S-shaped microfiber based diaphragm supported optical microphone

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Abstract

We propose and demonstrate a simple and highly sensitive optical microphone based on S-shaped tapered fibre (STF). The short pigtailed end of the STF is attached to the centre of a thin circular nitrile diaphragm. The applied acoustic signal deforms the nitrile diaphragm and due to the affiliation, the STF structure gets modified leading to change in the bending angles of the two STF bends. As a consequence, the photodetector output, detecting the reflected light intensity of the STF, varies in accordance with the applied acoustic signal. Various properties of the proposed sensing setup can be easily tailored by changing the diaphragm diameter and thickness, and the shapes and size of the STF. For an optimized configuration, the proposed sensor achieves a sensitivity of 3.07 mV Pa⁻¹ and a minimum detectable pressure of 36.48 mPa Hz⁻¹. The sensor shows a linear behaviour up to 1300 Hz and the experimental value of its first order natural frequency is 1455 Hz.

1. Introduction

In the last decade, a large number of acoustic sensors (i.e. microphones) have been proposed for structural health monitoring of major civil constructions, operational monitoring of machines, recording bioacoustics signals, seismic analysis and many other civil and defence applications [1–5]. Depending on the application, the microphone having the most suitable properties is selected. The transducing principles of the traditional microphones are based on piezo-capacitance, piezo-resistance and piezoelectricity [6–11]. Among these, piezoelectric polymer-based microphones have achieved a lot of commercial success owing to their high sensitivity and ability to be moulded in diverse geometries [12, 13]. However, the cumbersome fabrication process employed to attain piezoelectricity and to mould them, adds to the complexity and cost of the microphone. Additionally, when these sensors are exposed to highly conducting, and explosive or erosive environment for a long time, their performance deteriorates and starts showing functional irregularities. Recently, the optical fibre-based microphones are attracting a great research interest due to their salient merits of fast response, small size, high sensitivity, corrosion resistance, electromagnetic immunity and so on [14].

Few of the leading and most promising fibre-based microphones are based on techniques such as fibre Bragg grating, interferometry and fibre lasers. Takahashi et al and Fisher et al are one of the first researchers’ groups who successfully utilized FBG for acoustic sensing [15, 16]. In order to improve the responsivity of FBGs at very low-pressure levels, Moccia et al used a ring-shaped polymer’s coating and demonstrated a microphone with a minimum detectable acoustic signal of about 10 mPa Hz⁻¹ [17]. The excellent multiplexing capability of the FBG based microphones has been effectively utilized for condition monitoring of marine lifting surfaces and also for crack monitoring in historical masonry [18, 19]. However, the requirement of temperature compensation techniques and the sophisticated fabrication process increases the complexity of the sensor and its cost as well. In another microphone configuration, the strain-dependent lasing frequency of fibre lasers has been exploited to measure the acoustic signal. Liang et al utilized fibre-laser-based ultrasound sensor for photoacoustic imaging [20]. Vivek et al improved the packaging of fibre laser by polymer shell encapsulation for better practical applications [21]. However, the necessity of an unbalanced interferometer and phase modulator adds to the sensor complexity. The fabrication of microphones, based on interferometric techniques, such as
Fabry–Perot, Mach-Zender, Michelson, or Sagnac is relatively less complex and cost-effective [22–25]. However, materializing the wavelength/phase dependent principles requires the use of costly interrogators, which inevitably adds to the overall cost of the microphone system. In our previous publications, we have demonstrated an intensity dependent sensing scheme which utilized a low cost and easily fabricated tapered fibre along with a nitrile diaphragm for acoustic sensing [26]. This SMF taper based acoustic sensing structure addresses the issue of costly interrogator while retaining the advantages of simple structure and ease of fabrication. Still, the acoustic sensitivity is not satisfyingly high, and the sensor works in transmission mode, which increases the overall size of sensing setup and limits its applications. Apart from the simple and straight fibre structure, researchers have used a number of bent optical fibre structures to achieve higher sensitivity. Balloon-shaped fibre structures have been used for sensing displacement, temperature and refractive index [27–29]. Similarly, C-shaped, U-shaped and S-shaped fibre structures have been used for sensing refractive index, lead ion (Pb<sup>2+</sup>) in aqueous medium and magnetic field, respectively [30–32].

