A Simple, High Sensitive Fiber Optic Microphone Based on Cellulose Triacetate Diaphragm

Sekip Esat Hayber, Timucin Emre Tabaru, Serkan Keser, and Omer Galip Saracoglu

***Abstract*—We present a high sensitive fiber-optic microphone (FOM) with a wide measuring range based on a cellulose triacetate diaphragm in this work. The average signal-to-noise ratio (SNR) of the proposed FOM is measured 50.86 dB in at the frequency range of 100 Hz–20 kHz. In the same spectrum range, the highest SNR for the 2-kHz frequency under 103.16 mPa acoustic pressure is measured at 72.20 dB with 2 Hz resolution bandwidth, which corresponds to a noise-limited minimum detectable acoustic pressure level of 17.91 μPa/$\sqrt{}$Hz. The proposed sensor has advantages of high sensitivity, low cost, and easy fabrication. According to the assessments based on the obtained results, the FOM can be used for medical spectroscopy, imaging applications, and for long-distance listening and voice recognition in the military-public security.**

***Index Terms*—Fabry–Perot, fiber-optic microphone, polymer diaphragm.**

I. Introduction

FIBER optic microphones (FOM) are the strongest candidates for communication and sensing applications under extreme conditions due to the inherent advantages of fiber optic systems. The most important advantages are their high immunity to any electromagnetic interference, small dimensions, and being lightweight. Other important features include their capacity to work in long distances without a repeater between the detection zone and the electronic unit, easy adaptation to existing fiber optic networks, high resolution, and high sensitivity. The usage of metal-free and current-free FOMs has become inevitable for communication in which there is severe electromagnetic interference in some special application areas, such as hospital's magnetic resonance and computerized tomography rooms where conventional electrical microphones cannot penetrate. Besides this, because the FOMs are well suited for long-distance listening and voice recognition, they are essentially used in military and public security that have recently become increasingly important. The FOM also is put forwarded quite satisfactory results in photoacoustic spectroscopy and imaging applications especially for human tissues and arteries. The first results of fiber-optic acoustic sensor were presented by Bucaro *et al.* and Cole *et al.* [1]–[4] in 1977 and studies have continued with the contribution of different researchers until now. Most of the fiber optic sensor devices in these studies were fabricated with Fabry-Perot (FP) interferometer [5]. Fundamental parameters characterizing fiber optic acoustic sensors or the FOM in the literature are Signal to Noise Ratio (SNR) of the output signal, Minimum Detectable Pressure (MDP) level, and bandwidth. Ma *et al.* achieved a flat frequency response between 0.2 kHz and 22 kHz in their FP-acoustic sensor study with a ~100-nm-thick multilayer graphene diaphragm. In these studies, they measured a MDP of 60 μPa/$\sqrt{}$Hz at 15 kHz and SNR of 57.5 dB [6]. Xu *et al., by* using a large-area nanolayer silver diaphragm, measured a MDP of 14.5 μPa/$\sqrt{}$Hz and a SNR of 43.3 dB [7]. Bandutunga *et al.* measured a MDP of 74 μPa/$\sqrt{}$Hz at 1 kHz and a SNR of 47 dB, by using a polyethylene terephthalate polymer diaphragm [8]. Tests of these studies and similar multi-tasked structures were performed by applying sinusoidal signals with constant frequency and amplitude. The FOM performance under a dynamic acoustical field has been examined in very few studies [9], [10].

A model for Perceptual Evaluation of Speech Quality (PESQ) was standardized by the International Telecommunication Union (ITU) as recommendation ITU-T P.862 (02/2001) [11]. PESQ compares an original signal with a degraded signal. The output of PESQ is a prediction of the perceived quality that would be given to degraded signal by subjects in a subjective listening test. It is asserted to have the highest correlation (0.935) with the subjective measurements [11]. The PESQ score is used to determine the noise level and distortion of the speech signals. The speech input levels, environmental noises, errors in the transmission channel are reflected in the PESQ scores. The PESQ score is obtained as a single number in the range of 1 to 4.5. PESQ scores range from 1 for unacceptable to 4.5 for excellent. The highest score, 4.5, means that no distortion is measured [11]–[13].

