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TITLE:

Design and Fabrication of an Optical Fiber Made of Water

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SHORT ABSTRACT:

This protocol describes the design and manufacture of a water bridge and its activation as a water fiber. The experiment demonstrates that capillary resonances of the water fiber modulate its optical transmission.

LONG ABSTRACT:

In this report, an optical fiber of which the core is made solely of water, while the cladding is air, is designed and manufactured. In contrast with solid-cladding devices, capillary oscillations are not restricted, allowing the fiber walls to move and vibrate. The fiber is constructed by a high direct current (DC) voltage of several thousand volts (kV) between two water reservoirs that creates a floating water thread, known as a water bridge. Through the choice of micropipettes, it is possible to control the maximal diameter and length of the fiber. Optical fiber couplers, at both sides of the bridge, activate it as an optical waveguide, allowing researchers to monitor the water fiber capillary body waves through transmission modulation and, therefore, deducing changes in surface tension.

Co-confining two important wave types, capillary and electromagnetic, opens a new path of research in the interactions between light and liquid-wall devices. Water-walled microdevices are a million times softer than their solid counterparts, accordingly improving the response to minute forces.

INTRODUCTION:

Since the breakthrough of optical fibers in communication, awarded with a Nobel prize in 2009¹, a series of fiber-based applications grew alongside. Nowadays, fibers are a necessity in laser surgeries², as well as in coherent X-ray generation^{3,4}, guided-sound⁵ and supercontinuum⁶. Naturally, the research on fiber optics expanded from utilizing solids into exploiting liquids for optical wave guiding, where liquid-filled microchannels and laminar flow combine the transportation properties of a liquid with the advantages of optical interrogation⁷⁻⁹. However, these devices clamp the liquid between solids and, therefore, forbid it to express its own wave character, known as capillary wave.

Capillary waves, similar to those seen when throwing a stone into a pond, are an important wave in nature. However, due to the obstacles of controlling a liquid without dampening its surface through channels or solids, they are hardly utilized for detection or application. In contrast, the device presented in this protocol has no solid boundaries; it is surrounded by and flows in air, allowing, therefore, capillary waves to develop, propagate, and interact with light.

To fabricate a water fiber, it is necessary to go back to a technique known as the floating water bridge, first reported in 1893¹⁰, where two beakers filled with distilled water and connected to a high-voltage source will form a fluidic, water thread-like connection between them¹¹. Water bridges can reach up to a length of 3 cm¹² or be as thin as 20 nm¹³. As for the physical origin, it has been shown that surface tensions, as well as dielectric forces, are both responsible for carrying the bridge's weight¹⁴⁻¹⁶. To activate the water bridge as a water fiber, we couple light in with an adiabatically tapered silica fiber^{17,18} and out with a silica fiber lens¹⁹. Such a device can host acoustical, capillary, and optical waves, making it advantageous for multi-wave detectors and lab-on-chip²⁰⁻²² applications.

PROTOCOL:

CAUTION: This experiment involves high voltage. It is the reader's responsibility to verify with the safety authorities that their experiment follows regulations before turning on the high voltage.

Note: Any kind of polar liquid can be utilized to produce liquid fibers, such as ethanol, methanol, acetone, or water. The polarity of the liquid dictates the stability and diameter of the created fiber^{23,24}. For best results, use deionized water with 18 M Ω resistance. Before choosing optical components, such as optical fibers and light sources, consult the literature to ensure a low absorption in the water/liquid fiber at the desired optical wavelength. The protocol can be paused at any given moment before filling the water reservoir (step 4.5).

1. Preparation of Water Reservoirs and Experimental Station

1.1. Manufacture two poly(methyl methacrylate) (PMMA) reservoirs with magnetic connectors for the pipette and the high voltage, according to **Figure 1**.

1.1.1. Cut two PMMA plates to 60 x 50 x 10 mm in size, drill cavities of 8 mm in depth and 7 mm in diameter on the backside of the plates. Glue connector magnets inside the cavities.

