Liquid-air based Fabry-Pérot cavity on fiber tip sensor

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Abstract: This paper presents a Fabry-Perot fiber tip sensor based on an air-liquid filled cavity. The cavity is sealed off by a thin gold coated membrane of parylene C, between 300 and 350 nm, creating a particularly flexible diaphragm. In order to retrieve and track the cavity of interest from other cavities formed within the sensor tip, a signal processing of the feedback signal is performed by inverse fast Fourier transform. The experimental sensor has been manufactured and tested for temperature, giving cavity length sensitivities of 6.1 nm/°C and 9.6 nm/°C for temperature increase and decrease respectively. The external gas pressure response gives a sensitivity of 15 nm/kPa. The fiber sensor has also been adapted for force sensing after silicone embedment and has shown a sensitivity of about 8.7 nm/mN. Finally, the sensor has been tested on insertion into a human temporal bone, proving that it could be an interesting candidate for insertion force monitoring for robotic cochlear implantation.

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OCIS codes: (060.2370) Fiber optics sensors; (120.0280) Remote sensing and sensors; (120.2230) Fabry-Perot; (120.5475) Pressure measurement; (120.6780) Temperature; (170.4940) Otolaryngology; (230.3720) Liquid-crystal devices.

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1. Introduction

In the context of a multidisciplinary project to improve cochlear implants (CIs), neuroprostheses to restore hearing in deaf patients, the addition of a pressure and temperature sensor at the tip of the electrode array was proposed to facilitate controlled insertion. Based on our experience with solid on liquid technology [1], we evaluated the use of a new miniature Fabry-Pérot interferometer (FPI) based on a fiber tip resonator. The original principle has been studied early in the 80’s [2]. Since then, substantial progress has been made and different fabrication techniques have been proposed to construct resonating cavities at the fiber tip [3], opening the door for sensing physical parameters in challenging conditions [4]. A first FPI with inclusion of liquid was constructed based on a hollow core fiber (HCF) [5] spliced to a standard fiber. The HCF was filled with liquid and remained exposed to external air, allowing the liquid to move inside the cavity when external pressure changes were applied. This solution is interesting but the drawback of potential liquid leakage limits its application in the context of medical sensing. In addition, complicated modifications would be necessary to adapt this type of sensor for measurements of force, further limiting its range of application. Another FPI sensor has been proposed using a resonating cavity that is partially filled with liquid and one air bubble acting as the compressible medium [6]. The air compressibility, together with the high thermal expansion of liquid compared to fused silica, allows the sensor to be highly sensitive to temperature changes as the overall cavity is hermetically and mechanically sealed off by an optical fiber plug. This also has the advantage of discriminating the well-known temperature/pressure simultaneous sensitivity of such kind of FPI sensors. Fused silica deformation due to external pressure changes in here will induce considerable smaller cavity length changes than temperature changes. Nevertheless, the sensor faces some liquid leakage above ~39 °C through the fiber plug sealing giving a nonlinear and irreversible response of the wavelength shift with temperature. Furthermore, the fiber tip sensor is merely limited to temperature measurement. A preceding study with a low-cost liquid-core fiber interrogator based on non-biocompatible materials has been reported with a HCF partially filled with diesel and sealed with epoxy [7]. An improved temperature monitoring has been realized with a slope of 9.51 pm/°C and a maximal temperature of 90 °C. However, such kind of sensors wouldn’t be useful for applications where longitudinal external forces or quick and small changes of external pressure would need to be monitored as in the context of cochlear implants. Real time forces in the range of a few hundred mN at the tip of the electrode array during insertion into the cochlea of the inner ear [8] need to be measured in real-time to avoid structural intracochlear damage [9].

In this paper we present a fiber tip FPI sensor that is based on an air/bubble filled cavity whose end is sealed off by a gold coated parylene membrane acting as the Fabry-Pérot diaphragm. The parylene membrane is deposited on liquid surface by using the SOLID technology described in [1]. Such a configuration allows the sensor to benefit from high sensitivities using air/liquids while being able to measure external pressure changes as well as forces applied to the membrane.

