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ABSTRACT

Photoacoustic imaging is a novel imaging method for medical and biological applications, combining the advantages of Diffuse Optical Imaging (high contrast) and Ultrasonic Imaging (high spatial resolution). A short laser pulse hits the sample. The absorbed energy causes a thermoelastic expansion and thereby launches a broadband ultrasonic wave (photoacoustic signal). The distribution of absorbed energy density is reconstructed from measurements of the photoacoustic signals around the sample. For collecting photoacoustic signals either point like or extended, integrating detectors can be used. The latter integrate the pressure at least in one dimension, e.g. along a line. Thereby, the three dimensional imaging problem is reduced to a two dimensional problem. For a tomography device consisting of a scanning line detector and a rotating sample, fiber-based detectors made of polymer have been recently introduced. Fiber-based detectors are easy to use and possess a constant, high spatial resolution over their entire active length. Polymer fibers provide a better impedance matching and a better handling compared with glass fibers which were our first approach. First measurement results using polymer fiber detectors and some approaches for improving the performance are presented.

Keywords: Photoacoustic Imaging, Integrating Detector, Fiber-Based Detector, Polymer Fiber

1. INTRODUCTION

Photoacoustic Imaging (PAI) is an upcoming imaging modality for biological and medical applications. A semitransparent sample is illuminated by a short laser pulse. Depending on the specific absorption rate (SAR) the electromagnetic radiation is absorbed in the sample followed by thermoelastic expansion - the so called photoacoustic effect. This way a photoacoustic signal (e.g. a broadband ultrasonic wave) is launched. Due to the optical generation of ultrasonic waves photoacoustic tomography combines the advantages of optical imaging (high contrast) and ultrasonic imaging (high spatial resolution). After propagating to the sample surface and through a coupling medium (e.g. water) a set of photoacoustic signals at different positions is measured for image reconstruction.

Several groups use conventional or modified piezoelectric transducers (or arrays of piezo elements) for detecting photoacoustic signals.[1,2] In 2004, our group introduced integrating detectors as a novel approach.[3] One possible geometry for such an integrating detector is a line which is easy to realize. Several approaches for such a line detector have been implemented and presented in the past. For example, Paltauf et al.[4] used a free-beam Mach-Zehnder interferometer and investigated the directivity of piezo line detectors.[5] Grün et al. presented fiber-based line detectors using either a Fabry-Perot interferometer (FPI) based on a glass fiber[6] or a polymer fiber in a Mach-Zehnder configuration.[7] A comparison of the sensitivity of all these different types of line detectors was given by Nuster et al.[8]

Although all approaches of fiber-based detectors were successful we are aiming toward a better sensitivity of fiber-based line detectors for photoacoustic imaging. A polymer fiber is more sensitive than a glass fiber.[8] On the other hand a Fabry-Perot interferometer is more sensitive than a Mach-Zehnder interferometer (as we used for measurements with polymer fibers[7]). Therefore the best solution would be a Fabry-Perot interferometer build in a polymer fiber. Such a fiber-based line detector would be optimized for sensitivity, which would be important for medical applications. For the glass fiber-based Fabry-Perot interferometer we used two fiber Bragg gratings (FBGs) which acted like mirrors. Up to now it is not possible to obtain stable fiber Bragg gratings in

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perfluorinated polymer fibers. For this reason we metalized the end faces of a fiber with silver and this way were able to create a Fabry-Perot interferometer in a perfluorinated polymer fiber.

In Sec.2 the principle set up of such a polymer fiber-based Fabry-Perot interferometer is described. First measurements and results using such a polymer-fiber Fabry-Perot interferometer are presented in Sec.3. Finally some further improvements are considered and conclusions are given.