In this paper, we propose a microphone system utilizing cost-effective materials i.e. tapered fibre and nitrile diaphragm. The tapered fibre is perpendicularly attached to the nitrile diaphragm. For achieving higher sensitivity, the tapered fibre is kept in an S-shaped configuration. The applied acoustic signal displaces the diaphragm which induces bending losses at the two bends of the S-shaped tapered fibre (STF). Hence, by monitoring the reflected light intensity of the STF we can deduce the applied acoustic pressure. A detailed analysis, involving different parameters of STF and diaphragm, is carried out for optimizing the performance of the proposed microphone.

2. Sensor design and its working principle

The two important parts of the proposed sensor head are a 6.4 mm long SMF taper and an 80 μm thin circular nitrile diaphragm. The SMF taper is created by using our in-house tapering station which is based on flame and brush technique. One side of the long taper is cleaved keeping a short pigtailed end and the other end is connected to one of the ports of the three-port circulator, as shown in figure 1. The second port of the circulator is connected to surface luminescent light emitting diode (SLED) source to couple light into the long-tapered section, and the third port is connected to the photodetector to detect the intensity variation of the reflected light. As the length of the tapered section is large, the reflected intensity is low and is expected to diminish further when bending is introduced to make it as S-shaped. With a view to enhancing the intensity of the reflected light, the pigtailed end of the tapered fibre, which is to be attached to the diaphragm, is coated with a ~1 μm thick gold layer using plasma deposition system. The gold coated pigtailed end of the taper is then attached to a circularly clamped nitrile diaphragm. The other end of the taper is placed on a computer-controlled stage. The stage is adjusted in such a way that two bends are created in the long taper and it makes a shape of ‘S’, as shown in figure 1. The micrograph of the STF is shown in figure 2 where the tapered fibre of 13.9 μm waist diameter and 6.4 mm length is kept in S-shaped configuration. At this configuration, the vertical distance (z) and horizontal distance (x) between the two taper ends is 2 mm and 4.15 mm respectively, as shown in figure 2.

The reflection spectra of the gold-coated tapered fibre attached to the diaphragm for different values of z is shown in figure 3(a). These reflection spectra are obtained by connecting the third port of the circulator to an optical spectrum analyser. From the graph, it is clear that the fringe contrast (FC) of the reflection spectra gets improved from a value of 4.82 to 14.88 dB when the z value is increased from 0 to 3 mm [33]. The increase in FC can be attributed to the formation of two prominent bends (Bend-1 and Bend-2, as shown in figure 2) which gives the tapered fibre shape of ‘S’. Higher FC enables the possibility of utilizing a narrow band source for the practical sensing applications.

The intensity of reflected light of the STF is primarily dependent on the bending angle of Bend-1 and Bend-2, and this dependence gets multiplied as the light travels to and fro through these bends. A decrease in bend
angle causes the coupling of more light from fundamental core and cladding to higher order unguided modes which leads to a decrease in the intensity of the reflected light. The applied acoustic pressure deflects the circular diaphragm and the deflection is maximum at the centre of the diaphragm. As the gold coated the pigtailed end of the tapered fibre is attached to the diaphragm centre, the pigtailed end also moves with the diaphragm under the influence of acoustic pressure. The horizontal movement of the pigtailed end causes a change in the x value which in turn changes the bending angles of the two bends leading to variation in the intensity of STF’s reflected light.

Figure 2. Micrograph of the S-shaped tapered fibre (STF).

Figure 3. (a) The reflection spectra and (b) fringe contrast variation of the STF with a change in vertical distance (z) between the two taper ends.
light. Hence, the acoustic pressure can be detected by tracking the intensity variation of the reflected light from the STF.

