Journal of Visualized Experiments

Silicon-tipped fiber-optic sensing platform with high resolution and fast response

--Manuscript Draft--

Article Type:	Invited Methods Article - JoVE Produced Video
Manuscript Number:	JoVE59026R1
Full Title:	Silicon-tipped fiber-optic sensing platform with high resolution and fast response
Keywords:	Fiber-optic sensing, Fabry-Perot interferometer, Silicon, temperature measurement, flow sensors, bolometry
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Additional Information:	
Question	**Response**
Please indicate whether this article will be Standard Access or Open Access.	Standard Access (US$2,400)
Please indicate the **city, state/province, and country** where this article will be **filmed**. Please do not use abbreviations.	East Lansing, Michigan, USA

TITLE:
A Silicon-Tipped Fiber-Optic Sensing Platform with High Resolution and Fast Response

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KEYWORDS:
Fiber-optic sensing, Fabry-Perot interferometer, Silicon, temperature measurement, flow sensors, bolometry

SUMMARY:
This work reports an innovative silicon-tipped fiber-optic sensing platform (Si-FOSP) for high-resolution and fast-response measurement of a variety of physical parameters, such as

temperature, flow, and radiation. Applications of this Si-FOSP span from oceanographic research, mechanical industry, to fusion energy research.

ABSTRACT:
In this article, we introduce an innovative and practically promising fiber-optic sensing platform (FOSP) that we proposed and demonstrated recently. This FOSP relies on a silicon Fabry-Perot interferometer (FPI) attached to the fiber end, referred to as Si-FOSP in this work. The Si-FOSP generates an interferogram determined by the optical path length (OPL) of the silicon cavity. Measurand alters the OPL and thus shifts the interferogram. Due to the unique optical and thermal properties of the silicon material, this Si-FOSP exhibits an advantageous performance in terms of sensitivity and speed. Furthermore, the mature silicon fabrication industry endows the Si-FOSP with excellent reproducibility and low cost toward practical applications. Depending on the specific applications, either a low-finesse or high-finesse version will be utilized, and two different data demodulation methods will be adopted accordingly. Detailed protocols for fabricating both versions of the Si-FOSP will be provided. Three representative applications and their according results will be shown. The first one is a prototype underwater thermometer for profiling the ocean thermoclines, the second one is a flow meter to measure flow speed in the ocean, and the last one is a bolometer used for monitoring exhaust radiation from magnetically confined high-temperature plasma.

INTRODUCTION:

Fiber-optic sensors (FOSs) have been the focus for many researchers due to its unique properties, such as its small size, its low cost, its light weight, and its immunity to electromagnetic interference (EMI)[1]. These FOSs have found wide applications in many areas such as environmental monitoring, ocean surveillance, oil exploration, and industrial process among others. When it comes to the temperature-related sensing, the traditional FOSs are not superior in terms of resolution and speed for the cases where measurement of minute and fast temperature variations is desirable. These limitations stem from the optical and thermal properties of the fused silica material on which many traditional FOSs are based. On one hand, the thermo-optic coefficient (TOC) and thermal expansion coefficient (TEC) of silica are $1.28\text{x}10^{-5}$ RIU/°C and $5.5\text{x}10^{-7}$ m/(m·°C), respectively; these values lead to a temperature sensitivity of only about 13 pm/°C around the wavelength of 1550 nm. On the other hand, the thermal diffusivity, which is a measure of the speed of temperature change in response to thermal energy exchange, is only $1.4\text{x}10^{-6}$ m^2/s for silica; this value is not superior for improving the speed of silica-based FOSs.

The fiber-optic sensing platform (FOSP) reported in this article breaks the above limitations of fused silica-based FOSs. The new FOSP utilizes crystalline silicon as the key sensing material, which forms a high-quality Fabry-Perot interferometer (FPI) on the end of the fiber, here referred to as silicon-tipped FOSP (Si-FOSP). **Figure 1** shows the schematic and operational principle of the sensor head, which is the core of the Si-FOSP. The sensor head essentially consists of a silicon FPI, whose reflection spectrum features a series of periodic fringes. Destructive interference occurs when the OPL satisfies $2nL=N\lambda$, where n and L are the refractive index and length of the silicon FP cavity, respectively, and N is an integer that is the order of the fringe notch. Therefore, positions of the interference fringes are responsive to the OPL of the silicon cavity. Depending on the specific applications, the silicon FPI can be made into two types: low-finesse FPI and high-finesse FPI. The low-finesse FPI has a low reflectivity for both ends of the silicon cavity, while the high-finesse FPI has a high reflectivity for both ends of the silicon cavity. The reflectivities of silicon-air and silicon-fiber interfaces are roughly 30% and 18%, thus the sole silicon FPI shown in **Figure 1a** is essentially a low-finesse FPI. By coating a thin high-reflectivity (HR) layer on both ends, a high-finesse silicon FPI is formed (**Figure 1b**). Reflectivity of the HR coating (either dielectric or gold) can be as high as 98%. For both types of Si-FOSP, both n and L increase when temperature increases. Thus, by monitoring the fringe shift, the temperature variation can be deduced. Note that for the same amount of wavelength shift, the high-finesse FPI gives a better discrimination due to the much narrower fringe notch (**Figure 1c**). While the high-finesse Si-FOSP has better resolution, the low-finesse Si-FOSP has a larger dynamic range. Therefore, the choice between these two versions depends on the requirements of a specific application. Furthermore, due to the large difference in full width at half maximum (FWHM) of the low-finesse and high-finesse silicon FPIs, their signal demodulation methods are different. For example, the theoretical FWHM of 1.5 nm is reduced by about 50 times to only 30 pm when both ends of the sole silicon FPI are coated with a 98% HR layer. Therefore, for the low-finesse Si-FOSP, a high-speed spectrometer would suffice for the data collection and processing, while a scanning laser should be used to demodulate the high-finesse Si-FOSP due to the much narrower FWHM that cannot be resolved well by the spectrometer. The two demodulation methods will be explained in the protocol.

The silicon material chosen here is superior for temperature sensing in terms of resolution. As a comparison, the TOC and TEC of silicon are 1.5×10^{-4} RIU/°C and 2.55×10^{-6} m/(m·°C), respectively, leading to a temperature sensitivity of around 84.6 pm/°C which is about 6.5 times higher than that of all silica-based FOSs[2]. In addition to this much higher sensitivity, we have demonstrated an average wavelength tracking method to reduce the noise level and thus improve the resolution for a low-finesse sensor, leading to a temperature resolution of 6×10^{-4} °C [2], in comparison to the resolution of 0.2 °C for an all silica-based FOS[3]. The resolution is further improved to be 1.2×10^{-4} °C for a high-finesse version[4]. The silicon material is also superior for sensing in terms of speed. As a comparison, the thermal diffusivity of silicon is 8.8×10^{-5} m^2/s, which is more than 60 times higher than that of silica[2]. Combined with a small footprint (*e.g.*, 80 µm diameter, 200 µm thickness), the response time of 0.51 ms for a silicon FOS has been demonstrated[2], in comparison to the 16 ms of a micro-silica-fiber coupler tip temperature sensor[5]. Although some research work related to temperature measurement using very thin silicon film as the sensing material has been reported by other groups[6-9], none of them possesses the performance of our sensors in terms of either resolution or speed. For example, the sensor with a resolution of only 0.12 °C and a long response time of 1 s was reported.[7] A better temperature resolution of 0.064 °C has been reported[10]; however, the speed is limited by the relatively bulky sensor head. What makes the Si-FOSP unique lies in the new fabrication method and data processing algorithm.

Besides the above advantages for temperature sensing, the Si-FOSP can also be developed into a variety of temperature-related sensors aiming at measuring different parameters, such as gas pressure[11], air or water flow[12-14], and radiation[4,15]. This article presents a detailed description of the sensor fabrication and signal demodulation protocols along with three representative applications and their results.

PROTOCOL:

1. Fabrication of Low-Finesse Sensors

1.1. Fabricate the silicon pillars. Pattern a piece of 200-µm-thick double-side-polished (DSP) silicon wafer into standalone silicon pillars (**Figure 2a**), using standard micro-electro-mechanical system (MEMS) fabrication facilitates.