1.1.2. For the capillary clamp, cut a stripe of PMMA to 45 x 10 x 2 mm and glue two magnets on the top side of it.

1.1.3. For the electric connector, wrap magnets in a small piece of metallic foil and connect it electrically with crocodile clamps to the high-voltage (HV) source. The reservoirs hold approximately 100 - 300 μ L of water. Place the wrapped magnets in fluidic contact with the water in the reservoir.

Note: Preferably, use magnetic connectors for clamps and high voltage. If possible, do not use any kind of glue to attach the clamps or the connectors, as many types of glues dissolve under the influence of high voltage or in the presence of electric arcs and diminish the water fiber stability or optical quality.

1.2. Mount one PMMA reservoir on a 5-degree-of-freedom (DOF) micro-positioning stage.

1.3. Thoroughly clean all connectors and areas with isopropanol (spectral grade) followed by deionized water. Blow-dry with nitrogen. Cover the PMMA water reservoir and all clamps with polytetrafluoroethylene (PTFE) tape to avoid any leaking or dripping of water.

1.4. Position the set-up under an optical microscope for imaging. Use far-field objectives (5X, 0.14 NA, and 34 mm WD for long water fibers and 20X, 0.42 NA, and 20 mm WD lens for short water fibers) to avoid unwanted grounding between the HV area of the water fiber and the electrically conductive microscope set-up.

1.5. Set up two optical fiber clamps on linear transitional stages, one behind each water reservoir, according to **Figure 1**. Each fiber coupler should be able to move back and forward within its micropipette (discussed in the following section).

2. Choosing the Micropipettes and Voltage

2.1. The inner diameter of the micropipette ensures a maximum radius of the fabricated water fiber. To create a 5- μ m radius water fiber, use 150- μ m-inner-diameter pipettes, paired with 125- μ m-diameter optical fibers. For thicker (20 - 90 μ m) and longer (800 - 1,000 μ m) water fibers, use micropipettes with an inner diameter of 850 μ m.

Note: As a rule of thumb, the water fiber maximum length is estimated by multiplying the maximal radius by 25. For details, refer to **Table 1**.

2.1.1. Break the micropipette by hand over an edge to a length of 3 cm.

2.2. To create water fibers with a diameter of up to 110 μm , apply a voltage between the two water reservoirs between 1.5 kV and 3 kV. For water fibers reaching up to a millimeter in length, apply up to 8 kV. Compare with **Figure 1** for electrical wiring suggestions.

3. Preparation of the Optical Couplers

Note: For the best transmission result, use a single-mode tapered fiber to launch laser light into the water fiber and a highly multimode reflowed fiber lens as the output coupler (core > 100 μm). However, for easy operation, use a low multimode fiber as the output coupler (for example, a 1550-nm single-mode fiber for a 780-nm wavelength).

3.1. Fabrication of a Tapered Fiber Coupler

Note: See **Figure 2**.

3.1.1. Strip the 780-nm single-mode fiber with a fiber stripper from its plastic cladding to expose an area of 10 - 15 mm of bare fiber. Clean the exposed area with delicate task wipes in combination with acetone. Pass the fiber through the desired micropipette before tapering it. Taper the fiber below the single-mode criteria with a slope smaller than 1/20.

3.1.2. Use a hydrogen flame for tapering the fiber with a flow rate of 140 mL/min, while simultaneously pulling the taper from both sides at 0.06 mm/s.

Note: The tapered portion is in total between 6 to 9 mm. If the fiber breaks before reaching the single-mode criteria, adjust the hydrogen flow to higher rates or place the fiber in a hotter area of the torch. If the area is longer, adjust the hydrogen flow to lower rates or place the fiber in a colder area of the torch.

3.1.3. Turn off the flame and carefully increase the tension in the fiber until it breaks at its thinnest spot. Use this tapered fiber as the input coupler.

CAUTION: The tapered fiber is fragile.

3.2. Fabrication of a Fiber Lens Coupler

3.2.1. Strip the 1550-nm single-mode fiber tip with a fiber stripper and clean the exposed area with delicate task wipes in combination with acetone. Choose and prepare a pipette as described above and pass the fiber through it.

