# Refined Bridging of Microfiber Plugs in Hollow Core Fiber for Sensing Acoustic Vibrations

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***Abstract*— This letter develops a novel, ultracompact, insulated, and refined fiber-optic device that is based on a pair of tapered fiber plugs that are bridged in a tiny section of a hollow-core fiber (HCF). The proposed fiber plugs are fabricated by a single-mode fiber taper and are inserted into the HCF. Two taper plugs are bridged with each other inside the section of HCF by fusion splicing. The two ends of the HCF are fused to close the hollow core and form a rigid structure. When the fabricated sensor is utilized to sense acoustic vibrations, the tiny vibration sensing element is insulated and protected against the robust HCF, so it not easily damaged or polluted. The experimental results demonstrated favorable responses to vibrations.**

***Index Terms*— Tapered fiber plug, hollow core fiber (HCF), vibration sensor, fiber-optic component, fiber-optic sensor.**

## I. INTRODUCTION

MANY technologies involve the detection of vibration, which can be performed to monitor the operation of machines in manufacturing systems, to monitor the structural health of buildings and even to predict natural disasters. Many fiber-optic sensors have been reported effectively to detect vibrations of their surroundings [1]–[11]. Among the above studies, intensity-based vibration sensors are simple and reliable. Chen *et al.* developed an optical fiber vibration sensor that is formed using a fused-tapered fiber coupler. The strain that is applied by vibration can change the optical power coupling ratios of the fiber coupler [2]. Another method for sensing vibrations is based on a fiber-to-tip micro cantilever configuration, in which light is coupled from a general single-mode fiber (SMF) to a tapered fiber tip. The displacement of the fiber tip that is induced by the vibrations can vary the optical power received by the fiber tip [3]. The above vibration sensors are very useful; however, the alignment of the fiber tip and the SMF are essential to the sensitivity of the sensor, which affects the difficulty of packaging the sensor. Simple acoustic vibration sensors that are based on non-adiabatic and adiabatic tapered fibers have been proposed in [4] and [6], respectively. The taper bending that is caused by vibration can result in a high SNR and a very good sensitivity. Recently, Lu *et al.* presented a vibration sensing scheme that is based on a suspended microcantilever that is integrated with a readout fiber. The sensing element is novel and ultracompact but a chemical etching process is required [5]. Another scheme is based on optical interferometric sensors, such as fiber Mach-Zehnder [7], [8], fiber Sagnac [9] and fiber Fabry–Perot [10], [11] interferometers, which have been used to sensitively detect the vibrations in the sensing field.

This work develops a novel and ultracompact fiber-optic vibration sensor that is based on a pair of tapered fiber plugs that are bridged inside a very tiny section of HCF. The proposed fiber plugs are fabricated from a general SMF taper. We previously proposed the use of such a tapered fiber plug to close a liquid-core fiber to provide optical and chemical stability of a fabricated fiber device [12]. Herein, a pair of arc-shaped tapered fiber plugs are inserted face to face into a tiny section of HCF and fused inside. The sensor can convert vibration signals into easily detectable optical power variations that can be measured. Vibrations that are generated by an acoustic speaker can be simply detected by directly measuring the transmission power of the sensor. Experimental results show that the proposed sensing configuration responds well to vibrations.

## II. EXPERIMENTAL AND OPERATION PRINCIPLE

The main part of the fiber-optic micro-vibration sensing element was fabricated with two matched and aligned taper plugs, which were fused using an especially designed electric arc method to bridge them. The taper plug bridge had a thinnest waist diameter of about $20\mu$m; it was placed inside a tiny section of HCF with a total length of approximately $330\mu$m. Each end of the HCF was fused to close the hollow core to form a rigid fiber structure. The fabrication processes were monitored under an optical microscope, as shown in Figs. 1(a)-1(e). First, in step (a): a fiber plug is inserted into an HCF, and then the junction of the taper plug and the HCF is spliced to fix them permanently, as displayed in Fig. 1(b). In step (c), a tiny section of the HCF with a length of around $330\mu$m is cleaved. In process (d), another taper plug that is size-matched with the first plug is inserted and aligned fusion is performed to make a bridge inside the HCF. Finally, the specially designed electric arc process is used to fuse and close another end of the HCF. The thinnest parts of the two taper plugs are fused to connect them to each other by exploiting the point effect of electrical charge. The fused taper bridge is bonded strongly so it can be used as a vibration element. Figure 2 shows micrographs of fabricated sensors with different structures. The dimensions