2. POLYMER OPTICAL FIBER FABRY-PEROT INTERFEROMETER

As reported by Nuster et al.[8] polymer fiber sensors are more sensitive than glass fibers. This is due to the better impedance matching of polymer fibers to the surrounding water and to the much lower Young's modulus. Therefore the next generation of fiber-based line detectors should be made of polymer fibers. Conventional polymer optical fibers (POFs) are PMMA-fibers. Such POFs are available as single mode fibers with a core diameter of $9\mu m$ - the same core diameter as provided by single mode glass optical fibers (GOFs). The disadvantage of such PMMA POFs is the high damping at our detection wavelength of 1550nm. To overcome this disadvantage there are two approaches. One could change the detection wavelength to the visible regime where the damping of PMMA fibers is much lower than in the NIR. However, this requires an expensive, tunable single-frequency fiber laser. The other possibility is the use of so called perfluorinated POFs where the hydrogen atom in the polymer is exchanged by a fluorine atom, which shifts the absorption band of the polymer. The damping of such a perfluorinated POF in the NIR is much less compared to a conventional PMMA POF.

During earlier experiments we used such perfluorinated graded index polymer optical fibers (GIPOF) from ChromisFiber with a core diameter of 50μm. Grün et al.[7] reported about first experiences in imaging with these perfluorinated GIPOFs in a Mach-Zehnder configuration. Unfortunately there are no perfluorinated polymer fibers with smaller core diameters available. The core diameter is a limiting factor for spatial resolution. The smaller the diameter the better the spatial resolution. Furthermore single mode fibers would be much better for interferometers than fibers with a bigger core diameter. Nevertheless, such graded index fibers were used for the experiment with the fiber-based Fabry-Perot interferometer reported in Sec.3.

In the glass fiber-based Fabry-Perot interferometer we used two FBGs as mirrors to build the Fabry-Perot cavity in the fiber. Since such stable fiber Bragg gratings for perfluorinated GIPOFs are not available yet another solution was realized. Both ends of the polymer fiber were metalized with a thin layer of silver. This way mirrors for a fiber-based Fabry-Perot interferometer in a polymer fiber were created. The thickness of the silver layer affects the performance of the interferometer. If the layer would be too thick all the light would be reflected and would not enter the Fabry-Perot cavity. If the layer is too thin the reflectivity would be too weak resulting in an interferometer with properties more like a Mach-Zehnder interferometer than a Fabry-Perot interferometer. After a first estimation it was decided to use layers of Ag in the range from 20nm up to 35nm. Experimentally it was discovered that the fiber with the 30nm layers provides the best performance and was therefore used for all GIPOF measurements presented in Sec.3.

For the set up a Fabry-Perot fiber with a cavity length of 0.9m was used. However, the long distance between the mirrors is adverse for the sensitivity in the interferometer. Although perfluorinated polymer fibers - compared to conventional PMMA fibers - provide much less damping at a wavelength of 1550nm (about 1dB/m) this value is quite high. Estimating a finesse of approx. 12 for the 0.9m long GIPOF Fabry-Perot interferometer this would result in a damping of 11dB. For future experiments shorter GIPOFs will be used to reduce the damping and improve the performance of the sensor. Another weak point of this detector set up is the connection between the regular single mode glass optical fibers (SM-GOF) with a core diameter of 9μm and the GIPOF with a core diameter of 50μm. To optimize the light distribution and propagation in the fiber a special configuration as shown in Fig.1 was used. A GIPOF with a FC/APC connector on one end and a FC/PC connector on the other end toward the metalized Fabry-Perot GIPOF was included. Despite all these improvements only a weak signal was measured and the use of an additional amplifier (compared to the setup with glass fiber-based Fabry-Perot interferometer) was necessary. However, as can be seen in the next section first measurements were successful and showed promise for this new type of fiber-based line detector to become a sensitive and adequate sensor for photoacoustic imaging.