3.2.2. Heat the tip with an electric fusion splicer or CO₂ laser at 15-W power, focused through a 200-mm lens, until the glass fiber end becomes liquid and forms a slightly rounded shape, known as a fiber lens.

4. Assembling

176
177 4.1. If not done yet, insert the fiber couplers into the desired micropipettes.
178

179 4.2. Clamp the micropipette, using the premanufactured, magnetic PMMA clamp, with the fiber
180 couplers onto the PMMA reservoirs. The non-tapered side of the micropipettes should reach into
181 the water reservoir. Clamp each of the fiber couplers on a linear positioning stage.
182

183 4.3. Connect the tapered fiber coupler to a 780-nm, continuous wave, fiber-coupled 10-mW laser
184 source and the fiber lens coupler to a power meter. Fill the reservoir with water and ensure that
185 no air bubbles are stuck in the micropipette. If necessary, push or pull them with the optical fiber
186 coupler (from step 3.1 or, accordingly, from step 3.2).
187

188 Note: At this stage, following the optical path, the stations are: the laser light source, the optical
189 fiber, (and this fiber goes through) the fiber clamp on a linear stage, the water in the reservoir
190 with electrical connection, the micropipette filled with water, the optical tapered fiber coupler,
191 free space (later: water fiber), the fiber lens coupler (now the second fiber), the micropipette
192 filled with water, the water reservoir with electric connection, the fiber clamp on a linear stage,
193 and, lastly, the power meter.
194

195 4.4. Connect the ends of the mounted micropipettes by adjusting the 5-degre-of-freedom mount
196 of the PMMA water reservoir to establish a fluidic contact between the micropipettes. Turn on
197 the light source and the power meter. Adjust the fiber couplers to have a transmission with the
198 help of the 5-DOF PMMA water reservoir mount.
199

200 Note: Use appropriate laser safety equipment.
201

202 4.5. Connect the high voltage electrically with the water reservoir by placing the magnetic
203 connectors wrapped in metallic foil over the magnetic counterparts in the PMMA water reservoir
204 and attaching crocodile clamps to the metallic foil. Connect the crocodile clamps *via* electrical
205 cables to the HV source (**Figure 2a**).
206

207 **5. Running the Experiment** 208

209 5.1. Increase the voltage to the desired value. A starting point for a very short and narrow bridge
210 is 1.5 kV. Stable bridges with 100 μm and more in length can be achieved with 2.5 - 3 kV.
211

212 5.2. Slowly increase the distance between the micropipettes to the desired length according to
213 the choice of the micropipettes (**Figures 2b** and **2c**). Adjust couplers and pipettes with the 5-DOF
214 stage and the 1-DOF stages to optimize the optical transmission.
215

216 5.3. Measure the coupling efficiency by taking a measurement on the power meter and taking
217 the ratio of the coupled-in to the coupled-out laser power.
218

5.4. Disconnect the power meter and connect a photoreceiver to the output fiber coupler. Connect the photoreceiver to an oscilloscope. Record time trace measurements of the transmitted light, representing the capillary water fiber oscillations.

5.5. Convert the time trace measurements *via* Fast Fourier Transformation to frequency domain. Take the central frequency over full width at half maximum to receive the capillary quality factor.

Note: Create a spectrogram to check for frequency jitter.

5.6. Use the top view microscope set-up to characterize the geometrical structure of the water fiber. The fiber radius is obtained at the thinnest portion of the water fiber.

REPRESENTATIVE RESULTS:

The coupling efficiency from a water fiber to a highly multimode fiber can be as high as 54%^{25,26}. The coupling efficiency to a single-mode fiber is up to 12%^{25,26}. Water fibers can be as thin as 1.6 μm in diameter and can have a length of 46 μm (**Figure 3**)^{25,26}, or they can be up to 1.064 mm in length with a diameter of 41 μm (**Figure 3**)^{25,26}. The transmission spectrogram reveals capillary oscillation of the water fiber, similar to that of a guitar string (**Figure 4**)^{25,26}. The capillary quality factors were estimated to be as high as 14 for long fibers^{25,26}. Considering the theory on water bridges, it is possible to estimate the ratio between the surface tension and the dielectric force^{25,26}.

