Time-Resolved Dynamics of Two-Dimensional Transverse Patterns in Broad Area Lasers

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We report the first direct experimental observation of the fast dynamics (nanosecond scale) of complex two-dimensional transverse patterns in broad area lasers. The laser emission bright peaks forming the transverse patterns are observed to be aperiodically flashing in time with different growing rates. These optical filaments do not move along the cross section during their lifetime, which is close to 2 ns. The experimental observations have also been reproduced by numerical integration of the Maxwell-Bloch equations.

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The formation and dynamics of transverse light patterns in broad area lasers and other nonlinear optical resonators have been a field of intense research in recent years [1–10]. In these systems, the pattern formation is dominated by bulk parameters and nonlinearities of the active medium, and they can exhibit a spatiotemporal chaotic dynamics which is usually called *optical turbulence* due to its analogy to hydrodynamic turbulence. However, there is a limiting factor to the experimental observation of this phenomenon: the observation of laser transverse patterns are usually limited to the time-averaged intensity with an integration time much greater than the typical fast time scale of the dynamics ($\geq$1 MHz). These time-averaged patterns show boundary determined nearly regular structures, as has been found in CO_2 lasers [10–13] and solid-state lasers [14,15]. More complex time-averaged patterns have been found in a vertical cavity surface emitting laser [16]. This behavior was associated with a combination of a polarization instability and the onset of multimode operation.

On the other hand, the spatiotemporal dynamics of regular broad area semiconductor lasers has been directly observed [17,18]. In this type of laser there is only one relevant transverse dimension and therefore the transverse patterns are 1D [19]. This fact allows to measure the time evolution of 1D instantaneous patterns by using a single-shot streak camera [18]. The formation and migration of filamentlike structures have been observed.

In a recent work, a novel technique was developed to obtain 2D infrared instantaneous laser patterns [20]. This setup allowed us to measure a single image per pulse, the minimum exposure time being 1–2 ns. By using this technique we were able to measure for the first time the 2D instantaneous transverse patterns in a broad area CO_2 pulsed laser [7,21]. The instantaneous laser pattern consists of a bunch of bright peaks randomly distributed in the transverse cross section. Yukalov studied theoretically the phenomenon of *turbulent photon filamentation* in broad area lasers [22]. He explained that these filaments are stretched along the cavity axis, aperiodically flashing in time, and are not correlated with each other.

However, up to now, it has not been possible to directly observe the fast dynamics of two-dimensional transverse patterns in broad area lasers, since it is not yet possible to measure the instantaneous intensity pattern of a laser along the time [13]. Motivated by this, and in order to observe the behavior of the laser emission bright peaks [7], we have developed a novel experimental setup that allows to measure two consecutive 2D instantaneous transverse patterns. These two instantaneous patterns are separated by a short-time delay which can be controlled. Therefore, by using this new technique we get an insight into the pattern formation and evolution problem in broad area lasers.

The experimental setup consists of a pulsed transversely excited atmospheric (TEA) CO_2 laser with a N_2: CO_2: He = 1: 4: 18 gas mixture. The Fresnel number is $\mathcal{F} = b^2/(\lambda L) \simeq 10$, where the resonator length is $L =$ 1 m, the laser aperture is $2b = 20$ mm, and the lasing wavelength is $\lambda = 10.6$ μm. An intracavity Brewster plate has been introduced to obtain a linearly polarized beam. The laser produces a 2 μs pulse composed of a short (60 ns width) high power gain-switch peak followed by a long quasistationary collisional transfer tail. Two consecutive quasi-instantaneous measurements of the pulse transverse profile are obtained with a fast opti-

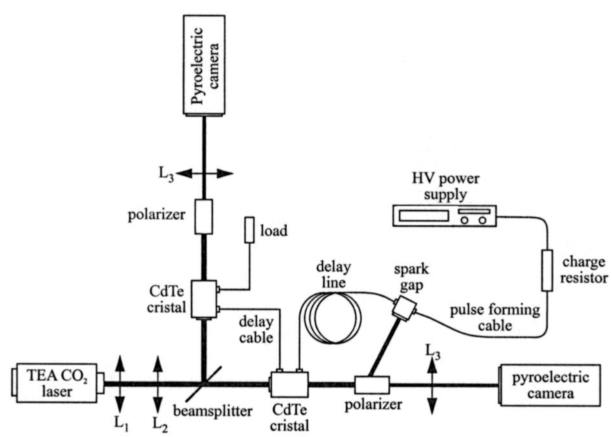

FIG. 1. Experimental setup.

