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The influence of the inhomogeneous gain profile on the spatio-temporal dynamics of broad-area class B lasers

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Abstract
A study on the spatio-temporal dynamics of broad-area Nd:YAG (yttrium aluminium garnet), Nd-doped phosphate glass and Nd-doped silicate glass lasers is presented to show the influence of the inhomogeneous gain profile and cross-relaxation phenomena on the spatio-temporal dynamics of the system. The suppression of the order–disorder transition shown in Cabrera et al (2006 Opt. Lett. 31 1067) for homogeneously broadened class B lasers is found for both glass lasers, independently of the strength of the cross-relaxation mechanisms. The results obtained indicate that a higher degree of inhomogeneous broadening leads to suppression of the filamentation in the transverse intensity pattern.

Keywords: laser, spatio-temporal dynamics, patterns

1. Introduction

Broad-area lasers are widely used where high output power is needed. The requirements of high gain and good heat dissipation make these lasers suitable candidates for applications. However, wide-aperture lasers develop complex spatio-temporal dynamics when operated above the laser threshold, including vortex dynamics [1], filamentation [2, 3], optical turbulence [4, 5] or intermittent dynamics [6]. Although applications such as parallel optical processing [7, 8] or situations where speckle must be reduced [9] can benefit from these complex regimes, this feature is generally assumed to be a harmful effect. Broad-area lasers usually suffer from emission of high-order transverse modes, which reduce the beam quality. Besides that, focused partially spatial coherent beams show large differences with respect to the fully coherent case [10].

Recently, a dynamical transition from boundary controlled intensity patterns to disordered patterns has been measured in a large-aperture homogeneously broadened Nd:YAG laser [11] and broad-area VCSELs [12]. The transition time to disorder depends on pumping and on the characteristic time constants of the population inversion and cavity field dynamics. Higher pumping and shorter population decay times cause the transition to take place at earlier times. Suppressing this transition would improve the beam quality and the spatial coherence of the output emission in class B lasers. Therefore, whether is possible or not to suppress or delay this transition arises as a natural question.

Controlling the spatio-temporal instabilities has been addressed in different works during the last decade. Most of them rely on the insertion of intracavity elements in order to produce weak spatial perturbations [13, 14]. Feedback with a Fourier-filtered controlled signal [15, 16] has also provided good results, stabilizing different patterns and avoiding the generation of spatial instabilities. Recently, theoretical and experimental studies on inhomogeneously broadened lasers have revealed significant differences in the spatio-temporal dynamics of these lasers. Using the parameters of far-infrared lasers (FIR) and He–Xe lasers, and for an infinitely transverse area, it was shown in [17] that the critical traveling wave selected at the first laser threshold persisted for higher pump values than the homogeneous broadened case. Besides that, the inhomogeneous profile provided a selection in the number of spatial frequencies for higher pumping. Mukherjee et al [18] theoretically studied the spatial dynamics of quantum-dot lasers. An improvement in the spatial coherence of the output beam was found when increasing the degree of inhomogeneous broadening.

These theoretical studies are based on a simplified model of the full integro-differential system of Maxwell–Bloch
equations for the single-mode inhomogeneously broadened laser. This approach was first introduced by Idiatulin and Uspenskii [19], and relies on a judicious discretization of the inhomogeneous gain profile in the spectral domain. Following this approach, Mezziane [20] studied the temporal dynamics of an inhomogeneously broadened laser and the emergence of self-pulsing behavior. They showed that a discretization of the gain profile with only three suitably spaced spectral components leads not only to qualitative but quantitative agreement with the experimental results for FIR lasers and He–Xe lasers. Including the spatial degrees of freedom makes it necessary to extend the discretization to at least five different components, as was shown in [17].

