Influence of Probe Geometry of Optical Fibers in Sensing Volatile Liquids Through Localized Surface Plasmon Resonance

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Abstract—We present a comprehensive analysis of influence of probe geometry on responses based on localized surface plasmon resonance phenomenon. Accordingly, plasmonic responses corresponding to diverse geometries such as D-type and tapered probes are exclusively analyzed. Incorporating noble metal nanoparticles such as AuNPs and AgNPs towards facilitation of LSPR, these two probes are systematically investigated for detection of one common analyte; i.e., methanol. It is found that sensing performances considerably vary in tune with the probe configuration. Further, the different noble metal nanoparticles also influence the overall sensing capabilities of detecting methanol in alliance with the diverse geometries. The sensitivity in case of D-type probe for detection of methanol is found to be $\sim 0.09644 \text{ mV/ppm}$ with AuNPs and $\sim 0.03038 \text{ mV/ppm}$ with AgNPs. On the other hand, the sensitivity for AgNPs coated probe is found to be $\sim 0.00389 \text{ mV/ppm}$ and $0.00379 \text{ mV/ppm}$ for AuNPs in case of tapered probe. The attained results yield formidable evidence how changes in geometrical shape of probes result in considerable alteration in sensing enactment.

Index Terms—Fiber optics, optical fibers, optical fiber applications, optical fiber devices, optical sensors, sensors, optical detectors.

I. INTRODUCTION

O PTICAL fiber sensors have grown tremendously over the years. Currently, optical fiber probes are preferred over bulky prism and microscopic system for plasmonic investigations [1]–[5]. The use of an optical fiber probe makes a sensing system simple, compact and cost-effective as well as portable [3]. The sensing performance of a sensor can be improved by utilizing optical fiber probes of variable geometries [2], [3]. Till date, several optical fiber sensors have been reported with variable geometries such as tapered, D-type, U-bent, hetero-core structured, arrayed fiber end face and so on [2]–[9]. Change in probe geometry affects the coupling of light with analytes and thereby alters distribution of evanescent wave onto the exposed portion of a probe [3]. Fiber optic sensor based on localized surface plasmon resonance (LSPR) phenomenon is one of the powerful tools for label free sensing and point of care applications [10]–[12]. Utilization of noble metal NPs aids control and optimization in sensing system [3]–[5]. Of late, extensive research has been carried out by adopting LSPR enhanced U-bent optical fiber probe based sensing of different volatile liquids, size of NPs as well as detection of heavy metal ions [6]–[15]. Different research groups have demonstrated techniques to enhance the sensitivity of the evanescent wave across the unclad region of the fiber by modifying the probe into different shapes such as tapered, tapered tip, biconal taper, straight and U-bent [7]–[35]. In many cases, the tapered as well as D-type fiber configurations outperform the U-shaped in many aspects. As for instance, the site area for interaction of analytes with impinging light for U-shaped fiber is comparatively smaller relative to either tapered or D-type configurations. Additionally, the bending of U-shaped fiber is another issue directly affecting the sensitivity. In such cases, D-type as well as tapered configurations are not dependent on such factors; making them reliable in many sensing schemes. Although there are copious literatures available discussing sensing schemes using either types; however, to the best of our knowledge, low cost LSPR based volatile liquid sensing using these probe geometries on a comparative scale has been rarely addressed.

The present work is aimed at outlining the influence of probe geometries towards sensing capabilities with respect to identical analyte. As a proof of concept, two different geometries of fiber probes has been utilized to detect the proposed analyte along with a comparative study between each shape. To get insight about the sensing performance of these two geometries, we have arranged our demonstration in a comparative scale. As such, we arrange the following sections encompassing the fabrication part, working principle, experimental design and lastly the analysis part on a comparative footing.