cal switching device (see Fig. 1). The system mainly consists of two CdTe crystals, two polarizers positioned with their transmission axes perpendicular to the laser polarization direction, and a beam splitter (50:50) that splits the laser beam. The transmitted and reflected beams from the beam splitter are directed to each one of the CdTe crystals. To cut the laser time slices, a high-voltage pulse ($V_\pi = 8.48$ kV) is used to produce a transverse Pockels effect in the CdTe crystals. This turns the polarization of the linearly polarized laser beam 90°. The beams are transmitted by the crossed polarizers as long as the high-voltage pulse lasts in each CdTe crystal. The switching system is self-fired using a spark gap that collects the rejected light from one of the polarizers. The voltage pulse duration τ is determined by the length of the coaxial pulse-forming line that links the spark gap and the high-voltage charge resistor and was kept as low as possible ($\tau = 1.7$ ns). Likewise, the relative position of the time slice within the laser pulse depends on the length of the delay line that links the spark gap and the switching device. The voltage pulse first reaches the CdTe crystal that is irradiated by the beam splitter transmitted beam, and then, through the delay cable, reaches the CdTe crystal irradiated by the beam splitter reflected beam.

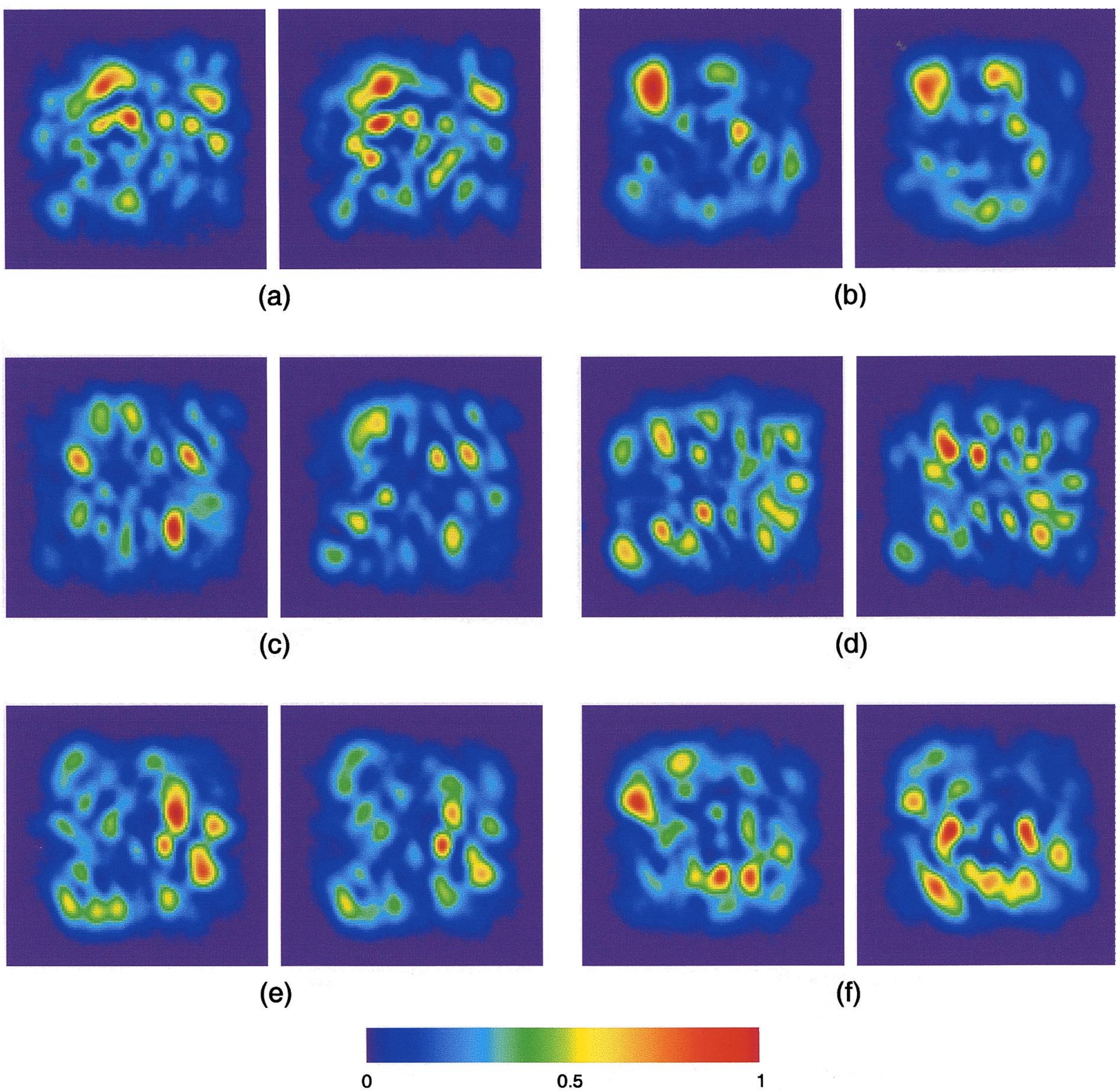

FIG. 2 (color online). Six representative pairs of instantaneous consecutive patterns separated by a time delay $t_d = 0.6$ ns. The transmitted pattern (left) is recorded a time t_d before than the reflected pattern (right). Experimental pattern dimension 20 × 20 mm.

The time delay t_d between both laser time slices is controlled by the length of the delay cable and in the experiment, was varied in the 0.6–6.7 ns interval. The transverse intensity pattern of each time slice is registered by pyroelectric cameras (Spiricon PYROCAM I).

Using the above-described experimental arrangement, we studied the temporal evolution of the transverse intensity profile by recording, for each laser pulse, two consecutive quasi-instantaneous patterns separated a time delay t_d. Figure 2 shows six representative pairs of instantaneous consecutive patterns separated by the shortest time delay we are able to achieve with this setup ($t_d = 0.6$ ns). Each pair represents the transmitted (left) and reflected (right) patterns. As can be observed for this time delay, a great similarity between the transmitted and reflected patterns is found. By looking in detail at these patterns, we