There are very few experimental results on the spatio-temporal dynamics of inhomogeneously broadened lasers. Huyet et al. [22] studied the spatio-temporal chaos arisen in a CO₂ laser at a pressure of 15 mbar, where the inhomogeneous Doppler broadening starts to contribute. However, at this pressure homogeneous collision broadening is still dominant. Works on He–Ne spatio-temporal dynamics have been reported as well [23], though no broad-area lasers have been explored. Quantum-dot lasers have also been studied experimentally [24], and a comparative analysis with a quantum-well laser with identical geometry has shown less filamentation and improvement of the beam quality in the former case. Very recently some of the authors measured instantaneous intensity profiles along the evolution of the output pulse for a Nd-doped phosphate glass laser [25]. A comparison of the measured dynamics with the already known case of the homogeneously broadened Nd:YAG laser [11] was also performed. The suppression of the order–disorder transition was found for a larger range of pump values used in the experiment, and for 10 times longer evolution times of the output laser pulse. However, the saturation properties of the Nd-doped phosphate glass more closely resemble a homogeneous broadening than a pure inhomogeneous gain profile [26]. Fast cross-relaxation mechanisms between different spectral components under the broad gain profile lead to a rapid exchange of the excitation between different atom packets. Therefore, gain saturation is more similar to a homogeneous line, and no spectral hole burning takes place [27]. Besides that, Mezziane [20] also showed that the inclusion of cross-relaxation terms increases the threshold of the appearance of temporal chaotic behavior for a single-mode inhomogeneously broadened laser. The presence of these processes could cause a minor excitation of each homogeneous atom packet due to the fast spreading of the excitation supplied by the pump, which consequently could suppress the transition to disorder. Thus, experimental results on the spatio-temporal dynamics of an inhomogeneously broadened laser with slow cross-relaxation phenomena must play an important role in order to clarify the effect of the inhomogeneous linewidth on the transverse pattern evolution.

To compare the obtained results with previous measurements, we have chosen as active medium a Nd-doped silicate glass. Because of their slower cross-relaxation mechanisms, Nd-doped silicate glasses tend to saturate much more inhomogeneously than do phosphates [21]. Table 1 summarizes the optical and thermal features of this medium, compared with the Nd:YAG rod studied in [11] and the Nd-doped phosphate glass used in [25].

### Table 1. Optical and thermal properties of the compared laser.

<table>
<thead>
<tr>
<th>Material</th>
<th>Nd-doped silicate glass</th>
<th>Nd-doped phosphate glass</th>
<th>Nd:YAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal expans. (10⁻²°C⁻¹)</td>
<td>90</td>
<td>99</td>
<td>80</td>
</tr>
<tr>
<td>Thermal conduct. (W m⁻¹ K⁻¹)</td>
<td>1.30</td>
<td>0.82</td>
<td>14</td>
</tr>
<tr>
<td>Fluorescence lifetime (µs)</td>
<td>330</td>
<td>350</td>
<td>230</td>
</tr>
</tbody>
</table>

2. Experimental results

The experimental setup is the same as that used in [11] and [25]. The laser is an air-cooled, low-pulse-energy (~70 mJ) flash-lamp-pumped prototype. As in the measurements described in those works, we use the same cavity geometry, formed by a high reflectivity mirror with a radius of curvature \( R = 10 \) m and a plane output coupler with reflectivity of 0.95. The Fresnel number of the system reaches a value of 35 for the Nd:YAG laser and 39 for Nd:glass lasers. This difference comes out because of the different refractive index of both rods. The same active medium dimensions and pump system were used to neglect the influence of different boundary conditions on the spatial dynamics. The active medium is a Nd-doped silicate glass, where the host is the Q-246 silicate (Kigre, Inc.). We run the laser in single-shot operation to avoid the effect of the different values of the thermal conductivity (see table 1) and thermal lensing appearance, while thermal expansion coefficients are very similar in Q-98 phosphate glass and Q-246 silicate glass. Therefore, differences caused by thermal induced birefringence can be neglected as well. However, careful analysis of these thermal effects should be done if this work is to be extended to continuous mode operation. Finally, no significant differences can be found in the fluorescence lifetime in the three materials compared in this study. Thus, only the inhomogeneous broadening and the cross-relaxation effects are expected to play a significant role in the spatio-temporal dynamics. A non-polarizing beam splitter (50:50) was placed behind the output coupler to separate the beams. The transmitted beam was carried to a photodiode (1 ns rise time), while the reflected beam reached an intensified IR-enhanced CCD camera with a 768 pixel × 494 pixel array. The spatial resolution was 50 µm/pixel, which allows us to observe the spatial structure forming the pattern. The minimum integration time for the recorded patterns was 1 ns, much lower than the characteristic time of the local intensity evolution. We take one snapshot per pulse. Both the integration time and the time within the pulse at which we record the snapshots (time delay) were computer controlled.