In the past years, promising results have been reported for the FOMs that comprise photonic-crystal [14], [15], graphene [6], [16], graphene oxide [17], silver [7], [18]–[20] diaphragms. These works contain challenging manufacturing processes. On the other hand, polymer materials provide easy manufacturing,

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low cost, and high-performance advantages so can be regarded as an alternative material for the optical sensor diaphragm. Thanks to their low elastic modulus, the polymer materials have the sensitivity needed for the FOMs [21]. Generally, some methods such as ultraviolet hardener adhesive [22], [23], the vacuum thermal evaporation deposition method [24], [25], spin coating, baking, and separation from the substrate processes [26] are used for polymer production. However, all of the above-mentioned manufacturing methods are complex, expensive, and the attained pressure sensitivities are not sufficiently high. Cellulose Acetate (CA), a natural polymer-based product, is the most important cellulose derivative obtained from an organic acid. CTA, a form of CA, is often used in industrial applications because it is more immune to environmental conditions such as heat and humidity. The film strips made of this material can work properly for many years without destruction. For over 60 years by means of these properties, it has been used as an optical compensation film for liquid crystal displays (LCD) on a polarizing plate [27]. The CTA film surface is smooth and has satisfactory optical properties. Moreover, it is resistant to water and oil, and even solvents such as acetone. This allows it to be used comfortably in liquid media. Due to these exceptional properties, the CTA has been chosen to be used as a diaphragm material.

In this study, we propose a simple and high sensitive FOM based on Extrinsic Fabry-Perot Interferometer (EFPI) structure. In order to achieve this goal, the CTA film, which is inexpensive, a good resistance to moisture and corrosion, was used for the first time in the literature. The proposed sensor tip can easily be combined with standard fiber components. In our experiments, sound signals with the constant frequency and amplitude are applied to the FOM. Next, the SNR and the MDP of the output signal are measured for different frequencies. The average SNR of proposed FOM is measured as 50.86 dB in the frequency range of 100 Hz−20 kHz. In the same spectrum range, the highest SNR values for the 2 kHz frequency under 103.16 mPa acoustic pressure is measured at 72.20 dB with 2 Hz resolution bandwidth, which corresponds to MDP of 17.91 μPa/$\sqrt{}$Hz. Additionally, for the first time in the literature, we have tested the performance of the FOM in long-distance listening and speech recognition applications by applying human speech signals to proposed FOM. This test is very important for military and public security. These speech signals are selected from the Texas Instruments Massachusetts Institute of Technology (TIMIT) database [28]. PESQ scores are calculated by comparing the original speech signals with FOM signals. Thus, an important part of the dynamic frequency spectrum has been evaluated. We observe that the obtained PESQ scores of the proposed FOM are remarkable and high. As a result of the assessments presented above, we propose that the FOM is well suited for long-distance listening and speech recognition in military-public safety applications and photoacoustic spectroscopy imaging in medical applications.

II. Working Principle and Sensor Fabrication

The FOM detection tip is comprised of two interfaces. The first one is the fiber-air interface and the second one is the air-diaphragm interface. After the light beam emerging from the light source passes through the circulator and comes to the first interface. Almost all of the light beam passes to the FP cavity and reaches to the second interface. Since the inner surface of the diaphragm is coated with a highly reflective material, a large part of the light beam is also reflected from the second interface and comes back to the first interface than enters the fiber. The light beam entering the fiber reaches the photodetector via passing through the circulator. The detector converts the light beam to the electrical signal and transmits it to the signal processing unit. While multiple reflections continue in the FOM system, if an acoustic pressure is applied to the diaphragm surface, the FP cavity length changes due to deflection at the center of the diaphragm. These ripples in the cavity cause changes in the phase and the intensity of the reflected light from the diaphragm. In Equation (1), I_r is the intensity of the light output from the FOM [29],

$$I_r = I_0 \frac{R_1 + \eta R_2 - 2\sqrt{\eta R_1 R_2}\cos\phi}{1 + \eta R_1 R_2 - 2\sqrt{\eta R_1 R_2}\cos\phi}. \quad (1)$$

