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A differential optical interferometer for measuring short pulses of surface acoustic waves

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ABSTRACT

The measurement of the displacements caused by the propagation of a short pulse of surface acoustic waves on a solid substrate is investigated. A stabilized time-domain differential interferometer is proposed, with the surface acoustic wave (SAW) sample placed outside the interferometer. Experiments are conducted with surface acoustic waves excited by a chirped interdigital transducer on a piezoelectric lithium niobate substrate having an operational bandwidth covering the 200–400 MHz frequency range and producing 10-ns pulses with 36 nm maximum out-of-plane displacement. The interferometric response is compared with a direct electrical measurement obtained with a receiving wide bandwidth interdigital transducer and good correspondence is observed. The effects of varying the path difference of the interferometer and the measurement position on the surface are discussed. Pulse compression along the chirped interdigital transducer is observed experimentally.

1. Introduction

Generation of intense short pulses of surface acoustic waves (SAW), either from the absorption of a short laser light pulse or from piezoelectric transduction, has important potential applications. In addition to surface phonon generation [1] and non destructive evaluation [2], it could for instance be used for acoustic soliton generation, higher harmonics generation, and more generally nonlinear acoustical signal processing. Indeed, the mechanical energy transported by SAW is strongly confined at the surface, causing a high density of elastic energy and induced strain in the supporting material. As a result, even a modest initial acoustic power could in principle be capable of inducing substantial nonlinear effects, especially if combined with pulse compression techniques similar to those used to achieve intense ultrashort laser light pulses using the chirped-pulse amplification (CPA) technique [3]. As a pre-requisite, it is needed to develop the measurement of short SAW pulses in the time domain.

Optical interferometry is a well-known technique for studying wave propagation and is often preferred over other methods for its high precision in studying wave profiles, amplitude and phase variations, standing wave patterns, or group delays [4]. Various interferometers have been developed and employed to study the ultrasonic motion of SAW. Both the Michelson interferometer depicted in Fig. 1(a) and the Sagnac interferometer depicted in Fig. 1(b) rely on the principle of interference between divided wavefronts. In both case, the SAW device or substrate supporting SAW propagation is placed within the interferometer. The Michelson interferometer compares an optical wavefront reflected on the vibrating specimen with a reference wavefront. It allows one for high resolution measurements but is extremely sensitive to fluctuations in path difference, causing a slow drift of the response over time. Various active stabilization methods [5–7] and heterodyne techniques [8–12] have been proposed to overcome this problem. In contrast, the Sagnac interferometer compares two time-delayed wavefronts that have traveled the same path of micro-optical elements, but in opposite directions. It is naturally immune to slow fluctuations in the lengths of the arms of the interferometer. It has been used for the selective detection of time-harmonic SAW propagation [13], but also for the detection of laser-generated ultrasonic short pulses [14,15]. One practical difficulty, however, is to manage the beam size difference that appears between the two different paths, as a result of focusing on the sample within the Sagnac loop [15].

The Sagnac interferometer belongs to the more general class of differential interferometers, whereby a wavefront is compared with its replica shifted either in space or time. As discussed by Monchalin [4], various differential interferometric techniques have been proposed to detect and measure surface vibrations. For example, Turner and Claus used lateral-shearing interferometry to measure the amplitude and direction of propagation of

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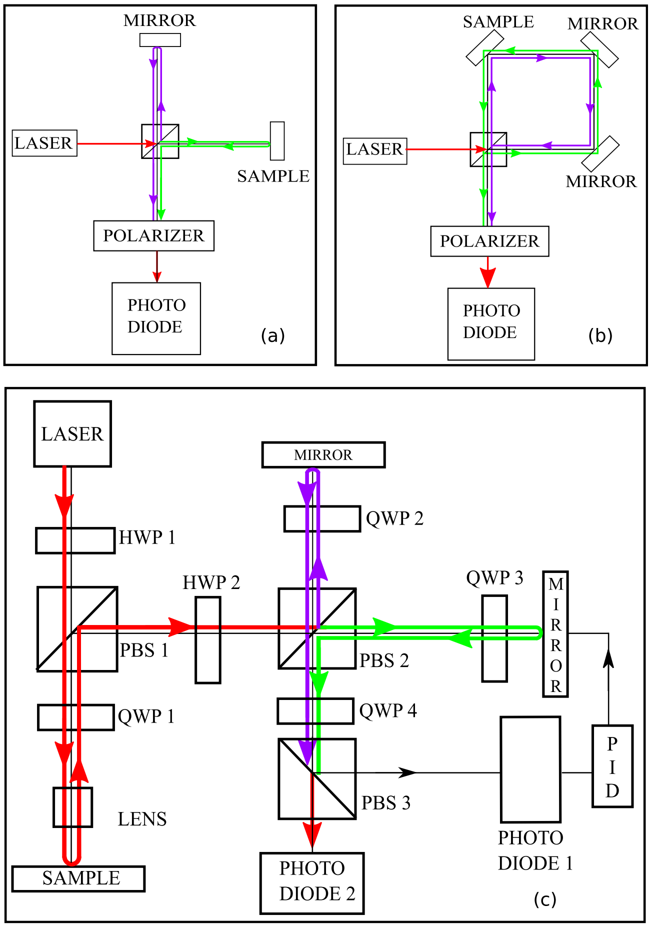

Fig. 1. Schematic representation of three optical interferometers for the measurement of surface acoustic wave short pulses. (a) Michelson interferometer with the vibrating sample inside one arm of the interferometer. (b) Sagnac interferometer with the vibrating sample inside the loop. (c) Time-shearing, or time-delay, differential interferometer with the vibrating sample before the interferometer. PBS: polarizing beam splitter, HWP: half wave plate, QWP: quarter wave plate, PID: proportional-integral-derivative controller.

ultrasonic surface waves [16]. Such measurements are suited for time-harmonic waves.

