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Time-resolved photoacoustic spectroscopy using fiber Bragg grating acoustic transducers

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Abstract

An acoustic transducer based on a fiber Bragg grating (FBG) is presented and characterized for use in time-resolved laser-induced photoacoustic spectroscopy (PAS) on solid samples. The photoacoustic wave was generated by pulsed laser excitation of immobilized carbon black or erbium oxide powder, and detected by recording either the transmission or reflection spectrum of a clamped fiber Bragg grating (FBG). The characterization of the FBGs photoacoustic response is based on the experimental comparison with a static lateral strain source and on theoretical analysis using the piecewise-uniform approach to photoelastic theory. The temporal resolution of the response is determined by the arrangement of the FBG with respect to the source of the acoustic wave and is better than 150 ns, as was verified in a deconvolution analysis.

The method has not only a fast time response but also is simple, inexpensive, and accurate as indicated by the good agreement of the experimental photoacoustic spectrum with previous measurements.

Keywords: Fiber Bragg grating (FBG); Photoacoustic spectroscopy (PAS); Laser-induced opto-acoustic spectroscopy (LIOAS); Acousto-optic spectroscopy; Chemical sensing; Er_2O_3; Erbium oxide

1. Introduction

In recent years fiber Bragg gratings (FBGs) have undergone a spectacular transformation from passive optical reflectors to active devices [1–7] used, for example, in temperature [8], strain [9], chemical [10] and acoustic [11] measurements. FBGs have been developed primarily as "mirrors" for light which is transmitted through single mode fibers. In their simplest form they consist of a periodic modulation of refractive index in the core of the fiber. Light is reflected from these gratings at wavelengths for which the Bragg condition is met [2]. The use of non-uniform gratings, in which the local period or depth of refractive index modulation varies along the axis, endows the FBG with new properties, such as custom-shaped reflection bands, an enlarged range of the reflection spectrum, or formation of more than one rejection band.

The emergence of modified FBGs and long-period gratings (LPGs) as chemical sensors is very promising, but has in the past been restricted to static measurements, i.e. those in which the response time is seconds or more. Here, we report on a new approach to chemical sensing based on time-resolved photoacoustic spectroscopy (PAS) [12–14]. With this technique the sensitivity of a FBG to strain is exploited as a means to detect the acoustic wave.

Because of its capability to quantify fast (<μs) nonradiative processes time-resolved PAS is the technique of choice for numerous kinetic studies, especially in condensed matter and heterogeneous chemistry [14]. For example, time-resolved PAS was successfully used to evaluate directly the trap state energetics of photogenerated electrons in nanocrystalline colloidal titanium dioxide dispersed in aqueous solution [15]. Time-resolving such a

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process requires a transducer with a response of better than 1 μs and in this case a 10 MHz piezoelectric transducer was employed. The FBG has special potential in photoacoustic measurements on such solid samples since the photocatalyst can be supported by the fiber, which contains the FBG, thus opening a different avenue to measuring nonradiative processes. With this contribution we intend to illustrate the first use of FBGs as fast, "all-optical" detectors for photoacoustic waves.

It is well known that FBGs can be used as "microphones", and there exists a considerable body of work describing the use of FBGs particularly as ultrasound transducers [11,16–26]. Furthermore, the capability of FBGs to detect acoustic waves in real-time makes them well suited in measuring nonradiative emission processes which are commonly initiated by photoexcitation of solids and liquids. An acoustic wave traveling through a supported FBG initiates a spectral change, similar to those initiated by a source of strain [27–32]. We found that the FBGs employed in the present study have the ability to respond to >7 MHz photoacoustic waves generated by photoexcitation of a solid sample with a nanosecond laser pulse. As will be shown below, the response time is limited in our case by the instrumental configuration used to interrogate the FBG and not inherently by the FBG itself.

To demonstrate the capability of the FBG "microphone" as a photoacoustic sensor, an acoustic wave was generated by <10 ns pulsed excitation of erbium oxide powders sandwiched between a thin glass slide and quartz plate. Erbium oxide is widely used as a dopant for optical fibers which are used in fiber lasers and optical amplifiers. The excitation was to a resonant excited state at around 520 nm and the photoacoustic response was recorded in real-time by detecting either the reflection or the transmission of the clamped FBG. The experimental time-resolved photoacoustic FBG spectrum is consistent with the calculated and experimental response assuming a local transverse load of a few Newtons. The focus of this report is the description of the operating principle of a new transducer and its characterization. A detailed comparison to existing photoacoustic techniques, in particular with respect to sensitivity and time resolution, is beyond the scope of this work and will be reported in the near future.