To optimise the proposed sensing setup for achieving maximum sensitivity, the reflected intensity of the STF for different values of $x$ at constant $z$ values is recorded. Such measurements are recorded for three distinct values of $z$. The results are shown in figure 4. With fixed $z$ values, the reflection intensity decreases slowly with variation in $x$ following a sigmoidal function like curve. For $z$ values fixed at 1 mm, 2 mm and 3 mm, the maximum gradient points are at $x = 5.23$ mm, 4.11 mm and 3.05 mm, respectively. The maximum gradient at positions $P_1(z = 1 \text{ mm}, x = 5.23 \text{ mm})$, $P_2(z = 2 \text{ mm}, x = 4.11 \text{ mm})$ and $P_3(z = 3 \text{ mm}, x = 3.05 \text{ mm})$, is $-0.16 \text{ dB m}^{-1}$, $-0.13 \text{ dB m}^{-1}$ and $-0.11 \text{ dB m}^{-1}$, respectively. These optimized positions are anticipated to induce maximum change in the reflection intensity due to the diaphragm deflection caused by the applied acoustic pressure. Hence, the acoustic sensitivity is expected to be maximum at these positions and therefore these optimised positions are selected for all the acoustic studies.

Apart from the experimental optimization STF’s structure, we also used the finite element method (FEM) to model and analyse the behaviour of the nitrile diaphragm under the influence of acoustic pressure. The results are shown in figure 5 as solid lines, which depicts the displacement of circularly clamped nitrile diaphragm of 80 $\mu$m thickness and 3 cm diameter under the influence of different acoustic pressure. It is observed that the deflection is maximum at the diaphragm centre and increases with the increase in applied acoustic pressure. The
central deflection \( (d) \) of the diaphragm for a homogeneous pressure \( (P) \) is mathematically defined as \([33]\),

\[
d = \frac{3(1 - \mu^2)r^4P}{16t^3E}\sqrt{f_m^2 - f^2 + 4f^2\xi^2},
\]

where, \( \mu, E, \xi, r \) and \( t \) are the Poisson’s ratio, Young’s modulus, the damping coefficient, the radius and the thickness of the diaphragm, respectively. \( f \) and \( f_m \) are the frequency of applied pressure and the mth order natural frequency of the diaphragm, respectively. The diaphragm deflection varies linearly for the acoustic pressure signals with a frequency less than the natural frequency \( (f \ll f_m) \) of the diaphragm and it is maximum at the natural frequency. The first order natural frequency \( (f_0) \) for a properly clamped circular diaphragm can be defined as \([26]\),

\[
f_0 = \frac{10.17t}{r^2}\sqrt{\frac{E}{12\rho(1 - \mu^2)}},
\]

For nitrile diaphragm, the values of Young’s modulus (E), material density (\( \rho \)) and Poisson’s ratio (\( \mu \)) are 2.3 GPa, 1300 kg m\(^{-3}\) and 0.49, respectively. Considering all these material parameters of the nitrile diaphragm the first order natural frequency is calculated to be 1592.76 Hz.

Now, to understand the effect of STF’s attachment to the diaphragm, we repeated the FEM analysis including an STF attached to the nitrile diaphragm and the considered model is shown in figure 6. The results are shown in figure 5 as dashed lines where we have considered the experimental parameters of STF in position \( P_2 \) \((z = 2 \text{ mm}, x = 4.11 \text{ mm})\). It is evident from the results that the inclusion of STF decreases the diaphragm displacement.

Similar studies are carried out to understand the effect of STF’s addition on the first order natural frequency \( (f_0) \). For this study, five fibre parameters are identified which can affect the resonance performance of the nitrile diaphragm: Fibre length between diaphragm and S-shaped taper \( (l_1) \), vertical distance between the two taper ends \( (z) \), horizontal distance between the two taper ends \( (x) \), diameter of S-shaped tapered fibre \( (d_{tp}) \) and fibre

![Figure 5. FEM results showing the diaphragm displacement under different acoustic pressure. The solid lines are for diaphragm alone structure whereas the dashed lined show the results for diaphragm attached with STF.](image)

![Figure 6. FEM modal of the S-shaped tapered fibre attached to the nitrile diaphragm.](image)
length between S-shaped taper end and the fibre clamping point on the computer-controlled stage \((l_2)\). We considered that the STF in position \(P_2\) (\(z = 2\) mm, \(x = 4.11\) mm) with values similar to experimental values listed in table 1 (figure 7) and simulated value of the first order natural frequency \((f_0)\) is 1464.7 Hz. The simulated value (1464.7 Hz) is slightly less than the theoretically calculated value of 1593 Hz (using equation (2)) and it can be attributed to the attachment of STF to the diaphragm.