II. FABRICATION

Accordingly, we fabricate D-type and tapered optical fiber probes as per expediency. We have taken a multimode silica optical fiber having core diameter of 800 $\mu$m with numerical aperture (NA) $\sim 0.39$. Prior to fabrication of these two probes, the ends of the fiber are subjected to a polishing pad. With a sharp surgical blade, we remove a portion $\sim 1$ cm of cladding to be followed by chemical etching using acetone to wipe off the residual part of cladding. The as-etched portion is then
controllably configured into a D-shape region as illustrated in Fig. 1. We then impregnate nanoparticles into this D-type region for execution of analysis. Likewise, in tapered optical fiber probe, the whole central cladding (∼1 cm) part is removed through chemical etching technique. The tapered waist has been fabricated by controlled heating and pulling technique. Each probe has been fabricated according to feasibility that can offer minimal loss. Utilizing aforementioned probes, methanol has been used as analyte with independent coating of two noble metal NPs onto the sensing region. Further, a low cost optical detector has been used to observe the responses in lieu of an expensive spectrophotometer. Importantly, the use of a simple
detector not only reduces the cost of the set-up but also makes the
set-up compact.

III. WORKING PRINCIPLE OF THE PROBES

In tapered optical fiber probe, the decladded portion aids
interaction between the evanescent fields with the surrounding
media (Fig. 1(a)). As depicted in Figure 1(a), it comprises of ta-
pered waist along with un-tapered transition regions. Moreover,
interaction depends upon several parameters of the tapered waist
i.e., the tapered diameter, length and the un-tapered transition
region shape, respectively. On the contrary, D-type optical fiber
probe contains a half of the core as the exposed portion. Here,
the sensing layer is formed by coating the nanoparticle onto the
exposed portion of the D-type probe (Fig. 1(a)) [1]–[6]. The
propagating electromagnetic wave follows attenuated total in-
ternal reflection (ATIR); owing to its half-removed core [1]–[6].
The propagation of light through a conventional optical fiber
depends on angle of incidence as well as the critical angle of the
incident light. While propagating from core to cladding region,
the evanescent wave gets absorbed to a certain penetration depth
in D-type probes.

IV. DETAILS OF EXPERIMENTAL SET-UP

The proposed sensing set-up is composed of a test chamber
where the probes are fixed individually while checking the
responses. After fabricating the probe with heating as well as
pulling technique [3], the exposed portion is cleaned and
impregnated with each noble metal NPs, independently. A
broadband light source [Thorlabs, SLS202L] has been used
which is followed by a collimator [Thorlabs, F810FC], and
on the other side of the set-up, an optical detector [Coherent
Optics, 1098313 RoHS] is affixed to observe the changes via
a collimator. Methanol, the test analyte, is kept inside test
chamber. The schematic is depicted in Fig. 1(b). Additionally, for
calibration purpose, a CMOS (metal-oxide: SnO2) sensing head
has been used during the experiment along with microcontroller
(Arduino Inc.) device has been used. The sensor can easily detect
the change in vapor concentration in real-time as illustrated by
Fig. 1(f). In order to attain the response from the sensing head,
the concentration of volatile liquid has been changed in known
concentrations and the corresponding output has been taken.
The calibrated curve in Fig. 1(f) shows the changes of the VLs
inside the chamber. The initial output of the sensing head has
been recorded to be ∼0.32 mV without introduction of VL and
is found to be increasing with rising concentration of volatile
liquid, accompanied by an eventual saturation stage of ∼6.7 mV
nearing 600 ppm.

The responses in each set of fiber probe have been measured in
terms of voltages with corresponding change in concentra-
tion of the proposed volatile liquid. Optical response of each
probe has been observed by impregnation of the NPs onto the
exposed portion with identical technique. Blank response for
each set of probes of the sensing set-up with each NP’s has
been noted before initiating the experiment. Initially, in absence
of methanol, the response of the sensing set-up is found to be
2.2 mV for AuNPs coated D-type and 2.1 mV for AgNPs
probe, respectively. After introduction of methanol onto the
test chamber, the response of the set-up starts increasing with
increase in concentration of the proposed analyte. Volatile nature
of methanol leads to change the effective refractive index of the
medium; adjacent to the NPs of the environment inside the

sensing performance, we take care that the analyses are carried
out in equal footing. It is of general consensus that dimension of
coating as well as morphological fluctuations can lead to
variations of the result in the context of sensing performance.
Equally important are the exposure times and dimensions of the
sensing region. In this direction, we have kept the dimension of
the exposed region at ∼1 cm. In this exposed region, impreg-
nation of AuNPs and AgNPs of identical sizes (∼40 nm) [see
S(a) and S(b)] has been carried out. Apart from this, the coating
thickness in case of both geometries is identical to make the
overall comparison more effective [see Fig. 1(e) for instance].
It is also followed by identical exposure times, accompanied by
identical concentration of volatile liquid.