FIGURE AND TABLE LEGENDS:

Figure 1: Schematics of the set-up. (a) This illustration shows the water fiber experimental set-up. (b) This sketch shows the water reservoir, the electrical connector, and the pipette clamp. (c) This panel shows the water-walled waveguide softness compared with common solids. This figure is reproduced in part from Douvidzon *et al.*^{25,26}.

Figure 2: Set-up photos. (a) This panel shows the PMMA-water reservoir on a 5-DOF mount. with the PMMA-pipette clamp, the micropipette, the optical fiber, and the electric connector. (b) This panel shows that a fluidic contact between the micropipettes is created. (c) This panel shows that the distance between the micropipettes is increased to establish a water fiber.

Figure 3: Water fiber characterization. (a) This panel shows a water fiber longer than 1 mm. The next two panels show (b) a micron-scale-thin water fiber, (c) the surface scattering due to capillary waves at the water fiber liquid-phase boundary. (d) This panel shows light propagation through the water fiber volume confirmed by a fluorescent dye measurement. This figure is reproduced from Douvidzon *et al.*^{25,26}.

Figure 4: Experimentally measuring the water fiber “guitar-string” modes. (a) This panel shows a time trace measurement. (b) A fluctuation spectrum reveals a fundamental mode and, at integer multiplications, its three overtones (dash lines). (c) This panel shows a fluctuation spectrogram of a 0.94-mm-long fiber with changing voltage and, correspondingly, changing the

fiber diameter, with voltage first constant, then increased, and finally, decreased. The color code describes the transmission. (d) This panel shows the fundamental frequency of the fiber as a function of the fiber diameter (circles) together with a theoretical prediction (dashed line). Horizontal and vertical error bars represent the uncertainty of eight consecutive, 250-ms-apart measurements of the central frequency and its corresponding fiber diameter. For all panels, the fiber length is 0.94 mm and the oscillation is optically interrogated with a photodetector. The diameter is measured *via* microscope. This figure is reproduced from Douvidson *et al.*^{25,26}.

Table 1: Water fiber length and radius. This table shows the water fiber length and radius with respect to the electric potential and the pipette diameter. This table is reproduced from Douvidson, *et al.*²⁵.

DISCUSSION:

To conclude, the major advantage and uniqueness of this technique is creating a fiber which hosts three different kinds of waves: capillary, acoustic, and optical. All three waves oscillate in different regimes, opening the possibility for multi-wave detectors. As an example, airborne nanoparticles affect the surface tension of liquids. Already at the current stage, it is possible to monitor changes in the surface tension through variations in the capillary eigenfrequency. Additionally, water-walled devices are a million times softer than their solid counterparts, improving the sensibility of sensors accordingly.

Based on experience with this set-up, we noticed a high dependency on the signal-to-noise ratio and the quality of the optical couplers. Therefore, it is recommended to pay close attention to the fabrication of the optical couplers. Consider an aquarium set-up to ensure a dust-free environment for the tapering station and the water fiber set-up. Also, the execution of the experiment involves a risk of breaking or damaging the tapered fiber coupler mechanically or through an electric arc. In that case, the optical transmission can drop and become noisy to such an extent that the capillary modes of the fiber are no longer visible in the spectrogram.

If capillary waves are not visible in the transmission measurements, remanufacture the couplers. Additionally, the water fiber and the optical fiber couplers do not attract each other. Adjusting the set-up for optimal transmission may require putting the water fiber a bit askew, to mechanically press the tapered fiber coupler inside the water fiber.

Another obstacle in this set-up to be aware of is the crucial electrical resistivity of the water. Even small amounts of ions in the liquid will cause the bridge to collapse. If the water fiber is shorter and less stable than expected, a contamination of the water might be the cause. Replace the water with 18 M Ω clean room water. Additionally, the high voltage attracts charged air particles in the surrounding of the water fiber, which dissolve and contribute to the instability. In this case, a closed chamber will help improve the water fiber longevity.

