Video Article

Fabrication of 1-D Photonic Crystal Cavity on a Nanofiber Using Femtosecond Laser-induced Ablation

Kali Prasanna Nayak[1], Jameesh Keloth[1], Kohzo Hakuta[1]

[1]Center for Photonic Innovations, University of Electro-Communications

Correspondence to: Kohzo Hakuta at k.hakuta@cpi.uec.ac.jp

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Abstract

We present a protocol for fabricating 1-D Photonic Crystal (PhC) cavities on subwavelength-diameter tapered optical fibers, optical nanofibers, using femtosecond laser-induced ablation. We show that thousands of periodic nano-craters are fabricated on an optical nanofiber by irradiating with just a single femtosecond laser pulse. For a typical sample, periodic nano-craters with a period of 350 nm and with diameter gradually varying from 50 - 250 nm over a length of 1 mm are fabricated on a nanofiber with diameter around 450 - 550 nm. A key aspect of such a nanofabrication is that the nanofiber itself acts as a cylindrical lens and focuses the femtosecond laser beam on its shadow surface. Moreover, the single-shot fabrication makes it immune to mechanical instabilities and other fabrication imperfections. Such periodic nano-craters on nanofiber, act as a 1-D PhC and enable strong and broadband reflection while maintaining the high transmission out of the stopband. We also present a method to control the profile of the nano-crater array to fabricate apodized and defect-induced PhC cavities on the nanofiber. The strong confinement of the field, both transverse and longitudinal, in the nanofiber-based PhC cavities and the efficient integration to the fiber networks, may open new possibilities for nanophotonic applications and quantum information science.

Video Link

The video component of this article can be found at https://www.jove.com/video/55136/

Introduction

Strong confinement of light in nanophotonic devices has opened new frontiers in optical science. Modern nanofabrication technologies have enabled fabrication of 1-D and 2-D Photonic Crystal (PhC) cavities for new prospects in lasing[1], sensing[2] and optical switching applications[3]. Moreover, strong light-matter interaction in these PhC cavities has opened new avenues for quantum information science[4]. Apart from PhC cavities, plasmonic nanocavities have also shown promising prospects[5,6,7]. However, interfacing such cavities to fiber-based communication network remains a challenge.

In recent years, tapered single mode optical fiber with subwavelength diameter, known as optical nanofiber, has emerged as a promising nanophotonic device. Due to the strong transverse confinement of the nanofiber guided field and the ability to interact with the surrounding medium, the nanofiber is widely adapted and investigated for various nanophotonic applications[8]. Apart from that, it is also strongly investigated and implemented for quantum manipulation of light and matter[9]. Efficient coupling of emission from quantum emitters like, single/few laser-cooled atoms and single quantum dots, into the nanofiber guided modes has been studied and demonstrated[10,11,12,13,14,15]. The light-matter interaction on nanofiber can be significantly improved by implementing PhC cavity structure on the nanofiber[16,17].

The key advantage for such a system is the fiber-in-line technology which can be readily integrated to communication network. Light transmission of 99.95% through the tapered nanofiber has been demonstrated[18]. However, the nanofiber transmission is extremely susceptible to dust and contamination. Therefore, fabrication of PhC structure on nanofiber using conventional nanofabrication technique is not very fruitful. Although cavity fabrication on nanofiber using Focused Ion Beam (FIB) milling has been demonstrated[19,20], the optical quality and reproducibility is not as high.

In this video protocol, we present a recently demonstrated[21,22] technique to fabricate PhC cavities on nanofiber using femtosecond laser ablation. The fabrications are performed by creating a two-beam interference pattern of the femtosecond laser on the nanofiber and irradiating a single femtosecond laser pulse. The lensing effect of the nanofiber plays an important role in the feasibility of such techniques, creating ablation craters on the shadow surface of the nanofiber. For a typical sample, periodic nano-craters with a period of 350 nm and with diameter gradually varying from 50 - 250 nm over a length of 1 mm are fabricated on a nanofiber with diameter around 450 - 550 nm. Such periodic nano-craters on nanofiber, act as a 1-D PhC. We also present a method to control the profile of the nano-crater array to fabricate apodized and defect-induced PhC cavities on the nanofiber.

A key aspect of such nanofabrication is the all optical fabrication, so that high optical quality can be maintained. Moreover, the fabrication is done by the irradiation of just a single femtosecond laser pulse, making the technique immune to mechanical instabilities and other fabrication imperfections. Also this enables in-house production of PhC nanofiber cavity so that the probability of contamination can be minimized. This protocol is intended to help others implement and adapt this new type of nanofabrication technique.