V. RESULTS AND DISCUSSIONS

The probe geometry can alter the sensing performance of a
sensing set-up. The evanescent wave being coupled with noble
metal NPs resides on the exposed portion of the probe that brings
measurable changes as detected by the optical receiver. Injection
of VLs near to the NPs coated probe varies the effective RI
of the adjacent environment according to LSPR phenomenon.
Accordingly, the variation has been observed in the output with
respect to the probes. For D-type, probe coupling occurs only
at the half of the cylindrical exposed portion. In tapered probe,
coupling hovers around the beam waist. Thus, with progressive
change in concentration of the proposed VL, the responses can be
changed; which, thereby, facilitate detection of the proposed VL.
As we propose to utilize two diverse geometries to investigate the
influence of probe towards sensing, we want to ensure ourselves
about response of these probes. To achieve this along with an ob-
jective of calibration, a sensing head along with microcontroller
(Arduino Inc.) device has been used. The sensor can easily detect
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test chamber, the response of the set-up starts increasing with
increase in concentration of the proposed analyte. Volatile nature
of methanol leads to change the effective refractive index of the
medium; adjacent to the NPs of the environment inside the
test chamber. With gradual rise in concentration, the effective refractive index of the medium alters. As such, it modulates responses of sensing set-up. The responses of each noble metal NPs for D-type probe are displayed in Figure 2. There is a dip observed in each set of NPs coated in case of D-type probe which is ascribed to the coupling of evanescent wave field with the half of the exposed portion of the fiber. In D-type probe, only half of the probe, probe is exposed; while the other half is utilized by the electromagnetic wave to complete the total internal reflection (TIR). This leads to attenuated TIR. This attenuated TIR prevails until the beam reaches at the core-cladding interface, which leads to the dip in the output. After the dip, we see a gradual rise in response with progressive increase in concentration. However, after a certain point, we observe that the response has entered the saturation stage. In case of AuNPs, the saturation is attained at a lower concentration as compared to AgNPs. Apart from this, AgNPs coated D-type probe results in a linear response spanning a higher range of concentration up to saturation. Thus, the variation has been observed in the output for AuNPs and AgNPs coated probe in presence of methanol. Eventually, there occurs saturation at 27.02 and 16.89 mV for AuNPs and AgNPs, respectively once complete vaporization of methanol inside the chamber takes place. In the working domain of 0-235.37 ppm, the sensitivity of the sensing set-up is found to be 0.0964 mV/ppm with limit of detection (LOD) of 174.24 × 10⁻² ppm for AuNPs and AgNPs, respectively. Since, tapered fiber probe is fully decladded at the center; the evanescent wave coupling occurs at the center to fulfill the total internal reflection at the end face of the probe. The LSPR principle followed by tapered probe is in similitude to that of D-type probe, except the coupling. This probe allows complete TIR without any attenuation as the complete central clad has been removed. Consequently, no dip has been observed.

The normalized response with respective change in concentration is depicted in Fig. 3 for AuNPs and AgNPs, respectively for better clarity. Similar to D-type probe, we observe gradual rise in response with increase in concentration. One notable feature is that the saturation stage is achieved at a faster rate corresponding to a lower value of concentration. The underlying reason for this behaviour may be attributed to the cessation of interaction of methanol with that of sensing region. Apart from this, since the coating of AuNPs and AgNPs on the sensing region is symmetric in nature, hence the steady growth is a formidable evidence of that. Interestingly, the role of the calibration curve can now be felt. The responses achieved in case of D-type as well as tapered mimic the response attained by the sensing head used for calibration. Starting from gradual rise to steady state, all phases yielded by the calibration curve are found to be reproducible in both these geometries; albeit with a little deviation. The corresponding sensing parameters are enlisted in Table I. It is quite evident that in case of tapered probe, the blank response in absence of analyte is quite low as compared to D-type fiber. D-type fiber exhibits augmented intensity relative to tapered one. However, in terms of intensity profile, tapered probe outsmarts

### Table I

| Noble metal NPs | D-type | Tapered | D-type | Tapered | D-type | Tapered |
|-----------------|--------|---------|--------|---------|--------|---------|
| AuNPs           | 0.99   | 0.99    | 0.09   | 0.00    | 174.24 | 6.09    | 0.00    | 0.00    |
|                 | 9      | 3       | 64     | 38      | 24 x 10³ | 3       | 235.1    | 37      |
| AgNPs           | 0.99   | 0.98    | 0.03   | 0.00    | 194.15 | 13.8    | 0.00    | 0.00    |
|                 | 3      | 8       | 04     | 39      | 75     | 23      | 470.1    | 369.8   |

Here, \( Y_m \) (dependent parameter) and \( X_m \) (independent parameter) represent voltage and concentration, respectively.