An outstanding aspect of this set-up is that any polar liquid can be utilized to create a liquid fiber, although deionized water is known for creating the longest, as well as, time-wise, the most stable water fibers. It is interesting to consider other liquids for different applications. Switching the

water to a liquid or a mix of polar liquids with fitting viscosity, surface tension, or optical properties allows researchers to trim the fiber exactly to their demands.

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DISCLOSURES:

The authors have nothing to disclose.

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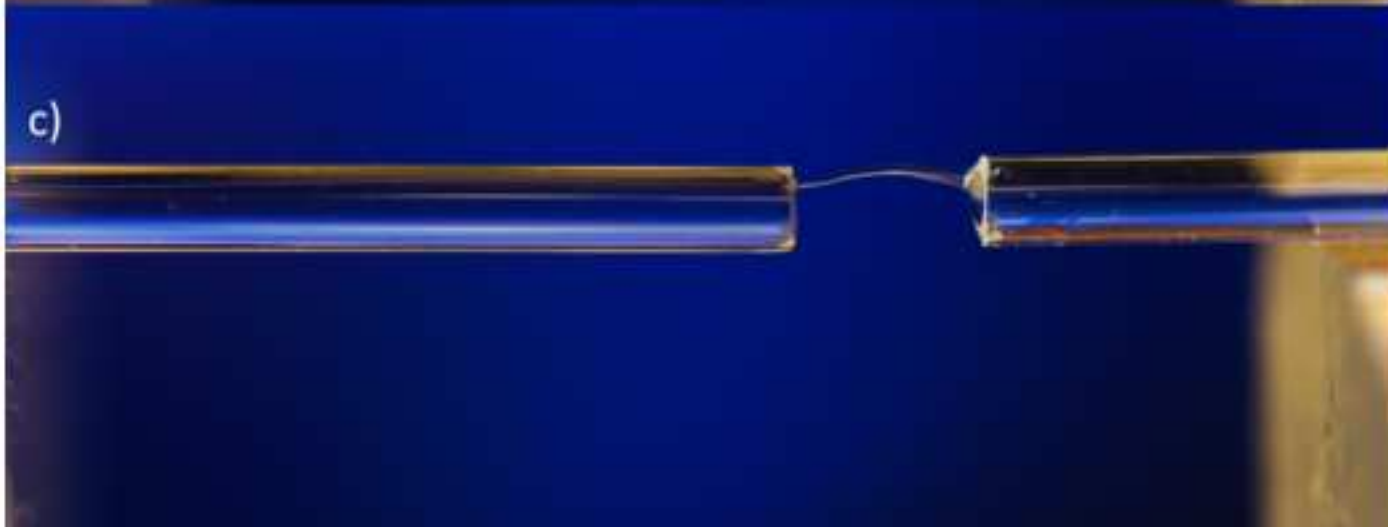
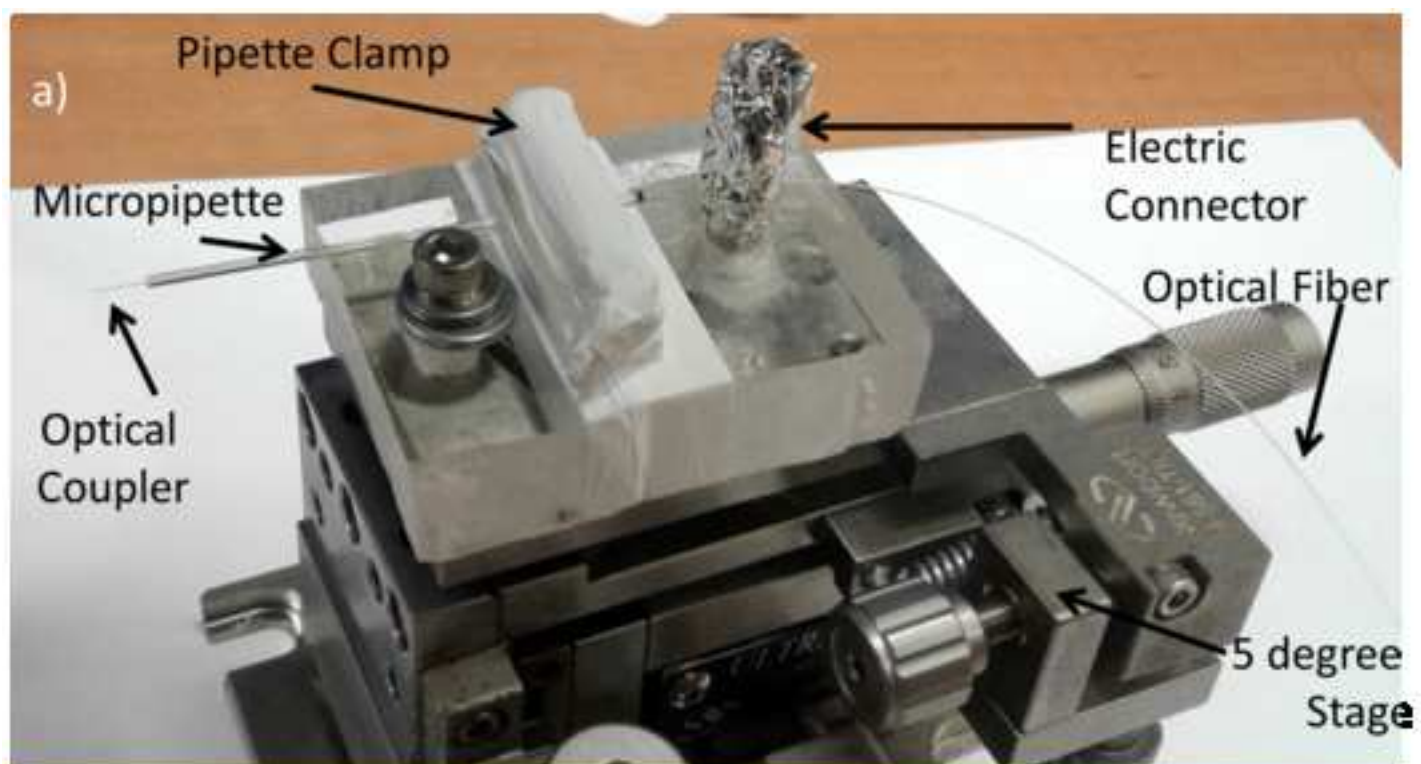


