Vacuum suppression of acousto-optic self-modulation in a broad-area Nd-doped yttrium-aluminum-garnet single-shot laser

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We report on the origin of an acousto-optic Raman-Nath self-modulation found in a broad-area Nd:YAG single-shot laser. Operating the laser device under vacuum conditions suppresses the spectral splitting associated with acousto-optic modulation by the shock waves produced by the discharge of the pumping flash lamps. This splitting is reproduced by a general class B laser model that takes into account the dynamical density grating generated by a stationary acoustic radial wave.

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The complex phenomena observed in high-power lasers form a vast and challenging field of research that has focused great attention during the last two decades. In class B solid-state lasers the nonlinear interaction of the laser field and the medium produces spatial and spectral hole burning, modal instabilities, restless optical vortex formation, beam filamentation, and many more complex phenomena [1–3]. Some of these effects reduce the spatial coherence, the energy yield or the general stability of the laser, and only a complete understanding of the dynamical processes involved can lead to the development of new laser devices free from these limitations. In other cases some of these phenomena can be exploited to create new applications or to achieve a better understanding of the nonlinear interactions that rule high-power laser spatiotemporal dynamics [4].

In a previous work [5] we reported a splitting of the transverse mode-beating frequencies of a broad-area Nd:YAG single-shot laser. We explained that finding as the coupling between the laser field and a stationary acoustic wave transverse to the direction of propagation through the Raman-Nath effect [6,7]. The hypothesis developed there is that this acoustic stationary wave is mainly originated by the shock waves produced in the surrounding air by the operating flash lamps, but as long as we didn't have experimental evidence against other mechanisms we couldn't discard alternative explanations. In the present work we present experimental evidence of the disappearance of the spectral splitting when the laser device is operated under vacuum conditions, which proves that the acoustic wave detected in our laser rod has been transmitted through the air. Therefore, this effect should be detectable in other pulsed laser devices pumped by flash lamps. In particular those aimed to provide a high-power output, where very intense currents are reached inside the lamps, should develop the dynamics under study in the present work. Moreover, the implications of a mechanical wave altering the density and thus the refraction index of the gain medium should be studied, as this dynamical anisotropy could play an important role in many nonlinear phenomena, such as spatial hole burning, transverse mode locking, or even in pattern formation and beam filamentation.

In our laser device the gain medium is placed in the center of a bielliptical cavity that has a flash lamp in each of its two outer focuses. When the laser shot is triggered the conductivity of these lamps changes violently and a very intense current breaks through them (see Fig. 2). Inside the pumping cavity two shock waves converge at the laser rod as the geometry of the chamber enforces this focusing. This sudden impact causes many vibrational waves to arise in the gain medium, although due to its cylindrical geometry it is expected that radial waves will play the most important role in the acousto-optic Raman-Nath modulation. Solving the pure radial wave equation in cylindrical coordinates a Bessel function of the first kind $J_1(\rho)$ is found as the spatial profile for the medium density, while the acoustic frequency can be approximately obtained thanks to the boundary conditions. An analysis of this equation gives a very good correspondence with the experimental findings [5].

In this work we confirm the previously explained mechanism by isolating the gain medium from the flash lamps without affecting the laser dynamics. We demonstrate the disappearance of the Raman-Nath modulation when the laser is placed inside a vacuum chamber operating at very low pressure (<1 mTorr). This setup inhibits the propagation of the shock waves from the lamps to the rod. Our measurements confirm that the air transmission is responsible for the most part of the vibrational energy transmitted to the laser rod.

Setup. The experimental setup is very similar as in Refs. [3,5] and is depicted in Fig. 1. The main device is a low-energy (<30 mJ) single-shot Nd:YAG laser that features a cylindrical laser rod 62 mm long and 6 mm in diameter. As stated before the optical pumping is produced by two parallel flash lamps, placed with the rod inside a double elliptical gold-plated pumping cavity. The lamps are excited by the discharge of a 100 μF capacitor allowing a maximum of 1600 V to be applied to the lamps. During laser operation the intensity crossing the lamps reaches up to 200 A (see Fig. 2). The 24 cm long laser resonator consists in a high reflectivity concave 10 m radius total reflector and a plane coupler (70% reflectivity).