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the D-type fiber, which is evidenced by the appearance of a dip in the latter. The absence of dip in tapered one makes the intensity profile better. Meanwhile, in terms of linearity, the D-type is superior with respect to the tapered one. In case of tapered one, sensitivity is less with AuNP. On the contrary, the same yields better sensitivity for AgNP relative to D-type one. However, D-type offers higher limit of detection which is inclusive of both NPs. On the other hand, tapered renders least limit of detection with AuNP as compared to AgNP. The values are considerably smaller than those obtained for D-type one. Similarly, both tapered and D-type provide substantial working domain in case of AgNPs where as working domain decline in case of AuNPs for both the geometries. Summarily, D-type yields better response than its counterpart does. All these comparative analyses are summarized in Table I.

By fitting the response curve as before, the empirical formula for tapered probe can be expressed as follows for AuNPs and AgNPs, respectively.

\[
Y_m^{\text{AuNPs}} = 3.134 - \frac{2.784}{1 + \left( \frac{X_m}{139.02} \right)^{2.4}} \\
Y_m^{\text{AgNPs}} = 2.62 - \frac{2.351}{1 + \left( \frac{X_m}{121.46} \right)^{2.6}}
\]

Meanwhile, Boruah and Biswas. 2019 [26] devised a D-shaped probe for sensing lead ion in aqueous solution with remarkable limit of detection as well as linear range. Similarly, Ying et al. 2020 [29] carried out a numerical analysis of grating structure on D-shaped optical fiber. They report a high sensitivity for their proposed design. Likewise, Cennamo et al. 2018 [30] carried out plasmonic sensing in D-shaped optical fibers with fluorescent optical fibers as light sources. They devised two D-shaped fibers in order to match the plasmonic sensing. However, none of these reported literatures highlighted the probe geometries in the context of sensing an identical analyte. Accordingly, this work systematically analyzes the impact of probe geometries towards sensing a common analyte through independent impregnation of noble metal nanoparticles, which is itself of the first kind.

VI. CONCLUSION

In summary, we have procedurally and systematically fabricated two optical fiber probes. We deploy these probes as a sensing tool for assessing volatile liquid concentration. We have established that there is a formidable evidence of impact of geometry of sensing probe even though identical instrumentation as well as analyte is used. It is found that the D-type probe is found to show good response towards changes than that of tapered probe. With AgNPs coating, the probes yield regression of \(\sim 0.99\) and \(\sim 0.98\). On the other hand, for AuNPs coated probe, the responses are found to be almost similar in each set of configuration. The former provides better responses as compared to AgNPs. The highest sensitivity is found to be \(\sim 0.0964\) mV/ppm for AuNPs coated D-type optical fiber probe. It is quite apparent that each set of probe is quite responsive towards the plasmonic behavior of the NPs with respect to methanol. However, the tapered fiber also renders an excellent response in terms of intensity. Although, each probe can be used for detection of methanol in the range of 0-500ppm, there sensing performances evince that geometry does play a vital role in improving the capability of assessing. The simplicity in design due to use of the optical detector in lieu of spectrophotometer makes the whole implementation cost-effective and portable. Through a little tweaking in the functionalities, these probes can be extended to detect other volatile liquids and can be used to reduce the environment inhalation. With an excellent repeatability rate, these schemes can be extended for real time monitoring with embedded electronics.