Figure 1a shows the schematic diagram of the fabrication setup. The details of the fabrication setup and alignment procedures are discussed in[21,22]. A femtosecond laser with 400 nm center wavelength and 120 fs pulse width is incident on a phase mask. The phase mask splits the femtosecond laser beam in to 0 and ±1 orders. A beam block is used to block the 0-order beam. The folding mirrors symmetrically recombine the ±1-orders at the nanofiber position, to create an interference pattern. The pitch of the phase mask is 700 nm, so the interference pattern has a pitch (Λ_G) of 350 nm. The cylindrical lens focuses the femtosecond laser beam along the nanofiber. The beam size across (Y-axis) and along (Z-axis) the nanofiber is 60 µm and 5.6 mm, respectively. The tapered fiber is mounted on a holder equipped with piezo actuator (PZT) for stretching the fiber. A top cover with glass plate is used to protect the nanofiber from dust. The holder with the tapered fiber is fixed on a fabrication bench equipped with translation (XYZ) and rotation (θ) stages. The θ-stage allows rotation of the nanofiber sample in the YZ-plane. The X-stage can also control the tilt angles along XY- and XZ-plane. A CCD camera is placed at a distance of 20 cm from the nanofiber and at an angle of 45° in the XY-plane to monitor the nanofiber position. All the experiments are performed inside a clean booth equipped with HEPA (High-efficiency particulate arresting) filters to achieve dust-free conditions. Dust-free condition is essential to maintain the transmission of the nanofiber.

Figure 1b shows the schematic of the optical measurements. During fabrication, the optical properties are briefly monitored by launching a broadband (wavelength range: 700 - 900 nm) fiber-coupled light source into the tapered fiber and measuring the spectrum of the transmitted and reflected light using high resolution spectrum analyzer. A tunable CW laser source is used to properly resolve the cavity modes and to measure the absolute cavity transmission.

We present the protocol for the fabrication and characterization. The protocol section is divided in three subsections, nanofiber preparation, femtosecond laser fabrication and characterization of the fabricated samples.

Protocol

CAUTION: Wear safety glasses and strictly avoid direct exposure to UV lamp and all lasers including the femtosecond laser. Wear a clean room suit and gloves to avoid contamination. Dispose any fiber trash properly in the designated trash box.

1. Nanofiber Preparation

1. Use a fiber coating stripper to strip the polymer jacket of the single mode optical fiber for a length of 5 mm at two places separated by 200 mm. Clean the two mechanically stripped parts using cleanroom wipe dipped in methanol. Dip the fiber between these two stripped parts in acetone. Wait for 10 - 15 min till the jacket of the fiber fall apart. Take out the fiber from acetone and clean the entire stripped part using cleanroom wipe dipped in methanol.
2. Set the stripped fiber on the two stages of the Optical Nanofiber Manufacture Equipment (ONME) to fabricate the nanofiber.
    1. Launch the probe laser into the fiber and monitor the transmission using the photodiode and record the transmission data in the computer using the ADC card. Start the gas flow using the ONME software and ignite the flame. Load the pre-optimized parameter in the ONME software for the fabrication of tapered fiber with waist diameter of 500 nm and start the fabrication process.
    NOTE: The ONME is a commercially available device, designed to fabricate tapered optical fibers using standard heat and pull technique. It uses oxyhydrogen flame to heat the fiber and two motorized stages to pull the fiber. The gas flow and the stage movements are controlled by computer program. The pre-optimized parameters may be obtained from the vendor, upon special request.
3. After the fabrication, catch the tapered fiber to the nanofiber holder using the UV curable epoxy. Cover the nanofiber holder using the top cover with glass plate (shown in the **Figure 1a**). Put the sample inside a clean box and transfer to the femtosecond laser fabrication unit.

2. Femtosecond Laser Fabrication

1. Alignment of the fabrication setup
    1. Put a glass plate on the fabrication bench at a height of 15 mm. Irradiate the femtosecond laser for 5 s at pulse energy of 1 mJ. Identify the femtosecond laser induced ablation from the white light generation, and the appearance of ablation pattern as a damage-line on the glass plate.
    2. Repeat the procedure by changing the height of the glass plate using the X-stage of the fabrication bench. For each fabrication, translate the Y-stage of the fabrication bench by 1 mm to make the fabrication in a new position.
    3. Find the height for the strongest ablation line. At this position, fine tune the tilt angle and position of one of the folding mirrors to maximize the ablation. Also, fine tune the tilt of the X-stage of the fabrication bench to maximize the ablation.
    NOTE: The tilt angle of the folding mirror is tuned using the kinematic mirror holder tuning knobs and the position of the mirror is tuned by translating the Z-stage on which it is mounted.
    4. After the optimization, mark the position of the ablation line on the CCD camera software and remove the glass plate.
    NOTE: The control software for the CCD camera enables image capture and drawing marks on the captured image. It also enables saving the data of the captured image and the markings. Since the X-stage of the fabrication bench does not have absolute position reference, the CCD image is used as the position reference in the X-axis. The resolution of the CCD image is 10 µm per pixel.
    5. Using the Platinum (Pt)-coater, coat the glass plate for 60 s to deposit a 25 nm layer of Pt on the glass plate. Image the ablation pattern on the glass plate using a scanning electron microscope (SEM). If the ablation pattern shows periodic structure with a period of 350 nm (the expected interference fringe pattern) then the alignment is optimized. Else repeat the procedure (from Step 2.1.1 - 2.1.4) for lower pulse energies (down to 300 µJ) until a periodic ablation pattern is seen.