In contrast with our previous experiments the laser device was placed inside a vacuum chamber instead of on the optical table where the rest of the setup remains. A vacuum of roughly 10^{-4} Torr is attained.

To record the local intensity we select an area of 125 × 125 μm^2 by means of a diaphragm mounted on two orthogonal micrometric screws and attached to a optical fiber bundle (3 mm of core diameter) that transports the acquired laser intensity to a fast photodiode ($\sim$1 ns rise time). This allows us to see the transverse mode beating absent in the total intensity. The resulting signal was recorded with a 6-GHz oscilloscope.

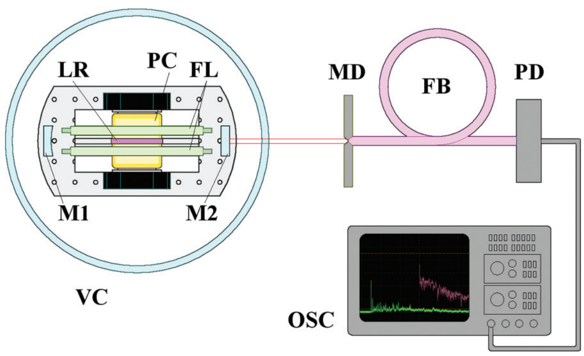

FIG. 1. (Color online) Experimental setup to measure local laser intensity outputs. VC: vacuum chamber; LR: laser rod; PC: pumping chamber; FL: flash lamps; M1: concave (10 m) total reflector; M2: plane output couple (70% reflectivity); MD: 125 x 125μm^2 moving diaphragm; FB: fiber bundle; PD: photodiode; OSC: oscilloscope.

To acoustically isolate the rod from the flash lamps we only need to lower the pressure until reaching a few torrs. However, at such pressure the electrical breakdown of the air can be produced between any point of the feeding circuit due to the Paschen effect [8]. To avoid this unwanted scenario we chose to reduce the pressure significantly below the limit at which the mean-free path between gas molecules' collisions is longer than our chamber dimensions. This pressure results to be ~2 mTorr [9], while the measurements were carried out at ~0.1 mTorr.

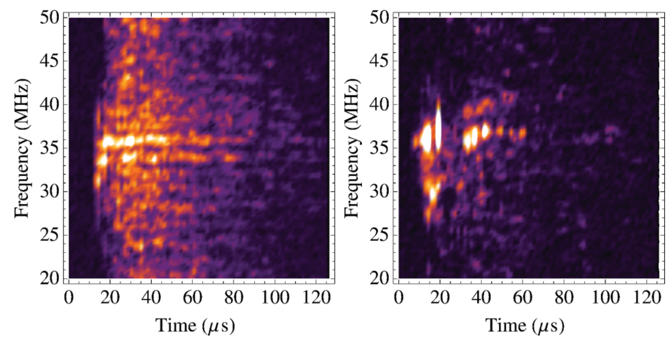

FIG. 3. (Color online) Left: Local intensity power spectrum evolution (spectrogram) at 750 V ($r = 2.73$) and atmospheric pressure. Ten laser output signals average. The superposition of the spectrograms of various shots draws straight, continuous lines every 1.6 MHz. The splitting transforms the expected transverse-mode beating line in a wide discrete band centered in the beating frequency. Right: Spectrogram at 750 V ($r = 2.73$) under vacuum conditions (less than 1 mTorr). Ten shots average. When the laser is shot in the absence of air the splitting disappears, resulting in an enhancement of the central line.

