Nonlinear acoustics is known as an extremely sensitive tool for the characterization of the nonperfectly contacting material surfaces and cracks [1–6]. Various nonlinear acoustic phenomena such as harmonic generation [1–4], subharmonic generation [3–6], rectification [6], modulation transfer [7], and acoustoelasticity [8] have been observed experimentally in the interaction of acoustic waves with cracks and fatsigued materials [8]. The inherent specificity and sensitivity of such nonlinear acoustic methods suggest their use for materials imaging with increased contrast and spatial resolution [2] and for the sensitive indication of fatigue damage, especially in comparison with conventional methods based on linear acoustics [8].

Nonlinear acoustics methods unfortunately share a common limitation in that the monitoring of the acoustic waves is conducted by actuators (e.g., piezoelectric elements or accelerometers), which are themselves in contact with the materials under test. Thus, any nonlinear acoustic transformations taking place as a result of interaction of the acoustic waves with contacts or interfaces associated with the transducers often mask those due to the interaction of the acoustic waves with the cracks under study.

To introduce the all-optical techniques for noncontact monitoring of the nonlinear acoustic phenomena is thus a challenging step in the development of not just sensitive, but simultaneously fast imaging methods for the nondestructive evaluation of materials. It has been shown that the new frequency components in the acoustic spectrum generated by the interaction of powerful ultrasound launched with piezoelectric transducers with cracks can be detected by a commercial laser vibrometer [9,10]. As well, it has also been demonstrated that the modulation of crack closure and, consequently, of crack rigidity can be achieved by thermoelastic stresses induced through heating of the cracked region by intensity-modulated IR laser radiation [11,12]. In these experiments, laser-induced modulation of crack parameters was manifested in the modulation of the ultrasonic surface acoustic waves reflected from the crack, which were both launched and detected using in-contact, interdigital transducers. Quite recently, intensity-modulated laser radiation has been used for the first time both to initiate crack breathing at a low frequency $f_L$ and to generate acoustic waves at a high frequency $f_H \gg f_L$ for probing this crack breathing [13,14]. However, the mixed acoustic frequencies $f_{m,n} = mf_H \pm nf_L$, where $m$, $n$ are the integers, generated in the nonlinear acoustic process were detected by an in-contact accelerometer.

In this Letter, we report all-optical monitoring of the nonlinear acoustic frequency-mixing processes in the vicinity of a crack. The crack is induced by thermal loading of a 50 mm × 25 mm × 3 mm plate of colored glass. The crack, which completely penetrates the thickness of the plate, is 5 mm in length.

A schematic of the experimental apparatus is given in Fig. 1. To induce crack closing, or periodic closing and opening, i.e., breathing, the crack is heated by a 532 nm, 2 W cw laser (Coherent, Inc., Verdi), unmodulated or periodically intensity modulated, respectively. 100% modulation at low frequency $f_L = 1$ Hz is achieved by an acousto-optic modulator (AA Opto-Electronics, Inc., Model MQ180). The laser radiation is focused on the crack on the large face of the glass plate in a spot with a radius of 100 µm. The penetration depth of the visible light in the glass plate has been determined by optical transmission measurements to be 0.3 mm. The local separation between the crack faces in the laser-irradiated region is sensitive enough to initiate crack breathing at a low frequency $f_L$ and to modulate the acoustic waves at a high frequency $f_H \gg f_L$ for probing this crack breathing [13,14].

