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Observation of the "Luxemburg–Gorky effect" for elastic waves

V.Yu. Zaitsev [a,*], V. Gusev [b], B. Castagnède [c]

[a] Institute of Applied Physics RAS, 46 Uljanova St., Nizhny Novgorod 603950, Russia
[b] Laboratoire de Physique de l'État Condensé, Av. O. Messiaen, 72085 Le Mans Cedex 9, France
[c] Laboratoire d'Acoustique de l'Université du Maine, Av. O. Messiaen, 72085 Le Mans Cedex 9, France

Abstract

An experimental observation of a new nonlinear-modulation effect for longitudinal elastic waves is reported. The phenomenon is a direct elastic wave analogy with the so-called Luxemburg–Gorky (L–G) effect known over 60 years for radio waves propagating in the ionosphere. The effect consists of the appearance of modulation of a weaker initially non-modulated wave propagating in a nonlinear medium in the presence of an amplitude-modulated stronger wave that produces perturbations in the medium properties on the scale of its modulation frequency. The reported transfer of modulation from one elastic wave to another was observed in a resonator cut of a glass rod containing a few small cracks. Presence of such a small damage drastically enhances the material nonlinearity compared to elastic atomic nonlinearity of homogeneous solids, so that the pronounced L–G type cross-modulation could be observed at strain magnitude in the stronger wave down to 10^{-7} and smaller. Main features of the effect are pointed out and physical mechanism of the observed phenomena is discussed. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Nonlinearity; Wave interaction; Modulation; Microstructure; Damage; Crack detection

1. Introduction

Presently, there is general consensus that presence of defects (cracks, contacts, etc.) may strongly increase nonlinearity of solids in comparison to weak atomic nonlinearity of ideal crystals and homogeneous amorphous materials. This nonlinearity results in the violation of the superposition principle. Therefore, nonlinearity-induced components of elastic excitations may be used as a very sensitive indicator of structural damage in the material [1–5]. It is essential that apparently similar effects could be caused by different particular nonlinear mechanisms, e.g., hysteresis [5], or dissipative nonlinearity [6], or purely elastic material's nonlinearity. The latter may be, e.g., power-type nonlinearity like in intact materials, or a "diod-like" contact nonlinearity [2,7], etc.

In the present communication, observation of a new nonlinear acoustic effect is reported. The phenomenon is the direct analogy with the so-called Luxemburg–Gorky (L–G) effect known for radio waves propagating in ionosphere plasma [8]. The L–G effect consists of appearance of modulation of a weaker wave propagating in presence of another amplitude-modulated stronger (pump) wave that produces perturbations in the ionosphere-plasma conductivity on the scale of its modulation frequency. The acoustic analogue of the L–G effect is implemented for longitudinal waves excited in a rod resonator containing a few small cracks that drastically enhance its nonlinear response. High "structural sensitivity" of nonlinear acoustic properties of solids may be elucidated using quite simple and instructive models [9]. However, the level of "useful" nonlinearity-induced signals often remains quite small, therefore, a very important problem for the nonlinear elastic wave spectroscopy is the proper choice of nonlinear effects to be used. In particular, a nonlinear modulation method was patented [4] as an effective tool for crack detection and location, since an intensive low frequency vibration may induce opening and closing of cracks thus causing modulation of another (probe) higher-frequency wave.

* Coresponding author. Fax: +7-831-2-36-59-76.
E-mail address: vladimir.zaitsev@mech.kuleuven.ac.be (V.Yu. Zaitsev).

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2. Resemblance and difference between conventional and L–G type modulation

The conventional modulation method is schematically shown in Fig. 1. In the investigated sample, an intensive (pump) lower-frequency oscillation at frequency Ω is excited together with a weaker probe signal at higher frequency $\omega \gg \Omega$. The probe wave exhibits practically no modulation in an intact, weakly nonlinear sample, whereas in the damaged sample, pronounced modulation is observed. Fig. 2 shows examples of real signal records [10] that were obtained for probe signals at frequencies 20–25 kHz and the pump vibrations at 20–60 Hz excited in an aluminium plate that contained a single fatigue crack about 5 mm in length.