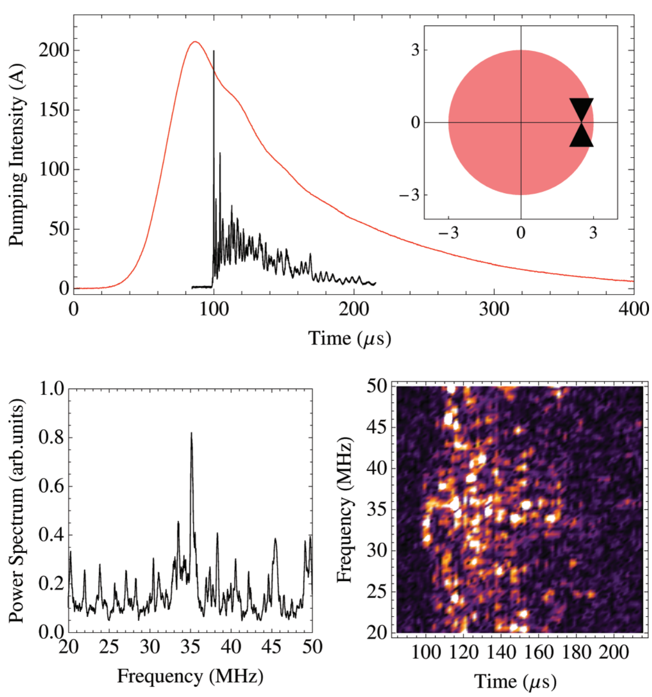

FIG. 2. (Color online) Top: Pumping current (red) and local intensity output (black, arbitrary units) at atmospheric pressure. Inset: section of the laser spot. The local intensity is measured at 2.5 mm from the center of the rod. Bottom left: local intensity spectrum of the same single laser output showing the transverse beating line, placed near 35 MHz, and many small splittings. Bottom right: local intensity spectrogram of the same shot. The transverse beating is visible over a wide area centered on the expected frequency of 35 MHz. In this single-shot spectrogram the relaxation oscillations are distinguishable as intensity variations every 20 μs. Since at the beginning of the laser output these oscillations are not synchronized, averaging over many shots makes this oscillation disappear.

The coupling between the optical field and the acoustic waves can be seen in the spectrogram of the local intensity as a splitting of the peaks corresponding to the transverse mode beating. This splitting can be observed at any selected point within the laser spot. However, it is in the outer shell of this spot where well-defined sidebands can be seen [5] therefore revealing a stronger coupling in this area. Moving the diaphragm mounted on two orthogonal micrometric screws allows us to focus in these places for a better comparison between air and vacuum conditions.

Results. Figure 3 depicts the experimental average spectrogram of the local intensity evolution of ten different output signals at atmospheric pressure (left) and vacuum conditions (right). In the first case the density modulation induces a multiple spectral scattering, so the expected averaged beating frequency splits in a band of continuous lines placed every 1.6 MHz, the frequency of the stationary acoustic wave. In the latter case the transverse beating is still visible but no splitting is noticeable, in agreement with our hypothesis.

The expected frequencies of the resonator can be estimated using [10] $\omega_{q,m,n} = \frac{\pi c}{L}[q + \frac{\Delta\varphi}{\pi}(m + n + 1)]$ [11], where L is the optical length of the laser cavity, $\Delta\varphi$ is the variation of the Guoy phase and q, n, and m are integers. It must be noted that although transverse modes are defined in cw lasers their application to transient dynamics is completely correct [12]. This equation gives an axial beating of 565 MHz while transverse modes will generate an interference of about 30 MHz (and its respective harmonics). Taking this into consideration we can conclude that the band present in Fig. 3 and centered in 35 MHz has a transverse origin.

To find a clear and wide splitting it is crucial to choose an appropriate point in the laser spot. The spatial grading is more intense where the stationary acoustic wave reaches its