Figure 3

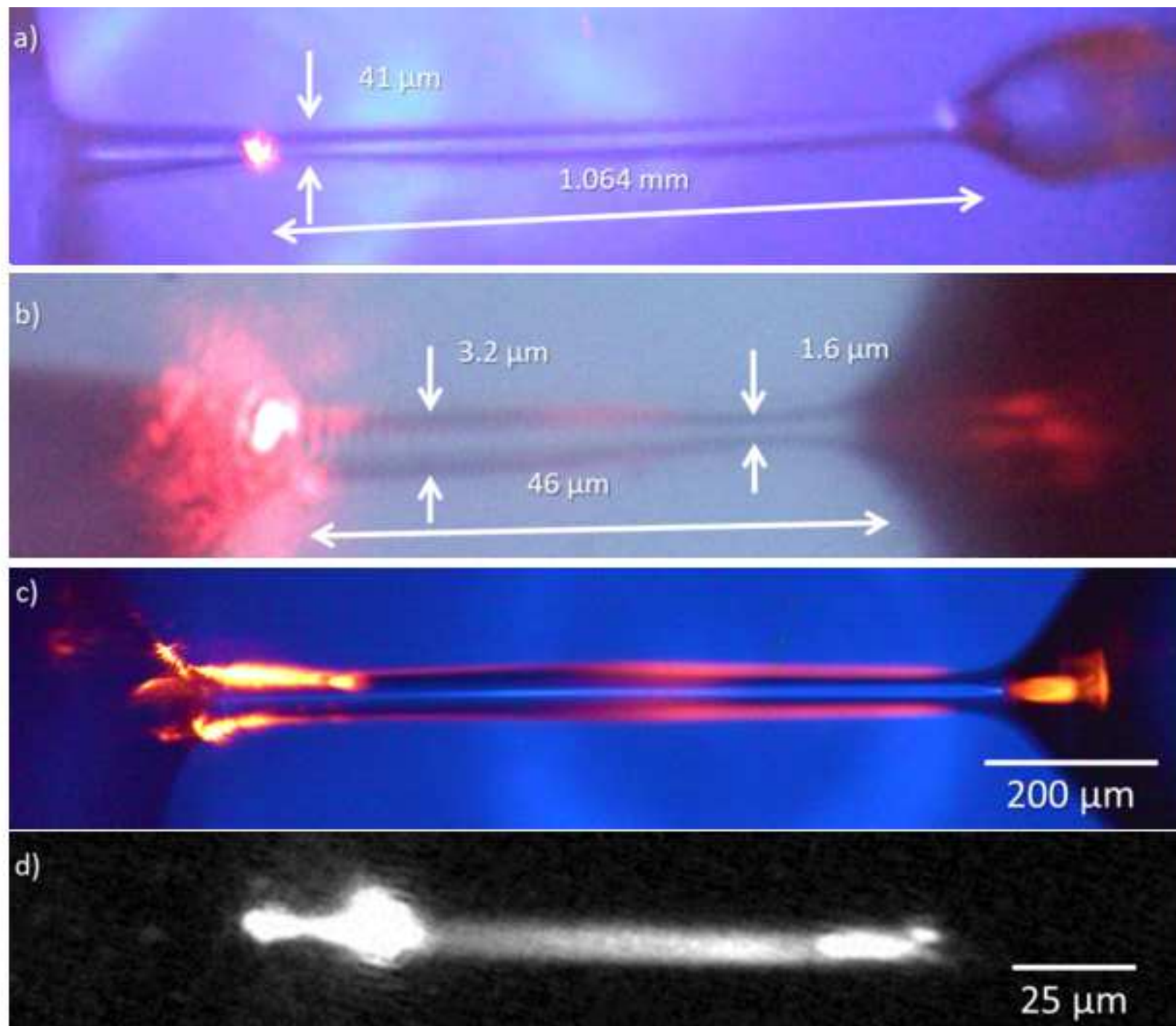