The principle of the L–G type cross-modulation effect is shown in Fig. 3. In this case, the modulation frequency Ω is significantly smaller than both carrier frequencies $\omega_{1,2}$ for the pump and probe waves, whereas the ratio between ω_1 and ω_2 may be quite arbitrary. The perturbation of the defects produced by the pump wave on the scale of its modulation frequency induces the modulation of the probe wave. In the reported experiment, for convenience, the effect was realized for resonant Young modes in a glass rod (8 mm in diameter and about 30 cm in length). The pump and probe oscillations were excited by independent piezo-actuators and registered by a light accelerometer. The L–G type cross-modulation exhibits extremely high "structural sensitivity", which is illustrated in Fig. 4 that displays high contrast between the modulation spectra of the probe wave obtained in the intact reference rod and in the damaged one. The latter contained three thermally produced cracks. In the insertion in Fig. 4, the lower-resolution spectrograms are shown, which display the relative levels of the pump and probe waves. Normally, two lower modes at 1/4 and 3/4 wavelength resonances were used (at frequencies 3.6–3.8 kHz and 10–12 kHz, respectively), each of them could be used as either probe or pump wave. Typical Q-factors for the modes were between 150 and 300. Note that the damaged and reference rods exhibited no certain differences either in Q-factors or in resonance frequencies. The pump wave was AM modulated with 100% depth at modulation frequency of several Hz, so that the fundamental frequency together with the sidelobes could be positioned within the same resonance peak. In contrast to quite

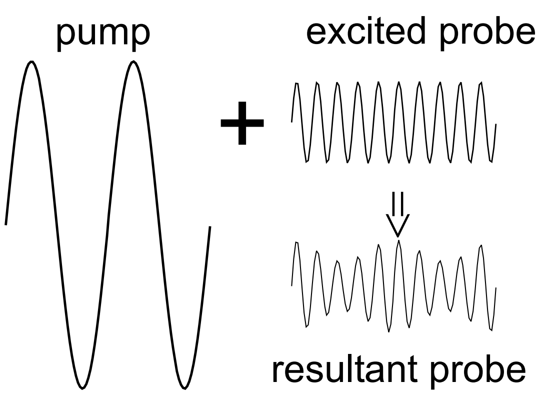

Fig. 1. Schematically shown conventional nonlinear modulation of a probe wave caused by a low frequency pump excitation.

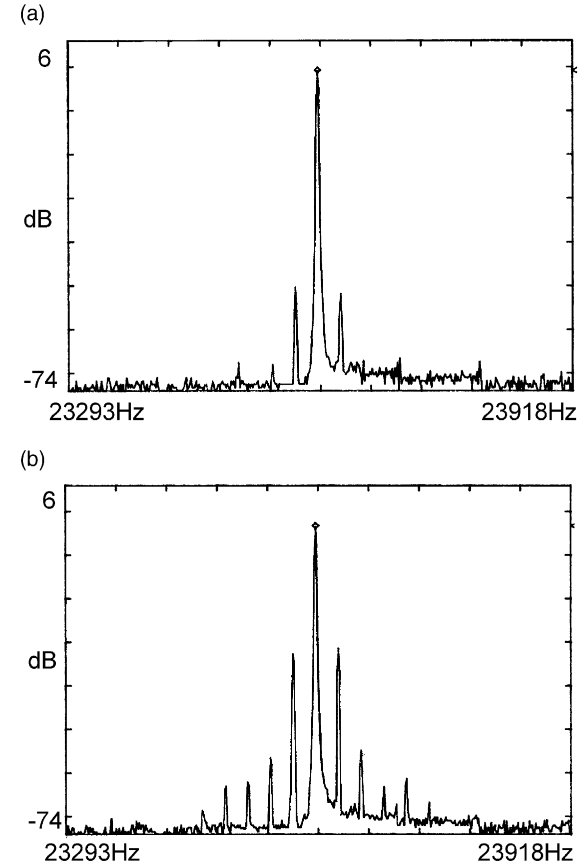

Fig. 2. Experimental example [10] of conventional nonlinear modulation: (a) reference intact sample exhibiting sidelobes lower than −55 dB; (b) damaged sample exhibiting sidelobes 25–30 dB higher than those in the reference sample.

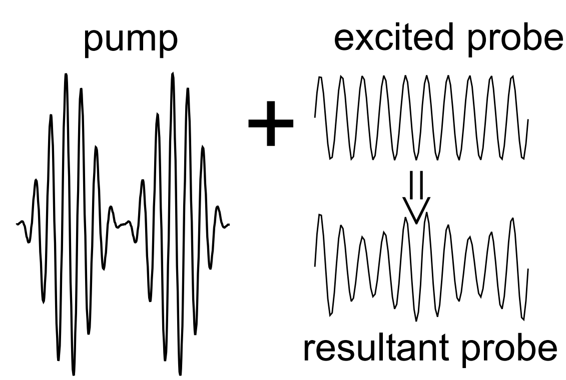

Fig. 3. Schematically shown L–G type cross-modulation of a probe wave caused by an amplitude-modulated pump excitation.