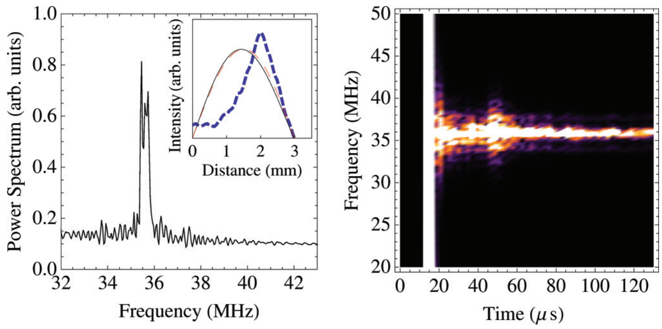

FIG. 4. (Color online) Left: Local intensity spectrum at 2.6 mm from the center of the beam, obtained from the numerical integration of Eqs. (1) and (4). The amplitude of the acoustic wave is $\epsilon = 0.05$, and $\lambda_{ac} = 6$ mm. Inset: Bessel function $J_1(kr)$ (black, thin line), $\sin(r)$ function (red, dashed line) and experimental population inversion (blue, thick, small-dashed line). The amplitude of the acoustic stationary wave matches that of the Bessel function $J_1(kr)$. Right: Spectrogram of the same simulated laser intensity output. Splitting of the transverse-mode beating peaks with a separation of 1.6 MHz between lines is obtained, in agreement with the experimental findings.

maximum, and the amplitude profile of the stationary wave matches that of the Bessel function $J_1(kr)$, which shows its first two zeros in $kr_0 = 0$ and $kr_0 = 3.8$ and its first maximum in $kr = 1.83$ (see inset in Fig. 4). As $r_0 = 3 \times 10^{-3}$ m must be the radius of our YAG rod the position of the second zero gives $k = 1226$ m^{-1} and thus the first maximum of $J_1(kr)$ will be in $r = 1.5$ m^{-3}. It must be pointed out that the place where the stationary acoustic wave is more intense is not necessarily the point where a higher splitting will be observed, as optical pumping losses and nonlinear optical effects also have an important role in the coupling between transverse mode beating and acoustic oscillations (for a comparison of the splitting recorded in different points see Ref. [5]). As a result of all of these phenomena the scattering of the optical field is much more effective in the outer parts of the laser rod (see inset in Fig. 4 for a comparison between the first Bessel radial function and the pumping profile in a 6 mm diameter laser rod). In our laser device the most optimal points for recording the splitting were located 2.5 mm from the center of the ∼6 mm wide circular beam and thus very close to the spot border.

It must be noted that even in vacuum conditions the gain medium mechanical isolation from the flash lamps is not complete. As the laser rod and flash lamps are mounted on a teflon body vibrations can still propagate from the flash lamps to the gain medium. However, this mechanism seems to have a much weaker influence on the active medium than direct air-mediated excitation, according to our measurements. As expected and aside from the inhibition of the splitting no further change is observed in the spectrum of the local intensity in the MHz range.

Numerical model. In order to explore the insights of acousto-optic splitting we performed numerical simulations including the density modulation generated by stationary radial acoustic waves inside the laser rod, finding a very good agreement with our experimental measurements. It is worth mentioning that our simulations do not rely on a description of the dynamics based on a small subset of empty cavity modes or on universal order parameter equations as it is customary to reduce the complexity of the system. In contrast, we integrated the full Maxwell-Bloch system of equations without any previous assumption, apart from the standard adiabatic elimination of the polarization [13] for class B lasers. This model has proved to be of great numerical performance and physical precision, and reproduces our laser dynamics not only qualitatively but also quantitatively [3].

This system, under the mean-field, rotating-wave, slowly varying envelope and adiabatic approximations and assuming zero detuning of the laser frequency with respect to the atomic frequency, is

$$\frac{\partial E}{\partial t} = ia(\nabla_\perp^2 - 4s^2)E + [D - \eta(x,y)]\,E \tag{1}$$