2. Sensor description

The proposed FPI sensor is based on a tip that has a longitudinal and central hole whose role is to trap air inside when a liquid drop is placed at its output. For that purpose, both HCF and
fiber capillaries (FC) can be used. With such configuration, when an environment parameter changes, the liquid will move or change in volume while the trapped air will play the role of compressible medium. In order to encapsulate the liquid and to form a fully deformable and reflective diaphragm, a parylene membrane is deposited and subsequently gold coated. With such structural configuration, a Fabry-Pérot cavity is formed between the junction of the lead fiber and the gold coated parylene membrane. Then, any environmental parameter change will induce a Fabry-Pérot cavity length that will be monitored by using its feedback spectrum. The cavity configuration proposed and the ways to produce it allow to design various arrangements depending on application and sensitivities foreseen. Consistency of sensors can also be ensured by the use of mature industrial techniques.

Fig. 1. Multistep manufacturing process.

The first step in the fabrication process is to place a capillary around the lead fiber as depicted on Fig. 1(a). The role of this capillary is to protect the splice between the lead fiber and the HCF or FC. The splice is realized by using a filament fusion splicer LFS-4000 – Fig. 1(b). Then, in order to keep the fiber tip geometrically short and also to have a small Free Spectral Range (FSR), the HCF or FC is cut at a length of around 300 – 600 µm from the splice – Fig. 1(c). According to the final application, the fiber tip length can also be chosen at any specific value. Depending on the used cutting process, the protective capillary can either or not cover the splice area during the cut. In our case, the cut is realized by a CT-03 fiber cleaver and the splice needs to be protected to avoid its breakage. It is then glued on its end to the lead fiber, leaving free the other end to avoid any external stress on the cavity – Fig. 1(c). The liquid is then placed at the tip by wetting a standard fiber with the desired liquid and subsequently by dipping this later with the fiber sensor tip – Fig. 1(d). By capillarity, the liquid enters into the core of the HCF or the FC’s central hole. In our case, we have used Baysilone® oil that has good biomedical compatibility and a low vapor pressure, which is mandatory for the parylene deposition [1]. The fiber sensor has then to be parylene C coated in order to create the thin membrane on the oil surface – Fig. 1(e). The final parylene C thickness has been chosen to be between 100 and 150 nm in order to maximize the membrane deformability. The final step in the overall process consists in gold coat the parylene
membrane for good reflectiveness at standard telecom wavelengths – Fig. 1(f). Gold coating thickness is thicker than the conformal parylene membrane with 200 nm to guarantee a sufficient physical vapour deposition (PVD) on the concave surface, in regard to a minimal influence on the membrane deformability for the specific application. An image of a FC based sensor is shown on Fig. 2 where we can clearly see the remaining air bubble in the lead fiber – FC interface.

3. Signal processing

The presence of an air bubble within the FPI cavity will result in a feedback spectrum that is composed of the interferograms of the different sub-cavities resonances. The transfer function of a dual Fabry-Perot (FP) cavity can be expressed as [10]

$$I(\lambda) = A_1 - A_2 \exp\left(-\frac{j4\pi L_{\text{air}}}{\lambda}\right) + A_3 \exp\left(-\frac{j4\pi}{\lambda}\left(L_{\text{air}} + n_{\text{liquid}} L_{\text{liquid}}\right)\right)$$

$$= A_1^2 + A_2^2 + A_3^2 - 2 A_1 A_2 \cos\left(\frac{4\pi L_{\text{air}}}{\lambda}\right) - 2 A_1 A_3 \cos\left(\frac{4\pi n_{\text{liquid}} L_{\text{liquid}}}{\lambda}\right) + 2 A_2 A_3 \cos\left(\frac{4\pi}{\lambda}\left(L_{\text{air}} + n_{\text{liquid}} L_{\text{liquid}}\right)\right)$$