Where I_0 is the optical intensity of the incident light, R_1 and R_2 are the reflectance coefficients at the fiber-air and air-diaphragm interfaces, respectively., and these values are calculated with (3) [30]. η is the power transmission coefficient in the FP cavity [31], ϕ is the optical phase that can be expressed as

$$\phi = \frac{4\pi n_m L}{\lambda}. \quad (2)$$

n_m and L denote the refractive index of the medium in the FP cavity and the cavity length ($n_m = 1$ for air), respectively. λ is the wavelength of the optical source.

$$R = \frac{(n-1)^2 + \kappa^2}{(n+1)^2 + \kappa^2}. \quad (3)$$

In Equation (3), n is the refractive index of the fiber core for the first interface. The type of the fiber that is used for the circulator in our work is SMF-28e, therefore n_{fiber} is 1,449. κ is the extinction coefficient of the fiber core, this value is zero for dielectrics. In this case, the first interface reflectance value R_1 is calculated as 3.36%. For the second interface, n represents the refractive index of the diaphragm material, and $n_{\text{diaphragm}}$ is 1.49 for the CTA diaphragm. κ is also zero for the CTA diaphragm. Consequently, R_2 is calculated as 3.87% for the second interface. The inner surface of the CTA is coated with Aluminum (Al) which is a highly reflective material. n_{Al} and κ of Al are 1.5785 and 15.658, respectively. Using these values, the reflectance value R_2 is increased to 97.49%. Thanks to this increased value, almost all the light beam striking the inner surface of the diaphragm returns to the FP cavity than reaches the photodetector. Principal mechanism of the diaphragm-based FOMs is expressed by the dynamic vibration analysis of diaphragms in addition to the above-mentioned the optical interference theory. The mechanical properties and geometric dimensions of the diaphragm material determine the sensitivity of the sensor system to acoustical pressure and its resistance to the severe ambient conditions under which it operates.

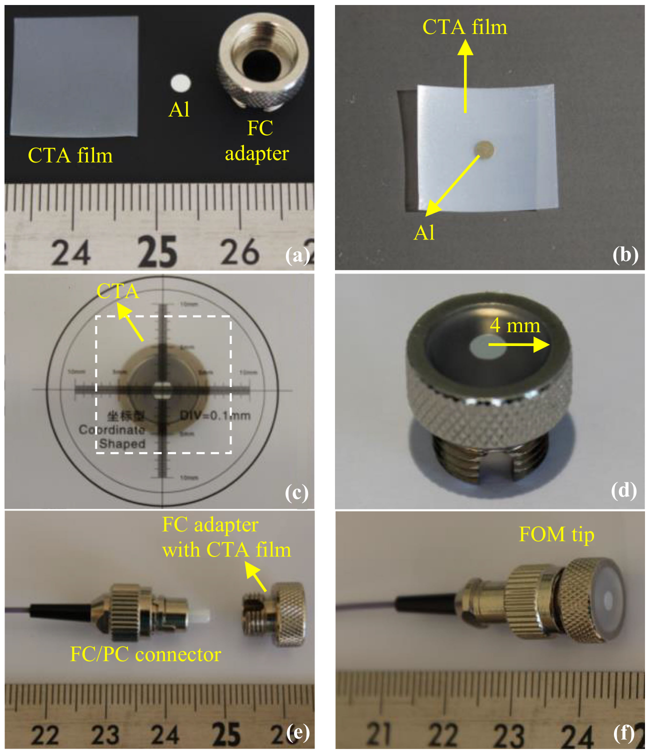

Fig. 1. (a) Self-adhesive CTA film, Al circular sheet, standard FC adapter. (b) Al is fixed to the CTA film. (c) Al is fixed to the center of the FC adapter with micrometer calibration ruler. (d) Cutting excess parts of the CTA. (e)–(f) Screwing the FOM tip to the FC/PC connector.