2. Fabrication of apodized PhC cavity
    1. Place the tapered fiber on the fabrication bench approximately parallel to the ablation line marked on the CCD camera.
    2. Send a probe laser (power = 1 mW) through the tapered fiber and observe the scattering from the tapered fiber on the CCD camera. The strongest scattering part corresponds to the nanofiber region due to its subwavelength diameter.
    3. Translate the Z-stage of the fabrication bench to center the nanofiber to the ablation line position marked on the CCD camera.
    4. Switch off the probe laser and irradiate the femtosecond laser with minimum pulse energy (<10 µJ). Translate Y-stage to overlap the nanofiber with the femtosecond laser beam. The overlap is identified by the illumination of the nanofiber, observed on the CCD camera. NOTE: The nanofiber is now aligned with respect to the femtosecond laser beam along Y and Z-axis.
    5. In order to align the nanofiber along the X-axis, translate the X-stage to overlap the nanofiber position to the ablation line position marked on the CCD camera.
    6. Translate the Y-stage to maximize the overlap of nanofiber with the femtosecond laser. Observe the reflection of the two first orders from the nanofiber (appears as two bright spots on the glass plate of the top cover). Observe the movement of these reflection spots while translating the Y-stage back and forth.
    NOTE: If these spots move towards one side then nanofiber is not parallel to the ablation line. In this case, rotate the rotation stage to make the nanofiber parallel to the ablation line. When they are parallel, the reflection spots will appear as a flash.
    7. After making the nanofiber parallel to the ablation line, translate the Y-stage to maximize the overlap between the femtosecond laser beam and nanofiber, by measuring the power of the femtosecond laser scattered into the nanofiber guided modes using a photodiode at the end of the tapered fiber. After maximizing the overlap, rotate the rotation stage to the angle of fabrication θ = 0.5 deg.
    NOTE: For maximum overlap between the femtosecond laser beam and nanofiber, one would expect the power of the femtosecond laser light scattered into the nanofiber guided modes to be maximized.
    8. Block the femtosecond laser with the power meter and set the pulse energy to 0.27 mJ. Change the femtosecond laser settings to the single-shot irradiation mode.
    NOTE: In this mode, only a single pulse is generated when the fire-switch is pressed, otherwise there is no laser output.
        1. Remove the power meter from the laser beam path and fire a single femtosecond laser pulse. This completes the fabrication process.

3. Fabrication of defect-induced PhC cavity
    1. Check the alignment of the setup by observing the ablation on a glass plate as described in the section 2.1. After finding the height for the strongest ablation line, insert a 0.5 mm copper wire at the center of the laser beam just before the phase mask. The copper wire should be along the Y-axis (perpendicular to the ablation line).
    2. Check the ablation pattern on the glass plate while changing the position of the copper wire along the Z-axis. Fix the position of the copper wire when the ablation pattern shows a single gap at the center of the ablation line.
    3. After the alignment, perform the femtosecond laser fabrication on the nanofiber following the procedure detailed in the section 2.2. For this fabrication, set the angle of fabrication to θ = 0 deg.

3. Characterization of the Fabricated Samples

1. Measurement of optical properties
    1. Prepare the setup for the optical measurements as shown in **Figure 1b**. Launch the broadband light source into the tapered fiber and measure the transmission and reflection spectrum before and after the fabrication using the spectrum analyzer. After fabrication, the transmission spectrum will show a stopband corresponding to the Bragg resonance of the fabricated sample.
    2. Rotate the paddles of the fiber inline polarizer to select the polarization and take the spectra for two orthogonal polarizations X-pol and Y-pol.
    NOTE: For the X-pol (polarization along the nano-craters) the stopband will be blue-shifted[21] (towards the shorter wavelength) and the scattering from the nanofiber will be stronger. So, select the polarizations by looking at the spectrum and the CCD camera.
    3. For one of the polarizations, take the transmission spectra by stretching the tapered fiber using the PZT (shown in **Figure 1b**). Take the spectra by stretching the tapered fiber in steps of 2 µm until the maximum stretching length of 20 µm (limited by the PZT scanning range). Observe that the Bragg resonance will be red-shifted (towards the longer wavelength) by stretching the tapered fiber. From these spectra, calculate the shift of the Bragg resonance, per unit stretching length.
    4. For resolving the cavity modes and measuring the absolute cavity transmission, use the tunable CW laser source. Launch the laser into the tapered fiber and monitor the transmission using a photodiode.
    5. Set the laser wavelength to the red-side edge of the stopband for Y-pol and use the fiber inline polarizer to minimize the transmission. In this way, the X-pol component is suppressed and only the Y-pol is selected. Set the laser wavelength to further out of the red-side band-edge and record the transmission while stretching the tapered fiber from 0 - 20 µm.
        1. Repeat the measurement by changing the laser wavelength to blue-side in steps of 0.3 nm until the entire stopband is covered. From these data, reconstruct the entire spectrum using the data for the resonance shift per unit stretching length measured in step 3.1.3.
        NOTE: For a typical sample, the stopband (Bragg resonance) along with the cavity modes shifts by 2 nm by stretching the tapered fiber by 20 µm and the typical free spectral range for the cavity modes are between 0.05 - 0.5 nm. For a given wavelength of the input laser one can measure at least 3 - 4 cavity modes by stretching the tapered fiber. The frequency spacing between the modes is inferred from the data for the resonance shift per unit stretching length measured in step 3.1.3. Repeating the measurement by changing the laser wavelength in steps of 0.3 nm, at least 2 - 3 consecutive cavity modes are re-measured in the successive measurements. One can reconstruct the entire spectrum by overlaying the transmission data for the successive measurements while matching position of the re-measured cavity modes.
    6. Now measure the spectrum for the other polarization using similar procedure as mentioned in steps 3.1.5 and 3.1.5.1.