NOTE: The patterned wafer is bonded on another larger silicon wafer using a thin layer of photoresist. The bonding force of the photoresist is strong enough to hold the pillars upright, but also weak enough to detach from the substrate for later steps.

1.2. Prepare the lead-in fiber. Strip off the plastic coating of the distal end of a single-mode optical fiber. Clean the stripped section using a lens tissue dipped with alcohol. Cleave the cleaned fiber using an optical fiber cleaver.

1.3. Apply a thin layer of UV-curable glue on the end-face of the cleaved lead-in fiber (**Figure 2b**). Put a little drop of UV-curable glue on a piece of glass slide. Thin the glue layer by spin-coating or manually swinging the glass slide. Transfer the glue layer to the fiber end by pressing the end face of the lead-in fiber against the glass slide.

1.4. Attach a silicon pillar to the fiber end. Align the lead-in fiber with one of the silicon pillars, meanwhile monitor the real-time reflection spectrum of the silicon FPI using a spectrometer. Use a UV lamp to cure the glue when a satisfactory spectrum is observed (**Figure 2c**).

NOTE: In general, the curing process takes around 10 to 15 minutes.

1.5. Detach the sensor from the substrate. After the UV glue is fully cured, lift up the lead-in fiber along with the silicon pillar detached from the substrate (**Figure 2d)**.

NOTE: Some residual photoresist is remained on the top surface of the silicon pillar (**Figure 2e**). For most cases, the photoresist residual does not affect the function of the sensor. If needed, the photoresist layer can be removed by alcohol.

1.6. Examine the fabricated sensor head. Use a microscope to examine the geometry of the fabricated sensor head. A typical image of a sensor successfully fabricated is seen in **Figure 2f**.

2. Fabrication of High-Finesse Sensors

2.1. Coat both sides of a silicon wafer with high-reflectivity mirrors. Coat one side of a 75-µm-thick double-side-polished silicon wafer with a 150 nm thick gold layer using a sputtering coating machine, and coat the other side with a high-reflectivity (HR) dielectric mirror.

NOTE: The dielectric HR coating was done by an outside company; reflectivity of this coating was tested to be no less than 98% by the company. However, detailed materials and structure of the coating are unknown due to the proprietary protection by the company, see the **Table of Materials** for more information.

2.2. Prepare the collimated lead-in fiber. Splice a short section of graded-index multi-mode fiber (GI-MMF) with a single-mode fiber, and then, under an optical microscope, cleave the GI-MMF with a quarter of the period of the light trajectory within the MMF left to form a fiber collimator (**Figure 3a**).

NOTE: The GI-MMF is used to expand the modal field diameter so that a spectrum with a better visibility can be obtained[4,16]. The length of the GI-MMF, which is around 250 µm in this work, is exactly one quarter of the period of the ray trajectory.

2.3. Attach a fragmented double-side coated silicon to the lead-in fiber. Assemble a high-finesse sensor by following the similar steps of attaching a silicon pillar to the fiber end for fabricating low-finesse sensors (steps 1.3 – 1.5).

NOTE: The side with the dielectric coating will be attached to the collimator to let in the coming light (**Figure 3b, 3 c**). In this case, the previous silicon pillar is replaced with a silicon fragment, which was not patterned. In the future, the patterned silicon wafer will be coated with the high-reflectivity mirrors, so that the sensors are more uniform and easier for fabrication. The difference in the fabrication steps of 1.3-1.5 is that a reflection spectra notch with proper visibility should be obtained first before the glue was transferred to the end face of the collimator.

2.4. Polish the irregularly-shaped silicon fragment into a circular shape using a fiber polishing machine.

2.5. Examine the fabricated sensor head. Use a microscope to examine the sensor head to make sure a desirable circular shape is achieved (**Figure 3d**).

3. Signal Demodulation for Low-Finesse Si-FOSP

NOTE: The system used for demodulating the low-finesse Si-FOSP is shown in **Figure 4a**. The following detailed steps help set up the system and perform the data processing.

3.1. Connect a C-band broadband source to port 1 of an optical circulator.

3.2. Splice port 2 of the optical circulator with the lead-in fiber of a low-finesse sensor.

3.3. Connect port 3 of the optical circulator to a high-speed spectrometer which communicates with a computer for data storage.

3.4. Check the spectrum of the sensor to make sure the system works properly. See the typical spectrum shown in **Figure 4b**.

4. Signal Demodulation for High-Finesse Si-FOSP

NOTE: The system used for demodulating the high-finesse Si-FOSP is shown in **Figure 5a**. The following detailed steps help set up the system and do the data post-processing.

4.1. Sweep a tunable DFB laser using a current controller.

NOTE: The peak-to-peak sweeping voltage, which varies for different lasers and controllers, should be large enough to cover the spectrum notch.

4.2. Connect the output of the tunable to port 1 of an optical circulator.

4.3. Splice port 2 of the optical circulator to a high-finesse sensor.

4.4. Connect port 3 of the optical circulator to a photodetector.

4.5. Use a data acquisition device to read the output of the photodetector, which is stored by a computer.

4.6. Check the spectrum of the sensor to make sure the system works properly. See a typical frame of spectrum shown in **Figure 5b**. Find the valley position using a polynomial curve fitting.

REPRESENTATIVE RESULTS:

Si-FOSP as an underwater thermometer for profiling ocean thermoclines

Recent oceanographic research has demonstrated that the blurring of underwater imaging stems not only from turbidity in contaminated waters but also from temperature microstructures in clean ocean[17,18]. The latter effect has been the focus of many oceanographers, aiming to find an effective way to rectify the blurred images[19], to better understand and improve optical communication in the water, as well as to develop means of quantifying turbulence in the ocean[20,21]. The Si-FOSP used as a temperature sensor has been demonstrated to outperform its current counterpart for measuring the swift temperature variations of water turbulence[22]. In this application, the low-finesse sensor shown in **Figure 1a** along with the signal demodulation system in **Figure 4a** is used. Given the superior performance of the Si-FOSP temperature sensor, it has been developed into a patented underwater instrument[23] (**Figure 6a**), which is intended to characterize the thermoclines of open waters. This sub-section presents the results of a field testing (**Figure 6b**) on the Flint Creek Reservoir in Mississippi, USA.

Figure 6c shows a measured thermocline of the Flint Creek Reservoir on September 13th, 2016. The blue curve was obtained by the Si-FOSP temperature sensor, while the red and black curves were obtained by two reference commercial CTDs (oceanography instruments for measuring conductivity, temperature, and depth of seawater). Obviously, the Si-FOSP temperature sensor agrees with the reference sensors, but with more details of the temperature structures (see the inset of **Figure 6c**) that may give a bunch of extra information. The more informative data collected by the Si-FOSP temperature sensor is expected to impact many branches of oceanographic research.

Si-FOSP as a large-dynamic-range flow sensor

Measurement of gas or liquid flows is pivotal to various academic and industrial sectors, which may provide important information to oceanography, weather research, process controls, transportation, and environment monitoring. Representative results of the Si-FOSP working as a flow sensor will be demonstrated. A low-finesse Si-FOSP is used for this application. However, since this flow sensor needs the sensing head to be actively heated by another laser, the system used is slightly different from that shown in **Figure 4a**. Specifically, an extra heating laser is used to activate the sensing head, and a detailed description of the system for flow measurement has been reported[12-14].

Figure 7a shows the Si-FOSP flow sensor situated in a water tank, with a side-by-side comparison to a commercial flow sensor. Obviously, readout of the fiber sensor generally agrees with that of the commercial flow sensor, as shown in **Figure 7b**; however, the Si-FOSP flow sensor exhibits a much clearer response when the water flows calm down, as illustrated by the close-up view in **Figure 7b**.