Let us summarize the first results previously obtained in Nd:YAG lasers [11] and Nd-doped phosphate glass lasers [25]. As has been mentioned before, high-order Gauss–Hermite modes or standing waves composed the intensity patterns in
Figure 1. Transverse intensity patterns for (a) Nd:YAG and (b) Nd-doped phosphate glass laser. (a) Pumping 2.7 times above threshold and 77 μs of delay. (b) Pumping 4.8 times above threshold and 31 μs of delay. Units in mm in both figures.

Figure 2. Transverse intensity patterns for Nd-doped silicate glass laser at different times along the pulse evolution. (a) 7 μs, (b) 8 μs, (c) 24 μs and (d) 50 μs. Pump energy 4 times above threshold. Units in mm in all the figures.

Figure 3. (a) Transverse pattern for Nd-doped silicate glass laser at pumping 4 times above threshold and 7 μs of delay. (b) Spatial Fourier spectrum of pattern shown in (a). (c) Average spatial Fourier spectrum of 10 transverse patterns measured at the same delay. (d) Transverse pattern for Nd-doped silicate glass laser at pumping 4 times above threshold and 50 μs of delay. (e) Spatial Fourier spectrum of pattern shown in (d). (f) Average spatial Fourier spectrum of 10 transverse patterns measured at the same delay. Units in mm in figures (a) and (d) and mm$^{-1}$ in figures (b), (c), (e) and (f).

Figure 4. Spatial power spectra of Nd:YAG (top row) and Nd-doped silicate glass (bottom row) lasers. (a) and (d) show the spectra at the beginning of the output pulse, while (b) and (e) and (c) and (f) show the spectra at 200 and 250 μs, respectively.

measured in [25] is shown together with the average spectrum in the upper row of figure 4 for comparison purposes. On the other hand, and for similar pumps, Nd:YAG lasers presented highly disordered patterns since almost the beginning of the laser emission. A smaller and not constant characteristic length due to the filamentation in many spatial structures after the dynamical transition to disorder was also found (see bottom row of figure 4). During this stage loss of spatial coherence is
expected and cross-correlation between the temporal evolution of the local intensity in two spatially separated points of the transverse plane will suffer a rapid decay with the separation distance. Figure 5 represents the measurements of the spatial correlation for the three solid state lasers analyzed at the highest pump we were able to achieve with our experimental setup. The local intensity is measured by two small diaphragms of 100 × 100 µm² (smaller than the observed spatial structures) located after the laser output. One of them is placed on a translation stage, which allows one to obtain series of data at different positions across the beam. Behind both diaphragms, two fiber optic bunches transmit the light to two photodiodes (1 ns rise time). Finally, the local intensities are recorded in a 6 GHz bandwidth oscilloscope. The values shown in figure 5 are calculated according to the formula,

\[
C(x_0, \Delta x) = \max \left[ \frac{\int_{-\infty}^{\infty} I_1(x_0, t) I_2(x_0 + \Delta x, t + \tau) \, dt}{\sqrt{\int_{-\infty}^{\infty} I_1(x_0, t)^2 \, dt \int_{-\infty}^{\infty} I_2(x_0 + \Delta x, t)^2 \, dt}} \right], \tag{1}
\]

where \(I_1(x_0, t)\) and \(I_2(x_0 + \Delta x, t)\) are the normalized local intensities measured at the points \(x_0\) and \(x_0 + \Delta x\) at the transverse plane, respectively. It can be seen how, as expected, the spatial correlation rapidly decays in the disordered stage of the Nd:YAG laser, pointing out that each spot in which the transverse intensity profile breaks up follows an almost independent evolution. On the contrary, both Nd:glass lasers show a higher degree of spatial correlation, which reflects the ordered spatial structures that fill the transverse plane.

Figure 5 also shows a slower decay of the spatial correlation in the Nd-doped silicate glass, compared with the Nd-doped phosphate glass. This can be a consequence of the larger inhomogeneous linewidth in the former case, being \(\Delta_{\text{val}} \simeq 80\, \text{cm}^{-1}\) and \(\Delta_{\text{phos}} \simeq 60\, \text{cm}^{-1}\). The characteristic time of cross-relaxation mechanisms, absent in Nd:YAG and much slower in silicate than in phosphate glass lasers, seems not to play a role in the phenomenon, being only related to the degree of inhomogeneous spectral broadening.