2. Imaging the fabricated sample

1. Put the fabricated sample on a 2 cm long metal plate and fix the two ends of the tapered fiber to the metal plate using UV curable epoxy. Make sure the irradiation side of the sample faces the metal plate so that the shadow side can be imaged.
2. Use the Pt-coater to coat the sample for 30 s and deposit a layer of Pt with a thickness of around 10 nm. Place the sample into the SEM. Take the SEM image of the sample at every 0.1 mm over the entire fabricated region.

Representative Results

Figure 2 shows the SEM image of a typical segment of the fabricated nanofiber sample. It shows that periodic nano-craters are formed on the shadow side of the nanofiber, with a periodicity of 350 nm corresponding well to the interference pattern. The inset shows the enlarged view of the sample. The shape of the nano-craters is almost circular and the diameter of a typical nano-crater is around 210 nm.

Figure 3a shows the fabrication results for the apodized PhC cavity. The typical profile of the nano-crater array along with the corresponding nanofiber diameter for different fabrication angle (θ) and pulse energy are shown. The circles denote the nano-crater diameter and the squares are the corresponding nanofiber diameter. The lines are the Gaussian fits to the profiles. The data shown in black and green correspond to samples fabricated with θ = 0 deg, using pulse energy of 0.35 and 0.17 mJ, respectively. The data shown in red and blue correspond to samples fabricated with θ = 0.5 deg using pulse energy of 0.35 and 0.27 mJ, respectively. As one can see, the nano-craters are formed over a length of 2-3 mm along the nanofiber where the diameter of the nanofiber is uniform. An apodization in nano-crater diameter is observed corresponding to the Gaussian intensity distribution of the femtosecond laser beam. It is clearly seen that the diameter of the nano-craters is reduced for weaker pulse energy. Moreover, the width of the apodization profile of the nano-craters is reduced by increasing the angle of fabrication.

The fabrication result for the defect-induced PhC cavity is shown in **Figure 3b**. A double peak-like profile is observed. A gradual change in the diameter is observed at the outside edges of the peaks, whereas the diameter changed rapidly at the inside edge of the peaks. A defect region of 0.5 mm with no nano-craters is observed between two peaks. The length of the defect region corresponds well to the thickness of the copper wire inserted in to the femtosecond laser beam.

Figure 4 shows the transmission spectra for an apodized PhC cavity sample whose diameter profile is shown in blue in **Figure 3a. Figures 4a** and **4b** show the typical transmission spectra for X- and Y-polarizations, respectively. The spectrum for the X-pol shows a stopband region from 793.7 - 798.8 nm, where the transmission drops to a few percent. The stopband for the Y-pol is red-shifted and broader compared to the X-pol. The sharp peaks observed in the red-side of the stopband are the cavity modes. The finesse and peak transmission of the typical cavity modes are listed in **Table 1**.

Figures 5a and **5b** show the transmission spectra of the defect-induced PhC cavity for X- and Y-polarizations, respectively. As one can see, sharp cavity modes appear on either side of the stopband. However, the mode spacing in the blue-side is much larger than that in the red-side of the spectra. The finesse and peak transmission of the typical cavity modes are summarized in **Table 1**.