Si-FOSP as an EMI-immune bolometer for high-temperature plasma physics

Scientists investigating high-temperature plasma physics in tokamaks are trying to convert the exhaust power of magnetic confinement fusion reactors into photon emission to mitigate the heat flux impinged onto the plasma facing components[24]. **Figure 8a** shows the interior of a tokamak[25]. The photon emission is typically measured by a bolometer. While resistive and infrared video bolometers have achieved a noise equivalent power density (NEPD) of 0.2 W/m^2 and 0.23 W/m^2, respectively, in a laboratory environment[26,27], they are vulnerable to the harsh environment associated with the high-temperature plasma. The Si-FOSP reported in this work stands out as a promising alternative to the existing bolometers. To obtain a resolution as high as possible, the high-finesse version shown in **Figure 1b** will be used. Also, slightly different from the single-channel demodulation system shown in **Figure 5a**, a two-channel system will be used to compensate for the drift of the laser by using another dummy reference[4,15].

Figure 8b gives the measured results of one Si-FOSP bolometer in a laboratory environment, in comparison with another resistive bolometer. Our Si-FOSP bolometer has a NEPD of 0.27 W/m^2 which is close to those of the electronic counterparts[26,27]. Noting that the Si-FOSP bolometer has inherent resistance to the EMI typically found in high-temperature plasma physics, it is expected to hold great promises toward practical applications in tokamaks.

FIGURE AND TABLE LEGENDS:

Figure 1. Schematics showing the low-finesse (a) and high-finesse (b) Si-FOSP. (c) Simulated reflection spectra of the two versions of Si-FOSPs with a 75 µm thick silicon cavity. The minute shift of the spectrum (from solid to dashed curves) is much better discriminated by the high-finesse sensor.

Figure 2. Fabrication of low-finesse Si-FOSPs. (a)-(e) Schematic fabrication steps and (f) image of a fabricated sensor head compared with a human hair.

Figure 3. Fabrication of high-finesse Si-FOSPs. (a)-(c) Schematic fabrication steps and (d) image of one fabricated sensor. Inset in (d) shows the top view of the sensor head. GI-MMF, graded-index multi-mode fiber; HR, high-reflectivity.

Figure 4. (a) Schematic system of the demodulation system and (b) one typical frame of reflection spectrum for a low-finesse Si-FOSP.

Figure 5. (a) Schematic system of the demodulation system and (b) one typical frame of scanned spectrum for a high-finesse Si-FOSP.

Figure 6. Representative results as an underwater thermometer. (a) Image and (b) field deployment of the prototyped sensor instrument. (c) Measured thermocline of Flint Creek Reservoir, Mississippi, USA, on September 13th, 2016.

Figure 7. Representative results as a flow sensor. (a) Image of the flow testing arrangement and (b) comparison between the measured flow field by the Si-FOSP and that of a commercial flow sensor.

Figure 8. Representative results as a bolometer for high-temperature plasma research. (a) Image of the inner high-temperature plasmas space in a tokamak[25] and (b) measured results in a laboratory environment. This figure is adopted and modified from Wikimedia Commons.

DISCUSSION:

The choice of the size (length and diameter) of the silicon FPI is made upon the tradeoff between requirements on the resolution and speed. In general, a smaller size provides a higher speed but also reduces the resolution[2]. A short length is advantageous for obtaining a higher speed, but it is not superior for obtaining a high resolution due to the expanded FWHM of the reflection notches. Using HR coatings to reduce the FWHM can help improve the resolution, but it will limit the dynamic range due to the signal demodulation using laser scanning. A smaller diameter increases the speed, but the diameter should be larger than the modal field diameter of the lead-in fiber so that a good spectrum can be achieved. It is, however, also found that a silicon diameter larger than that of the fiber helps improve the sensitivity for bolometry due to the reduced conduction heat loss to the fiber[4]. Therefore, the choice of the sensor size is highly dependent on the specific applications.

Although we only demonstrate the very basic structures, fabrication protocols, and signal demodulation systems for the Si-FOSP, there are various techniques that can fit it into other applications or further improve the performance. For example, instead of using UV-curable glue to attach the sensor, a fusion splicing technique can be applied to elevate the operation temperature above 1000 °C[28]. With such a high operation temperature, innovative types of photonic devices can be made, such as micro-heaters, infrared emitters, and bubble generators. Another example is the self-temperature compensated gas pressure sensing using the wavelength difference when the heating laser is turned on and off[11]. Furthermore, through the development of novel peak recognition techniques[29,30], temperature measurement over extended dynamic range can be realized.

ACKNOWLEDGMENTS:

This work was supported by U.S. Naval Research Laboratory (Nos. N0017315P0376, N0017315P3755); U.S. Office of Naval Research (Nos. N000141410139, N000141410456); U.S. Department of Energy (Nos. DE-SC0018273, DE-AC02-09CH11466, DE-AC05-00OR22725).

DISCLOSURES:

An U.S. patent (No. 9995628 B1) has been issued to protect the related technologies.