However, \(C(x_0, \Delta x)\), as calculated with equation (1), only accounts for linear correlation. To clarify if there is any non-linear dependence between local intensities, we follow the approach of Huyet et al [22] and calculate the higher correlation moments, defined as,

\[
C_{pq}(x_0, \Delta x, \tau) = \max \left[ \frac{\int_{-\infty}^{\infty} I_1(x_0, t)^q I_2(x_0 + \Delta x, t + \tau)^r \, dt}{\sqrt{\int_{-\infty}^{\infty} I_1(x_0, t)^{2q} \, dt \int_{-\infty}^{\infty} I_2(x_0 + \Delta x, t)^{2r} \, dt}} \right]. \tag{2}
\]

The results for the different lasers can be seen in figure 6 where the linear correlation is also shown for comparison. Higher non-linear correlations are always smaller than linear correlation for the whole range of \(\Delta x\). Therefore, linear correlation obtained with equation (1) gives the most relevant measurement and accounts for the decorrelation of the local intensity across the pattern.

Filamentation in broad-area lasers is usually explained as a spatio-temporal instability of the high-order transverse modes sustained by broad-area lasers. To see if spatial modes are still present in the dynamics of the Nd:YAG laser, the temporal Fourier spectrum of the local intensity has been calculated. Figure 7 compares the spectra of the local intensity for the three lasers at a pump energy 4.5 times above threshold, where the transition to disorder takes place at very short times from the beginning of the laser emission in the Nd:YAG laser. Peaks
Figure 6. $C_{pq}(t, \Delta x)$ cross-correlation moments for (a) Nd:YAG, (b) Nd-doped phosphate glass and (c) Nd-doped silicate glass. Corresponding to axial and transverse mode beating are clearly recognizable for all of the lasers (see figure inset for details of transverse modes peaks). Due to the difference in the index of refraction between glass and YAG matrix, the positions of the peaks are slightly shifted. Therefore, spatial modes contribute to the dynamics even when filamentation in small and disordered structures is present. This result was also obtained in broad-area CO$_2$ lasers [2] in a similar dynamic regime. On the other hand, Huyet et al [22] showed in a CO$_2$ laser as well, that for larger Fresnel numbers ($F > 30$), the peaks associated with transverse modes disappear, leading to spatio-temporal chaos. Although the Fresnel number of our broad-area Nd:YAG laser reaches a value of $\sim 40$, the presence of transverse modes reveals a not so disordered dynamics as in the case of [22].

Moreover, this beat frequency due to modal interference has been resolved in the power spectrum of the global intensity, where a spatial integration of the whole transverse beam profile was carried out. Figure 8 shows the spectra of Nd:YAG and Nd-doped phosphate glass global intensities. The spectrum corresponding to Nd-doped silicate glass is not shown for the sake of clarity, but presents the same peak as the Nd-doped phosphate glass spectrum. This feature cannot be explained by the presence of conventional Hermite–Gauss transverse modes, where a spatial integration would cause the transverse mode beat frequency to vanish due to perfect orthogonality between modes. Thus, non-orthogonal transverse modes must be present in the spatio-temporal dynamics of the lasers under study. This type of mode has been previously reported in other laser systems. Otsuka et al [33] studied a sheet-like end-pumped LiNdP$_3$O$_12$ laser, showing beat frequency peaks in the global oscillation spectrum due to non-orthogonal transverse modes. In this case, the strongly asymmetric pump profile causes an asymmetric refractive index distribution in the transverse direction through the thermally induced refractive index change. Consequently, the lateral symmetry is lost, and the cavity eigenmodes are no longer the usual Hermite–
Gaussian resonator modes, but depend on the temperature distribution caused by the pumping. Besides that, Kawai et al [34] reported the appearance of this kind of mode in a highly-doped microchip Nd:YAG ceramic laser. Here, the spatial inhomogeneity across the beam caused by the high doping concentrations was responsible for the appearance of non-orthogonal transverse modes.

In our laser system, the three active media are cylindrical rods side pumped by two parallel linear flash lamps. The rod and the flash lamps are located inside a double elliptical gold-plated cylindrical pumping cavity. Inside this cavity, the two linear flash lamps are placed at the focus of the ellipses along the cylindrical cavity, while the rod is placed between the lamps in the same horizontal plane (see [11] for further details). In this configuration, pump distribution across the transverse plane of the rod may not be radially symmetric. Then, an asymmetric gain distribution may be expected and non-orthogonal transverse distributions may be sustained. This theory is supported by the competition between a ‘Cartesian symmetry’ imposed by the pumping geometry and circular symmetry due to the cylindrical rod that can be seen in the intensity patterns of the three lasing media. A deeper study on the dynamics and characteristics of these non-orthogonal modes is being carried out by our group and will be addressed in a future work.