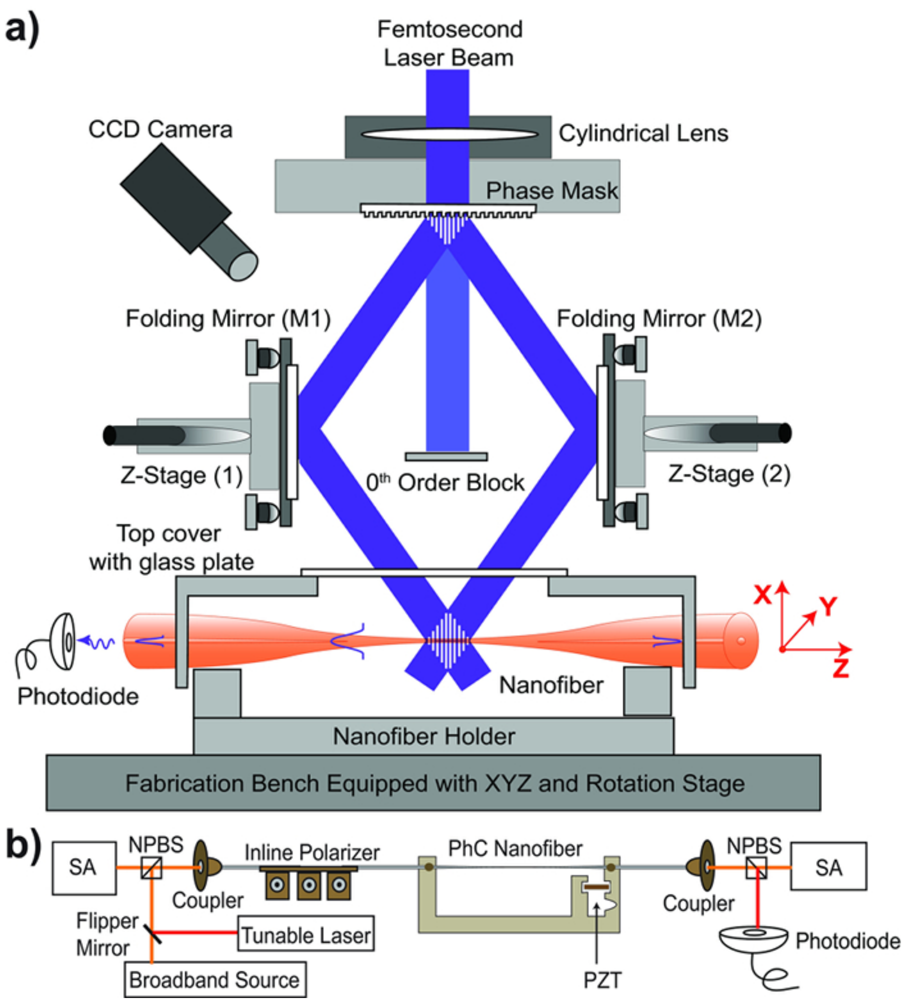

Figure 1: Schematic Diagram of the Experiment. (a) Schematic diagram of the fabrication setup. A two-beam interference pattern is created on the nanofiber using a phase mask as the beam splitter and two folding mirrors (see text for details). A cylindrical lens is used to line focus the femtosecond laser along the nanofiber. A zero-order block is used to avoid any residual zero order light in the interference region. A photodiode is connected to one end of the tapered fiber to observe the scattering of the femtosecond laser into the nanofiber guided modes. A CCD camera is used to monitor the nanofiber position. **(b)** Schematic diagram for the measurement of optical properties. The transmission and reflection spectra of the fabricated nanofiber samples are simultaneously measured by varying the polarization of the input light. PhC, PZT, NPBS and SA denote photonic crystal, piezo actuator, nonpolarizing beam splitter and spectrum analyzer, respectively. This figure has been modified from[21]. Please click here to view a larger version of this figure.

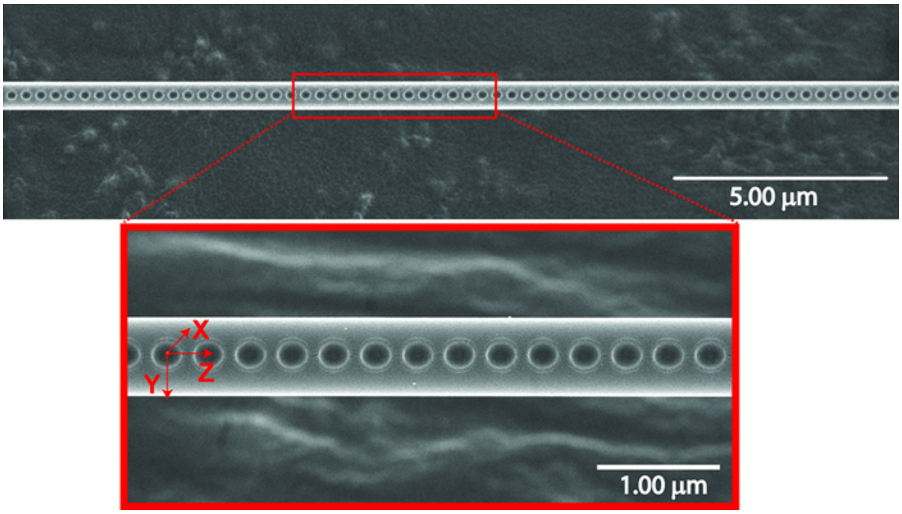

Figure 2: SEM Image of a Fabricated Sample. SEM image of a typical sample fabricated using single-shot irradiation. The inset shows the enlarged view. The periodic nano-crater structures are observed on the shadow side of the nanofiber. This figure has been modified from[21]. Please click here to view a larger version of this figure.