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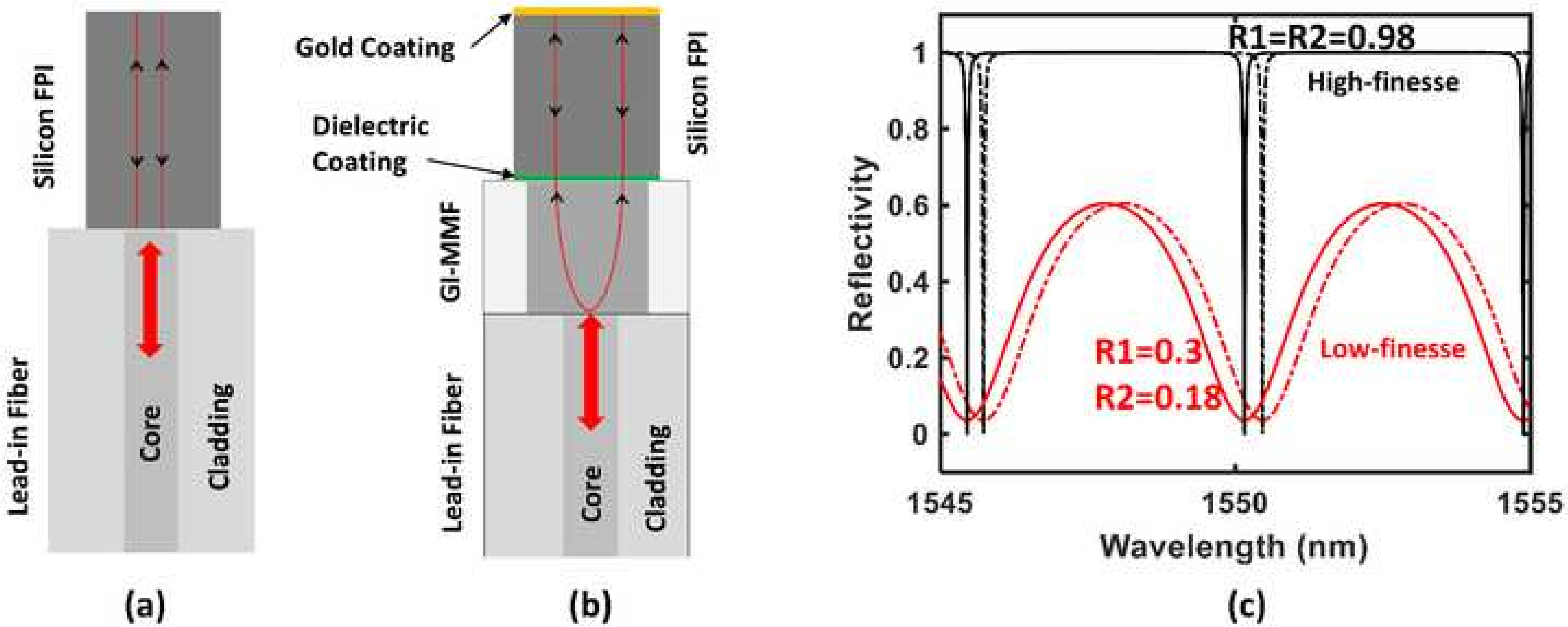
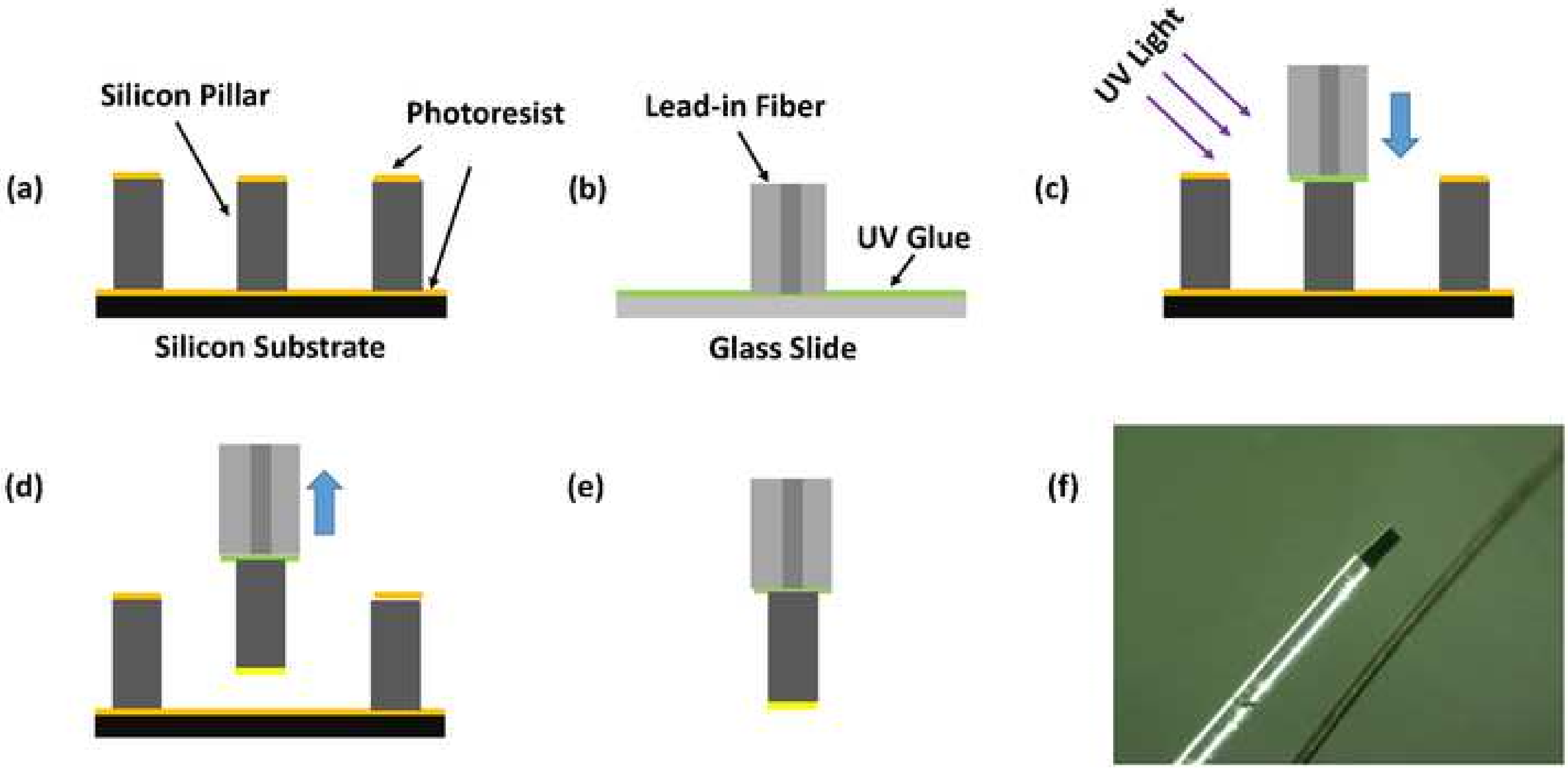


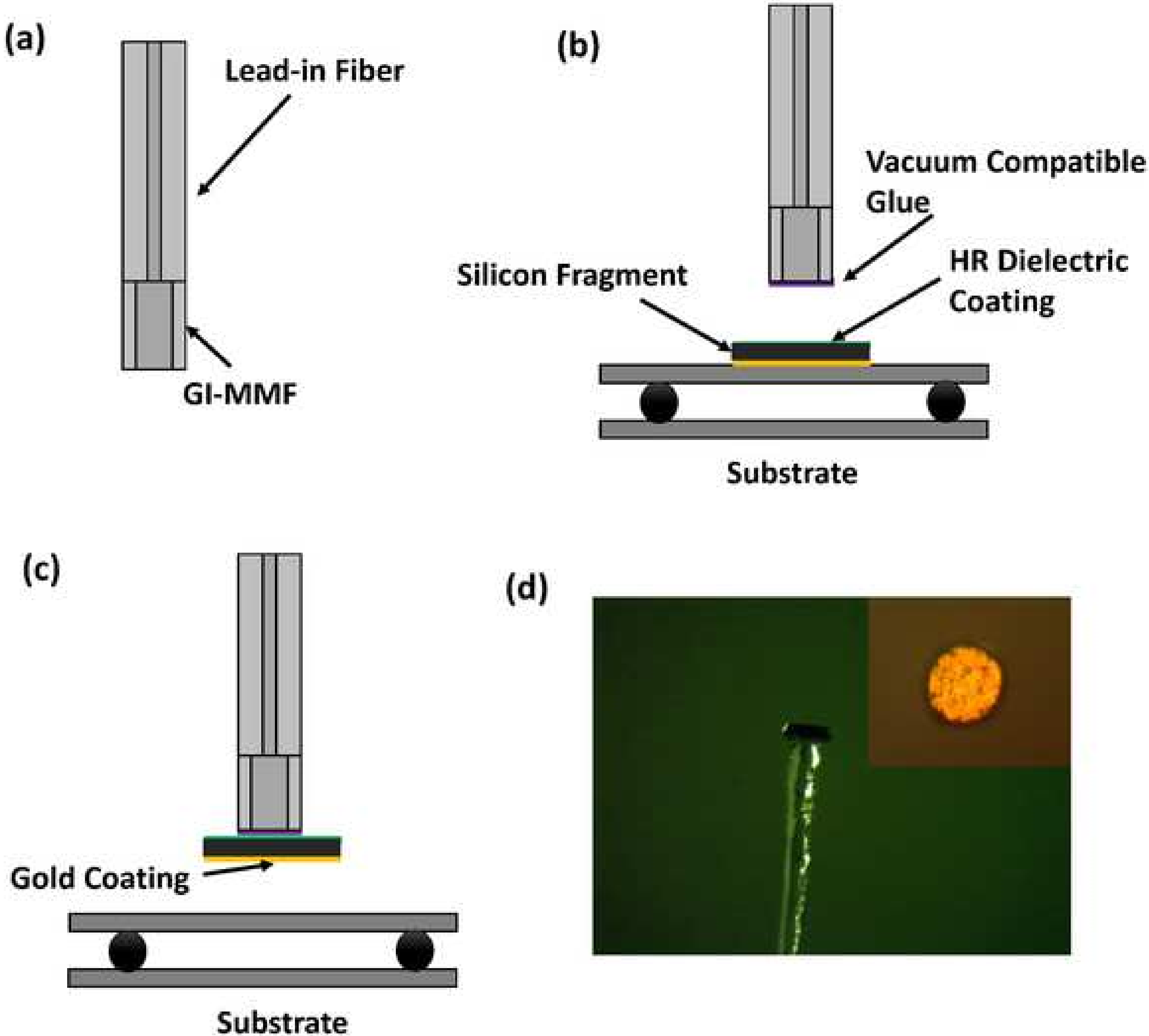
Silicon FPI
Lead-in Fiber
Core
Cladding
(a)
Gold Coating
Dielectric Coating
Silicon FPI
GI-MMF
Lead-in Fiber
Core
Cladding
(b)
R1=R2=0.98
High-finesse
R1=0.3
R2=0.18
Low-finesse
Reflectivity
Wavelength (nm)
1
0.8
0.6
0.4
0.2
0
1545
1550
1555
(c)