Fig. 1 shows the Al coating on the inner surface of the CTA film and the sensor with the FC adapter. Production stages of the sensor tip are as follows. Firstly, a piece of Al with a radius of 1.1 mm and a thickness of 15 μm is fixed onto the self-adhesive CTA film having a thickness of 60 μm as shown in Fig. 1(b). Al is fixed to the center of the FC adapter with an internal radius of 4 mm. Micrometer calibration ruler is utilized to ensure that the centering is done accurately during the bonding of the combined structure to the FC connector as illustrated in Fig. 1(c). The excess parts of the CTA film are cut off as shown in Fig. 1(d). Finally, the sensor tip is screwed to the FC/PC ferrules of the circulator to obtain the FOM tip as shown in Fig. 1(e) and (f). The produced FOM tip can be used with a wide variety of sensor system elements such as single-mode or multi-mode fiber, circulator or coupler due to the easy screwing to standard FC type fiber optic connectors. In addition, an external air hole is opened to compensate for the internal and external pressures between the interfaces of the sensor.

The experimental setup is depicted schematically in Fig. 2. A laser diode with the wavelength of 1550 nm is used as a light source in the measurement setup (Ideal Fiber Master 33-929). 1525–1610 nm Single Mode Fiber (SMF) with FC/PC (Thorlabs 6015-3-FC) is used as the circulator. A high-speed fiber-coupled InGaAs biased photodetector (Thorlabs DET08CFC-M, 5 GHz) is chosen to measure the reflected optical signal from the FOM tip. The photodetector responsivity

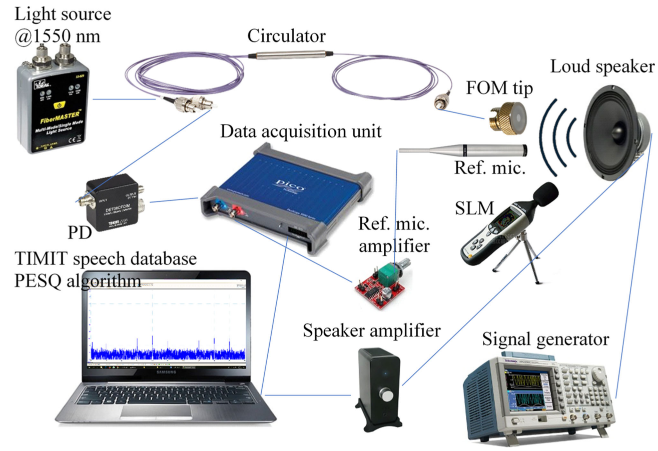

Fig. 2. The schematic diagram of the experimental setup for FOM system.

is in the range of 800−1700 nm and the peak wavelength is 1550 nm. The signals received from the detector are measured by a PC oscilloscope and data logger (Picoscope 3206MSO, 200 MHz analog bandwidth, 1 GS/s real-time sampling, 512 MS buffer memory). The PC oscilloscope also includes a spectrum analyzer and the frequency domain measurements are carried out with this instrument. The spectrum analyzer in this instrument is of the Fast Fourier Transform (FFT) type, which, unlike a conventional sweep spectrum analyzer, can display the spectrum of a single nonrepeatable waveform. The experimental data acquired from the pc oscilloscope is then processed by MATLAB software and rendered graphical.

III. Experimental Results and Discussion

The SNRs are obtained by applying sinusoidal sound signals with a single harmonic in the range of 100 Hz−20 kHz to the sensor tip for sensing the FOM performance. A sound level meter (SLM) is used to measure the Sound Pressure Level (SPL) of the applied sound signals. The average SNR of the proposed FOM is measured as 50.86 dB in the frequency range above mentioned as shown in Fig. 3(a). At the measurements made using with 0.1 Hz resolution bandwidth, the peak SNR for 500 Hz under 91.52 mPa acoustic pressure is determined at 70.15 dB, which corresponds to an MDP of 89.95 μPa/$\sqrt{}$Hz. Fig. 3(b) shows the highest SNR for 2 kHz frequency under 103.16 mPa acoustic pressure and the SNR is measured as 72.20 dB with 2 Hz resolution bandwidth, this corresponds to an MDP of 17.91 μPa/$\sqrt{}$Hz. The average MDP of FOM system is shown in Fig. 3(c). Acoustic pressure response of the FOM at 2 kHz frequency is also given in Fig. 3(d).

