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Characterization of the spatio-temporal response of optical fiber sensors to incident spherical waves

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Abstract

A theoretical framework is presented for calculating the opto-acoustic response of optical fiber ultrasound sensors with several layers of coating. A harmonic point source generating a spherical wavefront with arbitrary position and frequency is assumed. The fiber is acoustically modeled by a layered cylinder on which spherical waves are scattered. The principle strains on the fiber axis are calculated from the scattering of the acoustic waves and used in a strain-optic model to calculate the phase shift of the guided modes. The theoretical results are compared to experimental data obtained with a sensing element based on a π-phase-shifted fiber Bragg grating and with photoacoustically generated ultrasonic signals.

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Keywords: Optical fiber; spherical wave; scattering

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1. Introduction

Optical fiber-based sensing of ultrasound is a well-established alternative technique to classical ultrasound detection, with e.g. hydrophones, and regularly used to detect waves up to tens of megahertz. The measurement principle is based on the changes of the refractive index in the optical fiber core due to mechanical stresses/strains [Wild and Hinckley (2008); Flax et al. (1982); Cole et al. (1977); Jarzynski et al. (1981)]. Recently, optical fibers found their application in biomedicine to detect photoacoustically generated ultrasonic waves in tissue [Grün et al. (2010, 2009); Rosenthal et al. (2011c, 2012); Berer et al. (2012); Veres and Kollar (2002)]. In photoacoustic imaging the imaged object is naturally represented by a finite sum of point-like acoustic sources, and the resulting wavefront may be described by a finite sum of spherical waves. Therefore, knowledge of the response of the sensor to point sources allows enhancing the reconstruction process by incorporation of this information, e.g., in a model-based inversion algorithm [Rosenthal et al. (2011a)]. Experimental estimation of the response using point-like acoustic sources [Rosenthal et al. (2011b); Caballero et al. (2013)] are, however, unreliable for a sufficient calibration and the incorporation of acoustic

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modeling [Veres and Berer (2012); Veres (2010); Veres et al. (2011)] is a promising approach to achieve a better estimation of the response.

Optical fibers were already characterized as hydrophones for normally [Cole et al. (1977)] and obliquely [Dorighi et al. (1997)] incident plane waves. Although, scattering of spherical acoustic waves on a cylinder was treated in the literature [Piquette (1986); Li and Ueda (1990)]. due to their mathematical complexity these solutions did not find their way into practical applications. To evaluate the frequency response of a coated optical fiber to an incident spherical wave, first a fundamental solution to the scattering of plane waves from a layered cylinder is obtained by using the transfer matrix method for cylindrical geometries [Huang et al. (1996)]. Then the incident spherical wave is described in cylindrical coordinates by using an integral representation [Piquette (1986); Li and Ueda (1990)] which allows the evaluation of the acoustically induced strains using the fundamental solution. Finally, the response of the optical fiber is calculated as the integrated phase shift of the propagating light due to the acousto-optical coupling. The analytically calculated response of the fiber is compared to experimentally measured responses. Experimental responses are recorded by using a π-shifted fiber Bragg grating (FBG) sensor similar as described in [Rosenthal et al. (2011c)]. Photoacoustically generated ultrasonic signals originating from a microsphere are acquired with the FBG sensor and compared to analytically obtained results.

2. Solution of the scattering problem

A fundamental solution of the scattering of incident plane waves from a multilayered cylinder embedded in a nonviscous fluid is given in [Huang et al. (1996); Veres et al. (2014)]. For an arbitrary layer j in cylindrical coordinates (r, θ, z) they can be represented by an expansion of Bessel functions. This solution can be modified to describe a spherical wavefront in cylindrical coordinates originating from a point source [Li and Ueda (1990)]. The resulting normal strains on the fiber axis can be expressed by using the normal strains calculated from the incident plane wave [Veres et al. (2014)]:

$$
\begin{aligned}
\varepsilon_1^{sph} &= \int_{-\infty}^{\infty} \sum_{n=0,2} \chi(\lambda)\epsilon_n P_n^0(\lambda)\varepsilon_{1,n}^{plane}(\lambda)d\lambda, \\
\varepsilon_2^{sph} &= \int_{-\infty}^{\infty} \sum_{n=0,2} \chi(\lambda)\epsilon_n P_n^0(\lambda)\varepsilon_{2,n}^{plane}(\lambda)d\lambda, \\
\varepsilon_3^{sph} &= \int_{-\infty}^{\infty} \sum_{n=0,2} \chi(\lambda)\epsilon_n P_n^0(\lambda)\varepsilon_{3,n}^{plane}(\lambda)d\lambda, \quad \text{with:} \quad P_n^0(\lambda) = \frac{(-i)^n i}{2} H_n^2\left(\sqrt{k_w^2 - \lambda^2}\, d\right),
\end{aligned}
\tag{1}
$$

where the propagation constants are expressed as $k_{lr}^j = \sqrt{(k_l^j)^2 - \lambda^2}$ and $k_{tr}^j = \sqrt{(k_t^j)^2 - \lambda^2}$ with k_l^j, k_t^j being the longitudinal and shear wave numbers and λ is the wave number along the axis of the cylinder. The integrals are infinite along the real $\lambda-$axis. This integration is carried out by using a numerical technique with finite limits [Veres

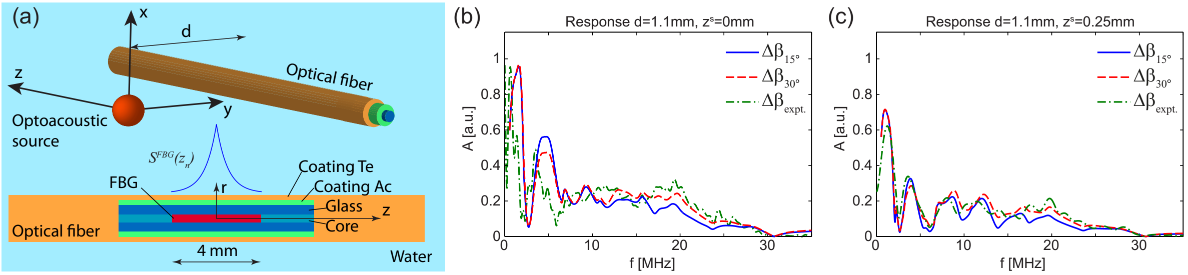

Fig. 1. (a) Experimental arrangement: an opto-acoustical source (R = 50 μm) is scanned parallel to a FBG sensor in a distance of d. (b) Integrated response of the fiber by the combined phase shifts along 15° and 30° compared to experimental results. (c) Response of the fiber by shifting the source parallel to the fiber axis. The strains are normalized to $|\varepsilon_3|$ for the d = 1.1, mm..