3. Discussion of the results

The experimental findings shown in this work can be counterintuitive at first glance. Inhomogeneously broadened lasers are known for showing a lower second laser threshold for temporal instabilities. Thus, more complex spatial intensity profiles could be expected for these type of lasers when the aperture is increased. However, previous theoretical studies based on Maxwell–Bloch semiclassical equations predict less filamentation and an improvement of spatial coherence with increasing degree of inhomogeneous broadening. Mukherjee et al [18] showed by means of a stability analysis of the nonlasing solution, a general flattening of the neutral stability curve. Therefore, a strong competition between spatial waves with different wavenumbers can be expected. This result was also obtained in [17] by some of the authors. In spite of that, Mukherjee et al found that the spatial homogeneous solution is selected just above threshold. Besides that, they showed that spatial frequency selection in inhomogeneously broadened lasers becomes independent of the linewidth enhancement factor $\alpha$ and cavity detuning in opposition to the homogeneous broadened case. The role of this parameter in spatial dynamics was previously studied by several authors [35, 36]. A larger value of this factor leads to an increase of filamentation. Therefore, an independent spatial frequency selection of the $\alpha$-factor is a significant result found in inhomogeneously broadened quantum-dot lasers. Although it is well known that solid state lasers present a smaller $\alpha$-factor than semiconductor lasers, recently experimental measurements of this parameter in a Nd:YAG microchip laser evidence a rather large value of the linewidth enhancement factor in the range of unity [37]. This opens the question if similar mechanisms take place in our solid state laser and the quantum-dot lasers studied in [18].

Another mechanism that may play a role is the presence of spatial hole burning, which may lead to several axial modes oscillating. In spite of this, the close agreement between numerical simulations performed with the single-mode Maxwell–Bloch system of equations and the experiments in Nd:YAG lasers seems to indicate that all the excited longitudinal modes perform the same spatio-temporal dynamics (see [11]). This has already been shown in CO$_2$ lasers, where despite the presence of different axial modes, the single-mode semiclassical model described very accurately the spatio-temporal dynamics of the system [2]. In any case, the mentioned agreement with the single-mode models show that no important role is played by the many excited axial modes in the dynamical transition to filamentation. Moreover, the experimental results shown in the present manuscript agree qualitatively well with the predictions made by Mukherjee et al in [18], where again a single-mode model is used to theoretically address the influence of the inhomogeneous broadening on spatial dynamics.

Besides that, the results presented in this work clarify the role of the cross-relaxation effects in the spatio-temporal dynamics of Nd-doped glass lasers, open in [25]. In this reference, the Nd-doped phosphate glass laser was studied, showing the same suppression of filamentation found in Nd-silicate lasers. However, the effect of the degree of inhomogeneous broadening could not be separated from the spreading of the excitation caused by fast cross-relaxation mechanisms. In this work it is shown that these mechanisms do not play an important role on the spatial dynamics but it is the inhomogeneous broadening that is responsible for the behavior found in both types of Nd:glass lasers.

4. Conclusions

In conclusion we have analyzed the influence of inhomogeneous broadening on the spatio-temporal dynamics of class B lasers. Time-resolved measurements of the pattern evolution of a broad-area Nd-doped silicate glass allow us to compare its dynamics with Nd:YAG and Nd-doped phosphate glass lasers. New measurements of the spatial correlation of the three lasers show that the inhomogeneous gain profile tends to suppress the transition to disorder measured in [11]. The comparison between the dynamics of Nd-doped silicate glass and Nd-doped phosphate glass shows no significant influence of the cross-relaxation mechanisms in the suppression of such transition. These measurements support the theoretical predictions made in [17] and [18] where the inclusion of inhomogeneous broadening was shown to suppress the filamentation and improve the spatial coherence of the laser beam. Generation of non-orthogonal transverse modes has been observed due to light amplification asymmetry caused by the pumping geometry. This feature is shared in the three lasing media studied in the present work.

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