Analysis of a Single Lens Fiber Optical Microphone Configuration

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Abstract — **This work reports the analysis of a single lens fiber optical microphone configuration. The proposed microphone is basically constituted by only two optical fibers, a single lens, a reflective membrane, a laser, and a photodetector. A theoretical analysis was conducted to determine the main modulation parameter of the microphone. The system was able to detect sound waves up to 6 kHz with a dynamic range of 50 dB, and it was compared with more complex optical microphones. Such configuration is simple and low cost with potential for voice communication and sensor application.**

Index Terms **— Fiber optical microphone, voice communication, optical sensor.**

I. Introduction

The fiber optical microphone, FOM, has been research subject of different areas. Interest on this device is related to the advantages that an optical sensor has over conventional sensors, such as electrical and chemical passiveness and electromagnetic interference, EMI, immunity [1]. In addition, long distances between the microphone and the electronic circuit are supported due to the low loss characteristic of optical fiber. These features make feasible the employ of a FOM as an alternative way to applications in surveillance, military, medicine, robotics, and noncontact or nondestructive essays [1]-[6].

As an example, for military purposes, it can be mentioned an optical microphone array to capture acoustic signatures of vehicles such as battle tanks, aircrafts, helicopters and submarines, and provide accurately the position, velocity, classification and direction of motion [5]. In medicine, FOM is used to record a speech simultaneously with the magnetic resonance imager, MRI, in measurements of vocal tract [4].

At the Photonics Laboratory of the Instituto Tecnológico de Aeronáutica, ITA, there is a research program in course to develop photonics systems for distributed sensors, surveillance, and nondestructive essays that fits the development of a FOM. Such researches started with fiber optical reflective sensor, FORS, to displacement measurement [6]-[7] and its microphone applications [8].

FORS is a well established technique since 1960 decade [9]. One can find in the available literature several papers about this type of sensor and its applications, among which microphone and hydrophone applications could be highlighted [10]-[13]. In the FORS sensor, one fiber (transmitting fiber) is used to convey light from a remote light source to a reflective surface. The reflected light is collected back by another fiber (receiving fiber) and directed to the photodetector. The distance variation, d, between the fibers ends and the reflective surface is the cause of light intensity modulation. If this surface is a suitable membrane, one can convert the displacement caused by acoustic waves to light modulation. Fig. 1 shows the general scheme of a FOM based on FORS.

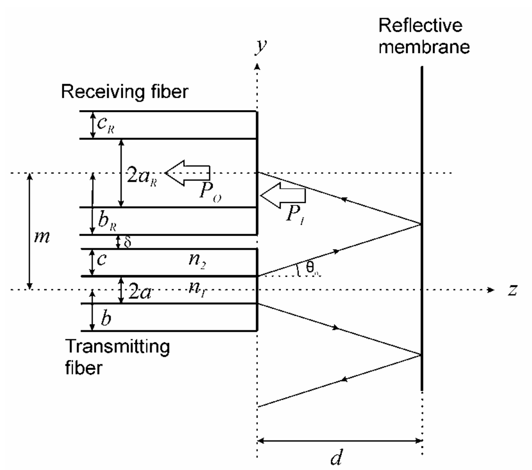

Fig. 1. General scheme of FOM with the principle of FORS.

One drawback of FORS is the amount of light lost due to the conical shape of the beam emitted by the optical fiber. A possible solution could be the use of more than one receiving fiber around the transmitting fiber (fiber bundle) [14]. This kind of solution increases the sensitivity of the system, but also increases its cost, especially when transmitting over long distances. Other solution is to work with lenses to collimate the optical beam. Such possibility was proposed earlier and is based on integrated microoptics mounting where two lenses are used: one to collimate the beam from the transmitting fiber and the other to focus the beam on the receiving fiber [15].

The purpose of this work is to analyze a two fibers and single lens FOM configuration, instead of previous works that deal with fiber bundle or two lenses. Next sections show a developed theoretical model about the principles of such lens configuration, laboratory mounting, experimental results and a comparative discussion with previous works.

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II. THEORY

The microphone head was conceived to be simple and in this way it consists of one transmitting and one receiving optical fiber, one lens, and one reflective membrane, as shown in Fig. 2. The light emerges from the transmitting fiber in a conical shape limited by the critical angle θ_o, until it reaches the lens. This angle is given by $\theta_o = \sin^{-1}(NA/n)$ where NA is the transmitting fiber numerical aperture and n is the air refractive index. The distance, d_o, between the lens and the transmitting fiber is set to obtain a collimated beam after lens. This distance is given by $d_o = f - a/\tan(\theta_o)$, where f is the lens focal distance, and a is the transmitting fiber radius. The collimated beam reaches the membrane with incidence angle θ relative to the membrane normal, and is reflected with the same angle. Total deviation is equal to 2θ. After going through the lens again, the beam is focused reaching the receiving fiber core. The tilt of the membrane is necessary since transmitting and receiving fiber are spatially separated.