Table 1. Experimental values of STF’s at position \(P_2\).

| Parameter | Value | Unit |
|-----------|-------|------|
| \(l_1\)  | 10    | mm   |
| \(z\)    | 2     | mm   |
| \(x\)    | 4.11  | mm   |
| \(d_{fpr}\) | 13.9  | \(\mu\)m |
| \(l_2\)  | 10    | mm   |

Figure 7. (a), (b), (c), (d) and (e) Variation of the diaphragm’s simulated first order natural frequency \((f_0)\) with \(l_1, z, x, d_{fpr}\) and \(l_2\), respectively.

Now, to access the effect of these parameters individually, we kept the value of four parameters fixed at experimental values (table 1) and varied the value of only one parameter. This study is repeated for all five parameters and results are shown in figure 7. The data points circled in red are corresponding to the STF parameters listed in table 1. One can see from these results there are three parameters, \(l_1, d_{fpr}\) and \(l_2\), which affect the resonance frequency prominently. With the increase in these parameters \((l_1, d_{fpr} \text{ and } l_2)\), \(f_0\) decreases. Rest of the two parameters, \(z\) and \(x\) have very little effect on the resonance frequency.
3. Experimental results and discussion

The schematic diagram of the experimental setup used to characterize the proposed STF based sensing setup using a reference microphone is shown in figure 8. The thin circular diaphragm is attached to a ring-shaped steel mount. The gold coated pigtailed section of the tapered fibre is carefully attached to the centre of the nitrile diaphragm with the help of a laser alignment system. The system is cured for 12 h at room temperature to ensure tight bonding between the diaphragm the gold coated pigtailed end of the tapered section. Once curing is done, the diaphragm with the tapered section is placed in front of a commercial sound source (Sony), as shown in figure 8. The other end of the tapered fibre is tightly secured on a 3-axes computer-controlled stage and then connected to 3-port circulator. By appropriately controlling the 3-axis stage, the horizontal and vertical distances between the two taper ends (x, z) are changed to attain the S-shape out of the 6 mm long tapered fibre section. The other two ports of the circulators are connected to a broadband SLED light source (Thor Labs, SLD1005S) and a photodetector (Thor Labs, S144C). For STF characterization, the photodetector is set to detect the transmission intensity at 1550 nm. The photodetector output is recorded using a 1 GHz digital oscilloscope system (Tektronix, TDS 2014C). A commercial free-field microphone with a preamplifier (B&K, 4189-2671) is used as a reference microphone to characterise the STF based acoustic sensor which is positioned beside the STF sensor head. The output of the reference microphone is also recorded using the same digital oscilloscope.

Acoustic signals of different intensity and frequency are generated using the acoustic source and the corresponding response from both the microphones viz. the reference and the proposed STF, are recorded simultaneously by the digital oscilloscope. These acoustic testing are done for optimised STF positions $P_1$, $P_2$ and $P_3$. Figure 9 shows the result of one such testing where the STF configuration is kept at position $P_1$ and its response is recorded for acoustic signals of different frequencies. The time domain response with minimal noise and the frequency domain response with sharp peaks, shown in figures 9(a) and (b), respectively. These figures suggest that the STF based sensor can very effectively and accurately sense the applied acoustic signal of varied intensity and frequency.

To calculate sensitivity, acoustic signals of different intensities are produced while keeping the acoustic frequency constant. Figure 10(a) shows, the time domain response for 600 Hz acoustic signals at different intensities with STF at position $P_1$. For higher acoustic pressure, the deflection of nitrile diaphragm is high which induces more bending at the two bends of the STF. As a result, the peak to peak response of the photodetector output also increases. This testing is done for all the three optimized positions and the peak to peak voltage ($V_{pp}$) of the photodetector with respect to the applied acoustic pressure is plotted in figure 10(b). The increase in the $V_{pp}$ is linear for all the three optimized positions of the STF and the slope of these response gives the sensitivity of the STF at that position. For STF positions $P_1$, $P_2$ and $P_3$, the sensitivity is 1.49 mV Pa$^{-1}$, 1.31 mV Pa$^{-1}$ and 0.99 mV Pa$^{-1}$, respectively.

