



Ultrashort strain soliton formation in sapphire and ruby

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Abstract

We discuss the development of ultrashort strain solitons in sapphire and ruby using Brillouin spectroscopy and numerical results of the Korteweg–de Vries equation. We demonstrate that solitons are formed in unexcited ruby, showing no significant difference with sapphire in phonon properties in the frequency regime under study. Further, the role of the radiative tail in the evolution of the low-frequency Brillouin spectrum is investigated. It is shown that its influence on the typical oscillation pattern is limited, confirming our earlier interpretation in terms of Bragg reflections and spatial resonances of the soliton train.

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PACS: 63.20.–e; 62.30.+d

Keywords: Picosecond; Soliton; Phonon; Brillouin scattering

1. Introduction

Recent experiments on ballistic propagation of picosecond strain pulses over millimeter distance in crystals have revealed new information on the development of their internal structure. Next to the influence of linear phenomena, such as phonon dispersion [1] and diffraction [2], the *nonlinear* effects of self-steepening and breakup into strain solitons have been observed [3,4]. In this paper, we discuss in detail some of the results of Ref. [4] on the formation of ultrashort soliton trains and their detection by Brillouin scattering. In this analysis, special attention is paid to the contribution of the

two archetypical parts of the wavepacket: the soliton train and the trailing dispersive tail. For this purpose, we make use of numerical calculations based on the well-known Korteweg–de Vries (KdV) [5,6] equation.

Additionally, to corroborate our experiments on soliton propagation in photoexcited ruby [7], we repeated the Brillouin-scattering experiments of Ref. [4], using a $9.7 \times 10 \times 15\text{-mm}^3$ specimen of *c*-cut, 500 ppm ruby. The surface perpendicular to the *c*-axis is covered with a 100-nm chromium film, in which high-amplitude, picosecond strain pulses are produced by means of opto-elastic generation using an amplified ultrafast laser setup. Subsequently, the development of these strain pulses in the crystal is probed via Brillouin scattering of a single-mode argon-ion laser beam, using a quintuple-pass Fabry–Pérot interferometer and photon-counting apparatus.

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2. Results and discussion

A typical result of the evolution of the 22-GHz frequency component travelling along the ruby c -axis, at an intermediate pump fluence of $\sim 4.5 \text{ mJ/cm}^2$, is shown in Fig. 1. The oscillation pattern observed in this experimental trace is typical for soliton formation [4] and can be explained quantitatively by the KdV equation (line in Fig. 1), using the known parameters for the elastic constants and phonon dispersion of sapphire [8,3]. The wavepacket obtained from this simulation, shown in Fig. 1(a), contains the typical features of an ultrashort soliton train. During propagation, the front part of the initial bipolar strain pulse is shaped into a series of equidistant ultrashort solitons with linearly decreasing amplitudes, while the trailing edge is converted to a tail oscillating with high frequency. Our experiment thus clearly demonstrates the development of a soliton train along the ruby c -axis.

In the remaining part of this paper we will compute the individual contributions of the soliton train and radiative tail to the Brillouin-scattered intensity. The shape of this tail, as shown in Fig. 1(a), should not be confused with the purely linear

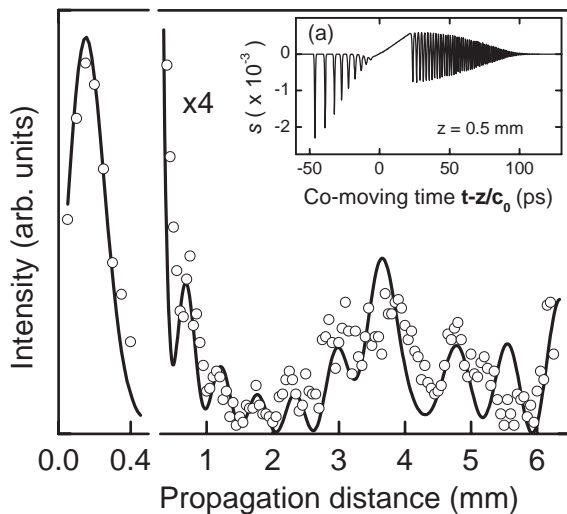


Fig. 1. Dependence of Brillouin-scattering intensity on propagation distance z in ruby at a temperature of 5 K. Line: simulations using the KdV equation. Inset: waveform obtained from simulation after 0.5 mm propagation distance.

dispersive forms of Ref. [3], where the initial pulse itself is short enough to induce dispersive spreading even in the low-amplitude regime. In the current experiment, the initial frequency components of the wavepacket are below 100 GHz, which is too low for dispersion to play a role within the length of our crystal. The strain amplitude, however, is extremely high (up to 0.2%), ensuring a significant nonlinear steepening mechanism.