In this paper, we propose a time-delay differential interferometer in which the sample supporting SAW propagation is placed before and outside the interferometer. As a result, it allows stable maneuvering of the sample, reducing irregular overlap between the incident and reflected beams that might cause a loss in amplitude and then measurement inaccuracies. However, unlike the Sagnac interferometer, it is not immune to slow fluctuations in the differential path length and it has to be stabilized using a proportional-integral-derivative (PID) controller. Using this setup, we investigate the measurement of short SAW pulses, with smallest durations of about 10 ns, generated by a chirped wideband interdigital transducer. In Section 2, we describe the working principle of the differential interferometer and present a mathematical analysis of the interferometric measurement. The results of an experiment devised to measure and analyze the operation of this interferometer, are discussed in Section 3, and an overall summary is provided in Section 4.

2. Working principle of the differential interferometer

The differential interferometer we have developed is depicted in Fig. 1(c). The interferometer setup is an extended version of a homodyne Michelson interferometer implementing time-shearing. A single-mode narrow-linewidth diode laser (New Focus, model Velocity 6305) with a wavelength of 651 nm and a nominal power of 7.4 mW is used as a highly coherent light source. The coherence length of the laser exceeds several hundred meters and was not a limitation in our experiments. A half-wave plate (HWP1) is placed before a polarizing beam splitter (PBS1) to adjust the input polarization. The beam is first transmitted to the sample, reflects on it, and enters the interferometric part of the setup after reflection inside PBS1. A quarter-wave plate (QWP1) provides the required polarization rotations. Four mirrors and a reflected light objective (Olympus, ultra long working distance model MSPlan 100×) are used to provide an extended path to the laser beam such that the SAW device can be placed horizontal to the optical table and the incident beam is normal to the SAW device. The spot size on the sample surface is smaller than 2 μm. This value must remain significantly smaller than the SAW wavelength in order to resolve pulse propagation. Note that after double pass through the objective the ellipticity of the laser beam is mostly corrected and the beam size inside the interferometer is about 1 mm. HWP2 and PBS2 split the laser beam into two beams of equal intensity and orthogonal polarization in the interferometer. At the exit of the interferometer, the two orthogonally polarized beams are recombined with a quarter-wave plate (QWP4) and a polarizing beam splitter (PBS3) to provide two outputs. The interference signal detected by photodiode 1 (Electro-Optics Technology, Silicon pin detector ET-2020) is used to actively stabilize the path length difference to a single quadrature point using a proportional-integral-derivative (PID) controller for the position of one of the mirrors. The position of the mirror is controlled by a piezoelectric actuator (Thorlabs, model KC1-PZ/M, ±4 μm linear travel range) receiving the correction signal. Since the SAW signal varies on a time-scale that is much shorter than the PID response time, it remains decoupled from the correction signal. The interference signal detected by photodiode 2 (Thorlabs model DET10A/M, 1 ns rise time) provides the SAW measurement.

The output intensity on photodiode 2 after recombining the wavefronts exiting the two arms of the interferometer is

$$I(t) = I_1 + I_2 + 2m\sqrt{I_1 I_2}\cos(\phi_2(t) - \phi_1(t)) \tag{1}$$

with I_i and ϕ_i the intensity and phase in arm i. The visibility m, a number between 0 and 1, is introduced to account for possible reduction of the interference intensity because of loss of either spatial or temporal coherence. The interferometer is operated so that $I_1 \approx I_2$ to maximize interference visibility. The phase variation in either arm can be decomposed as

$$\phi_i(t) = \Phi_i + \frac{4\pi}{\lambda} u(x, t - L_i/c) + \psi_i(t) \tag{2}$$

with Φ_i a static configuration phase, independent of time, the vibration-induced deterministic phase $\frac{4\pi}{\lambda} u(t - L_i/c)$ where $u(x,t)$ is the displacement at position x that is to be measured, and $\psi_i(t)$ a random phase including all fluctuations. L_i is the optical path length of arm i, so L_i/c measures the wavefront delay, with c the speed of light. In order to provide maximum sensitivity, the stabilized interferometer is operated so that $\Phi_2 - \Phi_1 = \pi/2$ *modulo* π. Writing $\Delta u(x,t) = u(x, t - L_2/c) - u(x, t - L_1/c)$ and $\Delta\psi(t) = \psi_2(t) - \psi_1(t)$, we have

$$I(t) = I_1 + I_2 + 2m\sqrt{I_1 I_2}\sin\left(\frac{4\pi}{\lambda}\Delta u(x,t) + \Delta\psi(t)\right). \tag{3}$$

The response of the interferometer is thus nonlinear with the out-of-plane displacements $\Delta u(x,t)$. However, assuming that the displacements are small compared to the optical wavelength and that