Reaching the shock limit via synchronous laser ultrasonics

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In recent years, controlling emergent phenomena in correlated materials through collective lattice vibrations has attracted more and more attention. Strain engineering methods favoring superconductivity [1], ferroelectricity, or adequate for tuning excitonic, magnetic, metal-insulator transitions [2] are among the latest examples. Large elastic static strains of several percents can be applied to bulk or nano samples up to the onset of plasticity or fracture. However, the excitation of ultrashort vibrations carrying out large strains to percent levels—the threshold at which many physico-chemical properties of materials would be significantly perturbed—still remains a challenge. Conventional laser-shock experiments, based on single-shot laser absorption in a transducer layer, can generate the strains required, although at the price of irreversible sample damage and noisy data.

Using ultrafast optics to build up propagative strain waves from the linear to the nonlinear regime, we introduce a non-destructive method of laser-shock wave generation and detection. The methodology is based on the synchronous spatiotemporal laser excitation of numerous distinct photoacoustic sources for additive superposition of multiple strain waves, as shown in Fig. 1. An input beam is split into a pulse train by using a FACED device [3]. The output is then focused on a sample as an array of lines, each arriving a set amount of time after the preceding. Each line in turn generates a thermoelastic response from the material, launching acoustic waves in both directions. The array of lines is spaced such that the waves propagating along one direction constructively superpose. The surface displacement of the propagating wave can be monitored using phase-mask interferometry [4] or time-resolved reflectivity.

The current approach can efficiently excite substantial strain waves in the range of a few percents, up to the mechanical failure, at a kHz repetition rate for optimal detection sensitivity, and offers new possibilities for the extensive study of subtle strain-induced effects in correlated materials where lattice degrees of freedom play a crucial role.

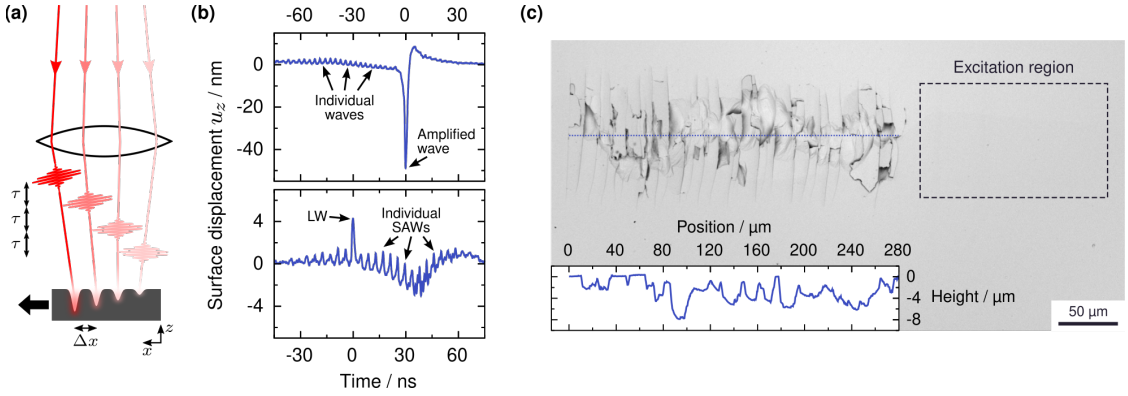

Fig. 1. (a) A pulse train with a temporal separation τ is focused on the sample surface; each laser pulse is laterally displaced by an amount Δx to match the propagation of the generated wave. **(b)** Displacement of a Nb:STO sample surface measured as a function of time upon thermoelastic excitation, for two different phase-matching conditions (surface acoustic wave and longitudinal wave). **(c)** SEM image of the surface of a Nb:STO sample showing SAW-induced damage hundreds of microns away from the excitation region. Inset: depth profile along the dotted line, extracted from confocal microscopy.

References

[1] A. Cavalleri, Photo-induced superconductivity, Contemp. Phys. 59 (2017) 31. https://doi.org/10.1080/00107514.2017.1406623.

[2] M. Rini, R. Tobey, N. Dean, J. Itatani, Y. Tomioka, Y. Tokura, R.W. Schoenlein, and A. Cavalleri, Control of the electronic phase of a manganite by mode-selective vibrational excitation, Nature 449 (2007) 72. https://doi.org/10.1038/nature06119.

[3] J.-L. Wu, Y.-Q. Xu, J.-J. Xu, X.-M. Wei, A.C.S. Chan, A.H.L. Tang, A.K.S. Lau, B. M. F. Chung, H. C. Shum, E.Y. Lam, K.K.Y. Wong, and K.K. Tsia, Ultrafast laser-scanning time-stretch imaging at visible wavelengths, Light Sci. Appl. 6 (2016) e16196. https://doi.org/10.1038/lsa.2016.196.

[4] C. Glorieux, J.D. Beers, E.H. Bentefour, K. Van de Rostyne, and K.A. Nelson, Phase mask based interferometer: Operation principle, performance, and application to thermoelastic phenomena, Rev. Sci. Instrum. 75 (2004) 2906. https://doi.org/10.1063/1.1781386.