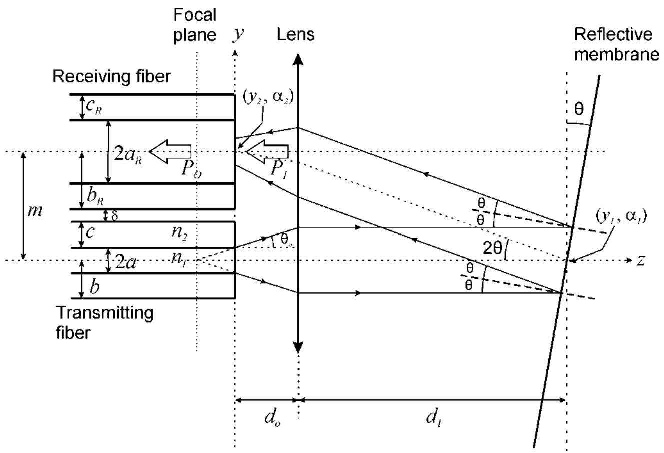


Fig. 2. Detailed scheme of FOM head with a single lens and tilted membrane.

To determine how amplitude modulation occurs in this FOM configuration it is necessary to determine the power transfer coefficient between the two optical fibers as a function of the relevant parameters as follows.

The intensity distribution profile of the optical beam from transmitting fiber can be regarded as gaussian and can be written in cylindrical coordinate as

$$I(r) = I_I e^{\frac{-\Lambda r^2}{w^2}} \tag{1}$$

where r is the radial coordinate, I_I is the optical intensity at the center of the cross section plane, Λ is a constant related to the modal power distribution in the fiber, and w is the beam radius. An important difference from FORS is that, due to lens effect, w is not variable, i.e., the spot size does not change with d_I variation. To find the relation between the optical power P_I and the optical intensity I_I on the entrance plane of receiving fiber, one can use the following integral

$$P_I = \iint I(r) dS = \int_0^{2\pi} d\phi \int_0^{\infty} I(r) r dr = \frac{\pi w^2}{\Lambda} I_I \tag{2}$$

where dS is related to the spot area S. Then the optical intensity in terms of P_I can be written as

$$I(r) = \frac{\Lambda}{\pi w^2} P_I e^{\frac{-\Lambda r^2}{w^2}}. \tag{3}$$

The optical power coupled to the receiving fiber can be calculated integrating (3) over incident light area on core:

$$P_O = \iint I(r) dS_R = \frac{2\Lambda P_I}{\pi w^2} \int_{r_1}^{r_2} \phi r e^{\frac{-\Lambda r^2}{w^2}} dr \tag{4}$$

where dS_R is related with the intersection area, S_R, between spot and fiber core, $\phi = \phi(r) = \cos^{-1}[(m^2+r^2-a_R)/2mr]$, $m = a+a_R+c+c_R+\delta$ is the distance between the core center of the fibers. The parameter δ is the gap separation between the two fibers. Finally, disregarding transmission losses in interface air-receiving fiber, the power transfer coefficient is as follows:

$$\eta = \frac{P_O}{P_I} = \frac{2\Lambda}{\pi w^2} \int_{r_1}^{r_2} \phi r e^{-\frac{\Lambda r^2}{w^2}} dr. \tag{5}$$

With (5) it is possible to calculate η for each spot position relative to the center of receiving fiber. Such position determines the integration limits. The two parameters which can cause variations in spot positions are d_I and θ.

Analyzing only the central ray of the reflected beam, knowing its position and angle (y_1, α_1) at the membrane and using ABCD matrix, it is possible to determine the position and angle (y_2, α_2) at the receiving fiber. Since θ is quite small, a paraxial approximation and the following ABCD matrix are used:

$$\begin{bmatrix} y_2 \\ \alpha_2 \end{bmatrix} = \begin{bmatrix} 1 & d_o \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/f & 1 \end{bmatrix} \begin{bmatrix} 1 & d_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} y_1 \\ \alpha_1 \end{bmatrix}. \tag{6}$$

Firstly, it is evaluated how longitudinal variations in distance between membrane and lens, d_1, can cause variations on spot position, y_2, with a fixed angle θ. The distance d_o is constant, to keep the optical beam collimated. Then, with (6) it can be determined the spot position, y_2, varying the distance d_1, and finally obtain η as function of d_1. The curve showed in Fig. 3 was plotted through computational simulation with the following parameters: $\theta \cong 11.3$ mrad, $f = 5$ mm, $NA \cong 0.12$, $\theta_o \cong 12.12$ mrad, $d_o \cong 4.97$ mm, $w = 4$ µm, $a = 4$ µm, $c = 56$ µm, $a_R = 30$ µm, $c_R = 30$ µm, $\delta = 0$, $m = 120$ µm, $\Lambda = 2$, $y_1 = 0$, $\alpha_1 = 2\theta$, and d_1 ranges from 50 mm to 350 mm.