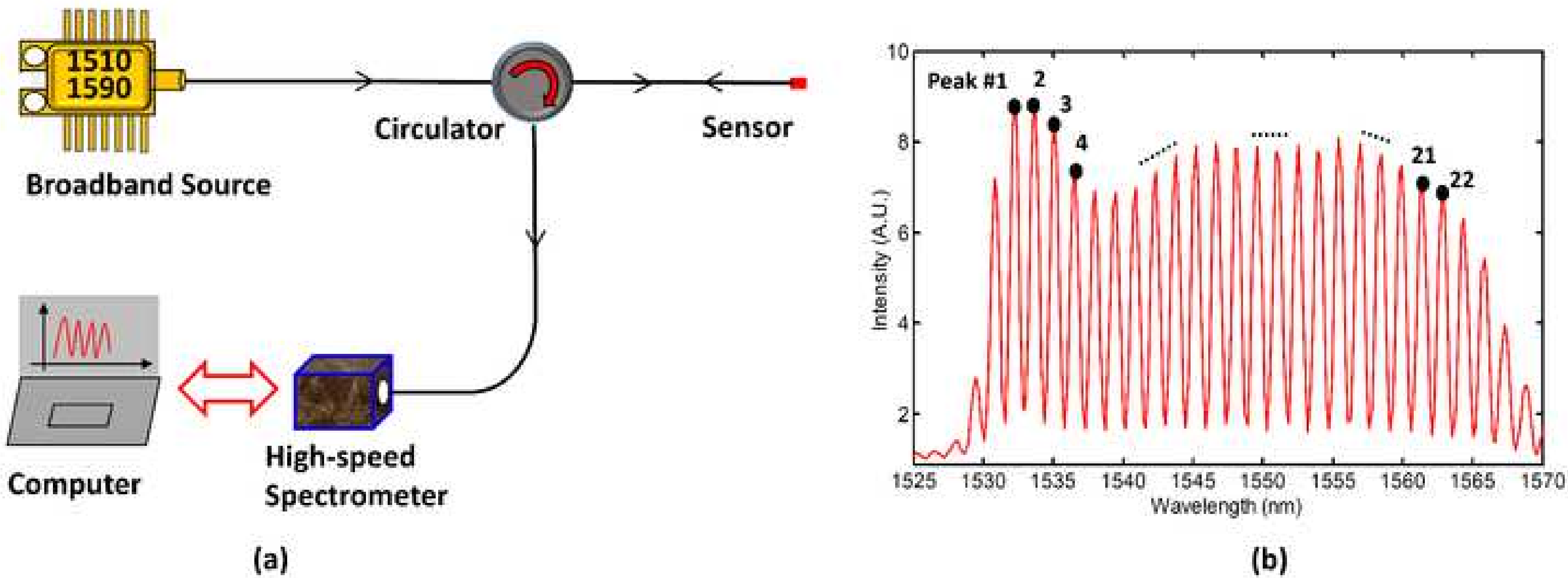


Silicon Pillar
Photoresist
(a)
Silicon Substrate
Lead-in Fiber
(b)
UV Glue
Glass Slide
UV Light
(c)
(d)
(e)
(f)

Figure

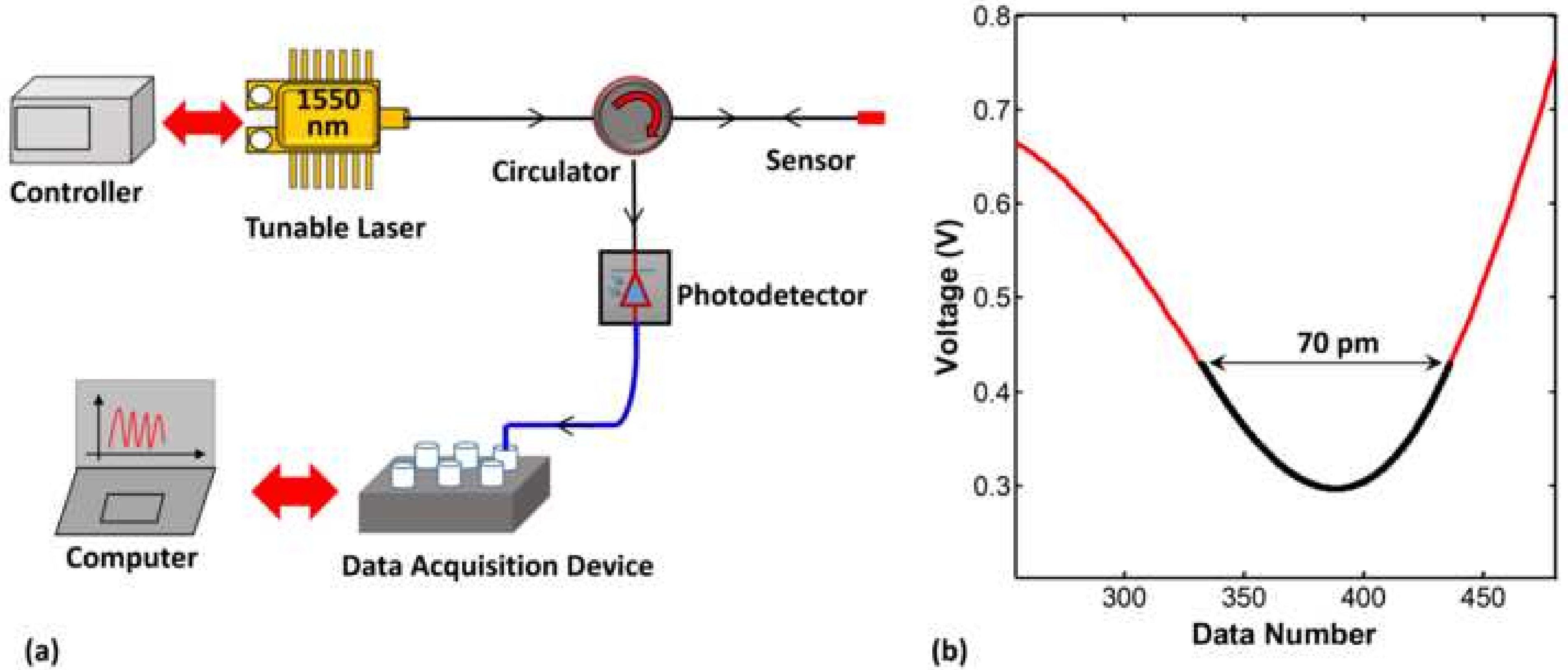
Click here to access/download;Figure;Figure 3.tif




1510
1590
Broadband Source
Circulator
Sensor
Computer
High-speed
Spectrometer
(a)
Peak #1
2
3
4
21
22
Intensity (A.U.)
Wavelength (nm)
(b)

