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Wide bandwidth fiber-optic ultrasound probe in MOMS technology: Preliminary signal processing results

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ABSTRACT

An ultrasonic probe consisting of two optical fiber-based miniaturized transducers for wideband ultrasound emission and detection is employed for the characterization of in vitro biological tissues. In the probe, ultrasound generation is obtained by thermoelastic emission from patterned carbon films in Micro-Opto-Mechanical-System (MOMS) devices mounted on the tip of an optical fiber, whereas acousto-optical detection is performed in a similar way by a miniaturized polymeric interferometer. The microprobe presents a wide, flat bandwidth that is a very attractive feature for ultrasonic investigation, especially for tissue characterization. Thanks to the very high ultrasonic frequencies obtained, the probe is able to reveal different details of the object under investigation by analyzing the ultrasonic signal within different frequencies ranges, as shown by specific experiments performed on a patterned cornstarch flour sample in vitro. This is confirmed by measurements executed to determine the lateral resolution of the microprobe at different frequencies of about 70 μm at 120 MHz. Moreover, measurements performed with the wideband probe in pulsed-echo mode on a histological finding of porcine kidney are presented, on which two different spectral signal processing algorithms are applied. After processing, the ultrasonic spectral features show a peculiar spatial distribution on the sample, which is expected to depend on different ultrasonic backscattering properties of the analyzed tissues.

1. Introduction

In recent years, high frequency ultrasound imaging has been the focus of intense research work, and several possible applications have been proposed, particularly in the field of biological tissue analysis [1–4]. Since high frequency piezo-transducers are very difficult to manufacture due to physical limitations of the transduction principle [5], Thermoelastic Ultrasound Generation (TUG) [6] has been explored as a possible way to produce high-frequency, wideband ultrasound. Using this method, light is delivered to an optically absorbing coating, and the result is a sudden thermal expansion of the material, which generates ultrasound waves [7–9]. This pressure increase propagates through the surrounding medium as a mechanical wave that can be properly used for imaging purposes [10–17]. Conventionally, a pulsed laser is used to generate the ultrasound but recently also coded excitation techniques have been proposed by means of laser diodes [18].

In order to obtain high performance ultrasonic optoacoustic transducers, intensive research on the absorption material has been carried out over the years, using carbon and plastic compounds of carbon, carbon nanotubes or gold nanoparticles as absorbing layers [19–22]. Since the nineties, our group has been involved in optoacoustic research, using layers of optically absorbing materials to obtain fully fiber optic ultrasonic transmitters [23,24], and a wide-band ultrasonic probe has been developed by using an optoacoustic transmitter in conjunction with an acousto-optical receiver [25,26]. The receiving element, consisting of an optical fiber hydrophone, is based on an extrinsic Fabry-Perot interferometer, interrogated by a continuous wave laser beam, the thickness of which is modulated by the ultrasonic wave received [27].

It is well known that the main problem with high frequency ultrasound use on biological tissue is its rather high attenuation, in the order of 1–2 dB/MHz/cm. As a result, the use of optoacoustic devices and high-frequency ultrasonic transducers in general is particularly attractive if the transducer is sufficiently miniaturized to be used endoscopically. Otherwise, high-frequency ultrasonic imaging applications are limited to specific cases in which the tis-

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sue can be accessed at close range by bulk devices, such as analysis of exterior organs (skin or eyes).

To create a fully fiber optic ultrasonic transducer and preserve the miniaturization we have proposed a new Micro-Opto-Mechanical-System (MOMS) technology [28–30]. This transducer provides an acoustic pressure with a peak-to-peak value of about 3 MPa in the near field and a rather flat emission spectrum extended beyond 150 MHz [31]. The strong miniaturization of the proposed microprobe may make it possible to solve the problem of low ultrasound penetration, as it can be driven via catheters or endoscopes into the natural orifices of the human body to reach the organ under investigation in a percutaneous manner, using the needle of a syringe as a guide. Moreover, the high resolution of the microprobe and its wide ultrasonic operation range may enable the performing of a minimally invasive "virtual biopsy" [19] of mass lesions, avoiding any tissue removal and with minimal suffering for the patient. It must be noted however, that compared to piezo technology, acousto-optical probes are still technologically immature, particularly in view of the need to combine miniaturization with multiple pixel devices for imaging. However, new solutions are under investigation for facilitating the fabrication of miniaturized optical-acoustical devices that could be operated in array endoscopically [17,32–35]. With regard to potential application of acousto-optical devices in tissue analysis, a significant amount of work has recently been presented on optoacoustic imaging, in which direct laser irradiation of biological tissues is utilized for generating high-frequency ultrasound [36,37]. In this case, no ultrasonic emission source is needed because the ultrasonic source is the investigated tissue itself. Fewer results, on the contrary, have been reported on the interaction of high frequency, wideband ultrasound waves with tissues, particularly with the use of minimally invasive tools.