where $A_1$, $A_2$, and $A_3$ are the amplitudes of the reflected light from the lead fiber to the HCF/FC interface, the air-liquid interface and the gold-coated parylene membrane, respectively, $L_{\text{air}}$ is the air-bubble cavity length, $L_{\text{liquid}}$ the liquid cavity length, $n_{\text{liquid}}$ the refractive index of liquid, and $\lambda$ is the wavelength. The parylene thickness has been neglected here due to its extremely small value compared to intrinsic cavities lengths.

Equation (1) being the transfer function of the FPI, it doesn’t take into account the spectrum profile of the source. In order to retrieve the final spectrum profile, Eq. (1) has to be multiplied by the spectral distribution function of the source $I_0(\lambda)$ which can be approximated by a Gaussian profile [11]:

$$I_s(\lambda) = I_0 f(\lambda) = \frac{I_0}{\sqrt{2\pi\Delta\lambda}} \exp\left[-\frac{(\lambda - \lambda_0)^2}{2\Delta\lambda^2}\right]$$
where $I_0$ is the total input optical intensity, $f(\lambda)$ the distribution function, $\Delta \lambda = \delta \lambda_{FWHM} / (8 \ln 2)^{1/2}$, where $\delta \lambda_{FWHM}$ is the 3 dB light source bandwidth. Thus, final spectrum, $I_{FPI}$, is given by:

$$I_{FPI}(\lambda) = I_0(\lambda)I(\lambda)$$  \hspace{1cm} (3)

Figure 3 shows a typical optical spectrum resulting from the multiple reflections within the FPI cavity by using an amplified spontaneous amplified (ASE) light source FLS-2300B from EXFO. As predicted by Eq. (3), the spectrum is irregular and unfortunately, the information of interest cannot be obtained in a straightforward manner. In order to filter out and track easily the main cavity changes, a Fourier domain signal processing is used. Similar techniques are commonly used in the field of optical coherence tomography (OCT) [12]. Fourier-domain OCT is based on the well-known Wiener-Khintchine theorem: the measured power spectrum is related to the autocorrelation function of the optical field by a Fourier transform. This relation is also the basis of Fourier Transform Spectrometry: In that case, an interferogram is recorded while scanning one arm of an interferometer, yielding an interference signal $I(\tau)$ as a function of the time delay $\tau$ between both interfering light beams. The spectrum is then obtained by applying a Fourier transform of the temporal signal $I(\tau)$. In Fourier-domain OCT, we do exactly the contrary: the spectrum is measured, and the interference signal (which is given by the autocorrelation function of the optical field) is obtained by inverse Fourier transform. Figure 4 shows the calculated interferogram for optical time delays between 5 to 10 ps, corresponding to optical path differences ranging from 1.5 mm to 3 mm. Several autocorrelation peaks are observed, because of the multiple reflections inside the cavity. In a first step (initialization phase of the sensor), the highest autocorrelation peak is detected. From Fig. 4, we see that the maximum peak is located around 6 ps, corresponding to an optical path difference (OPD) of 1.8 mm. Assuming that the highest peak is caused by the interference between the beam reflected by the end of the lead fiber and the beam reflected by the deformable membrane, the OPD should be given by $2(L_{air} + n_{liquid}L_{liquid})$. Figure 5 shows a zoomed portion of the interferogram, in the vicinity of the maximal value of this autocorrelation peak. When the cavity length changes, the fringe pattern will move on the right side if the cavity length increases, and on the left side if it decreases. We can estimate the peak position variations by considering only five 90° phase-shifted samples next to the initial maximal peak (dots labeled $I_1 – I_5$ in Fig. 5). Indeed, the cavity length variations can be determined by calculating and monitoring the phase of the interference signal using the so-called 5-frame error compensation algorithm [13]

$$\phi = \tan^{-1}\left(\frac{2(I_3 - I_4)}{I_1 + I_5 - 2I_3}\right)$$  \hspace{1cm} (4)

Note that an unwrapping of the phase estimated by Eq. (4) must be done to enable phase variations larger than $\pi$.  

