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A novel approach based on simulation of tunable MEMS diaphragm for extrinsic Fabry–Perot sensors

Sekip Esat Hayber [a], Timucin Emre Tabaru [b], Omer Galip Saracoglu [b,c,*]

[a] Department of Electronic and Automation, Ahi Evran University, Kirsehir 40300, Turkey
[b] Clinical Engineering Research and Application Center, Erciyes University, Kayseri 38039, Turkey
[c] Department of Electrical and Electronic Engineering, Erciyes University, Kayseri 38039, Turkey

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ABSTRACT

A new tunable structure with a Three Leaf Clover (TLC) geometry has been proposed for use in diaphragm-based acoustic pressure sensors. The sensitivity and frequency response of this new structure, which will be an alternative to conventional circular diaphragms, was accomplished using Finite Element Method (FEM) and numerical analysis techniques. As a result of the analysis, sensitivity and frequency response approaches were obtained for the tunable-TLC structure. These approaches provide researchers to design diaphragms more convenient. Conventional circular diaphragms can be easily converted to TLC diaphragms by means of micro-electromechanical systems (MEMS) thus can be tuned up to 5 times for sensitivity and up to 1/3 times the fundamental frequency without altering the thickness and radius of the diaphragm. Obtained approach expressions were compared with FEM results for practical design purposes in a wide range of tunable parameters, and the average errors were below 2.5% for the sensitivity and below 0.5% for the fundamental frequency response, respectively.

1. Introduction

Diaphragm-based fiber optic sensors have been utilized in many application areas due to their high sensitivity, small size, immunity to electromagnetic interference, flexibility, easy adaptability to construction, low energy consumption and resistance to severe environmental conditions. Some of these are biomedical [1,2], gas detection [3–5], underwater applications [6–8], infrasound [3,9,10] and ultrasound applications [8,11,12], acoustics [13–16], pressure [17–19], acoustic pressure [20–22], and partial discharge [23–25].

Diaphragm-based sensors are most commonly consisted of with the principle of Extrinsic Fabry–Perot Interferometry (EFPI) [2]. Similarly, the most common use of the Fabry–Perot (FP) interferometry is in diaphragm-based applications where one of the two reflective surfaces is formed with a diaphragm [19–26]. Since the diaphragm is the most important part of the diaphragm-based EFPI fiber acoustic pressure sensors [27], the operating performance of the sensor is directly determined by the diaphragm design. The most important parameters affecting this performance are operating range, sensitivity, linearity and tunability. These are achieved by center deflection and frequency response analysis, which are the two most important characters of the diaphragm [12]. Sensitivity and frequency response of the sensor can be adjusted by changing the thickness and surface length of the diaphragm. For example, reducing the thickness of the diaphragm increases sensitivity, however, this situation may not suitable for each diaphragm material, because it is a difficult process to produce the diaphragm in sub-micrometer thickness for the most commonly used silicon or silica materials [18,21]. Although another way to increase sensitivity is to increase the surface length of the diaphragm, this results in large sensing tips which are not useful for sensor miniaturizations. In many studies, the effect of diameter on the frequency and sensitivity has not been utilized since the inner diameter (125 μm) of the standard ceramic ferrules determines the size of the diaphragm [11,18,21,25]. Considering these restrictions, one can conclude that tuning can be made much easier with geometries that have parameters other than thickness and surface length. With the aid of the developing Micro Electromechanical Systems (MEMS), it is easy to produce diaphragms in desired geometries [23,24,28,29].

In this study, the sensitivity and frequency response of the diaphragm geometry proposed as Three Leaf Clover (TLC) with an innovative approach to conventional circular diaphragm geometry is analyzed by Finite Element Method (FEM) and analytical methods. As a result of FEM and theoretical analysis, an approximate expression is developed

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[*] Corresponding author at: Department of Electrical and Electronic Engineering, Erciyes University, Kayseri 38039, Turkey.
E-mail addresses: sehayber@ahievran.edu.tr (S.E. Hayber), etabaru@erciyes.edu.tr (T.E. Tabaru), saracog@erciyes.edu.tr (O.G. Saracoglu).

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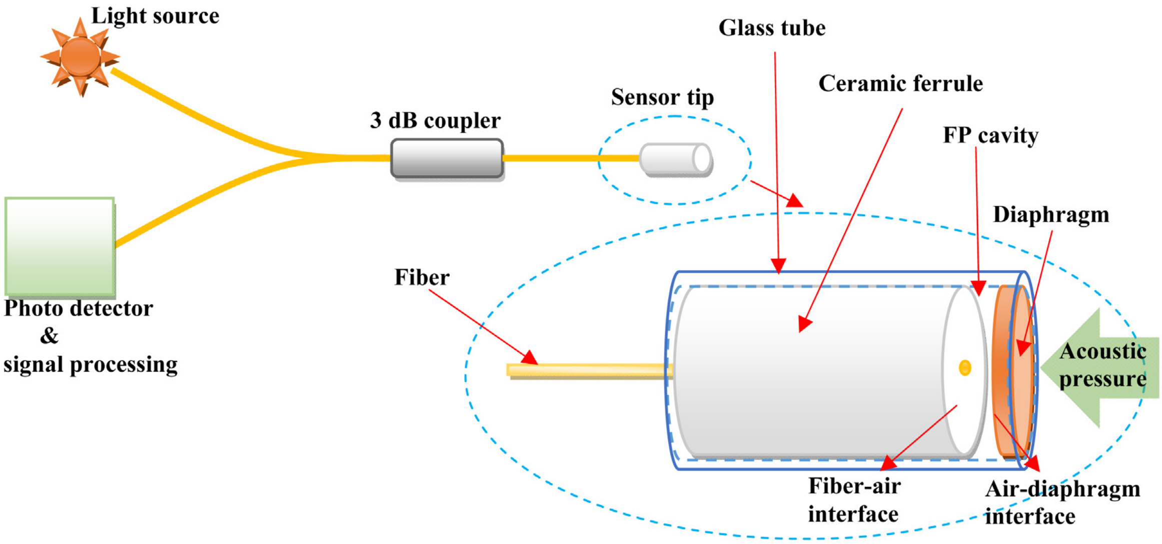

