Multifunctional Flexible and Wearable Sensing System Based on Optical Microfiber Interferometry

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Contributions

R.J conceived ideas and provided necessary suggestions to implement the work. P.M. designed the probe, conducted the experiment. S.S. did the simulation work. P.M, H.K, S.S and R.J have prepared the manuscript and compiled the entire work.

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Abstract

Optical segments based flexible systems are the key for the development of futuristic advanced wearable devices for health monitoring, robotics, and ultraprecision positioning in industrial applications. Here, we have demonstrated an processed optical microfiber based multifunctional sensing system, which overcomes the various limitations of most widely reported electronics and material-based flexible devices. By optimizing the position of the post processed microfiber
configuration in optimized Polydimethylsiloxane (PDMS) thickness and controlling the interference between the fundamental mode and higher order modes of microfiber to form and tunable interference pattern, we are able to make an efficient, simple, flexible and economical optical wearable vector bending system with a sensitivity as high as 1.01nm/degree. In addition, this skinmountable sensing sensor shows a remarkable and ultrasensitivity of -3.07 nm/°C. This ultrahigh sensitivity, mechanical robustness, with the excellent flexible and biocompatible nature also makes this sensing system a dominant candidate for wearable medical devices for elder-care facilities, physiological monitoring, athletic training, and rehabilitation program.

**Introduction**

Flexible devices have long drawn the attention of researchers for health monitoring, environmental detection, micro-force recognition, and precise industrial movements. In the form of skin-like system, they promote the development of robotics, smart clothing and numerous physiological monitoring devices. The affectability and sensitivity of such devices are determined by its detecting mechanism and discovery components. Most previous works on wearable sensor have focused on two measure detecting mechanisms: a) materials response to target changes and b) electrical response such as resistive, capacitive, triboelectric and piezoelectric based approaches. Graphene, Molybdenum Sulfate, Carbon Nanotube, and distinctive nano-materials are the most common materials utilized to create the material response-based flexible devices for detecting small temperature variations, pressure changes, bending, and moistness fluctuations. However, such sensing system have parasitic repercussions, low performance, non-intrinsic electrical security and electromagnetic interference, which hamper the working efficiency and restrict their wide applications as wearable gadgets. But, optical segments incorporated on adaptable substrates were not explored more. These systems
offer exceptional benefits like distant checking capacity, high affectability, non-electromagnetic
disturbances, real-time monitoring, and intrinsic electrical security apart from features like
reconfigurablity and scaleability.

One such optical segment is optical microfibers which possess strong evanescent fields\textsuperscript{24–27}
and are sensitive to microforce or relocation.\textsuperscript{28,29} Further, when light propagate through the optical
microfiber, it excites the higher order modes which interferes with the fundamental modes of single
mode fiber to form interference pattern whose period can be tailored depending upon requirement
and the interference pattern shifts when subjected to external perturbations.

On the other hand polydimethylsiloxane (PDMS) is an excellent material to embeed optical
microfiber due to its biocompatibility and robust mechanical stability\textsuperscript{30,31} apart from providing
mechanical stability to the microfiber which otherwise is fragile and difficult to use. PDMS
incorporated optical microfiber also exhibit low loss, high-temperature steadiness with high
flexibility. Such an encapsulation also solves the demerits of conventional thermometers such as
glass breaking, mercury poisoning, long-term affectability and biocompatibility. These devices
can also be directly affixed to the human body to detect small bending of different body joints like
the neck, knee, elbow and arms to name few where most conventional goniometers based system
cannot be utilized like the comfort and ease provided by flexible PDMS assisted systems. Recent
reports on knot resonator,\textsuperscript{32} straight and bend micro-nano fiber\textsuperscript{33} are very delicate due to their
miniature diameter, less sensitive, difficult to mount on skin as light enters from one side and
comes out from other, non-tailorable performance and uses the change in incident light intensity
for monitoring which make its widely susceptible to light source fluctuations. Hence, it remains a
challenge to develop robust and stable system which can be skin mountable, reconfigurable with
tailorable performance and high sensitivity under normal operating conditions.
Here, we demonstrate a post-processed microfiber based interferometric system which uses double microfiber configuration as it provides more stable optical spectrum with the reconfigurable features, enhanced performance, an extra degree of freedom to tune the notch wavelength and higher mechanical strength and stability compared to the single microfiber.\textsuperscript{34,35} The reconfigurable interference region of the microfiber is embedded in such a way that it can exhibits a U-shape and the two identically tapered regions remain parallel and termed as U-shaped cascaded microfiber interferometer (UCMI). This UCMI probe is suitably embedded in an optimized thin layer of PDMS for monitoring the body temperature and human body joints movements along with its directions. Owing to these advantages, it can be utilized for several health monitoring devices by directly mounting on human skins or fabric in form of a watch and patch to screen body temperature and detect a slight change in bending at different joint parts of the human body.