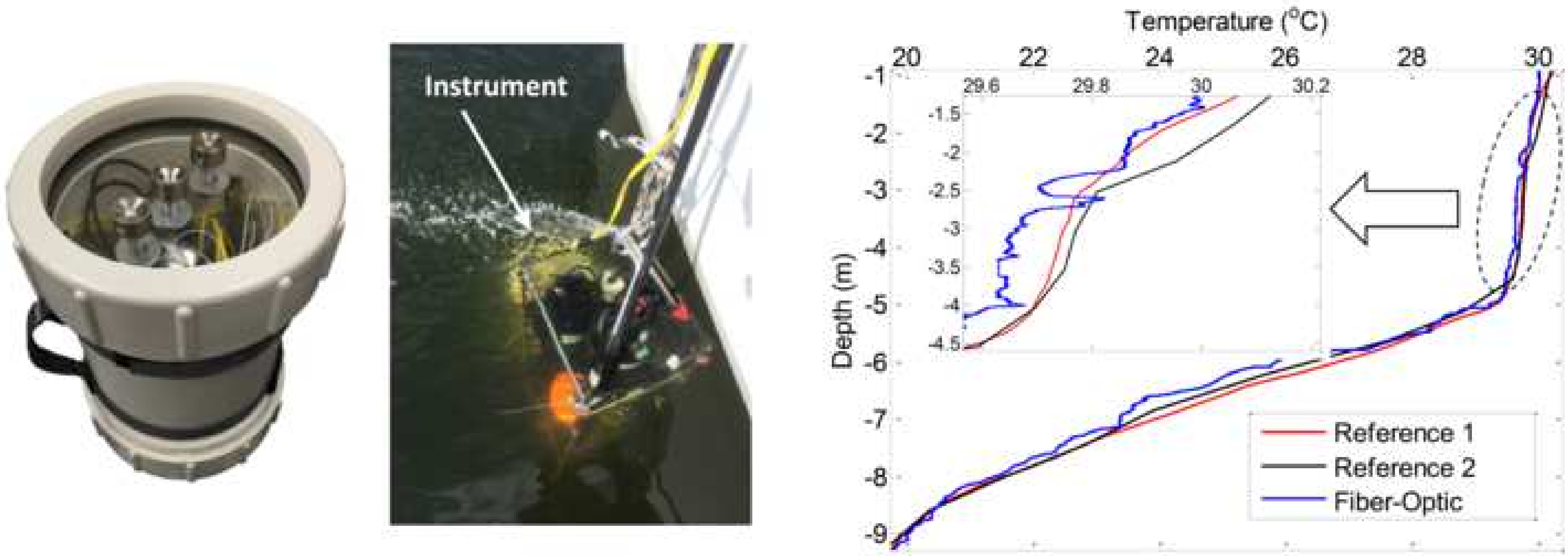
Figure

Click here to access/download;Figure;Figure 5.tif



Figure

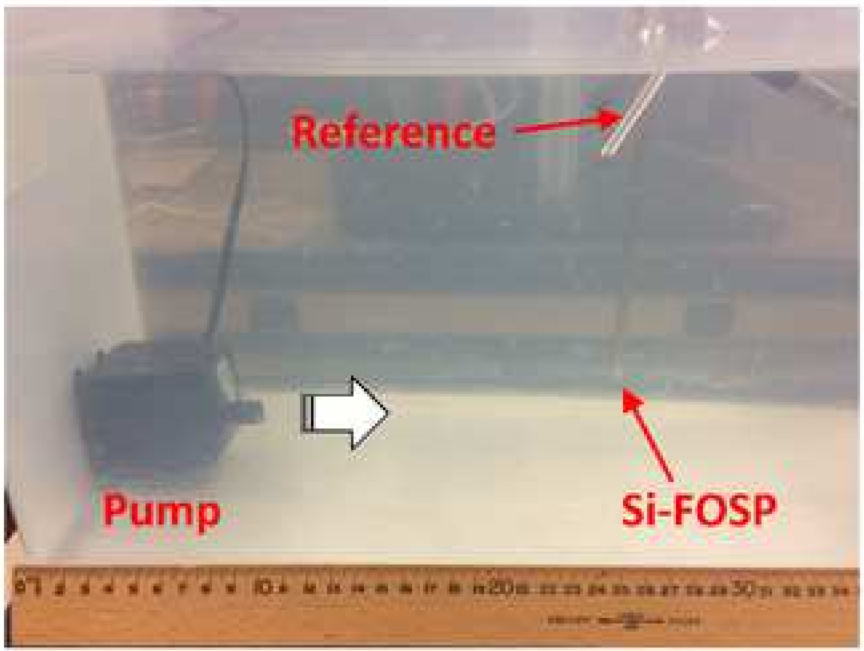
Click here to access/download;Figure;Figure 6.tif



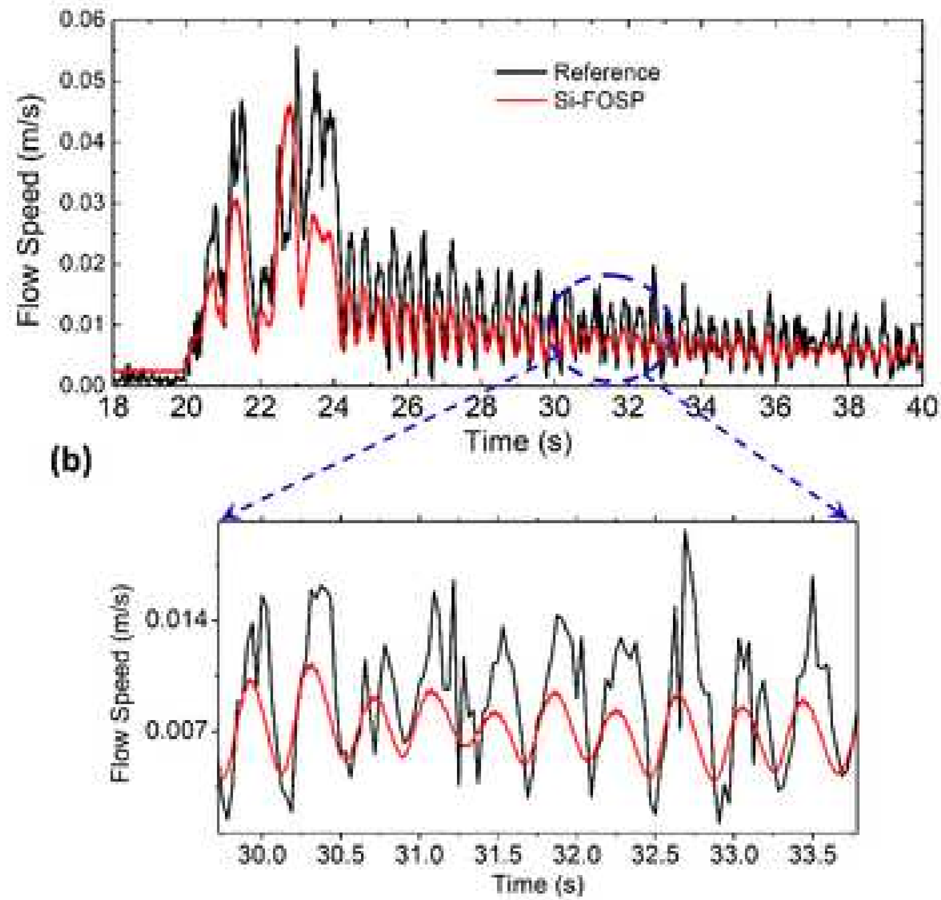
(a) (b) (c)

Figure

Click here to access/download;Figure;Figure 7.tif

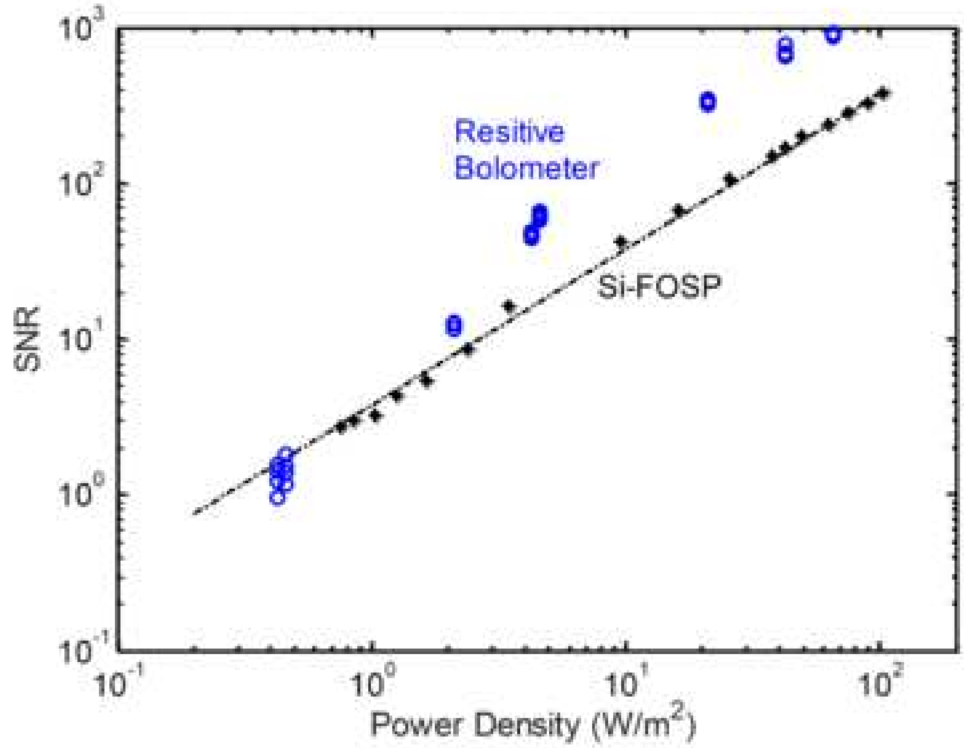


(a)