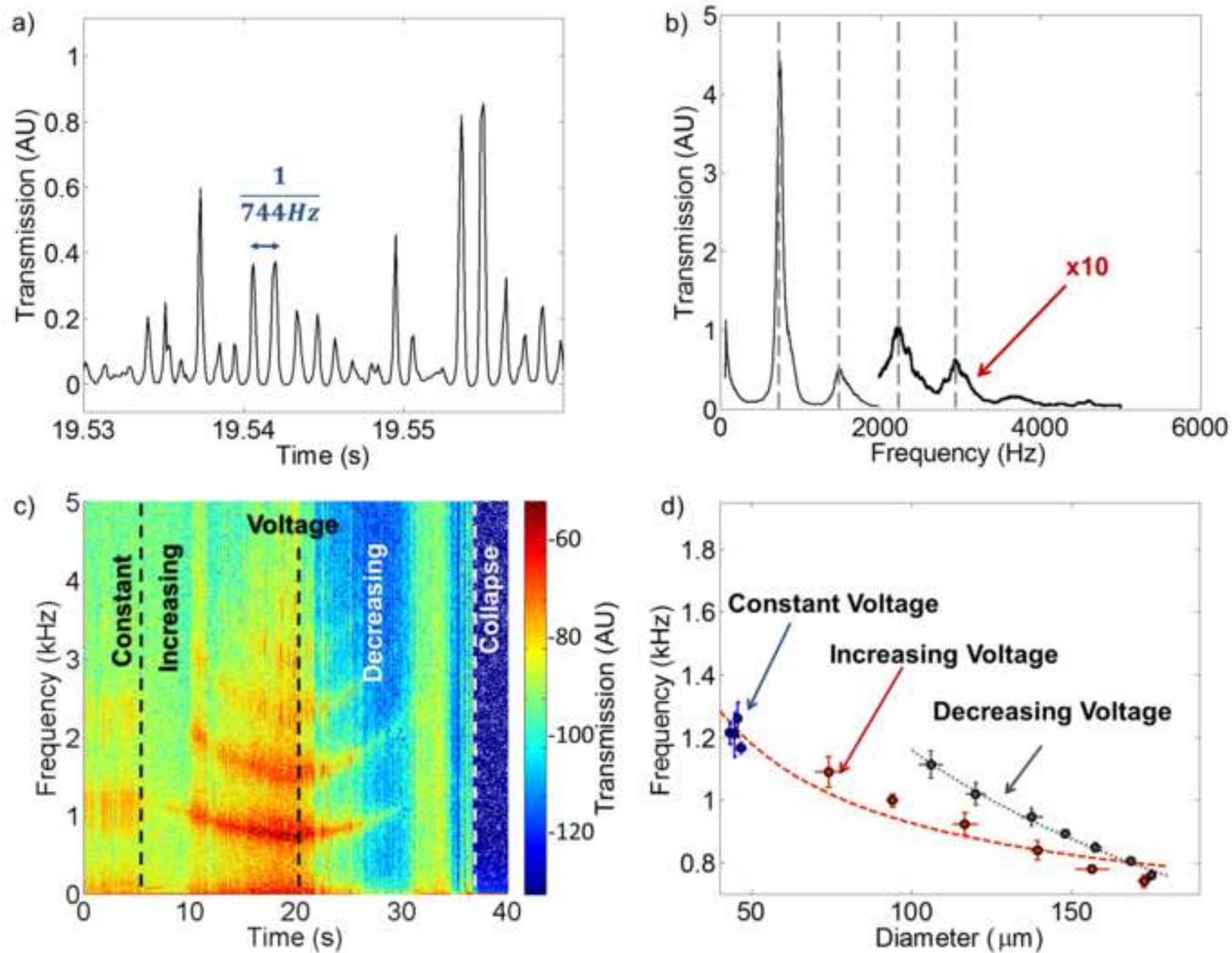