It is seen that the response of the FOM to the acoustic pressure is linear. After the SNR measurements, speech signals with variable amplitude and frequency are applied to determine the FOM performance in a continuous frequency band. These speech signals are selected from the TIMIT speech database. The speech signal in the TIMIT database has a sampling frequency of 16 kHz (16 bit, PCM format) [28]. In our experimental studies, the speech material of the TIMIT database has been randomly

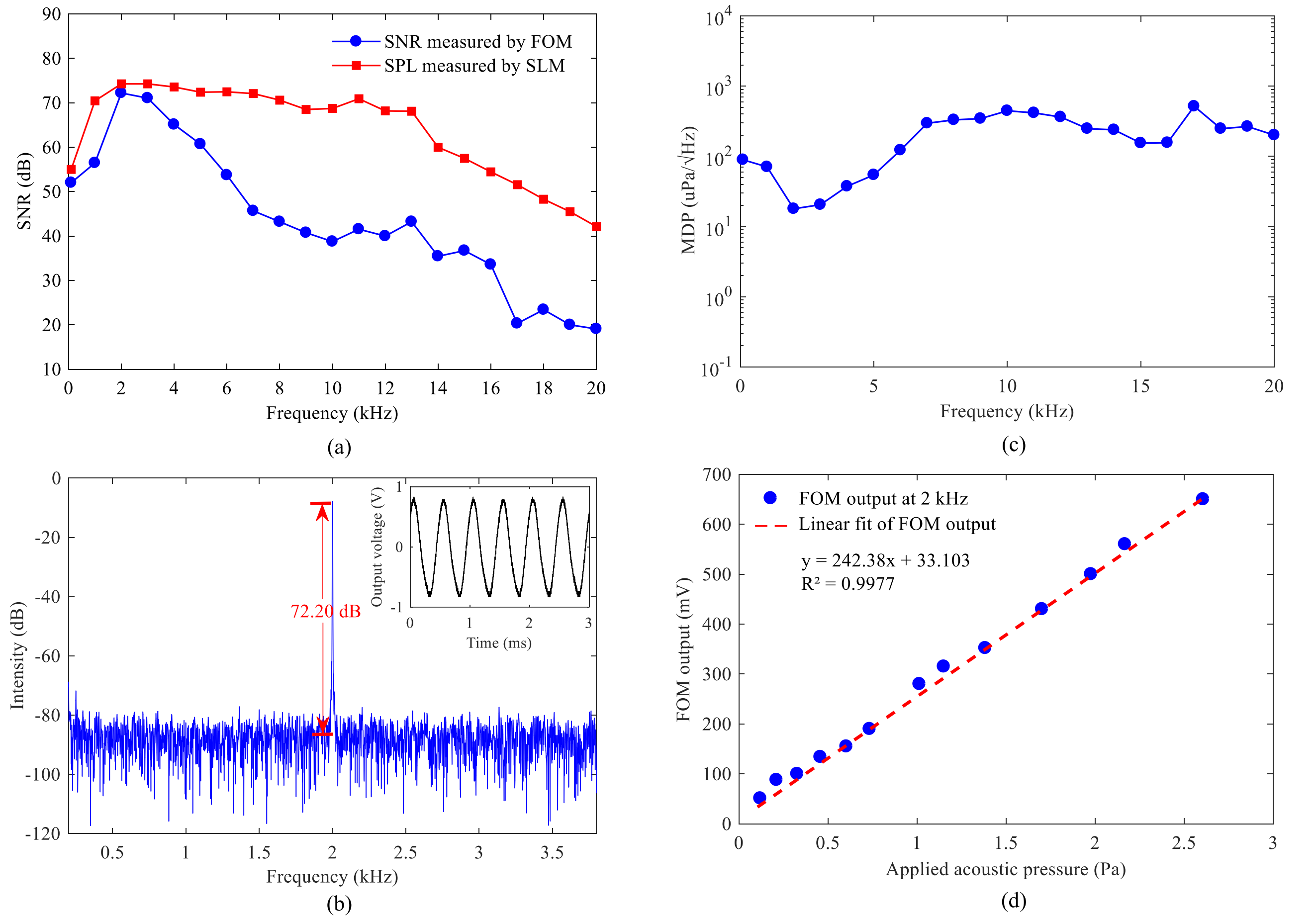

Fig. 3. (a) Frequency response. (b) maximum SNRs. (c) the MDP in the range of 100 Hz to 20 kHz. (d) acoustic pressure measurement performance of FOM.

selected 6 speech signals. The speech signals are applied by using a loudspeaker to the FOM and capacitive reference microphone (ref. mic.). Then, the obtained speech signals, which are produced by data acquisition unit, are converted to Waveform Audio File Format (WAV) and the comparison of the two microphones is performed with the obtained time and frequency domain responses. The results of time domain responses of SI891 and SI1199 are shown in Fig. 4(a) and (b), respectively. As seen in Fig. 4, the obtained speech signals, which are found using the FOM and ref. mic., are quite similar to the original speech signals. The results of frequency domain responses of SI891 and SI1199 are shown in Fig. 4(d) and (e), respectively. According to the obtained results, we have determined that the noise immunity of the proposed FOM is higher than the ref. mic. especially for