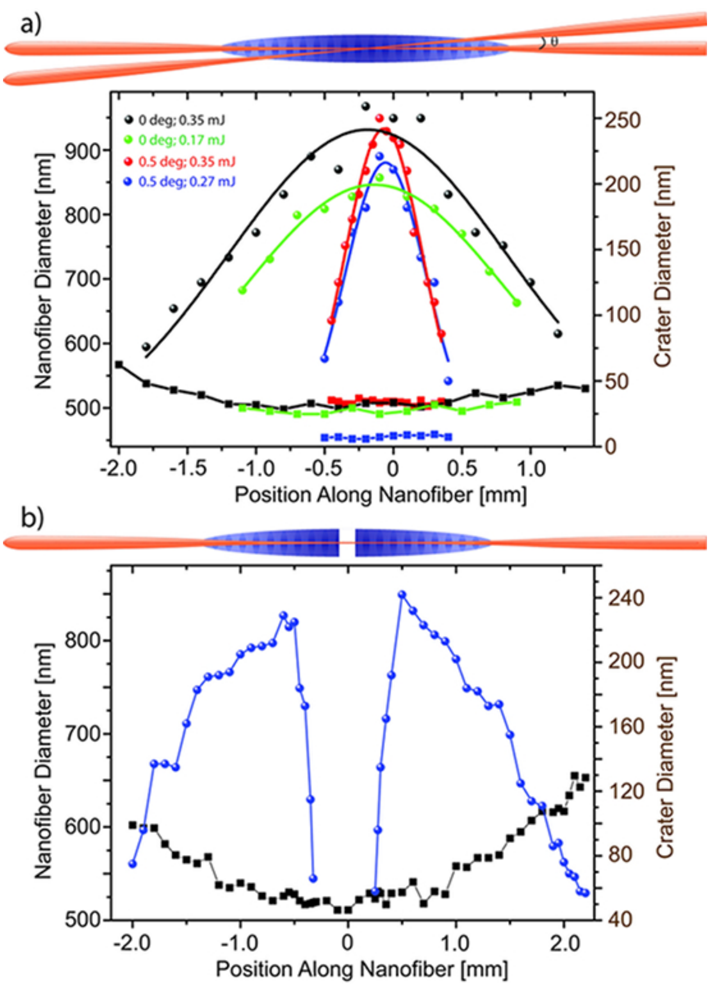

Figure 3: Diameter Profile of the Nano-crater Array on the Nanofiber along with the Brief Schematic of the Fabrication Method. (a) The diameter profile for the apodized PhC cavity. The circles denote the nano-crater diameter and the squares are the corresponding nanofiber diameter. The lines are the Gaussian fits to the profiles. The data shown in black and green correspond to samples fabricated with θ = 0 deg, using pulse energy of 0.35 and 0.17 mJ, respectively. The data shown in red and blue correspond to samples fabricated with θ = 0.5 deg, using pulse energy of 0.35 and 0.27 mJ, respectively. **(b)** The diameter profile for the defect-induced PhC cavity fabricated using a pulse energy of 0.4 mJ. The blue circles and the black squares show the nano-crater diameter and the nanofiber diameter, respectively. This figure is reused from[22]. Please click here to view a larger version of this figure.

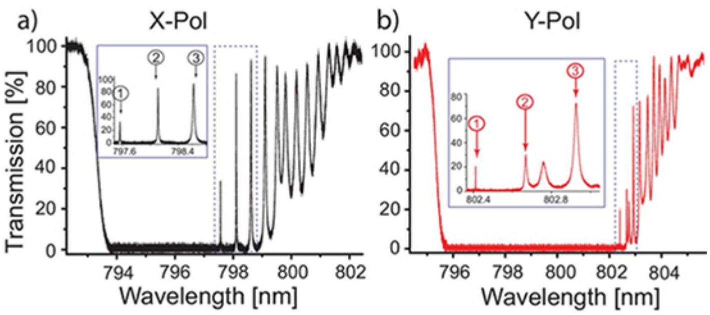

Figure 4: Transmission Spectra of the Apodized PhC Cavity. Transmission spectrum of apodized PhC cavity for **(a)** X-pol and **(b)** Y-pol. The parts of the spectra, marked by blue boxes are enlarged and shown in the insets. This figure is reused from [22]. Please click here to view a larger version of this figure.

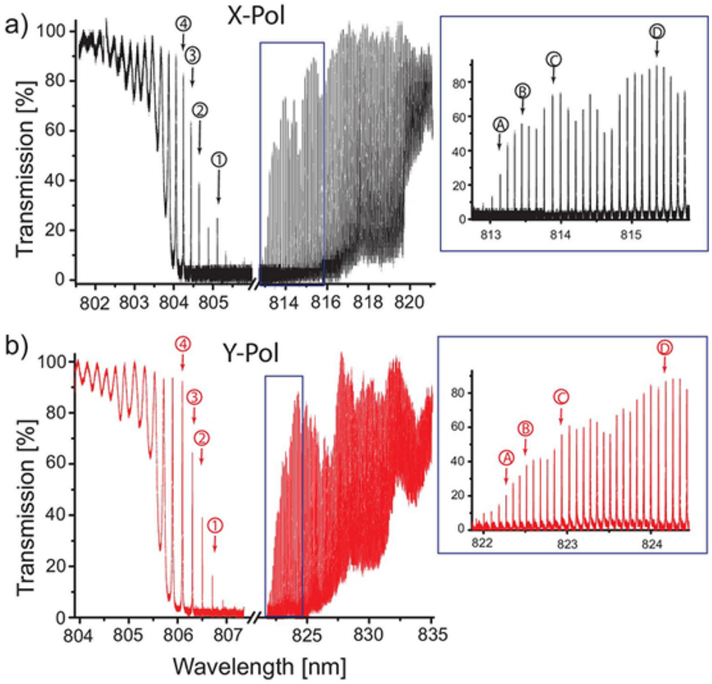

Figure 5: Transmission Spectra of the Defect-induced PhC Cavity. Transmission spectrum of the defect-induced PhC cavity for **(a)** X-pol and **(b)** Y-pol. The parts of the spectra, marked by blue boxes are enlarged and shown in the insets. This figure is reused from[22]. Please click here to view a larger version of this figure.