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Experiments with an all-optical method for the study of the nonlinear acoustics of cracks in solids are reported. Nonlinear acoustic waves are initiated by the absorption of radiation from a pair of laser beams intensity modulated at two different frequencies. The detection of acoustic waves at mixed frequencies, absent in the frequency spectrum of the heating lasers, by optical interferometry or deflectometry provides unambiguous evidence of the elastic nonlinearity of the crack. The high contrast in crack imaging achieved by remote optical monitoring of the nonlinear acoustic processes is due to the strong dependence of the efficiency of optoacoustic conversion on the state of the crack. The highest acoustic nonlinearity is observed in the transitional state of the crack, which is intermediate between the open and the closed ones. © 2011 Optical Society of America
region diminishes (increases) due to thermoelastic expansion when the temperature in the vicinity of the crack increases (diminishes). The temperature rise is caused by the absorption of optical energy, while the fall in temperature is due to heat conduction. To probe local modifications in the crack state, the acoustic waves are photogenerated by an 800-nm, 1 W diode laser, focused in the same spot as the first laser. The diode laser is 100% modulated in intensity at high frequency \( f_\text{H} = 16 \text{ kHz} \), by modulation of the current from its power supply. The modulation frequency \( f_\text{H} \) was chosen to maximize the amplitude of the detected signal. We have estimated that this frequency corresponds to one of the standing wave resonances of the asymmetric Lamb modes propagating parallel to the long side of the plate. The acoustic resonances due to the symmetric Lamb modes are expected at frequencies exceeding 45 kHz. The dominant component of the plate surface motion, induced by the flexural waves, is out-of-plane surface displacement, which favors detection by optical deflectometry. The nonlinear acoustic process of the interaction of the acoustic waves of frequency \( f_\text{H} \) with the thermoelastic motion of the crack at frequency \( f_\text{L} \), results, in general, in the excitation of new spectral components \( f_{\text{m.n}} = mf_\text{H} \pm nf_\text{L} \). In our experiments, the signals with the highest amplitudes lie at those frequencies \( f_{\text{m,n}} = f_\text{H} \pm nf_\text{L} \), which are inside the width of the plate resonance noted above. Theoretical analysis has demonstrated that the physical origin of the observed nonlinear parametric process is modulation of the reflectivity of the laser-generated probe acoustic waves incident on the crack by the opening and closing of the crack [14,15]. In other words, crack breathing at the site of the crack modulates the efficiency of the thermoelastic optoacoustic transformation [15].

We have found that the amplitudes of the out-of-plane displacements of the plate surface, that are generated by the acoustic nonlinearity of the crack, are sufficiently high to be detected not only by the deflectometry apparatus shown in Fig. 1 but also by a commercial vibrometer (Polytec Inc., Model OFV302). The parameters important for optimization of the deflection technique [16,17] are the laser spot radius \( a_0 \) at the surface and the distance \( z \) from the surface of the sample to the knife, which is introduced to block exactly one-half of the optical power. The relative variation of the power on the photodiode, introduced after the knife, is described by \( \Delta P / P = \Delta x / a \), where \( \Delta x \) is the lateral displacement of the beam at the surface of the knife caused by a change in the angle of the probe beam reflection induced by acoustic vibration of the sample, where \( a = a_0 \sqrt{1 + (z/z_d)^2} \) is the radius of diffraction laser beam and \( z_d = \pi a_0^2 / \lambda \) is the diffraction length where \( \lambda \) is the wavelength of probe light. The displacement of the probe beam \( \Delta x = 2 az \) is determined by the maximum value of angle of the deflection of the surface \( a = 2 uz / \Lambda \), where \( \Lambda \) is the wavelength of the acoustic wave and \( u \) is the amplitude of the surface displacement [18]. It follows that \( \Delta P / P \) is given by \( \Delta P / P = (\pi^2 / \lambda)(4 a_0 / \Lambda)(z/z_d)[1 + (z/z_d)^2]^{-1/2} / u \).

This formula predicts that the strategy for maximizing the sensitivity of the deflection method is to use a laser beam of maximum radius \( a_0 = \Lambda / 4 \) and observation distances exceeding the diffraction length. For the third flexural resonance of the glass plate, \( \Lambda / 4 \) is approximately 8 mm. Thus, the maximum sensitivity \( \pi^2 (u / \lambda) \) in the setup pictured in Fig. 1 can be obtained by broadening of the initial 1 mm radius of the cw green laser nearly by 1 order of magnitude and using observation distances exceeding 600 m. This possible optimization has appeared unnecessary, because even 10 times lower sensitivity, experimentally achieved with a beam of 1 mm radius at 10 m observation distance, is sufficient for the monitoring of the nonlinear acoustic phenomena by deflectometry with a high signal-to-noise ratio. Interferometric sensitivity with a Mach–Zehnder interferometer is given by [19,20] \( \Delta P / P = (4 / \pi) (\pi^2 / \lambda) m \), confirming that the sensitivities of both techniques are similar.