the frequencies above 3 kHz. The acoustic box is not used in the measurements because it is intended to test the actual media performance of FOM. For this reason, it was seen that environmental noise was less affected than the ref. mic. because FOM is highly immune to electromagnetic interference. The resonance frequency of the diaphragm at 3, 4.5, 6 kHz is stimulated by the harmonic at 1.5 kHz in the test signal SI891. In resonances at 4.5 kHz and later, the amplitude begins to dampen due to SNR. For this reason, the response at 3 kHz is maximum because of maximum SNR.

TABLE I
PESQ Scores of FOM and Reference Microphone

	SI891	SI1199	SI1473	SI1746	SX28	SX102	Average
FOM	3.61	3.63	3.70	3.60	3.60	3.68	3.64
Ref. mic.	3.46	3.57	3.65	3.52	3.49	3.64	3.56

Measurements are carried out at different time periods with the FOM to examine the aging effect. Fig. 4(c) shows the results of time domain responses measurements made at different time intervals. There is a 75-day difference between the first measurement time and the second measurement time. Fig. 4(f) shows the frequency domain responses of the same measurements. In these long-term usage tests, no difference between the measured audio signals due to the aging have been observed.

Scores of PESQ, a quality criterion, are obtained through the comparison of original speech signals with obtained speech signals by different algorithms implemented in MATLAB. The average PESQ scores of the ref. mic. and the FOM are calculated as 3.56 and 3.64, respectively. These results are shown in Table I.