3. MEASUREMENTS AND RESULTS

For a comparison of the graded index polymer optical fiber Fabry-Perot interferometer (GIPOF FPI) and the earlier used glass optical fiber Fabry-Perot interferometer (GOF FPI) the fringe patterns of the two types of fiber-based interferometers were measured. As a first result one can see (Fig.3) that the amplitude of the fringes from the polymer Fabry-Perot is about seven times smaller than the fringes of the optimized GOF FPI. Hence, the power of the detection laser for the glass fiber-based FPI was decreased to get comparable values. These first experiments demonstrated some of the problems of an interferometer built in a graded index fiber. Unlike in the single mode glass fiber-based FPI more than one mode was excited in the graded index fiber. This was found to depend on the coupling between the single mode glass fiber and the GIPOF. Moving one of the two fibers resulted in more or less coupling of light and affected the number of modes. The excitation of more modes resulted in broadened or multiple fringes. Bending the fiber or adjusting the position of the fiber next to the connector improved the fringe pattern and the amplitude. In doing so the amplitude of the fringes rose from several mV up to 500mV - which was the maximum after optimization. One could also see a change of distance between the fringes during manipulating the fiber. These observations suggest that the present configuration is not practicable for a moving detector in photoacoustic imaging. Some efforts will have to be spent for future setups using a GIPOF FPI sensor. To investigate the influence of the graded index fiber and the coupling of multiple modes into the interferometer another experiment with a single mode glass fiber was done. Both ends of the glass fiber were metalized as above, using a layer of 30nm. For comparison with the other fiber-based detectors the output amplitude was maintained at 500mV. The behavior of the metalized single mode glass FPI was the same as of the glass fiber-based FPI with the FBGs. This experiment allowed us to conclude that it is indeed the fiber diameter, not the use of metal mirrors that degrades the fringe pattern in the GIPOF FPI sensor. The implementation of such a polymer fiber-based detector using a single mode fiber would be much more practicable.

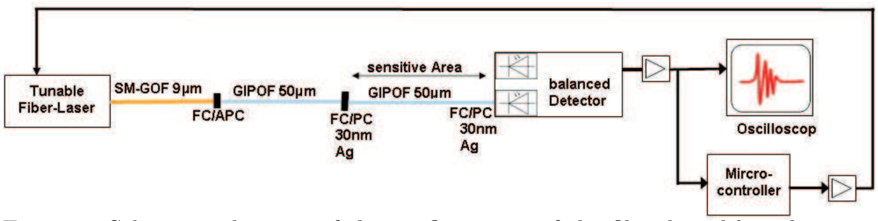

Figure 1. Schematic drawing of the configuration of the fiber-based line detector. All the used fiber types and connectors are depicted.

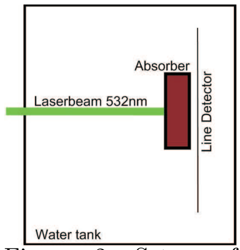

Figure 2. Setup of the photoacoustic measurements. The beetroot juice sample was located about 10mm in front of the different line detectors and illuminated with a 7ns laser pulse with a pulse energy of approx. 12,5mJ.

After this comparison of the fringe patterns first photoacoustic measurements were carried out. A sample of beetroot juice was used as absorber. Beetroot is a good absorber for the used excitation wavelength of 532nm. The sample was illuminated by a laser beam with a diameter of 6mm, a pulse duration of 7ns and a pulse energy of about 12.5mJ. The line detector was located at a distance of about 10mm. In Fig.1 a scheme of the used fibers and connectors can be seen whereas in Fig.2 the configuration for the acoustic measurements is depicted. Three different measurements were made, always detecting the same photoacoustic signal generated by the absorbing sample. This way one could compare the sensitivity of the glass fiber-based FPI and the polymer fiber-based FPI sensors.