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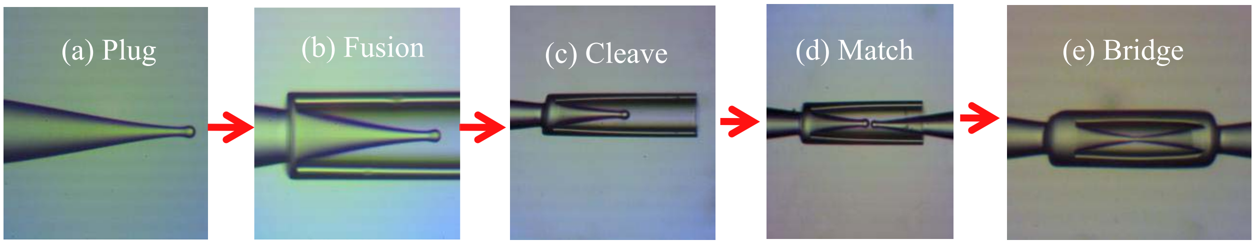

Fig. 1. (a)–(e) Fabrication of tapered fiber bridge that is formed within a small section of a hollow core fiber.

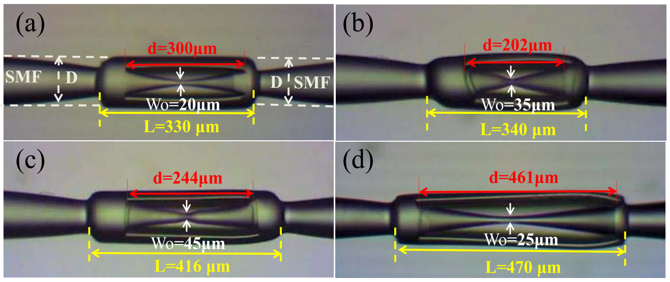

Fig. 2. Micrographs of tapered fiber bridge in vibration sensors with various structures with $W_0$, d and L of (a) 20, 300 and 330, (b) 35, 202 and 340, (c) 45, 244 and 416, (d) 25, 461 and 470 $\mu$m . $W_0$ is the smallest width of the matched taper plugs. L and d denote the length of the HCF and the tapered fiber bridge, respectively.

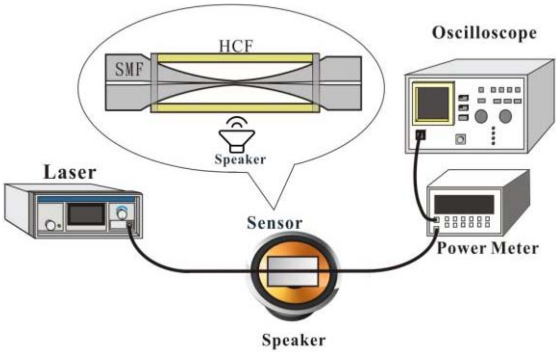

Fig. 3. Experimental setup for sensing vibration. Inset presents side-view of tapered fiber bridge in HCF.

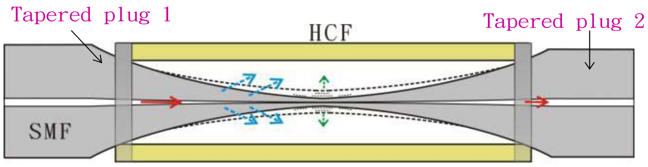

Fig. 4. Schematic diagram of proposed sensor under vibration.

of each sensor match those of a commercial SMF after the refined fabrication. The main part of the tapered fiber bridge is very well insulated and protected in the HCF. The entire structure can be regarded as a sensitive tapered fiber that is concealed inside another fiber. Thus, the developed device can be embedded in any other materials, including solid, liquid and even corroded materials for vibration testing. The proposed vibration sensor is then attached to a plastic plate with dimensions of 4.1cm × 1.5cm × 0.04mm near and above a commercial speaker, which is utilized as an acoustic vibration source. Figure 3 presents the experimental setup for vibration sensing. Light from a tunable laser with a wavelength of 1550nm propagates into the sensor, and the output power is detected by a power meter. The electronic signals from the power meter are directly collected using an oscilloscope. The tapered fiber bridge is bent by the vibration from the speaker, varying the output laser power. The vibration causes the output power of the sensor to oscillate at the current driving vibration frequency. The time-domain power signals are then collected and converted to frequency spectra using the fast Fourier transform.