The results of the experiments, which could be called static, are presented in Fig. 2(a). In these experiments, the heating of the crack is generated by an unmodulated green laser, \( f_\text{L} = 0 \text{ Hz} \), so that there are no frequency-mixing processes. In the first experiment, the dependence of the acoustic signal on the power of the heating laser at the fundamental frequency \( f_\text{H} = 16 \text{ kHz} \), which had been detected by the vibrometer, was determined. The experimental data in Fig. 2(a) indicate a transition from low to high efficiency of the optoacoustic conversion at \( f_\text{H} \), when the power of the cw heating laser increases from 40 to 120 mW. The strongest dependence of the optoacoustic conversion efficiency on the power of the heating laser is found at approximately 80 mW. This maximization phenomenon was documented earlier [14] in the experiments, where the acoustic waves were detected by a sensitive, in-contact accelerometer. Theory [15] attributes these observations to heating-induced transition of the crack from an open to a closed state.

From a physics point of view, thermoelastic generation of sound near the faces of an open crack is similar to that near a mechanically free surface and can be very inefficient [21]. Thermoelastic expansion of the locally heated region could first lead to creation of a small number of contacts between the crack faces and then to complete local closing of the gap between them. This process is accompanied by an increasing mechanical loading of one face of the crack by another, which can be viewed as a process of increasing the crack rigidity [15], with

![Fig. 2. (Color online) Dependence of the photoacoustic signal amplitude on the power of the heating laser at frequencies \( f_\text{H} \).](image-url)
a consequent increase in the optoacoustic conversion efficiency.

The results in Fig. 2(a) indicate that the rigidity of the crack is most sensitive to external action, i.e., the crack is the most nonlinear, acoustically, when the power of the heating laser is about 80 mW. This expectation is confirmed by the results of the frequency-mixing experiments, presented in Figs. 2(b) and 2(c). In these experiments, the heating green laser intensity is modulated at \( f_L = 1 \text{ Hz} \) and the acoustic signals at frequencies \( f_H \) and \( f_H \pm 2f_L \) are detected by a laser vibrometer [Fig. 2(b)] and by an in-contact accelerometer for comparison [Fig. 2(c)]. The maximum signals at mixed frequencies are detected at approximately 80 mW average power of the heating laser. The results in Fig. 2 demonstrate that the crack local nonlinearity, both in the open and closed states, corresponding to heating powers lower than 40 and higher than 120 mW, respectively, is weak in comparison with the nonlinearity of the crack in the state that is transitional from the open to the closed one. This transitional state is characterized by the incomplete local contact between the crack faces. Both in the open state, where there are no contacts between the asperities located at opposite faces of the crack, and in the closed state, where the contact between the crack faces is nearly perfect, crack rigidity weakly depends on elastic loading.

In Fig. 3 we present the results of one-dimensional photoacoustic imaging of a crack. In these experiments, conducted with a somewhat different sample, only the diode laser has been used with its intensity simultaneously modulated at \( f_L = 2 \text{ Hz} \) and \( f_H = 18 \text{ kHz} \). The frequencies \( f_H \pm 2f_L \) are detected by the probe beam deflection technique, which is tuned for the detection of the flexural waves propagating along the longest axis of the sample (Fig. 1). The position of the excitation beam relative to the crack was progressively modified in 50 µm steps by moving the sample in a direction perpendicular to the crack faces. From the data presented in Fig. 3, it follows that only the detection of mixed frequencies provides sufficient contrast for reliable determination of the position of the crack. In conclusion, we report here experiments, that demonstrate the utility of an all-optical method for studying the nonlinear acoustics of cracks. An important feature of the technique is the use of laser-induced heating to tune the crack locally to its most nonlinear state. The demonstrated all-optical initiation of nonlinear acoustic processes and detection of the nonlinear mixed frequency components in the acoustic spectrum suggest the possibility of fast and sensitive imaging of the cracks.

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References