Similar measurements are recorded for a range of acoustic frequencies at the three optimized positions and the results are shown in figure 11. The behaviour of STF at all three positions is very similar because the frequency response is mainly dependent on the diaphragm characteristics, such as diameter and thickness. The sensitivity of the STF is almost constant for frequency 1300 Hz and then steeply starts rising. At 1455 Hz, it reaches a maximum value of 3.07 mV Pa$^{-1}$, 2.79 mV Pa$^{-1}$ and 2.32 mV Pa$^{-1}$, respectively for STF positions $P_1$, $P_2$ and $P_3$. This frequency (1455 Hz) corresponding to maximum response is the experimental first order natural frequency of the nitrile diaphragm and which is in good agreement with the simulated value (1464.7 Hz). The small variation in the first order natural frequency can be ascribed to some non-uniformity in the surface of nitrile diaphragm and its thickness.
Further, the noise of the proposed sensor is also recorded in the absence of any acoustic signal and the results for the three STF positions are shown in figure 12. The average noise response of the proposed sensor is 0.112 mV, 0.085 mV and 0.069 mV, respectively for STF positions $P_1$, $P_2$ and $P_3$. With these values of noise response, the minimum detectable pressure can be calculated as 36.48 mPa Hz$^{-1}$, 30.46 mPa Hz$^{-1}$ and 29.74 mPa Hz$^{-1}$, respectively for STF positions $P_1$, $P_2$ and $P_3$. Additionally, the average noise power spectral density calculated using Welch’s method is $-56.05$ dB Hz$^{-1}$, $-59.25$ dB Hz$^{-1}$ and $-61.34$ dB Hz$^{-1}$, respectively for STF positions $P_1$, $P_2$ and $P_3$ [34].

![Figure 9](image-url)

Figure 9. (a) Time domain and (b) frequency domain response of the STF based acoustic sensor kept at position $P_1$, at three different acoustic frequencies 400, 600 and 800 Hz.
4. Conclusions

In conclusion, a simple and highly sensitive optical microphone based on S-shaped tapered fibre is proposed and demonstrated. The short pigtailed end of the STF is attached to the centre of a thin circular nitrile diaphragm. When the acoustic signal is applied to this sensing setup, the nitrile diaphragm deforms and due to the affixation, the STF structure gets modified leading to change in the bending angles of the two STF bends. As a consequence, the photodetector output, detecting the reflected light intensity of the STF, varies in accordance with the applied acoustic signal. For better results, the shape of the STF is optimized by changing the vertical and horizontal distance between the two taper ends with the help of computer-controlled stage. Three optimized positions $P_1$ ($z = 1\, \text{mm}, x = 5.23\, \text{mm}$), $P_2$ ($z = 2\, \text{mm}, x = 4.11\, \text{mm}$) and $P_3$ ($z = 3\, \text{mm}, x = 3.05\, \text{mm}$) with highest intensity gradients are identified and all the acoustic testing are performed for these positions. With the position $P_1$, the proposed sensor achieves the highest sensitivity of 3.07 mV Pa$^{-1}$ and a minimum detectable pressure of 36.48 mPa Hz$^{-1}$. The sensor shows a linear behaviour up to 1300 Hz and the experimental value of its first order natural frequency is 1455 Hz. Various properties of the proposed sensing setup can be easily tailored by changing the diaphragm diameter and thickness, and the shapes and size of the STF.

Figure 10. (a) Experimentally recorded time domain response of STF at position $P_1$, and (b) response of the proposed sensor at three optimized positions for the applied acoustic signal of frequency 600 Hz and different acoustic pressure.
Figure 11. Variation of proposed sensor’s sensitivity with frequency.

Figure 12. The photodetector output in the absence of any applied acoustic signal for different STF positions.
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