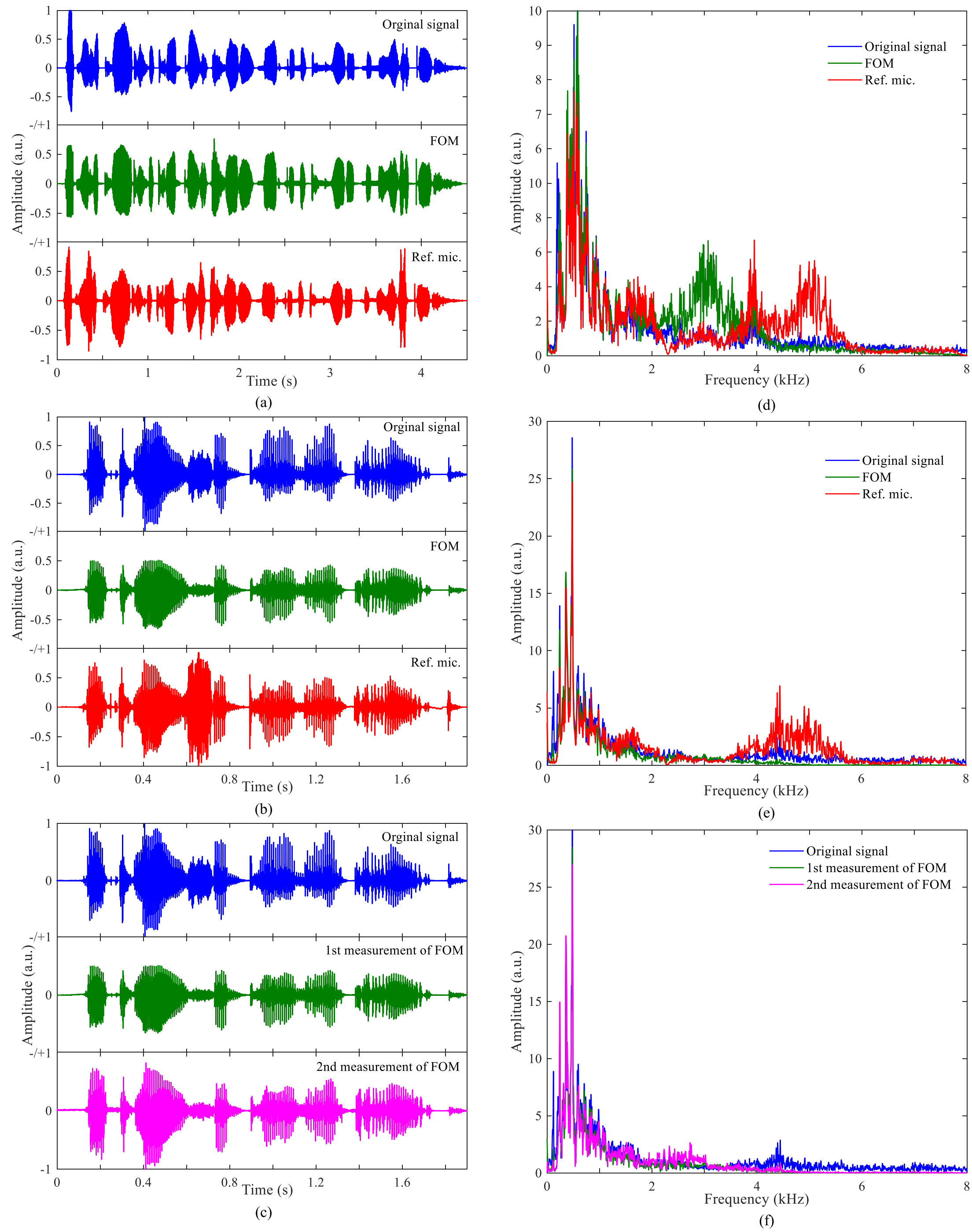

Fig. 4. The FOM's response to the human voice is compared to the original signal and reference microphone. Time domain results of (a) SI891, (b) SI1199, (c) Aging test of SI1199. Frequency domain results of (d) SI891, (e) SI1199, (f) Aging test the FOM by using of SI1199.

IV. Conclusion

A fiber optic microphone based on self-adhesive cellulose triacetate diaphragm with a simple and low-cost fabrication process has been produced. Discrete and continuous signals are applied to the FOM in the determined frequency band, and performance analyses for different applications are presented. The experimental results indicated that the FOM has a linear acoustic pressure response, a high performance, and a high sensitivity of 17.91 μPa/$\sqrt{\text{Hz}}$. Moreover, the performance of the produced FOM is compared with a conventional, commercial high-cost electrical microphone system. The average PESQ scores of the ref. mic. and the FOM are calculated as 3.56 and 3.64, respectively. The average PESQ value of the FOM shows that the quality of the speech signals obtained by the FOM is good [13]. In addition, the average PESQ value of the FOM is higher than that of the ref. mic. That is, the quality of the speech signals obtained by the FOM is better than that of the ref. mic. As a result of this study, we evaluate that the FOM is well suited for long-distance listening and speech recognition in military-public safety applications especially. The acoustic box is not used in this study because the actual medium performance of the FOM is desired to be examined. The use of an acoustic box introduces an ideal medium; hence the FOM performance parameters are expected to exceed determined values.

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