The difference in development of the compression and rarefaction parts of the bipolar strain pulse is caused only by the relative signs of the nonlinear and dispersive parts of the propagation equation. In the compressional front of the packet, nonlinearity counteracts the dispersion, leading to soliton formation, while at the tensile edge they cooperate in pulling apart the wavepacket. Only after the tail has been stretched out over an appreciable distance by dispersion, the strain amplitude decreases, and the propagation becomes approximately linear. The point at which the dispersive action becomes apparent in the self-steepening process coincides for both sides of the packet [6], leading to the same high-frequency content in the tail and in the soliton train. In contrast with the solitons, that remain nonlinear over the entire travelled distance, the stretching of the radiative tail leads to linear propagation and effectively decouples the terahertz spectrum from the low-frequency part, ‘freezing’ in the contribution of the tail in the Brillouin-scattered intensity.

To analyze the contributions to the Brillouin-scattering signal in a more quantitative way, we separated a simulated wavepacket into its two basic components. The development of the soliton train and the radiative tail were individually monitored over time and their low-frequency Brillouin intensities separately computed. In this procedure we considered the complete, complex form of the relevant Fourier components, to ensure that the coherent sum of the separate contributions produces the total scattered intensity. A typical evolution pattern of the Fourier coefficient of strain, $\tilde{\epsilon}_B$, at 22 GHz, separated into its soliton- and tail-induced components, is shown in Fig. 2. The small discontinuity in the traces around 0.4 mm is due to the replacement beyond

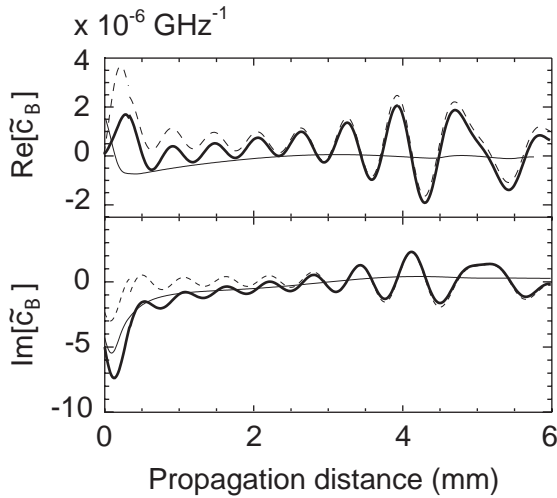


Fig. 2. Real and imaginary parts of Fourier component \tilde{c}_B (thick line) at the Brillouin frequency of 22 GHz, and separated into soliton (dash) and radiative tail (thin line) contributions.

that point of the soliton train in the simulation by its analytical form of Ref. [6], which gives a significant reduction of computational efforts without affecting the accuracy of our simulated wavepacket. From the figure, we can easily distinguish the different roles played by the soliton train and radiative tail in our Brillouin signal. The influence of the latter is limited to the first millimeter of propagation only, where the self-steepening mechanism has not yet upconverted all of the acoustic energy in the tail into the terahertz range. It is not involved in the typical oscillation pattern in the Brillouin intensity, but rather yields a small additional level decreasing with distance. The oscillations in the soliton trace of Fig. 2 can thus be attributed purely to the spatial resonances in the train, moving at different velocities, as we stated earlier in Ref. [4].

3. Conclusion

In conclusion, we have analyzed the separate influence of the soliton and tail contributions to

the observed Brillouin scattering data. We find that the influence of the radiative tail is appreciable only during the first hundreds of micrometers of propagation, after which it decays rapidly to zero. This confirms the expectation, that the semi-linear trailing radiation consists mainly of components in the high-frequency part of the phonon spectrum. Further, we have observed the formation of a soliton train in ruby, which turned out to be the same as in the case of pure sapphire. This result is not surprising, as it is known that the distortion of the LA-phonon spectrum due to the occupation of Al-sites by the additional Cr-ions is very small. Nevertheless, these observations corroborate our recent experiments on interaction of strain solitons and terahertz electronic two-level systems in ruby [7].

Acknowledgements

The authors wish to thank P. Jurrius, C.R. de Kok, and F.J.M Wollenberg for their technical assistance. This work was supported by the Netherlands Foundation ‘Fundamenteel Onderzoek der Materie (FOM)’ and the ‘Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO).’

References

- [1] H.-Y. Hao, H.J. Maris, Phys. Rev. B 64 (6) (2001) 4302.
- [2] O.L. Muskens, J.I. Dijkhuis, Physica B 316–317 (2002) 373.
- [3] H.-Y. Hao, H.J. Maris, Phys. Rev. B 63 (22) (2001) 4301.
- [4] O.L. Muskens, J.I. Dijkhuis, Phys. Rev. Lett. 89 (28) (2002) 285504.
- [5] G.B. Whitham, Linear and Nonlinear Waves, 1st Edition, Wiley, New York, 1974.
- [6] V.I. Karpman, Non-linear Waves in Dispersive Media, 1st Edition, Pergamon Press, Oxford, 1975.
- [7] O.L. Muskens, A.V. Akimov, J.I. Dijkhuis, Phys. Rev. Lett. 92 (2004) 035503.
- [8] J.M. Winey, Y.M. Gupta, D.E. Hare, J. Appl. Phys. 90 (6) (2001) 3109.