(b)

(a)


Resitive
Bolometer
Si-FOSP
SNR
Power Density (W/m^2)
10^3
10^2
10^1
10^0
10^{-1}
10^{-1}
10^0
10^1
10^2

(b)

Name of Material/ Equipment	Company	Catalog Number
200 Proof Pure Ethanol	Koptec	V1001
5 Channels Duplex CWDM	Fiber Store	5MDD-ABS-FSCWDM
Butterfly Laser Diode Mounts	Tholabs	LM14S2
CastAway CTD	Yellow Springs Instrument	
CTD	Seabird	SBE 19plus
Current Meter	Nortek	Vector
Data Acquisition Device	National Instruments	NIUSB4366
Digital Oscilloscope	RIGOL	DS1204B
Diode Laser	Thorlabs	LM9LP
Fixed BNC Terminator Kit	Thorlabs	FTK01
Function Waveform Generator	RIGOL	DG4162
High Precision Cleaver	Fujikura	CT-32
High Reflection Dielectric Coating	Evaporated Coating INC (ECI)	
I-MON 512 Spectrometer	Ibsen Phtonics	P/N: 1257110
InGaAs Biased Detector	Tholabs	DET01CFC
Laser Diode	Qphotonic	QFLD-405-20S
Laser Diode Current Controller	Tholabs	LDC 210C
Laser Diode Temperature Controller	Tholabs	TEC 200C
Latex Examination Gloves	HCS	
Micro Slides	Corning Incorporated	
Narrow Linewidth DFB Laser	Eblana	EP1550-NLW-B06-100FM
Optical Fiber Fusion Splicer	Sumitomo electric industries, LTD	3822-2
Optical Microscope and Monitor	Ikegami Tsushinki Company	PM-127
Optical Spectrum Analyzer	Yokogawa	AQ6370C
Polish Machine	ULTRA TEC	41076
Post-mountable Irises	Thorlabs	
Pump Laser	Gooch and Housego	0400-0974-SM
Si Amplified Photodetector	Thorlabs	PDA36A
Silicon wafer	University Wafer	
Single mode fiber	Corning	SMF-28

Single Mode Fused Fiber Coupler	Thorlabs	
SM 125 interogrator	Micron Optics	
Submersible Aquarium Pump	Songlong	SL-403
Superluminscent LED	Denselight Semiconductors	DL-BP1-1501A
Syringe Pump	Cole Parmer	74905-02
Travel Translation Stage	Thorlabs	LT1
UV curable glue	Epoxy Technology	PB109077
UVGL-15 Compact UV Lmap	UVP	P/N:95-0017-09
Variable Optical Attenuators	Tholabs	M-VA/00016951 P/N: VOA50-APC

Comments/Description

200 MHz 2 GSa/s
Wavelength: 632 nm

160 MHz 500 GSa/s

Materials and structure of the coating are unknown

FC/PC output:0-10V; Quantity: 2
Wavelength: 405 nm
1 A and 100 mA range
Quantity: 2

Wavelength:1550 nm

wavelength range: 600-1700 nm

Quantity: 2
Wavelength: 980 nm
Wavelength: 350-1100 nm
thickness: 10 µm, 200 µm, 75 µm, 40 µm

Wavelength: 1550 nm

wavelength range:1510-1590 nm

254/365 nm

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Title of Article: Silicon-tipped fiber-optic sensing platform with high resolution and fast response

Author(s): Guigen Liu; Qiwen Sheng; Weilin Hou; Matthew Reinke; Ming Han

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CORRESPONDING AUTHOR:

Name: Ming Han

Department: Electrical and Computer Engineering

Institution: Michigan State University

Article Title: Silicon-tipped fiber-optic sensing platform with high resolution and fast response

Signature: Ming Han Date: 08/30/2018

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October 10th, 2018

Paper #: JoVE59026

Silicon-tipped fiber-optic sensing platform with high resolution and fast response

Authors: Guigen Liu, Qiwen Sheng, Weilin Hou, Matthew L. Reinke, Ming Han

Dear Dr. DSouza,

We appreciate that you returned the reviewer comments and gave us the opportunity to revise our manuscript. While reviewers #2-4 provided comments concerning the technical contents which were in general supportive, reviewer #1 and the editorial review pinpointed some critical mismatches between the manuscript structure with the *JoVE* taste. In the revised text manuscript, in addition to addressing the minor technical concerns, the manuscript structure has been significantly modified to comply with the *JoVE* style. Revisions of the manuscript have been marked by red.

We hope the updated manuscript can be acceptable for publication in *JoVE*.

Sincerely,

Ming Han

Michigan State University, USA

-------------- Response to Reviewer Comments ----------------

Responses (**bold**) to comments (*Italic*) from reviewers and editor are provided as follows.

Editorial Comments:

• *Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammatical errors.*

Response: **The revision has been carefully proofread.**

• *Protocol Language: The JoVE protocol should be almost entirely composed of numbered short steps (2-3 related actions each) written in the imperative voice/tense (as if you are telling someone how to do the technique, i.e. "Do this", "Measure that" etc.). Any text that cannot be written in the imperative tense may be added as a brief "Note" at the end of the step (please limit notes). Please re-write your ENTIRE protocol section accordingly. Descriptive sections of the protocol can be moved to Representative Results or*

Discussion. The JoVE protocol should be a set of instructions rather a report of a study. Any reporting should be moved into the representative results.

Response: **This point has been followed, see the Protocol section of the revision.**

• *Protocol Detail: Please note that your protocol will be used to generate the script for the video, and must contain everything that you would like shown in the video. Please add more specific details (e.g. button clicks for software actions, numerical values for settings, etc) to your protocol steps. There should be enough detail in each step to supplement the actions seen in the video so that viewers can easily replicate the protocol.*

• *Protocol Highlight: Please highlight ~2.5 pages or less of text (which includes headings and spaces) in yellow, to identify which steps should be visualized to tell the most cohesive story of your protocol steps. Please see JoVE's instructions for authors for more clarification. Remember that the non-highlighted protocol steps will remain in the manuscript and therefore will still be available to the reader.*
1) The highlighting must include all relevant details that are required to perform the step. For example, if step 2.5 is highlighted for filming and the details of how to perform the step are given in steps 2.5.1 and 2.5.2, then the sub-steps where the details are provided must be included in the highlighting.
2) The highlighted steps should form a cohesive narrative, that is, there must be a logical flow from one highlighted step to the next.
3) Please highlight complete sentences (not parts of sentences). Include sub-headings and spaces when calculating the final highlighted length.
4) Notes cannot be filmed and should be excluded from highlighting.
5) Please bear in mind that software steps without a graphical user interface/calculations/ command line scripting cannot be filmed.