REFERENCES

[1] C. Caucheteur, T. Guo, and J. Albert, “Review of plasmonic fiber optic biochemical sensor: Improving the limit of detection,” Anal. Bioanal. Chem., vol. 407, pp. 3883–3897, 2015.
[2] B. Gupta, H. Dodeja, and A. Tomar, “Fibre-optic evanescent field absorption sensor based on a U-shaped probe,” Opt. Quantum Electron., vol. 28, no. 11, pp. 1629–1639, 1996.
[3] H.-Y. Lin, C.-H. Huang, G.-L. Cheng, N.-K. Chen, and H.-C. Chui, “Tapered optical fiber sensor based on localized surface plasmon resonance,” Opt. Express, vol. 20, no. 20, pp. 21693–21701, 2012.
[4] M.-H. Chiu, S.-F. Wang, and R.-S. Chang, “D-type fiber biosensor based on surface-plasmon resonance technology and heterodyne interferometry,” Opt. Lett., vol. 30, no. 3, pp. 233–235, 2005.
[5] H. S. Mackenzie and F. P. Payne, “Evanescent field amplification in a tapered single-mode optical fibre,” Electron. Lett., vol. 26, no. 2, pp. 130–132, 1990.
[6] D. Paul, S. Dutta, and R. Biswas, “LSMR enhanced gasoline sensor,” J. Phys. D: Appl. Phys., vol. 49, 2016, Art. no. 305104.
[7] D. Paul, S. Dutta, D. Saha, and R. Biswas, “LSMR based ultra-sensitive low-cost U-bent optical fibre for volatile liquid sensing,” Sens. Actuators B (Chemical), vol. 250, pp. 198–207, 2017.
[8] D. Paul and R. Biswas, “Highly sensitive LSPR based photonic crystal fiber sensor with embodiment of nanospheres in different material domain,” Opt. Laser Technol., vol. 101, pp. 379–387, 2018.
[9] D. Paul and R. Biswas, “Facile fabrication of sensing set-up for size detection of nanoparticles,” IEEE Trans. Nanotechnol., vol. 17, no. 3, pp. 596–602, May 2018.
[10] B. S. Baruah and R. Biswas, “Selective detection of arsenic (III) based on colorimetric approach in aqueous medium using functionalised gold nanoparticles unit,” *Mater. Res. Express*, vol. 5, no. 1, 2018.

[11] B. S. Baruah and R. Biswas, “Localized surface plasmon resonance based u-shaped optical fiber probe for the detection of Pb^{2+} in aqueous medium,” *Sens. Actuators B Chem.*, vol. 276, pp. 89–94, 2018, doi: 10.1016/j.snb.2018.08.086.

[12] B. S. Baruah and R. Biswas, “An optical fiber based surface plasmon resonance technique for sensing of lead ions: A toxic water pollutant,” *Opt. Fiber Technol.*, vol. 46, pp. 152–156, 2018.

[13] B. S. Baruah, R. Biswas, and P. Deb, “A green colorimetric approach towards detection of arsenic (III): A pervasive environmental pollutant,” *Opt. Laser Technol.*, vol. 111, pp. 825–829, 2019.

[14] B. S. Baruah and R. Biswas, “Mangifera indica leaf extract mediated gold nanoparticles: A novel platform for sensing of As(III),” *IEEE Sens. Lett.*, vol. 3, no. 3, Mar. 2019, doi: 10.1109/LSENS.2019.2894419.

[15] B. S. Baruah and R. Biswas, “Functionalized silver nanoparticles as an effective medium towards trace determination of arsenic (III) in aqueous solution,” *Results Phys.*, vol. 12, pp. 2061–2065, Mar. 2019. [Online]. Available: https://doi.org/10.1016/j.rinp.2019.02.044.

[16] Y. Tian, W. Wang, N. Wu, X. Zou, and X. Wang, “Tapered optical fiber sensor for label-free detection of biomolecules,” *Sensors*, vol. 11, no. 4, pp. 3780–3790, 2011.

[17] J. Villatoro, D. Monzon-Hernández, and E. Mejia, “Fabrication and modeling of uniform-waist single-mode tapered optical fiber sensors,” *Appl. Opt.*, vol. 42, no. 13, pp. 2278–2283, 2003.

[18] K. Q. Kieu and M. Mansuripur, “Biconical fiber taper sensors,” *IEEE Photon. Technol. Lett.*, vol. 18, no. 21, pp. 21–24, Nov. 2006.

[19] K. M. Mayer and J. H. Hafner, “Localized surface plasmon resonance sensors,” *Chem. Rev.*, vol. 111, no. 6, pp. 3828–3857, 2011.