Fig. 3. Optical spectrum at the output of the FPI cavity.
4. Experimental results

In order to characterize the sensor in temperature, pressure, force and for introduction force during implant electrode array insertion into a temporal bone, three sensors were manufactured. Different configurations of the sensor have also been tested and will be reported hereafter.

The first built-in sensor has been used for the pressure measurements and included a standard G.652 single-mode fiber as the lead fiber. The cavity in that sensor was realized by a FC with a central hole of 15 µm in diameter, an external diameter of 120 µm and a length of 596 µm. The liquid used was a silicone oil (Dow Corning DC 200/12’500). A parylene membrane with a thickness of around 120 nm has been deposited to form the deformable membrane. The second sensor was built for temperature and force measurements and featured a CL Micro 1550 21 fiber from OFS and an optical cavity based on a HCF with a central hole diameter of 10.4 µm, an external diameter of 93 µm and a length of 370 µm. The liquid used was a Baysilone 1000m type oil. A parylene membrane with a thickness of around 120 nm has been deposited as for the first sensor. This sensor has been subsequently embedded with silicone in order to use it for the longitudinal forces measurements. That embedment was necessary because the extremely low thickness of the membrane makes it an excellent candidate for small forces measurements, i.e. \( \leq \mu \text{N} \), but increases fragility beyond a point where we could use it in our measurement setup. The additional thickness induced by the silicone embedment was of around 100 µm. A third sensor was built for the cochlear implant.
insertion force measurements and was made of a standard G.652 single-mode fiber as the lead fiber. The cavity in that sensor was realized by a FC with a central hole of 15 µm in diameter, an external diameter of 120 µm, as for the first sensor, and a length of 446 µm. The liquid used and the silicone embedment were the same as for the second sensor.

4.1 Pressure measurements

The pressure measurements were performed with the first sensor using the experimental setup illustrated in Fig. 6. An amplified spontaneous emission source (ASE) was used as a white light source to illuminate the fiber tip through the optical circulator. The fiber tip was located inside a gas chamber whose internal pressure was decreased by the use of a pump. A pressure vacuum gauge reference DCP 3000 (VSK3000) was also inserted inside the gas chamber. The optical feedback signal from the fiber tip sensor was then redirected to an optical spectrum analyzer (OSA) Ando AQ6317B. A dedicated program has been written in order to signal process the spectra acquired by the OSA and retrieve the phase changes in the sensor.

The pressure investigation is illustrated in Fig. 7. Measurements start at a partial vacuum state of around 450 mbar. Around time 50s, the pump was stopped and then the chamber leakage allowed the internal pressure to rise up until atmospheric pressure. The little step observed around time 350s is originated from the chamber’s window to chamber’s joint unstuck due to the lower pressure difference between chamber’s inside and outside environment. Around time 410s, the pump was switched on again and then produced a little reduction in pressure inside the chamber as it can be observed in the Fig. 7 inset. This pressure reduction didn’t allowed the chamber joint to stick completely on the chamber’s window and then a strong air flow inside the chamber was generated. This air flow perturbed the FPI sensor as it can be seen on blue curve from Fig. 7 from time 410s to 470s. Once the joint has stuck to the chamber’s window, the FPI sensor has retrieved its postponed phase of sensitivity corresponding to the pressure change inside the chamber. From time 480s to 580s, the pump was kept working on a kind of established partial vacuum steady state. From time 580s the pump was stopped and leakage was increasing slowly as the pressure inside. Then, the chamber was suddenly fully opened and the FPI sensor perfectly detected this quick pressure change. Additionally, we noticed oscillations of the FPI sensor for quick and strong pressure changes, probably induced by capillary oscillations [14]. The measured phase change is of about 5.74 rad, corresponding to the applied pressure difference. This gives a sensitivity of about 0.12 rad/kPa corresponding to a cavity length sensitivity of about 15 nm/kPa.