**Results**

**Concept and Working principle**

For the proposed wearable system, the fabricated UCMI with optimized waist diameter (13 \(\mu\)m), waist length (1 cm) and interference length (6 cm) is placed along the plane of PDMS film as shown in Fig 1(a). Photographs of the real probe which is guiding the red laser light are also shown in Fig 1(b). Here, the shape of the interference length is chosen as U-type to allow simultaneous deformation of the two microfiber waist regions as the interference length apart from the fact that
U-type probe are associated with higher evanescent field which will provide higher performance to the sensing system. The optical microscope image of waist diameter is shown in Fig 1(c). The optical microscope image of waist diameter is shown in Fig 1(c). The optical microscope image of waist diameter is shown in Fig 1(c). The optical microscope image of waist diameter is shown in Fig 1(c). The optical microscope image of waist diameter is shown in Fig 1(c).

UCMI is embedded in an optimized thin film of PDMS having moisture erosion capability due to its hydrophobic nature for underwater applications as wearable and patch type devices. Fig 1(d) shows the optical transmission spectrum for the bare UCMI and PDMS embedded UCMI probe. Due to the PDMS embedding, the effective index difference increases due to the mode-coupling effect which not only shifts the interference pattern to higher wavelength but offers marginally broad free spectral range (FSR). However, the FSR can be controlled by controlling the waist diameter.
diameter of UCMI depending upon user’s requirement which in turns allows to tailor the performance together with field distribution around the UCMI.

To study the electric field mode propagation of the PDMS embedded UCMI, two micro-regions M1 and M2 each having taper lengths as 1 cm, waist diameter of 13 μm and waist-length of 1 cm, similar to the experimental probe is considered and shown in Fig 2(a). As can be clearly seen that there is an enhanced electric field near the M1 and M2 of the PDMS embedded probe which is responsible for enhanced performance of the proposed system as discussed and shown later. Fig 2a (i) and (ii) show the transverse cross-section of electric field distribution of conventional fiber and PDMS embedded UCMI, respectively. It is seen from the enlarged portion of the waist region that there is lesser electric field in M2 as compare to M1 due to bending loss around the U region as expected. The longitudinal electric field intensity of waist regions along z-direction is shown in Fig 2(b). It shows that the electric field intensity decreases at M2 and interacts with the surrounding PDMS medium. Similarly, the transverse electric field intensity of waist regions along the x-direction shown in Fig 2(c) manifests that the evanescent field comes out of microfibers (shown in both sides of the dotted regions). However, the intensity variation of the double micro fiber based interferometer can be given

\[ I = I_1 + I_2 + 2 \sqrt{I_1 I_2} \cos(\phi) \]  

Where, \( I_1 \) and \( I_2 \) represent the intensity of fundamental mode (LP\(_{01} \)) and higher order mode (LP\(_{0m} \)). \( \phi \) is the phase difference between these modes which can be evaluated from,

\[ \phi = \frac{2\pi(n_{eff1} - n_{eff2})L}{\lambda} \]
Where, \( n_{\text{eff}_1} \) and \( n_{\text{eff}_2} \) are the effective refractive indices of two higher order modes. \( L \) and \( \lambda \) represent the interference length and the wavelength of the input broadband source respectively.

Fig 2: Electric field distribution (a) simulated electric field mode profile of a PDMS embedded UCMI. Transverse electric field profile of (i) SMF and (ii) PDMS embedded microfibers (M1 and M2). (b) Longitudinal electric field intensity distribution of waist regions along x-direction for both microfibers M1 and M2.

Upon bending, effective indices of the cladding mode are modulated due to the stress effects on the surface of fiber as well as on PDMS film surrounding it. This effect modulates the confinement of guided light and introduces an additional phase difference between the interfering modes, leading to a variation of the fringe pattern at the output, proportional to the applied bending. A similar variation in the fringe pattern is observed with temperature change. Here, the phase difference is introduced due to a change in the refractive index of the surrounding temperature-dependent PDMS. The probe's sensitivity is enhanced as the evanescent field coming out due to
the microstructure of the waist region and the surrounding material causes the large variation of the guided modes to modulate the optical spectrum.