Figure 4 shows the operating principle of the proposed vibration sensor. Light propagates into tapered fiber plug-1 through the fiber plug bridge that excites high-order modes. The tapered region of the bridge oscillates with bending, strongly enhancing the evanescent wave of the high-order modes that leak out. Therefore, the intensity of the light that is received by tapered fiber plug-2 varies periodically with an amplitude that is related to the driving frequency and the driving power/amplitude of the acoustic speaker.

## III. EXPERIMENTAL RESULTS AND DISCUSSION

To investigate the effect of vibration on the proposed tapered fiber bridge, the sensor (a) in Fig. 2 is placed near to a commercial speaker at a room temperature of 25°C. The speaker is driven by a function generator that provides sinusoidal signals with various driving amplitudes/powers and frequencies. Laser light propagates into the fiber sensor, so the variation in the output power that is caused by the acoustic vibration can be detected by a power meter. The electronic signals are directly collected by an oscilloscope to obtain the power of the signals in the time domain and the frequency domain.

Figure 5 shows the experimental results obtained by the sensor when the speaker is driven by vibrations with various driving amplitudes/powers at a fixed frequency of 800Hz. Figure 5(a) plots the measured output power variation of the sensor in the time domain, as detected by the power meter, when the speaker is driven at 0.71 W, 0.27 W and 0.03 W. The vibration frequencies are readily obtained in the frequency domain using the oscilloscope, as presented in Fig. 5(b). A higher driving power of the speaker yields a higher frequency of the response signal. Figures 6(a)-(c) respectively plot the experimentally measured vibrations at 10 Hz, 1 kHz and 10 kHz with a driving power of about 0.7 W. The frequency responses with the corresponding high-order harmonics and corresponding optical responses output voltages obtained from the power meter are shown. The insets plot the measured optical signals in response to acoustic vibrations

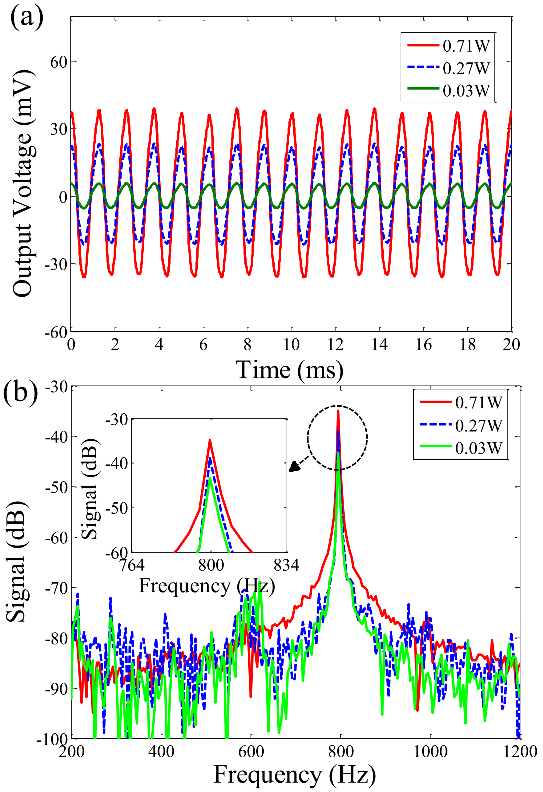

Fig. 5. (a) Output power of sensor in time domain, detected by power meter, and (b) measured frequency of vibration when driving power is 0.71W, 0.27W and 0.03W.

at 10 Hz, 1 kHz and 10 kHz. The output power that is associated with the micro-bending of the fiber taper bridge that is related to the acoustic vibrations. It was measured using a power meter that reveals good sinusoidal waveform with uniform amplitude. The demodulated frequency of vibration is close to that of the electrical signal with an SNR of over 45dB. The corresponding harmonics of the induced vibration frequency are ascribed to little axial misalignment between the vibration source and the fiber taper bridge. However, the signal at the main frequency overcomes the harmonics, enabling the vibration to be clearly measured.