2. Experimental details

The setup of the FBG photoacoustic sensor is shown in Fig. 1. A continuous wave (cw) tunable laser diode (Ando AQ4320D; $\lambda = 1520$ nm–1620 nm; $\Delta\lambda = 1.6$ pm) was used to probe the FBG response either by measuring its reflection or its transmission. The wavelength of the laser was selected so that it coincided with one of the reflection edges of the FBG. The FBGs were made by ITF Labs (Montréal, QC, Canada) had a period of 530 nm, a length of 7 mm and a maximum attenuation of 16 dB at around 1550 μm. Other FBGs with different period and attenuation spectra were also used and, as expected, their sensitivity to the

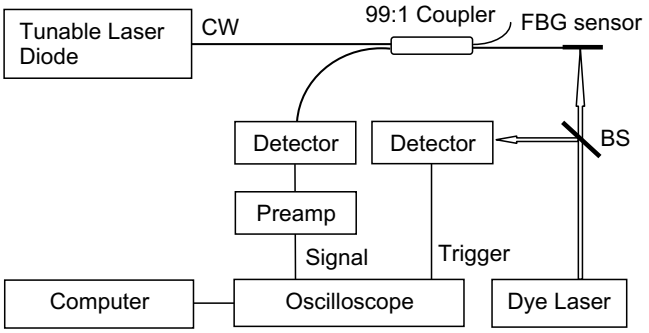

Fig. 1. Experimental setup for detecting time-resolved photoacoustic signals using a fiber Bragg grating sensor. Shown is the setup used for measuring the FBG reflectance spectrum.

photoacoustic wave increased with the slope of the spectrum, $dT/d\lambda$, at the probe laser wavelength. The laser was directed into the fiber Bragg grating using a coupler (Lightel Technology, splitting ratio 1:99, Corning SMF-28). The reflected light was directed to a detector (Thorlabs, D400FC, InGaAs, rise time: 0.1 ns), and the signal was amplified (Panametrics, 10 MHz, Tech Inc. USA) and averaged by an oscilloscope (Tektronix, TDS3054B, 500 MHz, 5GS/s), before being transferred to a computer.

The time-resolved reflection or transmission spectra were recorded using two configurations shown in Fig. 2a and b. In these configurations two different samples were used. Carbon black is known to have very fast and strong photoacoustic response due to a rapid radiationless decay of the primary excited state ($\tau < 10$ ns). For the initial characterization carbon black was therefore used as a sample in Configuration A and excited by a pulsed Nd:YAG laser (third harmonic at 355 nm, 10 mJ/pulse, $\Delta t < 10$ ns, irradiated area is $\sim$1 mm^2). Carbon black was also used as a time-reference in Configuration B. Additionally, Er_2O_3 was used as a solid sample in both Configurations A and B.

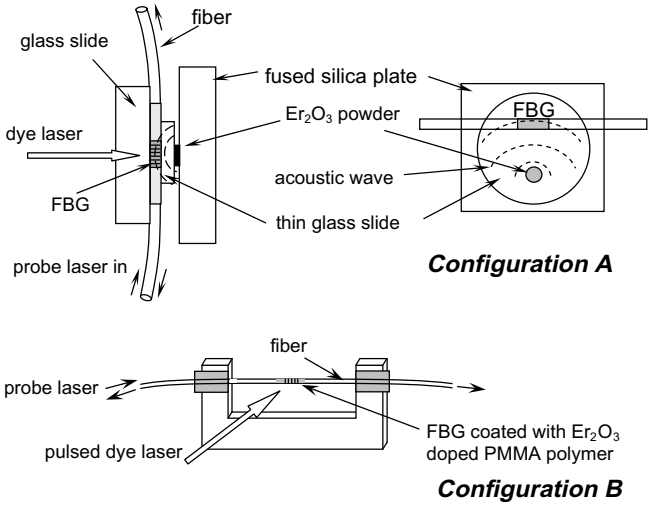

Fig. 2. Schematic illustration of the two fiber Bragg grating configurations. FBGs in both configurations were interrogated in reflection and transmission mode.