**Patch type probe for vector bending monitoring**

Miniaturized vector bending responses are investigated by attaching the developed patch type sensing system with a customized bending stage with high precision. Here, light from a broadband source gets coupled at one port of the probe and the spectral responses are detected at the other end using an interrogator. To monitor the detecting ability of the developed system, the probe can be attached to the neck and the transmission spectra is recorded as shown in Fig 3(a). With the small bend angle, the optical path length ($\Delta n_{eff}L$) changes due to variation of the effective index.

![Figure 3: Wearable Patch Type Vector Bending Monitoring System](image)

- **a)** Bending sensor as patch type. Typical bending spectral response of the probe for **b)** forward bending and **c)** reverse bending. **d)** Shift of the peak wavelength as a function of small angle bending point in the range from $0^\circ$ to $5^\circ$ for both forward and reverse. **e)** Transmitted power shift as a function of small angle bending point in the range from $0^\circ$ to $5^\circ$ for both cases.
of the interfering modes. This causes a shift of dip wavelength of the output interference spectral
responses towards the lower wavelength and it comes back to its original dip wavelength once the
bending is removed. Again for the decreasing angle, more light is associated with modes whose
effective index are closer to guided mode, constraining the guiding light which makes the red shift
of wavelength accordingly. Fig 3(b) and Fig 3(c) show the spectral responses for forward and
reverse angular variations. In Fig 3(d), the wavelength shift shows linear changes with the bending
angle with maximum sensitivity of 1.01 nm/degree, which is nearly equal to the best reported value
(1.22 nm/degree) using expensive speciality fiber having 50% lesser dynamic range and non-
wearable.\textsuperscript{37} In addition to the wavelength shift, the transmitted power also decreases for increasing
and increases for decreasing the vector bending angle due to the loss in field as explained in Fig
2. Fig 3(e) shows linear responses of the transmitted power shift with bending angle indicating the
maximum sensitivity of 0.692 dBm/degree. Therefore, the developed probe can be used in both
wavelength interrogation and intensity interrogation optical schemes, making the system
customizable depending on the user’s requirement and cost. The capability of the designed probe
makes this wearable system mostly reliable for body movement checking, diverse body joints
recognition for clinical treatment like spondylitis and mechanical precise positioning.

**Wrist watch type photonic thermometer for temperature monitoring**

In addition to the good capability and sensitivity to the small vector angle bending, this probe
can be used for body temperature measurement by functionalized it as a wearable watch type, as
shown in Fig 4(a). Here, the embedding material (PDMS) possesses a high negative thermo-optic
coefficient comparable to the silica- the fiber material. With the temperature variation, the
refractive index of the sensing surrounding region is changed. It offers the upgradation of guided-
mode at the detecting point changing the optical path length. To check the optical spectral
responses of the probe to variation of temperature, the sensing system is placed on temperature-controlled environment and output is detected using interrogator. Due to the contrast of negative thermo-optic coefficients, the dip wavelength shows a blue shift with temperature variation. The uniform transmittance spectral responses for heating and cooling ranging from 37°C to 42°C are shown in Fig 4(b)-4(c), respectively. As can be seen that the intensity of the transmitted power largely remains constant with the increase and decrease in temperature. However, as shown in Fig 4(d), there is a linear shift in wavelength to the variation of temperature both heating and cooling. This demonstrated sensor achieves the maximum sensitivity of -3.07 nm/°C
by defining it as \((d\lambda/dT)\) which is best to our knowledge. This value is greater than the record values of S tapered fiber (-2.07 nm/°C)\(^3\) and wavy structured MNF (1.8 nm/°C).\(^3\), and typical reported temperature sensors (120 pm/°C).\(^4\) To check the reversibility nature of the probe, the sensor is placed alternatively on two precisely temperature-controlled environment where one is fixed at 38°C and another is kept at 39°C temperature. The output real time responses are also detected with high speed interrogation monitor (IMON). At the fixed temperature, no variation in wavelength is observed as shown in Fig 4(e). This is repeated for multiple cycle and the stable nature is shown every time. It proves the stability and reversibility nature of this designed probe.

As can be seen from the inset that the response time of the proposed device is 1.8 min. In addition, PDMS in strong status offers stable physicochemical property in the temperature scope of −55 – 200°C. Consequently, this temperature sensor can work in a wider range, not restricted to the outcomes listed in this work. Thus, this highly sensitive and stable photonic sensing system can be used as secure body monitoring devices, smart clothes and robotics.