In Fig. 3 one can realize that a large displacement in z axis is necessary to have optical amplitude modulation. The plateau, in region (A) of Fig. 3 covers 183.4 mm of distance variation. Note that a variation from 10% to 90% needs a displacement of 29.9 mm, in linear region (B). In other words, regarding that membrane movement is a longitudinal displacement, the microphone would have a very low sensitivity.

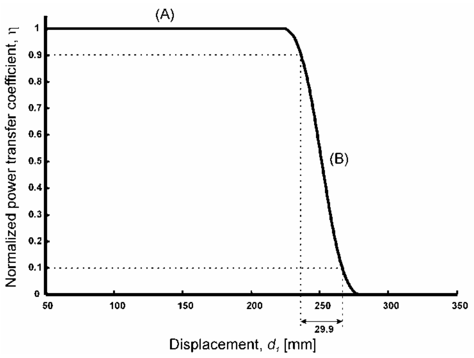


Fig. 3. Power transfer coefficient versus d_1 variation.

Secondly, to evaluate the y_2 displacement as a function of θ variation, for a given constant d_1, it was used (6) and the set of the following parameters: d_1 = 50 mm, f = 5 mm, $NA \cong 0.12$, $\theta_o \cong 12.12$ mrad, $d_o \cong 4.97$ mm, w = 4 µm, $a = 4$ µm, c = 56 µm, a_R = 30 µm, c_R = 30 µm, $\delta = 0$, m = 120 µm, Λ = 2, $y_1 = 0$, $\alpha_1 = 2\theta$, and θ ranges from 6 mrad to 17 mrad. Fig. 4 displays the result for η as function of θ.

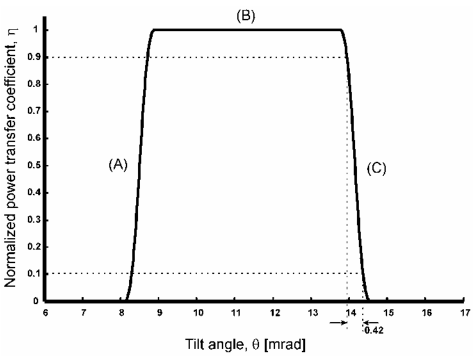


Fig. 4. Power transfer coefficient versus θ variation.

The curve showed in Fig. 4 indicates that small variations in membrane angle, θ, can cause large variations in η. In this case, a variation from 10% to 90% needs a tilt variation of 0.42 mrad. The characteristic curve of Fig. 4 can be used to choose a suitable static polarization point in which membrane tilt angle is converted in optical power variation. This curve presents two linear regions, (A) and (C), and polarization point can be chosen as the angle corresponding to half of η, i.e., in the middle of region (A) or (C).

As can be concluded, the operation principle of this microphone is quite different from FORS one. In FORS, the light intensity given by (1) varies with distance between membrane and receiving fiber, due to w dependency with d, as can be seen on Fig. 1. In the FOM proposed, the effect of lens turns w independent of d_1, as shown in Fig. 2.

The simulations displayed in Fig. 3 and Fig. 4 indicate that θ is predominant, instead of displacement d_1 over the modulation of light. This is a consequence of the collimating and focusing lens effect. Furthermore, this explains the misunderstanding of the two lens microphone [15], which uses the back and forward displacement of membrane to explain the light intensity modulation.

III. Experimental setup

The FOM proposed in this work was built using basically a light source, two step-index optical fibers, a lens, a membrane, and a photodetector. The transmitting fiber has the following characteristics: monomode, 1330 nm operating wavelength, 4/60 core/cladding radii, and refraction indexes n_1 = 1.465 (core) and n_2 = 1.460 (cladding). The receiving fiber has the following relevant characteristics: multimode, 30/60 core/cladding radii. The light source in this case was an He-Ne laser with 633 nm wavelength and 10 mW power. The reflective membrane used was a dielectric mica film. As the purpose of this work is not a membrane analysis, its parameters (material, radius, thickness, and mechanical tension) were not subject of concern. The lens had a 5 mm focal distance and a PIN photodiode OPF480 was employed as photodetector.