Figure	Mode	F	T [%]	FSR [cm^{-1}]	L [mm]
4(a)	(1,2,3)	(71, 39, 16)	(33, 87, 93)	7.94	0.54
4(b)	(1,2,3)	(500, 27, 11)	(21, 30, 73)	3.94	1.09
5(a)	(1,2,3,4)	(198, 115, 50, 21)	(25, 39, 64, 83)	3.34	1.28
	(A,B,C,D)	(86, 63, 48, 20)	(26, 56, 73, 90)	1.58	2.71
5(b)	(1,2,3,4)	(178, 104, 43, 22)	(17, 39, 65, 93)	3.15	1.36
	(A,B,C,D)	(48, 44, 24, 22)	(20, 38, 56, 87)	1.25	3.43

Table 1: Optical Characteristics of the Typical Cavity Modes. This table summarizes the optical characteristics of typical cavity modes marked in **Figures 4a, 4b, 5a** and **5b**. F, T, FSR, and L denote finesse, peak transmission, mode spacing, and estimated cavity length, respectively. This table is reused from[22].

Supplemental file 1: Photograph of the ONME Setup. Please click here to download this file.

Supplemental file 2: Photographs of the Femtosecond Laser Fabrication Setup. Please click here to download this file.

Discussion

The lensing effect of the nanofiber plays an important role in the fabrication technique, thereby creating nano-craters on the shadow surface of the nanofiber (shown in **Figure 2**). The lensing effect of the nanofiber also makes the fabrication process robust to any mechanical instabilities in the transverse direction (Y-axis). Moreover, due to single-shot irradiation, the instabilities along the other axes do not affect the fabrication as the irradiation time is only 120 fs (*i.e.* pulse width). As a result, periodic nanostructures with well-defined periodicity are fabricated over several thousands of periods, without taking any special care to suppress mechanical vibrations.

Many nanofabrication techniques like FIB milling, electron beam lithography and even femtosecond laser ablation, implement point-by-point fabrication. The point-by-point fabrication is well suited for rigid samples, where the mechanical stability can be guaranteed. In case of optical nanofibers, if the tapered fiber is kept hanging without touching any rigid substrate then mechanical instabilities affects the fabrication process. On the other hand, if the nanofiber is placed on a rigid substrate then contamination from the substrate itself or due to the etching of the substrate can degrade the optical quality. In particular, with respect to the FIB milling technique, additional drawbacks are mechanical instabilities due to charging up effects of the nanofiber and material modification due to contamination from the ion beam itself. Therefore, the protocol presented here for a single-shot optical fabrication on nanofiber is preferable to the point-by-point fabrication. However, point-by-point fabrication may be preferred for some applications where fabricating arbitrary pattern on the nanofiber is essential.

One crucial step in the protocol is the alignment of the fabrication setup. Since the fabrication is performed by femtosecond pulse with a pulse width of 120 fs, the optical path length difference between the ±1-orders should be minimized to ensure spatial overlap[23]. The path length difference should be less than 36 µm to ensure high visibility of the interference fringe. Hence, the position and the tilt angles of the folding mirrors should be precisely controlled. Although the femtosecond laser beam size along the nanofiber is 5.6 mm the interference region is less than 1 mm along the X-axis limited by the spatial overlap of the pulses. It should also be taken care that the femtosecond laser beam is incident exactly perpendicular to the phase mask and the fabrication bench should be parallel to the phase mask. Even a tilt of 10 mrad can induce enough path length difference to wash out the interference fringe. Finally, the axis of the cylindrical lens should be precisely perpendicular to the lines on the phase mask. Otherwise it will induce a rotation angle between the line focused ±1-orders reducing the overlap between them.

Another critical requirement for successful fabrication is the production of high quality nanofiber. To get high finesse cavity modes, the original nanofiber transmission should be > 95% and should be free from dust or any contamination. Any contamination on nanofiber will induce irregular intensity pattern resulting in non-reproducible fabrication and may even break the nanofiber. The quality of the nanofiber is judged from the high transmission and scattering pattern of the guided modes observed on the CCD camera.

The transmission spectra, shown in **Figures 4** and **5**, show stopband regions where more than 98% of the input light is reflected and transmission drops to a few percent. The transmission away from the stopband is around 100% ensuring that the fabrication does not induce significant loss and maintains the optical quality of the nanofiber. Moreover, the observed high finesse cavity modes (listed in **Table 1**) inside the stopband further ensures the quality of the fabrication. The stopband is well understood from the Bragg reflection from the periodic nano-craters on the nanofiber. The Bragg resonance ($\lambda_R = 2n_{eff}\Lambda_G$) depends on the effective index (n_{eff}) of the guided mode and the pitch (Λ_G) of the interference fringe. In the data presented in this protocol, the stopband is observed around a wavelength of 800 nm. The stopband and the cavity modes can be tuned over 10-15 nm by stretching the tapered fiber. However, to further change the resonance wavelength one must change the nanofiber diameter to realize a different n_{eff} or change the phase mask to realize a different Λ_G.