**Discussion**

We demonstrated a PDMS embedded U-type double microfiber interferometer as wearable, skin mountable and flexible device. This structure provides the advantages of tiny size, single ended and hardness limit. The enhanced evanescent fields around the two waist regions caused by micro configuration and the embedding material (PDMS) make this sensor more sensitive and functional nature. Again, the flexible and negative thermo-optic coefficient nature of PDMS also offers high bending sensitivity (1.01 nm/degree) along with its direction. It also extends remarkable sensitivity (-3.01 nm/°C) for the range of body temperature level (37°C - 42°C) and excellent stability. Besides, this device can be utilised for monitoring neck motion and body temperature in real time. These high performances counting with the excellent flexible and biocompatible nature also make
this sensor as a dominant candidate for wearable medical devices for or health-monitoring, elder-
care facilities, athletic training, and rehabilitation. Therefore, this new approach pledges scalebale
and wearable optical devices with good monitoring capability and repeatability for efficient
utilizations in smart clothing, human body monitoring and precisely movable engineering devices.

**Methods**

**Fabrication and manipulation of double microfiber probe:** For the UCMI sensor a well-
controlled customised flame burst technique is used to fabricate the double micro fiber. Here two
2 cm portions of the single mode fiber (SMF-28) are stripped keeping a 5 cm distance with jacket
between them. After cleaning those stripped portions with isopropanol, it is kept straight on the
station holding the two ends of it. Then, those portions are softened by the heat generated from a
hydrogen-oxygen gas based burner and pulled by two well controlled motors simultaneously for
the desired length and diameter of the micro regions. To make these regions identical, all the
parameters like speed and rotation number of motors, pulling distance and the pressure of both
hydrogen and oxygen gas for both regions are kept the same at the time of fabricating. Here, a
number of steps are followed to make a U-type pattern of the double micro fiber. First, one micro
region is placed on a glass slide and fixed with scotch tape. Then, a cylindrical shaped pole is kept
next to the interference locale and pushed the interference region with a precisely well controlled
probe mounted on a three dimensional stage to make the portion U size. This whole process is
performed under an optical magnifying lens, ensuring that the two tapered areas are perfectly
parallel and one remains next to the other.

**Fabrication of PDMS thin film:** PDMS thin film fabrication process also possesses a series of
steps. First, silicone elastomer (sylgard 184) and curing agent are mixed very well at the ratio of
10:1 for 10 minutes thoroughly. After that, the mixture is degassed keeping it in a high vacuum
chamber (desiccator). Subsequently, the desired amount of mixture is poured onto a glass plate
and left for 48 hours to polymerise very well. At last, it can be peeled off from the slide for use as
a thin film.

**Fabrication of wearable and flexible sensor:** For fabrication of wearable sensor, three steps are
followed here. At first, a PDMS thin film of 250 μm thick by pouring 0.5 ml degassed PDMS
mixture on a glass slide (76.2 mm × 25.4 mm) is made. In the next step, the U-patterned double
biconical microfiber is placed on the PDMS sheet. At last, the probe is enclosed by another thin
film of PDMS, followed by polymerising at room temperature for 48 hours. Now, the UCMI device
is ready for sensing purposes after peeling it from the glass slide.

**Sensing Studies:** For the sensing purposes, light is coupled through the sensor by a broadband
SLED source and an optical spectrometer (OSA, Yokogawa) is used to record the output
transmitted spectra at the detecting point of the sensor. For bending responses, two 3D translational
stages are used where one stage is moving upwards with the precisely controlled screw keeping
the other stage fixed. A very stable well controlled hot plate is also used to test the spectral
responses for the temperature variation ranging from 37° to 42°C. Again for temperature
sensing, real time responses are monitored by IMON.

**Numerical calculations:** FEM numerical calculations of 2D light propagation of the electric field
mode profile of the UCMI embedded in a PDMS film is carried out using the RF module in
COMSOL MULTIPHYSICS 5.5. All the optimized parameters scaled up with the probe used in
the experiment. The mesh element size is set to be smaller than 1/14 of the geometry for a good
pattern and to reduce the computation time. For wave excitation, the input ports are chosen which
can handle the propagating modes in waveguides efficiently and the excitation occurs at 1550 nm
to validate our experiment. The electric field intensity data of the waist region is recorded by fixing
a cutline along z-direction for longitudinal and another cutline along x-direction for transverse
propagation at the antinode position of the electric field to see the penetration depth at both the
microfiber M1 and M2.

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