Fig. 6. Experimental setup for pressure measurements. ASE (Amplified Spontaneous Emission); OSA (Optical Spectrum Analyzer).
4.2 Temperature measurements

The temperature measurements were performed using the second sensor in the experimental setup shown in Fig. 6 adapted for temperature measurement. For this, the FPI sensor was placed into a climatic chamber DE-54 E from Frigorex and, an F250 Mk II precision thermometer from ASL was used as a reference. Measurements were performed for temperature increase and decrease, respectively, in order to estimate the sensitivity range of the sensor as well as the eventual presence of an hysteresis.

Measurement of temperature increase has been realized from 26°C to about 50°C and the results are illustrated in Fig. 8. The sensor’s response adequately matched the temperature increase of the reference. We can appreciate the faster reaction of the fibre sensor compared to the reference, which has a greater inertia. The second part of the measurement, starting at time 24 min, shows the sensor reaction to the heating interruption. From time 24 min to 28 min we can observe a decrease of the measured phase in two slopes. These latter can be explained by the fact that at the beginning, from time 24 min to 25 min, the temperature decrease that is sensed by the fibre sensor is larger and is due to the sudden air flow interruption within the chamber. Then, a second phase decrease slope appears that corresponds to the natural temperature decrease inside the climate chamber inducing a slower temperature change. The reference thermometer inertia eludes this different temperature drops. At time 28 min, we can observe a large drop in the phase measured due to the door’s opening of the chamber, providing a quick cooler air flow within the chamber. The phase fluctuations measured from this time to the end are due to natural air flow generated by the temperature gradients within the chamber as the inner walls and parts were cooling as long as fresh air flow was entering the chamber. The measured temperature sensitivity measured is of 0.049 rad/°C corresponding to a cavity length sensitivity of about 6.1 nm/°C.
Measurement of temperature decrease has been realized from 58°C to about 26°C by stopping the climate chamber heating and then by opening the door’s chamber at 28°C. Results are illustrated in Fig. 9. Measurements show a good agreement of the sensor’s response with the reference measurement. The observed phase shift on the sensor measurement is of about 2.35 rad. We can see from the opening door (around time 8.6 h) that the fibre response is quicker than the reference. The measured temperature sensitivity if of $-0.077$ rad/°C corresponding to a cavity length sensitivity of about 9.6 nm/°C.

These experiments show that the second sensor sensitivity presents some hysteresis. It is believed that this hysteresis is coming from the sensor’s silicone embedment.

### 4.3 Force measurements

Force measurements have been performed using the second sensor. In order to apply a force of the fiber tip and record it, a high precision balance Kern ABS/ABJ was used. The fibre
sensor was held in place and then pushed against the balance. The weight measured on the balance was then transformed into force by just multiplying it by the gravity acceleration.

The force increase response of the sensor showed a good linear response as depicted in Figs. 10 and 11. As shown in Fig. 10, the sensor starts to become noisy as soon as the applied force starts to be important and provides some mechanical instabilities in the membrane deformation. These instabilities are probably not inherent to the sensor itself but are rather coming from the mechanical configuration used to perform measurements. Nevertheless, averaged values give a good linearity of the sensor phase versus the applied force, as one can see on Fig. 11. Even for noisy measurements, the linearity answer is preserved and we can extract a phase dependence of around $-0.07 \text{ rad/mN}$, which corresponds to a cavity length sensitivity of about 8.7 nm/mN.

