Interferometric measurement of acoustic velocity in $PbMoO_4$ and TeO_2

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We present a novel interferometric technique for the accurate measurement of acoustic velocity based on an optical phase shifter consisting of a pair of properly aligned acousto-optic modulators (AOMs). Results for the z-axis longitudinal mode velocities in lead molybdate ($PbMoO_4$) and tellurium dioxide (TeO_2) at 80 MHz are reported and compared with earlier results. A longstanding inconsistency in the $PbMoO_4$ velocity is resolved. © 2007 Optical Society of America

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1. Motivation

Lead molybdate ($PbMoO_4$) has remained a popular material for use in acousto-optic devices since its discovery more that 35 years ago [1,2]. Its high figure of merit and good optical and acoustic properties make it the crystal of choice in many modulator, deflector, and frequency-shifting applications [3].

Recently, while experimenting with a new optical phase-shifting method based on the acousto-optic interaction [4], we realized that a minor system modification would allow for the precise measurement of acoustic velocities [5], and we obtained results for longitudinal mode z-axis propagation velocities at 80 MHz in both $PbMoO_4$ and tellurium dioxide (TeO_2), another popular acousto-optic device material [6].

When compared with previously reported values [7], our results for TeO_2 agreed very well. However, when we looked for reference values for $PbMoO_4$ to confirm our results, we discovered that [1,2] (which are both from the same institution and share some authors), report slightly different values for the z-axis longitudinal mode velocity, namely, 3.75×10^5 cm/s in [1] and $(3.632 \pm 0.002) \times 10^5$ cm/s in [2]. The authors of [2] did not remark on this difference of $\sim 3\%$ [8], but it is much larger than our experimental error.

Attempts to find an independent experimental measurement for $PbMoO_4$ were unsuccessful; all books, papers, company brochures, and websites ultimately quoted either [1] or [2].

We present our experimental techniques, our results for TeO_2, and what we believe is the first experimental result for the z-axis longitudinal mode velocity at 80 MHz in $PbMoO_4$ since 1971.

2. Experiment

Our interferometric technique for the measurement of acoustic velocity takes advantage of an optical phase-shifting method employing acousto-optic modulators (AOMs) [5]. The schematic of our setup is shown in Fig. 1. A pair of AOMs is inserted into one arm of a modified Mach–Zehnder interferometer. The acousto-optic interaction of the incident laser beam (angular frequency ω_0, wave vector k),

$$E_0(z_0,\ t) = E_{0,0} \exp[i(k_0 z_0 - \omega_0 t)], \tag{1}$$

with the acoustic wave of angular frequency Ω, wave vector K, and phase Φ_1,

$$A_1 = A_{1,0} \exp[i(KX - \Omega t + \Phi_1)], \tag{2}$$

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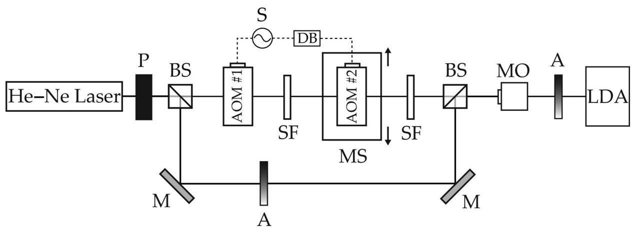

Fig. 1. Schematic of the experiment: P, polarizer; BS, beam splitter; M, mirror; A, attenuator; SF, spatial filter; S, rf source; DB, delay box; MS, micrometer stage; MO, microscope objective; LDA, linear diode array.

in AOM 1 results in a phase- and frequency-shifted positive first-order diffracted laser beam:

$$E_1(z_1,\ t) = E_{1,0} \exp[i(k_1 z_1 - (\omega_0 + \Omega)t + \phi_1 + \Phi_1)], \quad (3)$$

where ϕ_1 is an additional phase delay due to the optical path through AOM 1. This beam is taken to be the input of AOM 2, which is driven at the same rf frequency $\Omega/2\pi$ with a phase Φ_2 and aligned such that its diffraction to the negative first order cancels the optical frequency shift imposed on the beam by AOM 1. Therefore, the diffracted output of AOM 2 has the original optical frequency ω_0, but is phase shifted by $\phi_2 + \Delta\Phi$, where ϕ_2 is the total phase delay due to the optical path from the entrance of AOM 1 to the exit of AOM 2, and $\Delta\Phi = \Phi_1 - \Phi_2$ is the difference in phase between the rf driving signals. To detect the optical phase shift, we project the recombined beams of the Mach–Zehnder interferometer onto a linear diode array (LDA) using a microscope objective (MO) and observe the interference pattern on an oscilloscope. As in [5], we observed the fringes shifting when $\Delta\Phi$ was changed using a delay box (DB) in the line driving AOM 2.

The essential modification we introduced compared to the setup used in [5] is to put AOM 2 on a linear stage, which allowed us to translate the modulator in the direction of acoustic propagation. Now, a 2π optical phase shift can be produced for each acoustic wavelength Λ of stage translation, resulting in a shift of one full optical fringe. The acoustic velocity is, of course, the product of Λ and the rf driving frequency $\Omega/2\pi$.