$$\frac{\partial D}{\partial t} = -\gamma[D - r(t,x,y) + |E|^2 D]\,, \tag{2}$$

where Eq. (2) must be modified to include the acoustic wave excitation. In these equations $E(t,x,y)$ and $D(t,x,y)$ are the dimensionless slowly varying amplitudes of the electric field and macroscopic population inversion, respectively. The transverse Laplacian term in the field equation, with coefficient a, accounts for the diffraction, while $\vec{s}$ represents the dimensionless transverse coordinates normalized to the beam waist of the fundamental Gaussian mode. The inclusion of the term $-4ias^2$ accounts for the phase shift induced by the presence of the spherical mirror while the losses profile is represented by $\eta(x,y)$. The dimensionless time $\tau = t\kappa$ is used in both equations, with $\kappa = 1.38 \times 10^9$ s^{-1} being the inverse of the photon lifetime and its value chosen to fit the simulated spectra with experimental observations. On the other hand $\gamma = 3.1 \times 10^{-6}$ is the population constant decay, normalized to κ, while $r(t,x,y)$ is the pumping parameter and its temporal evolution was matched to the experiment (see Fig. 2).

The shock-wave induced acoustic wave can be included in Eq. (2) by modifying the density function, implicit in that equation because $D(x,t)$ is defined as $D(x,t) = \rho(x,t)d(x,t)$, where $d(x,t)$ is the microscopic population inversion. As stated before we introduced a density time- and space-varying modulation of the form

$$\rho(x,t) = \rho_0[1 + g(x,t)]. \tag{3}$$

Here $\rho_0 = 4.55$ g/cm^3 is the medium density and $g(x,t) = \epsilon\,\cos(2\pi\nu_{ac}t)\sin(2\pi x/\lambda_{ac})$ represents the density variation due to the stationary acoustic wave. In this equation λ_{ac} stands for the acoustic wavelength, $\nu_{ac} = V/\lambda_{ac}$ and $V = 9566$ m/s is the velocity of sound in Nd:YAG [5]. For simplicity we used sinusoidal density modulations instead of the radial waves described by the Bessel function (see inset in Fig. 4 for a graphical comparison between both functions).

As explained in our previous paper [5] and after some algebra Eq. (2) is transformed to

$$\frac{\partial D}{\partial t} = -\gamma[Df(x,t) - r(t,x,y) + |E|^2 D], \tag{4}$$

where $f(x,t) = 1 - (2\pi\nu_{ac}/\gamma)g(x,t)$. The inclusion of this new term leads to the appearance of a low-frequency modulation on top of the laser field dynamics. This new oscillation translates into the splitting of the transverse-mode beating peak, as it can be seen in the spectrogram of the simulated local density at 2.6 mm, shown in Fig. 4. The numerical results are in very good agreement with the experimental measurements, even considering a sinusoidal wave instead of the more realistic case of the Bessel function. Therefore, the studied effect does not fundamentally depend on the acoustic wave spatial profile but only on the coupling of the laser field with the generated density grating in the medium. The amplitude of this modulation is given by coefficient ϵ, which in our case we took as 0.05, i.e., a 5% modulation of the reference value ρ_0.

Conclusion. Removing the air inside the bielliptical cavity and therefore preventing the propagation of compression waves generated by the flash lamps inhibits the multiorder [14] splitting of the optical transverse field. This result supports our hypothesis that the Raman-Nath effect is responsible for the splitting through the coupling between an stationary acoustic wave, excited by a shock wave induced by the flash lamps, and the laser field. This unexpected splitting evidences a acousto-optic self-modulation of the local intensity. This effect is expected to be present in other pulsed laser systems pumped by flash lamps as it is the violent explosion produced in their discharge the origin of the effect and not a particular geometry of the cavity or gain medium. To this day most pulsed gain mediums are studied and modeled considering that their density—and so their index of refraction—features only the thermal lens anisotropy. We have demonstrated that this image is not complete enough when trying to reproduce some aspects of the local intensity dynamics.

Looking for this modulation in different materials, such as phosphate or silicate Nd-doped laser rods, is a subject for future research. The different mechanical properties of these gain media would allow the rise of stationary waves of different shape and frequency, and the resulting splittings will have separations than can be calculated in the same way we did with Nd:YAG.

Additionally, a careful tailoring of the characteristics of the gain medium or a controlled excitation of the vibrational waves could result in an enhanced and controlled spectral splitting and thus may be a simple and reliable source of optical multiplexed signals in the MHz spectrum.

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