRef]

32. Brunetti, G.; Sassanelli, N.; Armenise, M.N.; Ciminelli, C. High performance and tunable optical pump-rejection filter for quantum photonic systems. Opt. Laser Technol. 2021, 139, 106978. [CrossRef]

33. Oser, D.; Mazeas, A.; Ramos, C.A.; Le Roux, X.; Vivien, L.; Tannizi, S.; Cassan, É.; Labonté, L. On-chip photon pair source with pump rejection filter. In Proceedings of the European Quantum Electronics Conference, Munich, Germany, 23–27 June 2019; Optical Society of America: New York, NY, USA, 2019; p. eb_2_4.

34. Spencer, D.T.; Bauters, J.F.; Heck, M.J.; Bowers, J.E. Integrated waveguide coupled Si3N4 resonators in the ultrahigh-Q regime. Optica 2014, 1, 153–157. [CrossRef]

35. Conteduca, D.; Brunetti, G.; Pittazzuollo, G.; Tragni, F.; Dholakia, K.; Krauss, T.F.; Ciminelli, C. Exploring the limit of multiplexed near-field optical trapping. Photonics 2021, 8, 2060–2066. [CrossRef]

36. Liu, K.; Jin, N.; Cheng, H.; Chauhan, N.; Puckett, M.W.; Nelson, K.D.; Behunin, R.O.; Rakich, P.T.; Blumenthal, D.J. Ultralow 0.034 dB/m loss wafer-scale integrated photonic realizations 720 million Q and 380 μW threshold Brillouin lasing. Opt. Lett. 2022, 47, 1855–1858. [CrossRef]

37. Lambert, E.; Fiers, M.; Nizamov, S.; Tassaert, M.; Johnson, S.G.; Bieentman, P.; Bogaerts, W. Python bindings for the open source electromagnetic simulator Meep. Comput. Sci. Eng. 2010, 13, 53–65. [CrossRef]

38. Oskooi, A.F.; Roundy, D.; Ibanescu, M.; Bermel, P.; Joannopoulos, J.D.; Johnson, S.G. Meep: A Flexible Free-Software Package for Electromagnetic Simulations by the FDTD Method. Comput. Phys. Commun. 2010, 181, 687–702. [CrossRef] [PubMed]

39. Yablonovitch, E. Inhibited Spontaneous Emission in Solid-State Physics and Electronics. Phys. Rev. Lett. 1987, 58, 2059. [CrossRef] [PubMed]

40. Fan, S.; Joannopoulos, J.D. Analysis of Guided Resonances in Photonic Crystal Slabs. Phys. Rev. B 2002, 65, 235112. [CrossRef]
41. Li, M.; Mori, K.; Ishizuka, M.; Liu, X.; Sugimoto, Y.; Ikeda, N.; Asakawa, K. Photonic bandpass filter for 1550 nm fabricated by femtosecond direct laser ablation. *Appl. Phys. Lett.* 2003, 83, 216–218. [CrossRef]

42. Ye, S.; Cao, Q.; Wang, Q.; Wang, T.; Peng, Q. A highly efficient, stable, durable, and recyclable filter fabricated by femtosecond laser drilling of a titanium foil for oil-water separation. *Sci. Rep.* 2016, 6, 37591. [CrossRef]

43. Krüger, J.; Lenzner, M.; Martin, S.; Lenner, M.; Spielmann, C.; Fiedler, A.; Kautek, W. Single-and multi-pulse femtosecond laser ablation of optical filter materials. *Appl. Surf. Sci.* 2003, 208, 233–237. [CrossRef]

44. Purlys, V.; Maigyte, L.; Gailevičius, D.; Peckus, M.; Malinauskas, M.; Staliunas, K. Spatial filtering by chirped photonic crystals. *Phys. Rev. A* 2013, 87, 033805. [CrossRef]

45. Qiao, H.; Yang, J.; Wang, F.; Yang, Y.; Sun, J. Femtosecond laser direct writing of large-area two-dimensional metallic photonic crystal structures on tungsten surfaces. *Opt. Express* 2015, 23, 26617–26627. [CrossRef]