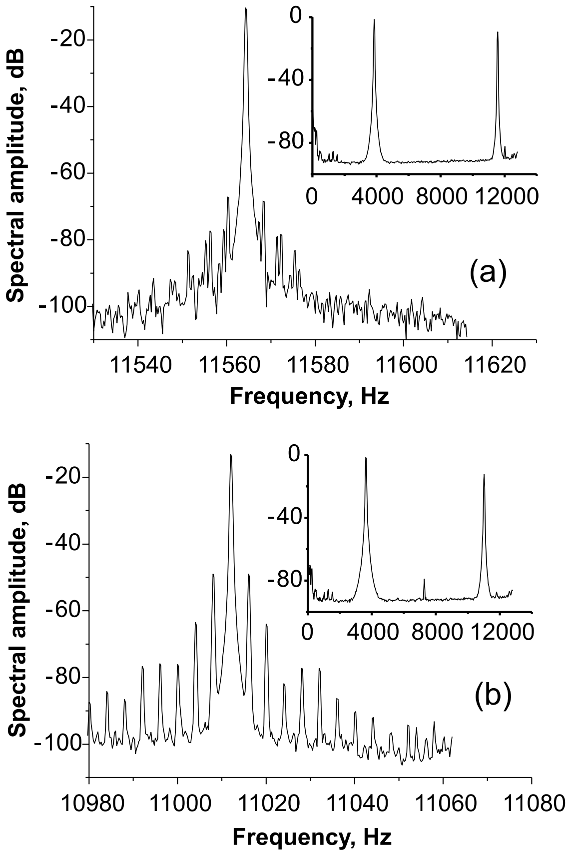

Fig. 4. Experimental spectra of the L–G type cross modulation: (a) reference intact rod exhibiting parasite sidelobes smaller than −60 dB; (b) damaged rod exhibiting multiple strongly increased sidelobes. In the insertions the lower-resolution spectra of the pump and probe waves are displayed.

similar linear responses, the level of sidelobes in the damaged sample was 20–30 dB higher than in the reference rod. The examples shown in Fig. 4 correspond to the pump strain about 8×10^{-7}, which could be made about four times larger at the setup used, so that the probe wave modulation could be significantly (10–15 dB) increased.

Comparison of Figs. 1–4 indicates that the L–G and conventional modulation spectra look rather similar. However, there are essential physical differences between them. Conventional modulation is determined by the *instantaneous* response of the material. In contrast, the L–G type cross-modulation is determined by the material response, which is *time averaged* over the pump carrier period. Further, in case of the L–G effect the modulation frequency Ω is essentially independent of both (pump- and probe-) carrier frequencies. Therefore, Ω may be chosen arbitrary low, which readily makes it possible to put the modulation sidelobes together with the initial probe signal within the same resonance, thus providing favorable conditions for observation of the modulation.

3. Main features of the L–G effect in the crack-containing sample

In this section, we point out some features of the L–G effect, which allow for highlighting important general aspects of nonlinear response of solids with microdefects and provide new insight in physical mechanisms of the microstructure-induced nonlinear effects.

(a) At a fixed pump amplitude, the pronounced L–G modulation was effectively induced down to smallest observable amplitudes of the probe wave (10^{-9} and less), at which its own nonlinearity was negligible. This indicates that L–G modulation should be *linear in the probe-wave amplitude*. Another confirmation of this conclusion is given in Fig. 5 displaying modulation spectra at two probe wave levels and fixed pump. In Fig. 5, ratio of the amplitudes of the corresponding sidelobes is with a high accuracy the same as for the central lines, which corroborates that the effect is linear in the probe wave amplitude.

(b) Being linear in the probe-wave amplitude, the modulation sidelobes essentially nonlinearly depend on the pump amplitude. Fig. 6 illustrates that with the pump-level increase, rapid growth (or sometimes non-monotonous behavior) of numerous higher-order spectral components was observed rather than monotonous growth of the first sidelobes.

(c) The spectral shape of the initial modulation of the pump and the nonlinearity-induced modulation spectrum for the probe wave were essentially different as shown in Fig. 7. This means that the discussed effect is not a simple transfer of the initial pump spectrum to the carrier frequency of the probe wave. The same feature is typical of the L–G effect for radio-waves, i.e., appearance of modulation sidelobes $\pm\Omega, \pm2\Omega, \pm3\Omega, \ldots$ at sinusoidal modulation of the pump.