All the measured signals were averaged 16 times for comparison. As can be seen in Fig.4 the signal detected with the GIPOF FPI at 500mV fringe amplitude is two times higher than the signal measured with the glass

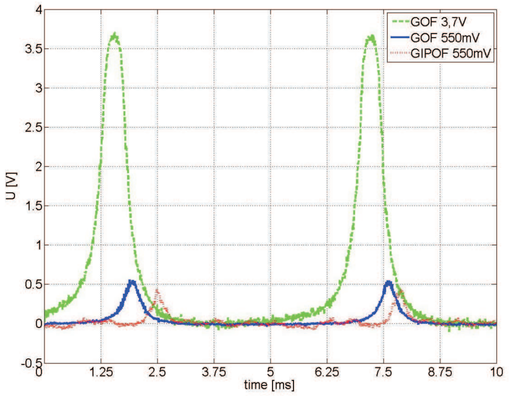

Figure 3. Fringe pattern of the used fiber-based Fabry-Perot interferometers. For comparison the fringes of the glass fiber-based and the polymer fiber-based FPI were set to the same level.

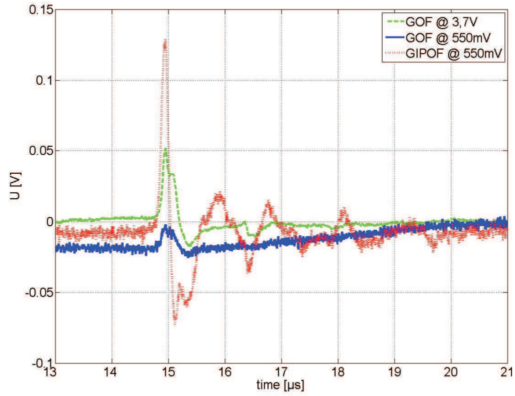

Figure 4. Comparison of the detected signals using the absorber set up shown in Fig.2. The used fiber-based GIPOF FPI detector is much more sensitive compared to the GOF FPI at the same fringe amplitude values.

fiber-based FPI at 3,5V. Compared to the signal from the glass fiber-based FPI at 500mV (which is more adequate for comparison) the GIPOF FPI is much higher. For a better evaluation we calculated the SNR of the three measured signals. The GIPOF FPI exhibits a SNR of 3,65 which is much more than the SNR of 0,66 of the GOF FPI at 500mV. The SNR=10,15 of the GOF FPI at 3,7V is much better than that of the GIPOF FPI - but due to the unequal amplitude of the fringes theses values are not comparable. So in conclusion the polymer fiber-based FPI is much more sensitive than the glass fiber-based FPI at the same fringe amplitude. In other words an enhancement of the fringe amplitude of the GIPOF FPI would increase its sensitivity by several times and would result in a line detector which is as sensitive as a free-beam detector described by Paltauf et al.[4]

To increase the fringe amplitude of the GIPOF FPI it would be necessary to enhance the light intensity in the resonator. One possibility could be to reduce the distance between the mirrors in the GIPOF FPI. A resonator length of 0,9m is not necessary for the imaging of small objects. For the tomography of an object with approximately 3cm size a line detector of 11cm length would be adequate. The damping of the detection laser in such a short fiber would be much less and approx. 8 times more light would pass through the Fabry-Perot resonator. This modification should be easily realizable and will be done in the near future. Another possibility could be the change of the detection wavelength. Using a wavelength in the visible regime would prevent high damping in the perfluorinated polymer fiber.

4. CONCLUSION AND OUTLOOK

A proof of principle for GIPOFs with metalized ends as Fabry-Perot interferometer was shown. This novel integrating fiber-based line detector is more sensitive than previously reported integrating fiber-based line detectors. Although there arose some difficulties, such as high damping in the fiber or the excitation of several modes, perfluorinated graded index polymer optical fibers show great promise to become really sensitive fiber-based line detectors for photoacoustic imaging. Although the damping can be reduced by using shorter fibers, some applications such as mammography require longer fiber detectors in the range of 50cm. A change of the wavelength, the development of single mode perfluorinated POFs or, as an alternative approach, so called "higher order mode stripping" - whereas the fiber is bended tight and higher order modes are coupled out from the fiber core - could be solutions.

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