To evaluate the features of the proposed taper bridge inside the HCF, experiments on the robustness and protection (insulation) of the tapered-based sensors herein were performed and compared [4], [6], [8]. In the robustness test, the weight load on the sensors was gradually increased to break these tapered devices. The experimental results indicate that the breaking forces of the general taper and our sensor with given the same tapered waist of 10$\mu$m were about 0.7N and 2.8N, respectively. The breaking point is in the thinnest region of the general abrupt taper, which is shown in Fig. 7(a). However, for the device proposed herein, the breaking point is far from either end of the sensor, as presented in Fig. 7(b). The main element of the proposed sensor is intact and it is well protected to prevent damage by the proposed refined fabrication of fusion splicing HCF section.

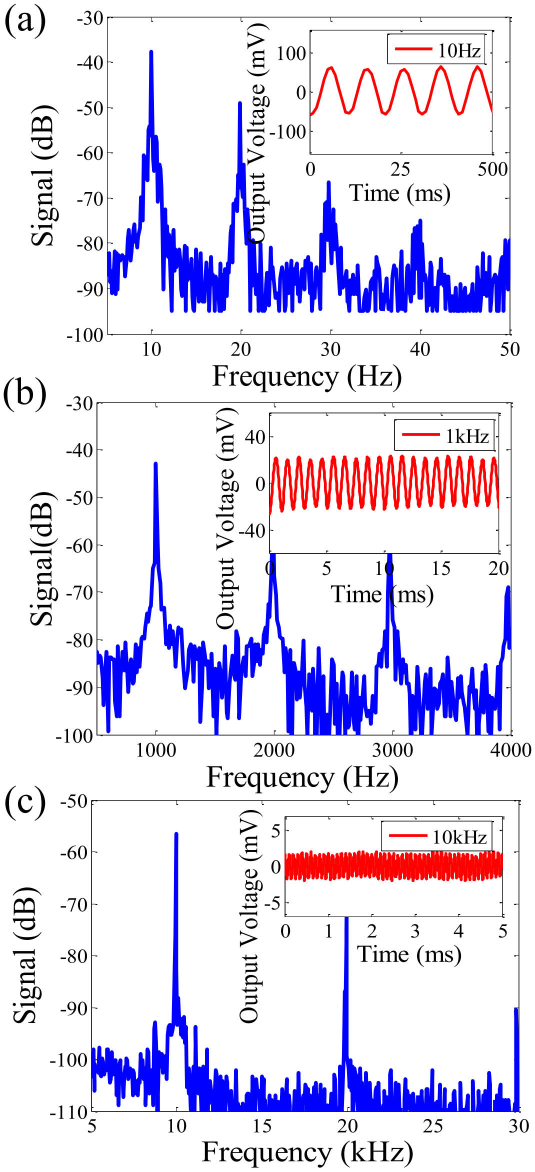

Fig. 6. Frequency-domain spectra of proposed vibration sensor that is caused to oscillate by a speaker at (a) 10 Hz, (b) 1 kHz and (c) 10 kHz. Insets show corresponding time-domain spectra.

Figure 8 shows experimental results concerning the protection (insulation) of the taper bridge by the HCF. By overlaying the above two taper sensors with materials under the non-vibration condition, a high power decay of the normalized transmission in the general taper was measured, as presented in Fig. 8 (a). However, for the developed sensor, the loss is very small (∼0.2dB variation), as shown in Fig. 8 (b). The results reveal that the thinnest tapered region can be isolated against the surrounding material by the HCF, preventing an optical power loss. The insulation importantly causes the light to propagate throughout the fiber sensor, unaffected by the surrounding medium.

Based on the results of the above experiments, the main sensing element of the device herein can be insulated within a fiber, preventing the attachment of pollutants or other materials. Such enclosed fiber sensors can be found elsewhere [5], [11]. Table 1 compares the results obtained using the reported fiber-optic vibration sensors. Different structures