From the cavity modes listed in **Table 1**, finesse values ranging from 30 - 500 can be realized. Due to the strong transverse confinement of the nanofiber guided modes, high cooperativity / Purcell factors are expected for such finesse values[16]. The broadband tunability along with strong confinement of field in such a fiber-based PhC cavity offers high demand for various applications ranging from nanophotonics to quantum information science.

In conclusion, we have presented a protocol for fabricating 1D PhC cavities on subwavelength diameter silica fibers using femtosecond laser induced ablation. Such fabrication technique may be implemented to make various nanophotonic devices from micro/nanofibers and may be adapted to other nanofabrication processes.

Disclosures

The authors have nothing to disclose.

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References

1. Painter, O. J. *et al.* Two-Dimensional Photonic Band-Gap Defect Mode Laser, *Science.* **284,** 1819-1821 (1999).
2. Loncar, M., Scherer, A., Qiu, Y. Photonic crystal laser sources for chemical detection, *Appl. Phys. Lett.* **82,** 4648 (2003).
3. Tanabe, T., Notomi, M., Mitsugi, S., Shinya, A., Kuramochi, E. All-optical switches on a silicon chip realized using photonic crystal nanocavities, *Appl. Phys. Lett.* **87,** 151112 (2005).
4. Yoshie, T. *et al.* Vacuum Rabi splitting with a single quantum dot in a photonic crystal nanocavity, *Nature.* **432,** 200-203 (2004).
5. Akimov, A. V. *et al.* Generation of single optical plasmons in metallic nanowires coupled to quantum dots. *Nature.* **450,** 402-406 (2007).

6. Noginov, M. A. *et al.* Demonstration of a spaser-based nanolaser, *Nature.* **460,** 1110-1112 (2009).
7. Zhang, X. Y., Zhang, T., Hu, A., Song, Y. J., Duley, W. W. Controllable plasmonic antennas with ultra narrow bandwidth based on silver nano-flags. *Appl. Phys. Lett.* **101,** 153118 (2012).
8. Tong, L., Zi, F., Guo, X., Lou, J. Optical microfibers and nanofibers: A tutorial, *Opt. Comm.* **285,** 4641-4647 (2012).
9. Morrissey, M. J. *et al.* Spectroscopy, manipulation and trapping of neutral atoms, molecules, and other particles using optical nanofibers: A review, *Sensors.* **13,** 10449-10481 (2013).
10. Kien, F. L., Dutta Gupta, S., Balykin, V. I., Hakuta, K. Spontaneous emission of a cesium atom near a nanofiber: Efficient coupling of light to guided modes, *Phys. Rev. A.* **72,** 032509 (2005).
11. Nayak, K. P., Melentiev, P. N., Morinaga, M., Kien, F. L., Balykin, V. I., Hakuta, K. Optical nanofiber as an efficient tool for manipulating and probing atomic fluorescence, *Opt. Express.* **15,** 5431-5438 (2007).
12. Nayak, K. P., Hakuta, K. Single atoms on an optical nanofiber, *New J. Phys.* **10,** 053003 (2008).
13. Nayak, K. P., Kien, F. L., Morinaga, M., Hakuta K. Antibunching and bunching of photons in resonance fluorescence from a few atoms into guided modes of an optical nanofiber, *Phys. Rev. A.* **79,** 021801 (2009).
14. Yalla, R., Nayak, K. P., Hakuta, K. Fluorescence photon measurements from single quantum dots on an optical nanofiber, *Opt. Express.* **20,** 2932-2941 (2012).
15. Yalla, R., Kien, F. L., Morinaga, M., Hakuta, K. Efficient Channeling of Fluorescence Photons from Single Quantum Dots into Guided Modes of Optical Nanofiber, *Phys. Rev. Lett.* **109,** 063602 (2012).
16. Kien, F. L., Hakuta, K. Cavity-enhanced channeling of emission from an atom into a nanofiber, *Phys. Rev. A.* **80,** 053826 (2009).
17. Kato, S., Aoki, T. Strong coupling between a trapped single atom and an all-fiber cavity. *Phys. Rev. Lett.* **115,** 093603 (2015).
18. Hoffman, J. E. *et al.* Ultrahigh transmission optical nanofibers, *AIP Advances.* **4,** 067124 (2014).
19. Nayak, K. P. *et al.* Cavity formation on an optical nanofiber using focused ion beam milling technique, *Opt. Express.* **19,** 14040-14050 (2011).
20. Kien, F. L., Nayak, K. P., Hakuta, K. Nanofibers with Bragg gratings from equidistant holes, *J. Modern Opt.* **59,** 274-286 (2012).
21. Nayak, K. P., Hakuta, K. Photonic crystal formation on optical nanofibers using femtosecond laser ablation technique, *Opt. Express.* **21,** 2480-2490 (2013).
22. Nayak, K. P., Zhang, P., Hakuta, K. Optical nanofiber-based photonic crystal cavity, *Opt. Lett.* **39,** 232-235 (2014).
23. Becker, M. *et al.* Fiber Bragg grating inscription combining DUV sub-picosecond laser pulses and two-beam interferometry, *Opt. Express.* **16,** 19169-19178 (2008).