Multimode fiber was chosen as receiving fiber due to the larger core capable of collecting more light than a monomode. In contrast, a monomode fiber was used as transmitting fiber because the LP_{01} mode is homogenous and symmetrically circular. It is different from the granulated light pattern of the multimode fiber, avoiding noise from scintillation light. Since the transmitting fiber used was monomode at 1330 nm wavelength and the source wavelength is 633 nm, other modes beyond LP_{01} will propagate. In this case it was necessary to filter undesired modes through small loops (approximately 0.5 cm radius) in fiber body.

The transmitting and receiving optical fibers were cleaved and held together with clue (cyanoacrylate ester). This end was placed in a holder. The lens was positioned between the membrane and the fibers. The membrane was mounted in a ring holder capable to set its angle. The light coupling from source to transmitting fiber was achieved by a positioning stage with an objective lens. The end of the receiving fiber was coupled to the photodetector. The whole optical system was mounted along a trail over a granite table. Fig. 5 shows the entire microphone head.

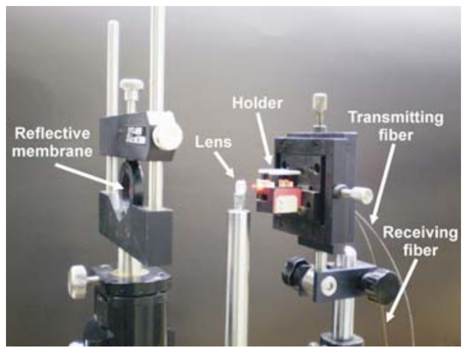


Fig. 5. Photography of the FOM head.

The signal from photodetector was amplified by a transimpedance amplifier followed by a band-pass filter with passband from 200 Hz to 20 kHz. Frequencies below 200 Hz were filtered due to spurious environment vibrations. The output signal from the filter was coupled to an oscilloscope and a spectrum analyzer., A loudspeaker driven by a signal generator was used to excite the reflective membrane. Fig. 6 displays the general scheme of FOM experimental setup.

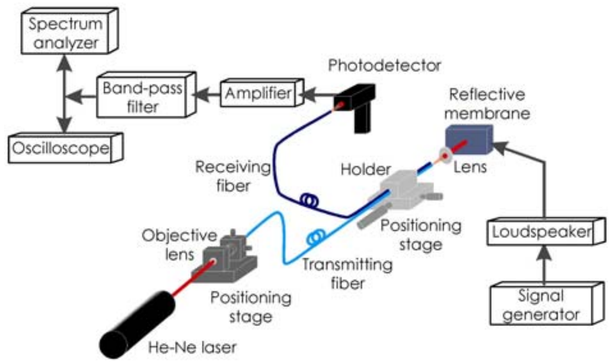


Fig. 6. Experimental setup of the FOM system under test.

To obtain high sensitivity and maximum dynamic range, according to theoretical analysis, the static calibration point was achieved setting the angle θ to drop η to half of its maximum value. At this point, the system is prepared to detect acoustic vibration.

Next section presents the measurements and discussion.

IV. Results and Discussion

In order to demonstrate the system operation, in time domain, a sinusoidal signal of 2 kHz was applied to the loudspeaker. Fig.7 shows the oscilloscope display. The input signal is located at the top while output signal is at the bottom. For input signal, vertical scale is 0.5 V/div and for output signal, vertical scale is 0.2 V/div. Time scale is 0.5 ms/div for both. The measured peak-to-peak voltage for input signal was 608 mV_{pp} and the output was 188 mV_{pp}. As can be seen in this figure, the system was capable of reproducing the 2 kHz sound wave coming from the loudspeaker without distortion.