Response: **This point has been followed, see the highlighted texts of the Protocol section.**

• *Discussion: JoVE articles are focused on the methods and the protocol, thus the discussion should be similarly focused. Please ensure that the discussion covers the following in detail and in paragraph form (3-6 paragraphs): 1) modifications and troubleshooting, 2) limitations of the technique, 3) significance with respect to existing methods, 4) future applications and 5) critical steps within the protocol.*

Response: **The original Conclusion section has been changed to Discussion, see the revision.**

• *Figures: Please remove the embedded figures from the manuscript. Figure legends, however, should remain within the manuscript text, directly below the Representative Results text.*

Response: **The point has been followed, see the revision.**

• *Figure/Table Legends: Please expand the legends to adequately describe the figures/tables. Each figure or table must have an accompanying legend including a short title, followed by a short description of each panel and/or a general description.*

Response: **The legends have been enriched, see the revision.**

• *References: Please make sure that your references comply with JoVE instructions for authors. Citation formatting should appear as follows: (For 6 authors or less list all authors. For more than 6 authors, list only the first author then et al.): [Lastname, F.I., LastName, F.I., LastName, F.I. Article Title. Source. Volume (Issue), FirstPage – LastPage, doi:DOI (YEAR).]*

Response: **The references have been reviewed to comply with the instructions.**

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Response: **All the commercial language has been removed in the revision.**

• *Table of Materials: Please revise the table of the essential supplies, reagents, and equipment. The table should include the name, company, and catalog number of all relevant materials/software in separate columns in an xls/xlsx file. Please include items such as lasers, instruments, fibers, software etc.*

Response: **The Table of Materials has been updated.**

• *If your figures and tables are original and not published previously or you have already obtained figure permissions, please ignore this comment. If you are re-using figures from a previous publication, you must obtain explicit permission to re-use the figure from the previous publisher (this can be in the form of a letter from an editor or a link to the editorial policies that allows you to re-publish the figure). Please upload the text of the re-print permission (may be copied and pasted from an email/website) as a Word document to the Editorial Manager site in the "Supplemental files (as requested by JoVE)" section. Please also cite the figure appropriately in the figure legend, i.e. "This figure has been modified from [citation]."*

Response: **Figure 8(a) of the revised manuscript is modified from Wikimedia Commons which are open to distribute with appropriate attribution.**

Reviewer #1:

Manuscript Summary:

The submission provides a rather comprehensive report of the authors' new sensing platform. It seems, however, to miss the mark in that the spirit of JoVE is in the protocol and performance of the work.

Major Concerns:

This misunderstanding is perhaps indicated by the first sentence: "In this video article, we introduce an innovative and practically promising fiber-optic sensing platform (FOSP) that we proposed and demonstrated recently, with an emphasis on the brief introduction of operation principle, demodulation methods, fabrication protocols, and representative applications." But a JoVE submission should be mostly about protocols: sensor fabrication, operation, and testing. Processes.

Response: **The manuscript has been significantly revised to abide by the JoVE style requirement.**

Section 1 "System Configuration" describes the physics of the sensor and should be part of an introduction. Please refer to the JoVE template, which specifies an introduction followed by the protocol.

Response: **The original System Configuration has been removed from the Protocol section and is incorporated in the Introduction part.**

Section 2 "Fabrication Protocol". The protocol should direct the reader to very specific actions. For example, rather than "A piece of 75 micon-thick DSP silicon wafer is cleaned first", something like "Cut a 75 micron-thick wafer to height-x by width-y. Clean the wafer with solvent-A and material-B by wiping......". Please review and edit the protocol steps to conform to this style.

Response: **The style has been followed, see the Protocol part of the revised text manuscript.**

Section 3 "Representative Applications and Results". Most of this section is application background. This section should be restricted to representative results. One or two data plots should suffice along with discussion of their significance. The application photos and schematic are inappropriate for the results section.

Response: **The application background has been made to be more concise. However, since a brief introduction of the background is necessary for the understanding of the representative results, they are not completely removed. The remaining concise background introduction will not interfere with the overall style, see the Representative Results section.**

Section 4 "Conclusion". JoVE articles typically end with a "Discussion" section, where the authors comment on the protocol, noting pitfalls or critical steps. Often the interesting and/or novel step(s) of the protocol are highlighted. The authors do not mention the protocol in their closing section.

Response: **The Conclusion part has been changed to Discussion part.**

Minor Concerns:
The text is generally well-written and clear, but might benefit from a review by a native English speaker. For example, replace "finesse" with "fidelity", "fastness" with "speed", "tokama" with "tokamak".

Response: **"finesse" is a commonly accepted term for this field, thus it is not changed. The other wording suggestions have been accepted.**

Reviewer #2:

Manuscript Summary:
This video article reports fiber-optics sensors (thermometer, flow meter and bolometer) based on a silicon Fabry-Perot interferometer (Si-FPI). The operation principles, preparation methods and representative practical applications of the sensors were clearly demonstrated. In particular, the interference generated from the reflection of the Si-FPI exhibits spectral shifts induced by temperature which serves as a basis for sensing and this reflection was also tuned by coating the Si sensor head affording either high- or low-finesse sensors. Overall, it was shown that the sensor platforms in this work have better sensing performance (superior sensitivity, thermal resolution and response time) than that of the conventional fiber optics sensors. The significance of the work is clearly highlighted, and the results are well communicated and structured; the manuscript is well written. In my view, this manuscript can be accepted for publication in Journal of Visualized Experiments, after the following concerns are addressed.

Major Concerns:
1. The sensor parameters should be represented by figures: for instance, in terms of temperature dependent spectral shifts and sensitivity (i.e., temperature vs. spectral shift, temperature vs. sensitivity, etc.).

Response: **We appreciate that the reviewer brought about an important point. However, since these results on wavelength shift vs. temperature have been well reported by our previous papers (Refs. [2][11-12]), they are not provided in this article to avoid redundancy. In the introduction part, these previous results have been cited explicitly, so that interested readers can refer to.**

2. Further details on the methods of determining (the experimental or theoretical) temperature resolution and response time should be given.

Response: **Similar to the point #1 of this reviewer, these results on resolution and response time have been well reported by our previous paper (Ref. [2]), they are not provided to avoid redundancy, but these important aspects have been mentioned in the introduction part.**

3. Figures should be adequately described in the caption without reference to the text in the manuscript (e.g. Fig. 4).

Response: **All the figure captions have been enriched.**

Minor Concerns:

4. The authors mentioned that superior sensing performance reported in this work is related to the size of the Si head and to the high thermal conductivity of Si; what would be the theoretical predication of the sensor´s response time and temperature resolution for a much smaller (much thinner) Si cavity/sensors (e.g., nanometric scale size), and what is the limitation to design such a device?

Response: **Thanks for pointing out an important aspect. The first paragraph of the Discussion part has been added to address this point.**

Reviewer #3:

Manuscript Summary:

The authors successfully demonstrated a miniature fiber-optic sensor. The protocol of fabrication and the result of the measurement are very interesting. I think the achievement is worth to publish.

Minor Concerns:

I am curious why the authors used the low-finesse type sensor for the measurement of ocean thermoclines.

Response: **A low-finesse Si-FOSP is demodulated using a high-speed spectrometer that covers a broad band of spectrum, which gives a much larger dynamic range. The high-finesse version can not provide enough dynamic range for this application.**

Reviewer #4:

Manuscript Summary:

The paper is interesting and worth to be published. There are only some questions that should be better addressed.

Minor Concerns:

**The Authors should clarify why graded-index multi-mode fiber (GI-MMF) that act as collimator have been used only in fabrication of the high-finesse sensor.*

Response: **For a high-finesse sensor, requirement on alignment of the lead-in fiber with the silicon FPI is much higher than a low-finesse sensor. A GI-MMF expands the diameter of the modal field diameter coming out of the fiber, thus, reducing the requirement on alignment. In step 2.2 of the Protocol section, a note has been added to clarify this point. References detailing this point have also been added.**

**How do they control the length of the GI-MM fiber ?*

Response: **A fiber cleaver was used to control the length of the GI-MMF under an optical microscope. The requirement on the length of the GI-MMF is not extremely restrict in obtaining a good spectrum. See step 2.2 of the Protocol section.**

**How is the fiber collimator affected by the temperature?*

Response: **Firstly, since the ray trajectory within the GI-MMF (i.e., collimator) is not affected much by temperature, the GI-MMF does not bring about much temperature-dependent influence. Furthermore, the notch positions of the spectrum are determined mainly by the silicon FPI, thus temperature of the collimator is not critical. In our experiments, as temperature changed, no distortion in spectrum shape was observed.**

**More in information should reported about the fabrication and the characteristic of HR dielectric coatings.*

Response: **The HR dielectric coating was done by a company; thus, the fabrication steps, coating materials, and structure are unknown due to the proprietary protection by the company, see the note of Step 2.1 of the Protocol section.**