We determined Λ by repeatedly (30×) measuring the stage displacement at different laser beam positions in AOM 2 and averaging the results. At each position we measured a displacement corresponding to ten 2π phase shifts. To increase the precision of this measurement, the stage drove a dial gauge, which we could read to better than 2.5 μm. This provided us with the ability to measure our Λs (which were in the range of tens of micrometers) to a precision of approximately one part in 200. Our rf driving source was stable to better than one part in 10^5, so any frequency variation is too small to affect our velocity results.

Our interferometric experiments were carried out using a pair of Crystal Technology devices (Model 4210) to measure the z-axis longitudinal mode velocity in TeO_2, and a pair of Isomet devices (Model 1205C) to measure the z-axis longitudinal mode velocity in $PbMoO_4$. In these devices, a longitudinal acoustic wave was generated by a $LiNbO_3$ transducer and propagated along the z axis. The polarization direction of our He–Ne laser beam was perpendicular to the z axis, and the diameter of the laser beam incident on the AOMs was 1 mm.

Finally, we confirmed the acoustic velocity, V, in each material using a single AOM and measuring the angle θ between the undiffracted beam and the first-order Bragg diffracted beam as was done in [7]. For small angles,

$$V = \frac{\Omega\lambda}{2\pi\theta}, \quad (4)$$

where λ is the optical wavelength and $\Omega/2\pi$ is the driving frequency.

3. Results and Discussion

Our interferometric technique yielded a z-axis longitudinal mode acoustic velocity $V = (4.27 \pm 0.01) \times 10^5$ cm/s for TeO_2, which agrees very well with the $V = (4.26 \pm 0.04) \times 10^5$ cm/s reported in [7]. This result from [7] also agrees with the result from our angle measurement, $(4.21 \pm 0.04) \times 10^5$ cm/s.

For $PbMoO_4$, we get $(3.75 \pm 0.01) \times 10^5$ cm/s and $(3.73 \pm 0.04) \times 10^5$ cm/s from our interferometric and angle measurements, respectively. These results agree well with the 3.75×10^5 cm/s reported in [1], but disagree with the later $(3.632 \pm 0.002) \times 10^5$ cm/s obtained in [2], where a pulse echo technique was used. We have no explanation for this discrepancy.

Since interferometric techniques are sensitive to temperature gradients, we were concerned about their effect on the accuracy of our results. Temperature gradients are produced in AOM 2 from the conversion of absorbed rf power to heat in the electrodes at the transducer–crystal interface and by the conversion of acoustic power to heat at the crystal–absorber interface opposite the transducer. These gradients can affect the accuracy of the velocity measurement in two ways.

First, there is the finite temperature coefficient of acoustic velocity $\eta = (1/V)(\mathrm{d}V/\mathrm{d}T)$, where $\eta = -117 \times 10^{-6}\ (°\mathrm{C})^{-1}$ for TeO_2 [9] and $\eta = -161 \times 10^{-6}\ (°\mathrm{C})^{-1}$ for $PbMoO_4$ [2]. This results in direct velocity changes when the temperature changes.

Second, temperature gradients result in index of refraction gradients via the temperature coefficients of refractive index $\gamma_o = (1/n_o)(\mathrm{d}n_o/\mathrm{d}T)$. Here, $\gamma_o = 1 \times 10^{-5}\ (°\mathrm{C})^{-1}$ for TeO_2 [10] and $\gamma_o = 3 \times 10^{-5}\ (°\mathrm{C})^{-1}$ for $PbMoO_4$ [2]. As will be seen, these index gradients play the dominant role in limiting our measurement accuracy. All our reported results were taken with an rf drive power in AOM 2 reduced to $<$25 mW from an initial 1–2 W to minimize the gradients' effects. Our diffraction efficiency at this rf level was ~1%, still large enough to provide a good signal-to-noise ratio on the photodiode array.

The fringe pattern at the output of our interferometer is determined by the difference in phase between the reference optical beam and the beam diffracted in AOM 2 and the interference angle between these beams. When we translate AOM 2, the phase should change (by 2π every Λ), but the interference angle should not. Unfortunately, at the higher rf powers, we observed angular changes at different laser beam-to-transducer distances in $PbMoO_4$ that were large enough to change the calculated value of the acoustic velocity by ~10%. Equal angular changes were observed in the undiffracted beam as well, so the effect was definitely not due to a change in acoustic velocity producing a diffraction angle change [see Eq. (4)]. The angular effect was not nearly as strong in TeO_2, but we operated at reduced rf power in that crystal as well.

From the observed ~10% velocity change, we could calculate an angular change and estimate an index gradient. Then using γ_o, we determined that temperature gradients of the order of a few degrees per centimeter existed in the $PbMoO_4$ crystal, consistent with the results in [2]. The contribution to direct velocity changes produced by these gradients through the temperature coefficient of velocity is seen to be orders of magnitude smaller than the ~10% change resulting from the index gradients. This discussion of potential errors gives us confidence that our velocity error ranges are correct for our experimental conditions.

4. Conclusion

We have successfully demonstrated a new interferometric technique for the measurement of acoustic velocity and applied it to z-axis longitudinal mode velocity measurements in TeO_2 and $PbMoO_4$. In the latter crystal, we find a velocity of $(3.75 \pm 0.01) \times 10^5$ cm/s, a result that resolves a discrepancy that has existed in the literature since 1971.

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