TABLE I
COMPARISON OF FIBER-OPTIC VIBRATION SENSOR DEVELOPED HEREIN WITH OTHERS

| Fiber-Optic Vibration Sensors | Frequency Range (Hz) | Amplitude ($V_{pp}$) | SNR | Key Structure | Insulated | Size of Main Element |
|---|---|---|---|---|---|---|
| This study | 10– 10k | 1.5-70mV | 45dB | Taper plug bridge | Yes | ~300-400μm |
| Y. Huang, *et al.*[1] | 200 | 150mV | 40dB | Tilted FBG | No | >10mm |
| R. Chen, *et al.*[2] | 10k– 1M | 82-100mV | 6.5 (a.u) | Tapered fiber coupler | No | ~7mm |
| L. Su, *et al.*[3] | 0– 1k | 0.01 (a.u.) | $2.8\times10^{-3}$ (a.u.) | Fiber-to-tip micro cantilever | No | ~100μm |
| B. Xu, *et al.* [4] | Few – 10k | 0.0028 (a.u.) | 73dB | Non-adiabatic fiber taper | No | ~1160μm |
| P, Lu, *et al.* [5] | 5 – 10k | 0.04-0.08(V) | 68dB | Enclosed suspended micro cantilever | Yes | ~600μm |
| Y. Li, *et al.* [6] | 30 –40 k | 0.3 (a.u) | 60dB | Adiabatic fiber taper | No | ~50mm |
| Y. Xu, *et al.* [8] | 1 - 500 k | 0.05V (15kHz) | 45-50dB | Tapered fiber M-Z interferometer | No | ~5cm |
| Q, Zhang, *et al.*[11] | 0.5 – 250 | 0.4V(10Hz) | - | Fiber Fabry-Perot interferometer | Yes | ~60mm |

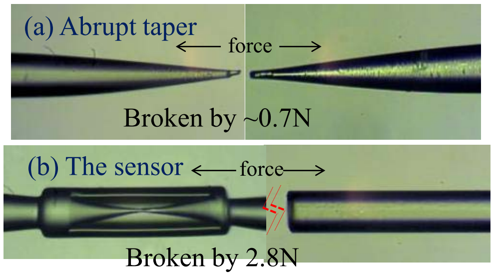

Fig. 7. Tapered fiber devices; (a) abrupt taper (general taper) and (b) taper bridge fused inside HCF, broken under strain.

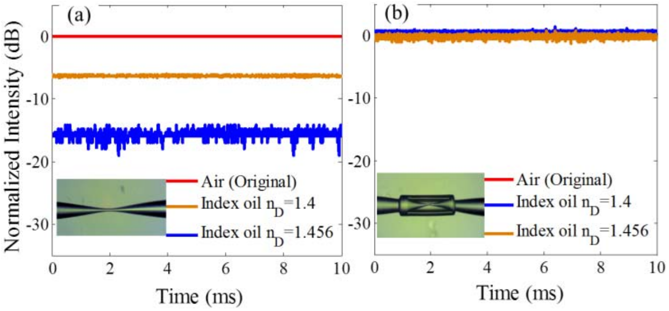

Fig. 8. Variation of normalized intensity of (a) abrupt taper and (b) proposed taper bridge overlaid with oils.

have been developed in the cited studies and each exhibits particular features and advancements. Our sensor herein has the advantage of being very tiny, with the tapered fiber bridge insulated and protected against the robust HCF, unlike the other sensors in Table 1. This great merit enables the proposed fiber sensor to provide stable dynamic vibration detection in a harsh environment, for example, a high temperature, high humidity and pollution. Notably, the developed sensor with high sensitivity and rapid response can be utilized to monitor power fluctuations that are associated with any vibrations. Additionally, the proposed device can be recoated with a fiber jacket to make it more rigid and stable for embedding inside other materials/objects or even immersed deep in water to detect earthquakes.

## IV. CONCLUSION

This work proposed a novel, ultracompact, insulated and refined fiber-optic sensor that is based on a miniature tapered fiber bridge in a hollow-core fiber. The device was used to measure the acoustic vibrations and it was found to respond sensitively. The sensor is based on micro-bending of the taper bridge that is induced by acoustic vibrations and changes the transmission power of the fiber sensor. The presented vibration sensor exhibited a wide frequency range from a few Hertz to more than ten kHz, with a good SNR. Moreover, the main structure, which comprises a tapered fiber bridge inside a tiny section of HCF, can be well insulated to improve the measurement stability. The sensing element is very tiny, so can be embedded inside or packaged with other materials/objects, and even immersed in water/liquid. Owing to these favorable characteristics, the refined fiber sensor has potential for sensing vibrations in various fields.

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