(d) The nonlinear shift of the sample resonance frequencies was of minor significance for the phenomenon. This statement is illustrated in Fig. 8, in which frequency response functions (FRFs) for the probe wave

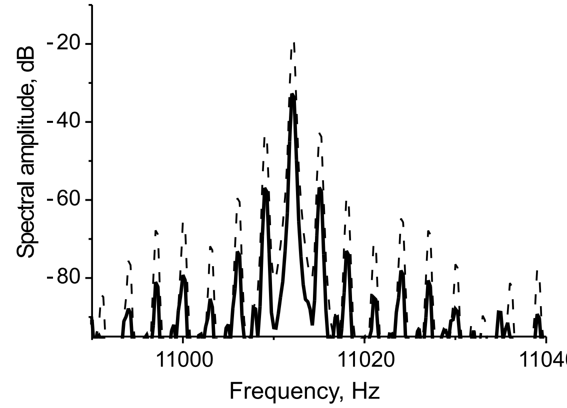

Fig. 5. Modulation spectra at five times difference in the probe wave amplitudes.

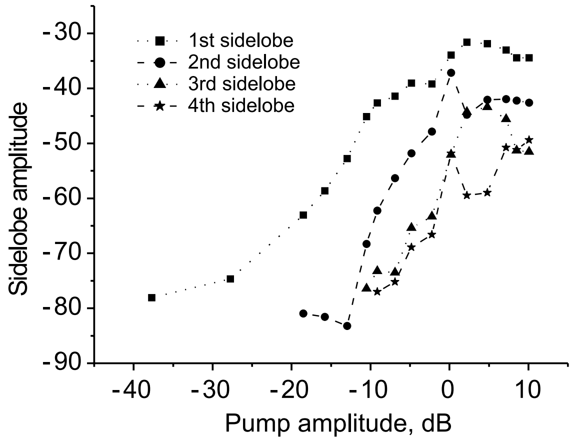

Fig. 6. Example of dependencies of sidelobe amplitudes on the pump amplitude.

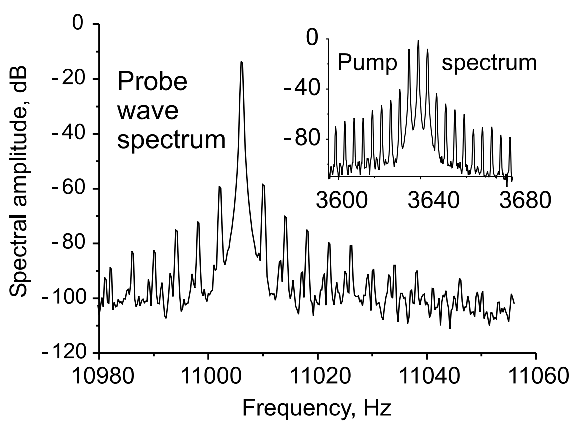

Fig. 7. Difference between the modulation spectra of the pump and the probe waves.

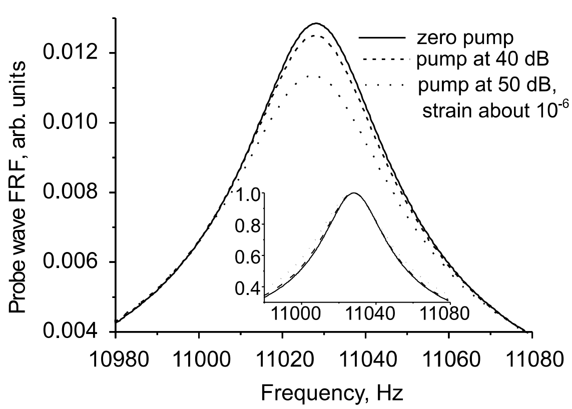

Fig. 8. Probe wave FRF obtained at different pump amplitudes. The insertion displays widening of the normalized resonance curves.

are displayed for different amplitudes of the pump. In these measurements, the pump wave was non-modulated and tuned near one of the resonances, whereas the frequency of the probe wave was swept around another resonance. The records clearly indicate that the position of the FRF maximum could remain practically unchanged, whereas the Q-factor for the probe wave significantly varied: the FRF maximum could noticeably (up to 10–25%) decrease, which corresponded to the respective increase of the width of the normalized resonance curves, as is shown in the insertion.