Fig. 1. The structure of diaphragm-based fiber optic EFPI sensor system.

for the TLC-shaped diaphragm. Thus, it is aimed to provide ease of design for sensor sensitivity and operating frequency. It has also become possible to produce tips with different frequency and sensitivity values without changing the diaphragm diameter and thickness. It has been shown that the sensitivity and the fundamental resonance frequency of the current sensor can be adjusted to 5 times and 1/3 times the desired value, respectively, without changing the diameter and thickness values, thanks to the proposed geometry.

2. Materials and methods

2.1. Conventional diaphragm geometry

Optical interference theory and diaphragm dynamic vibration analysis constitute the two basic principles of diaphragm-based EFPI sensors. The optic intensity at the sensor output is determined by the two basic mechanisms, which are optical interference theory and diaphragm dynamic vibration analysis. Fig. 1 shows that operating principle of this sensor system, which consists of a sensor tip, a semiconductor light emitter capable of operating in different wave lengths, an optical receiver and fibers providing the connection between the components. A 3 dB fiber coupler is used to receive the reflected signal and reduce the optical feedback which comes back to the source. The sensor tip consists of two interfaces, the first one is the fiber–air interface and the other one is the air–diaphragm interface. When the light beam emerging from the light source reaches the sensor tip, it encounters two the different interfaces. A part of the light is reflected from the first interface and the remaining part reaches the diaphragm surface through the air gap. A large part of the light beam is also reflected from the second interface and comes back to the first interface and enters the fiber. The light beam entering the fiber reaches the photodetector via passing through the circulator [25]. The detector converts the light beam to the electrical signal and transfers it to the signal processing unit. Thus, when the diaphragm is exposed to an acoustic pressure while continuous multiple reflections continue, a change in FP cavity occurs because of flexing of the diaphragm. The change in the FP cavity causes a variation in the phase of the light and this variation in phase affects the optic intensity at the output through the interferometer. Detection is achieved when the optic intensity at the output is related to the acoustic pressure acting on the diaphragm surface.

Diaphragm-based EFPI sensors are based on the dynamic vibration analysis of diaphragms in addition to the above-mentioned optical interference theory [19,23,25]. The mechanical properties and geometric dimensions of the diaphragm material determine the sensitivity and frequency response of the sensor system to acoustic pressure. The sensitivity and frequency response of the sensor must match the measurand. This is achieved if a diaphragm is designed which is sensitive to the intensity and frequency of the acoustic pressure. Under applied pressure, the center deflection of a circular and rigidly clamped round diaphragm is given by [29]:

$$d = \frac{3\left(1-\upsilon^2\right) P r^4}{16 E t^3} \tag{1}$$

where υ is Poisson's ratio, P is applied pressure, E is Young's modulus, r and t are radius and thickness of the diaphragm, respectively. The amount of the deflection at the center of the diaphragm depends on the mechanical properties (i.e., υ and E) of the diaphragm material and geometric dimensions (i.e., r and t). The sensitivity (S) to the amount of the deflection under unit pressure is defined by [10]:

$$S = \frac{d}{P} \tag{2}$$

The sensitivity increases with increasing amount of the radius and decreases with increasing thickness. The fundamental natural frequency of a circular and fixed diaphragm is [14]:

$$f = \frac{10.21t}{2\pi r^2}\sqrt{\frac{E}{12\rho(1-\upsilon^2)}} \tag{3}$$

where ρ is the mass density of the diaphragm. Sensitivity, as well as the frequency response, depends on the material properties and geometric dimensions. The effect of the radius and the thickness on the frequency is the opposite of the effect on sensitivity. That is, while the increasing amount of radius reduces the frequency, the increased amount of thickness increases the frequency.

2.2. New geometric approach for diaphragm design

The design of the sensors at the desired frequency and sensitivity values is of great importance for the detection of the measurand. For example, to obtain narrowband and high sensitivity acoustic sensors, the sensor should be operated the values where close to the resonance frequency. In some cases, diaphragm-based EFPI sensors require a wide range of flat frequency response, which must be at least three to five times greater than the highest frequency value of measured frequency [29]. Similarly, sensors that will detect infrasound [10] and ultrasound [8] signals should have different sensitivities. To achieve this, there are different diaphragm geometries in the literature [12,23,24,30,31], although, these geometries are not as common