![Fig. 10. Force increase response of a HCF based sensor.](image1)

![Fig. 11. Optical phase vs applied force for the force increase response of a HCF based sensor.](image2)

The force decrease response of the sensor is not shown in this paper because of a significant hysteresis brought by the sensor’s silicone embedment. We believe that a sensor without embedment should have a behaviour that is closely similar to the one observed with
pressure measurements, where no hysteresis was observed. However, without silicone embedment, the applied forces on the sensor would have been extremely low.

4.4 Cochlear implant insertion

A human temporal bone specimen was obtained from a body donor to the University Department of Anatomy under full ethical approval and prepared for the measurements of insertion forces during experimental cochlear implantation at the ARTORG center of the University Department of Otorhinolaryngology in Bern, Switzerland. The third sensor has been used for these experiments, with the main goal of monitoring the insertion forces applied during the advancement of the cochlear implant electrode array into the cochlea of the inner ear. The surgical access to the inner ear was done using the classical retroauricular approach including mastoidectomy, antrotomy, and posterior tympanotomy. The round window niche was identified, drilled and the round window membrane incised in the anterior third without suctioning out the inner ear fluid. The fibre was then inserted through the incision and slowly advanced into the basal turn of the cochlea under manual control by the surgeon.

Figure 12 shows the sensor inserted through the round window into the basal turn of the cochlea. Measurements are depicted on Fig. 13, where it can be observed that the sensor has detected a first touch when applied against the cochlea entrance (time 12s) at the level of the round window membrane. Then, a second force has been sensed at time 38s when touching the lateral cochlear wall at around 8-10 mm distance from the round window, corresponding to a prominent turn at the base of the cochlea. Measurements show that the further we go into the cochlea the more perturbed the sensor is as it works its way along the lateral cochlear wall. Finally, the sensor has broken at a distance of about 3 mm from the fibre tip. The break was due to the length of the sensor’s protective capillary that was too short and, due to the bending, acted as a lever on the fiber. In the experiments performed, the fracture of the fibre did not cause any obvious damage of the silicone coating and therefore we assume also not a structural damage of the cochlea itself. Longer protective capillary must be used in order to limit this fracture probability as well as use of reduced cladding optical fibers that will bring in more mechanical robustness to extremely tight bends. In order to not deteriorate the sensor, it has not been previously calibrated. But due to the silicone embedment, we assume that the observed phase changes correspond to a similar sensitivity as observed for the force measurements with second sensor. This means that the recorded forces should correspond to several tens of mN which is in good agreement with previous experiments [15,16].

![Fig. 12. Optical sensor introduction through the cochlear’s round window. View through the opened mastoid cavity and through a posterior tympanotomy (standard surgical view for cochlear implantation).](image_url)
5. Conclusion

Three different liquid-air based Fabry-Perot fiber tip sensors have been developed and tested for the sensing of temperature, force and insertion forces during experimental cochlear implantation. Sensitivities of 6.1 nm/°C and 9.6 nm/°C have been measured for the temperature increase and decrease, respectively, which are higher than most of the reported FPIs [3]. The sensor showed an excellent sensitivity of 15 nm/kPa for pressure measurements indicating that the sensor could even be used for acoustic applications. However, we observed that silicone embedding, which was needed for our setup, limited the sensitivity through hysteresis. Finally, for measuring insertion forces, a sensitivity of 8.7 nm/µN was measured indicating that the sensor is an excellent candidate for monitoring insertion forces during cochlear implantation. Future work with this promising sensor will explore its potential for acoustic measurements and optimize embedding/packaging methods to reduce hysteresis.

Acknowledgment

This work was supported by the EU commission under the project NANOCI (contract FP7-NMP.2011–281056). The authors thank Alexandra Homsy and Edith Laux for the continuous support and the fruitful discussions about SOLID technology. We acknowledge as well MED-EL for the silicone embedment provided to our sensors. We are particularly grateful to M. Roccio, S. Hahnewald, W. Wimmer, and M. Caversaccio from the ARTORG Center for biomedical engineering at the University departments of ORL and DCR for their valuable assistance in the experimental cochlear implantation experiment.