4. Possible physical mechanism of the phenomenon and conclusions

The aforementioned features suffice for discussion of the phenomenon mechanism(s). Property (a) indicates that nonlinear (with respect to *probe wave amplitude*) response of the sample had no importance for the observed modulation, and the effect was essentially *linear in the probe wave amplitude*. On the other hand, properties (b) and (c) indicate that *in the pump wave amplitude*, the *response of the damaged sample was essentially nonlinear*, and this nonlinearity exhibited pronounced non-smooth, "piece-wise", behavior. Property (d) clearly indicates that the effect is caused by an *essentially dissipative nonlinear mechanism.* Indeed, possible hysteretic losses were definitely negligible at very small probe-wave amplitudes. On the other hand, the role of the tiny nonlinear shift of the resonance frequency was also negligible, as well as the effect could not be explained by the spatial-scattering mechanism [11], since the effect was caused by a strongly localized defect, rather than by spatially distributed nonlinearity. The mentioned arguments lead us to the conclusion that the observed modulation is due to a dissipative mechanism, similar to that discussed in [10] for the case of conventional modulation. Namely, the influence of the pump wave on the crack opening affects the dissipation of the probe wave at the defect. The minor difference with the conventional modulation [10] is that in case of L–G modulation, the period averaged crack opening is important rather than the instantaneous reaction. Next, *physical origin* of this dissipation we attribute to *strong thermoelastic losses at the defect*, whose presence significantly affects just the dissipative properties of the system without significant effect upon its elastic properties. Despite the small volume of the crack, these losses are significantly increased due to high temperature gradients at the vicinity of the crack edges. Those gradients are not determined by the acoustic wavelength, but by the significantly smaller scale of the inter-edge microcontacts. A similar thermal mechanism is known for the anomalously strong sound dissipation in polycrystalline media. This effect alone might give increase in thermal losses by 2–3 orders of magnitude (depending on the frequency). In our case, however, there is an additional important factor, increased strain amplitude at microcontacts inside the crack. Those combined factors could cause thermal losses at a rather small crack, which are comparable to losses in the whole intact sample. More detailed quantitative estimates that will be published elsewhere, has confirmed that even a single small crack could induce such a strong thermo-elastic losses. If observed by means of conventional linear methods, these losses could be easily masked by other sources of dissipation. However, additional perturbation of the defects caused by the pump action induces amplitude modulation of the probe wave, which may be readily distinguished though other "background" losses may yet remain much stronger than the modulated losses at the crack. Thus the L–G effect opens very convenient possibilities for diagnostic applications.

Acknowledgements

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References

[1] O.V Rudenko, Nonlinear methods in acoustic diagnostics, Russ. J. Nondestruct. Testing 29 (8) (1993) 583.
[2] O. Buck, W.L. Morris, J.M. Richardson, Acoustic harmonic generation at unbounded interfaces and fatigue cracks, Appl. Phys. Lett. 33 (5) (1978) 371.
[3] V.A. Antonets, D.M. Donskoy, A.M. Sutin, Nonlinear vibrodiagnostics of delayer in layer construction, J. Mech. Compos. Mater. (5) (1986) 934 (in Russian).
[4] J.G. Sessler, V. Weiss, Crack detection apparatus and method, 1975, Patent US3867836.
[5] R. Guyer, P. Johnson, Nonlinear mesoscopic elastisity: evidence for a new class of materials, Phys. Today April (1999) 30.
[6] V.Yu. Zaitsev, V.E. Nazarov, Elastic waves in media with nonlinear dissipation, Acoust. Phys. 44 (3) (1998) 305.
[7] V.Yu. Zaitsev, Nonideally packed granular media: numerical modeling of elastic nonlinear properties, Acoust. Phys. 41 (3) (1995) 385.
[8] V.L. Ginzburg, To the theory of the Luxemburg–Gorky effect, Izvestia Acad. Sci. USSR, Ser. Phys. (12) (1948) 253 (in Russian).
[9] V.Yu. Zaitsev, A model of anomalous acoustic nonlinearity of micro-inhomogeneous media, Acoust. Lett. 19 (9) (1996) 171.
[10] V.Yu. Zaitsev, P. Sas, Nonlinear response of a weakly damaged metal sample: a dissipative mechanism of vibro-acoustic interaction, J. Vibr. Control 6 (2000) 803.
[11] V. Gusev, Parametrical amplification and attenuation of acoustic signals in media with hysteretic quadratic nonlinearity, Phys. Lett. A 271 (2000) 100.