Figure 4

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Figure 1.svg

Pipette's internal diameter			Water fiber		
Lens side [μm]	Taper side [μm]	Potential [V]	Radius [μm]	Length [μm]	
850	850	6000	51	830	Fig. 1b
850	850	6000	20.5	1064	Fig. 2a
850	150	1500	1.6 - 0.8	46	Fig. 2b
850	850	5000	32.5	820	Fig. 2c
150	150	3000	4.75	110	Fig. 2d
850	850	3000 - 8000	20 - 90	940	Fig. 3
850	150	2500	2.7 - 3	24 - 73	Fig. 4

Name of Material/ Equipment	Company
Deioniyzed Water	
Micropipettes, Borosilicate Glass, round, inner diameter 850 micron	Produstrial.com
Micropipettes, Borosilicate Glass, round, inner diameter 150 micron	Produstrial.com
High voltage, low current source, 3kV with 5 mA.	Bertan
High voltage, low current source, 8 kV with 0.25 mA.	Home build
Optical fiber	Corning
Optical fiber	Thorlabs
Optical fiber	Thorlabs
Fiber coupled laser	FIS
Photoreceiver	New Port/ New Focus
Oscilloscope	Agilent Technologies
2 Degree of freedom tilt stagestage	New Port/ New Focus
3Degree of freedom linear micro translation stage	New Port/ New Focus
A set of magnets	
Objective 5X	Mitutoyo
Objective 20 x	Mitutoyo
Zoom	Navitar
Microscope tube	
Isopropanol	Navitar
2 x Bare Fiber holder	Sigma Aldrich
2 x Translational Stage	Thorlabs
Block of PMMA for fabricating the water reservoir and pipette holder	Thorlabs
PTFE-Tape	
Fiber coupled, cw Laser Light Source	Gufero
	New Port/ New Focus

Catalog Number	Comments/Description
#133260	18MOhm resistance
#133258	
Model 215	
HI 780 C	5 meter
FTO 30	5 meter
FTO 30	5 meter
SMF 28E	
1801-FS	with fiber connection
DSO-X 3034A	
M-562F-TILT	
M-562F-XYZ	
MY5X-802	
MY20X-804	
12x Zoom	
1-6015 standard	
tube	
67-63-0	Spec Grad
T711-250	
DT12	
	150 x 60 x 10 mm
240453	
TLB-6712	765-781 nm



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