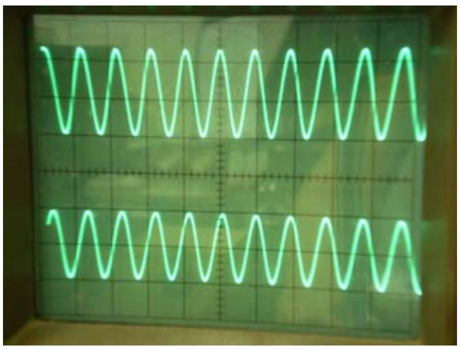
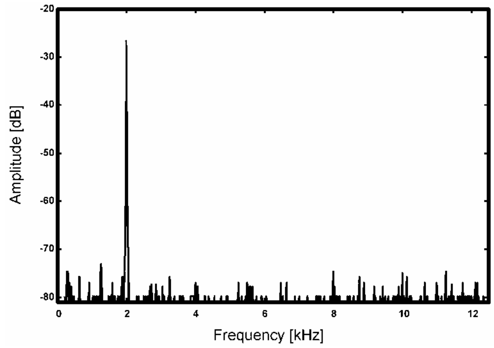
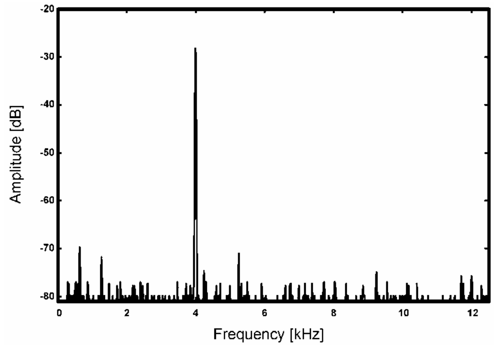


Fig. 7. Time domain output for input signal of 2 kHz. Input signal is on top and output signal is on bottom of photograph.

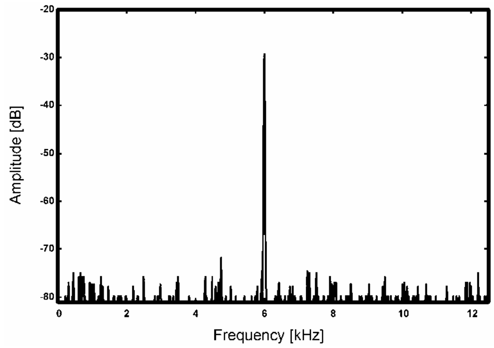
The output spectrum was analyzed for input sinusoidal signal at following frequencies: 2 kHz, 4 kHz and 6 kHz. The spectrum for each signal is shown in Fig.8. The dynamic range measured from these spectrums is better than 50 dB with a noise level around -80 dB up to 12.5 kHz.



(a)



(b)



(c)

Fig. 8. Frequency domain output for: (a) Input of 2 kHz. (b) Input of 4 kHz. (c) Input of 6 kHz.

Fig. 9 shows the frequency response from 300 Hz up to 12.5 kHz. In this figure one can see that frequency response is not flat over the entire range. This is due to the membrane parameters [13], [17]. However, signal to noise ratio is better than 30 dB from 300 Hz up to 6 kHz, which is suitable for voice communication and distributed sensors.

Taking in account the obtained results, in addition to the low cost and simplicity of the configuration, this system becomes competitive when compared to more costly and complex systems, that use DFB lasers, acousto-optical modulators and fiber optical directional coupler [1], fiber bundle [14], and interferometer mounting [17].

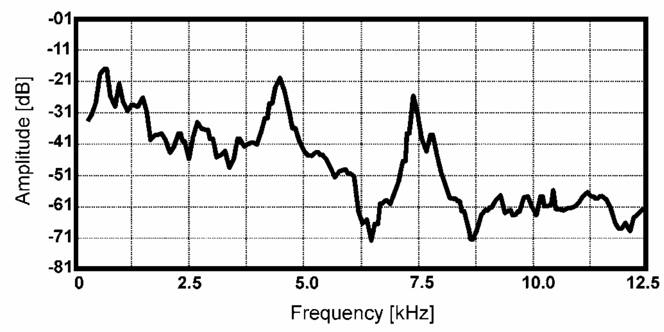


Fig. 9. Frequency response up to 12.5 kHz.

IV. CONCLUSIONS

This paper presents the theoretical analysis of a single lens FOM pointing out the differences relative to the well established microphone based on FORS. According to the presented theory it was shown that the main light intensity modulation parameter is the membrane tilt, as a consequence of the lens effect. This is quite different from FORS microphone in which the main parameter is the back and forward displacement of the membrane. The theoretical analysis also provides the characteristic curve of power transfer coefficient versus tilt angle. Such characteristic curve presents linear regions appropriated for light intensity modulation without distortion of the acoustic signal.

The experimental setup provided a dynamic range better than 50 dB for 2 kHz, 4 kHz, and 6 kHz frequencies, with a noise level around -80 dB. The frequency response up to 6 kHz is appropriated for voice communication and distributed sensors. The obtained results showed that this low cost and simple single lens configuration is competitive when compared to more costly and complex systems.

This single lens microphone can be used as an alternative for previous setups: in fiber bundle configuration, it can reduce the number of fibers; in the integrated microoptical mounting it can reduce the number of lenses and size.

It is important to mention that in the proposed configuration, the whole set of components is dielectric, including the membrane, which provides EMI passiveness.

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