[20] K. D. Long, H. Yu, and B. T. Cunningham, “Smartphone instrument for portable enzyme-linked immunosorbent assays,” *Biomed. Opt. Express*, vol. 5, 2014, Art. no. 3793.

[21] S. Agnihotri, S. Mukherjee, and S. Mukherjee, “Size-controlled silver nanoparticles synthesized over the range 5–100 nm using the same protocol and their antibacterial efficacy,” *RSC Adv.*, vol. 4, 2014, Art. no. 3974.

[22] R. N. Cassar, D. Graham, I. Larmour, A. W. Wark, and K. Foulds, “Synthesis of size tunable monodispersed silver nanoparticles and the effect of size on SERS enhancement,” *Vibrational Spectrosc.*, vol. 71, pp. 41–46, 2014.

[23] L. Polavarapu and Q.-H. Xu, “A simple method for large scale synthesis of highly monodisperse gold nanoparticles at room temperature and their electron relaxation properties,” *Nanotechnology*, vol. 20, p. 1, 2009.

[24] S. P. Usha, S. K. Mishra, and B. D. Gupta, “Fabrication and characterization of a SPR based fiber optic sensor for the detection of chlorine gas using silver and zinc oxide,” *Materials*, vol. 8, 2015, Art. no. 2204.

[25] Q. Zhang, C. Xue, Y. Yuan, J. Lee, D. Sun, and J. Xiong, “Fiber surface modification technology for fiber-optic localized surface plasmon resonance biosensors,” *Sensors*, vol. 12, pp. 2729–2741, 2012.

[26] B. S. Boruah and R. Biswas, “Probing lead ion contamination in aqueous solution through bio-inspired surface modification of gold nanoparticles on D-shaped fiber,” *IEEE Trans. Nanotechnol.*, vol. 18, pp. 770–775, Jul. 2019.

[27] B. S. Boruah, D. Gogoï, and R. Biswas, “Bio-inspired finger like Cu-electrodes as an effective sensing tool for heavy metal ion in aqueous solution,” *J. Electrochem. Soc.*, vol. 167, no. 2, 2020, Art. no. 027526.

[28] B. S. Boruah, R. Biswas, and N. Ojah, “Bio-inspired localized surface plasmon resonance enhanced sensing of mercury through green synthesized silver nanoparticles,” *J. Lightw. Technol.*, vol. 38, no. 7, pp. 2086–2091, Apr. 2020.

[29] Y. Ying, J. Wang, N. Hu, K. Xu, L. Sun, and G. Si, “Determination of refractive index using surface plasmon resonance (SPR) and rigorous coupled wave analysis (RCWA) with a D-shaped optical fiber and a nano-gold grating,” *Instrum. Sci. Technol.*, vol. 38, no. 7, pp. 2086–2091, 2020.

[30] N. Cennamo, F. Mattiello, R. V. Galatius, E. Voiculescu, and L. Zeni, “Plasmonic sensing in D-Shaped POFs with fluorescent optical fibers as light sources,” *IEEE Trans. Instrum. Meas.*, vol. 67, no. 4, pp. 754–759, Apr. 2018.

[31] R. Biswas and M. Pradhan, “A comparative analysis of all fiber optic sensors for detection of adulteration in fossil fuels,” *Opt. Quantum Electron.*, vol. 52, p. 62, 2020.

[32] R. Biswas and D. Saha, “Probing volatile liquid through an electrical sensor with up gradation to a breathalyzer for drunken drivers,” *Appl. Phys. A*, vol. 126, p. 313, 2020. [Online]. Available: https://doi.org/10.1007/s00339-020-03479-5.

[33] R. Biswas and P. K. Karmakar, “An inexpensive and novel optical scheme for assessing adulterants in emulsions,” *Biointerface Res. Appl. Chem.*, vol. 10, no. 6, pp. 6874–6880, 2020.

[34] B. S. Boruah, R. Biswas, and U. Neog, “Ultrasensitive trace determination of cadmium through a green synthesized hybrid PVA-Chitosan nanocomposite,” *Plasmonics*, vol. 15, pp. 1903–1912, 2020, doi: 10.1007/s11468-020-02121-8.

[35] R. Biswas, “Inexpensive hetero-core spliced fiber optic setup for assessing strain,” *Sens. Imag.*, vol. 21, p. 38, 2020.