In this paper, we present new experiments performed with the miniaturized ultrasonic probe previously reported in [30,31] on biological samples in vitro, aimed at assessing the capabilities of the device in producing a high resolution ultrasound image of the biological target and exploiting the lateral resolution of the probe, which depends on the frequency range of operation of the device. Moreover, we present a spectral analysis of the wideband ultrasound imaging of a porcine kidney finding in vitro performed using the miniaturized probe and the HyperSPACE method (Hyper SPectral Analysis for Characterization in Echography), formerly used to discriminate the densities of structures [38] in conventional ultrasound imaging, especially for characterization of breast diseases [39,40].

2. Materials and methods

The setup used for the experiments presented in the next section includes the aforementioned MOMS ultrasonic transducers with two fibers: one for the optoacoustic source and one for the detector. The basic designs of the MOMS ultrasound emitter and detector are schematically represented in Fig. 1.

The ultrasound emitter consists of a thin carbon layer with high optical absorption, deposited and patterned on the upper surface of a silicon microstructure. A micro-machined cavity acts as a fitting

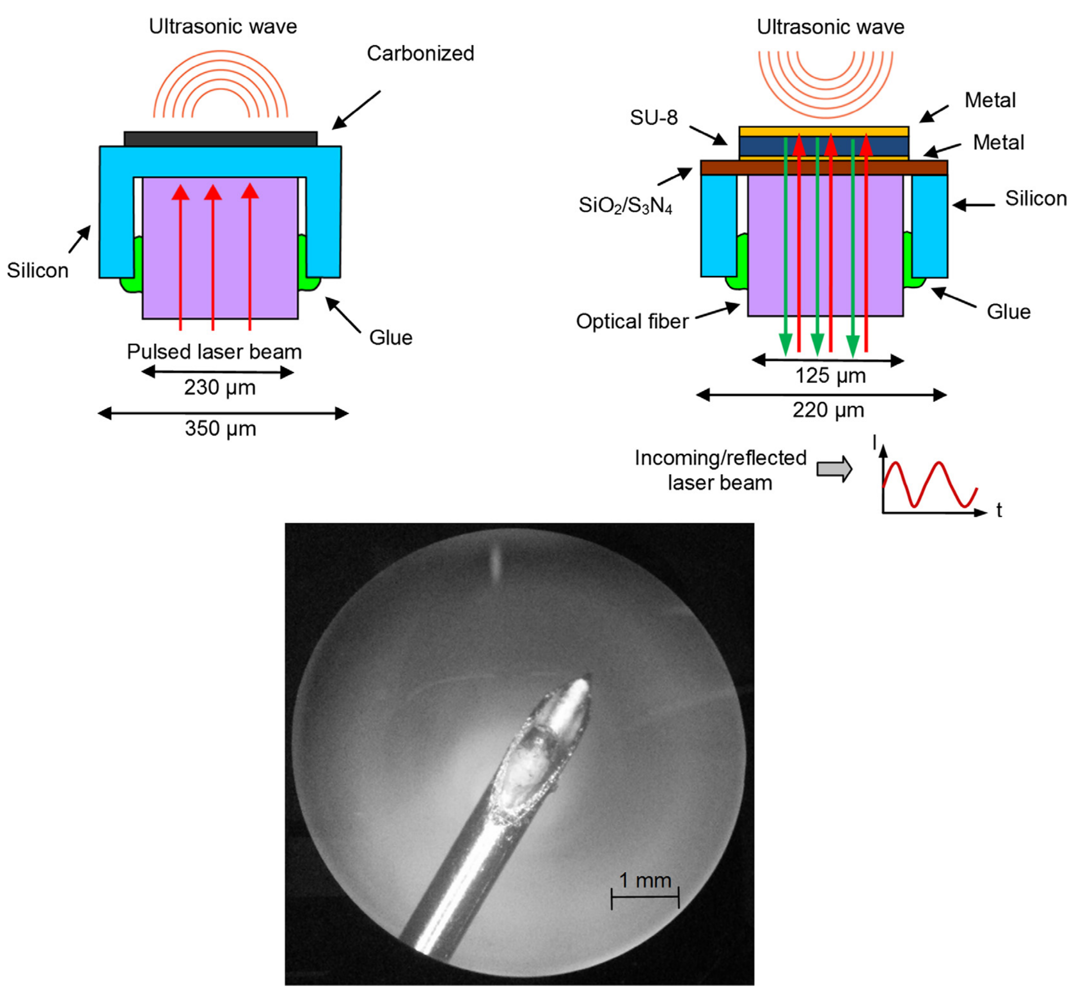

Fig. 1. Optoacoustic MOMS ultrasound source (top left) and detector (top right) inserted in a 21-gauge syringe needle (bottom).