can extract some conclusions on the spatiotemporal dynamics of the filaments. (1) There is a continuous creation and vanishing of filamentary structures. (2) The optical filaments do not move along the cross section during their lifetime. This finding is in contrast with the migrating filamentary behavior observed in 1D patterns of semiconductors lasers [18], where the filaments migrate from one edge of the 1D-transverse pattern to the opposite. This migration was partially attributed to the spatial carrier diffusion which is not present in our CO_2 gas laser. (3) The filaments grow at different rates. Furthermore, the intensity of some filaments grows while the intensity of others decreases. These observations suggest a low spatial correlation that agrees with the local-intensity cross correlation function experimentally obtained on CO_2 lasers [10,23]. This spatiotemporal chaotic dynamics could lead, in fact, to peculiar instantaneous patterns that are dominated by very few bright filaments [see, for example, Fig. 2(b)], which are rather different from the typical regular time-average intensity patterns [see Fig. 1(d) in Ref. [7]].

What happens as we increase the time delay between consecutive patterns? To answer this question we show in Fig. 3 representative pairs of consecutive instantaneous patterns with a time delay (a) $t_d = 4.3$ ns and (b) $t_d = 6.8$ ns. It can be observed that both patterns become clearly dissimilar and without any common filamentary structures. This means that all of the optical filaments existing in the transmitted pattern have vanished at the time the reflected pattern is recorded, and the positions at which the new filaments appear in the reflected pattern are, in general, different from the positions occupied by the filaments of the transmitted pattern.

In order to quantify the degree of similarity between consecutive patterns, or in other words, in order to obtain information about the dynamical behavior of filaments, we calculate the maximum of the cross correlation function between two consecutive images separated a time t_d. In Fig. 4 we plot this cross correlation versus time delay t_d. As expected from the discussion above, we clearly see in this figure a fast decay of the cross correlation. The filament lifetime, which is related to the correlation decay, is around 2 ns, which is in good agreement with the local laser intensity measurements reported in Ref. [21].

In order to theoretically analyze the fast dynamics of the 2D transverse patterns, we directly integrate the two-level Maxwell-Bloch equations

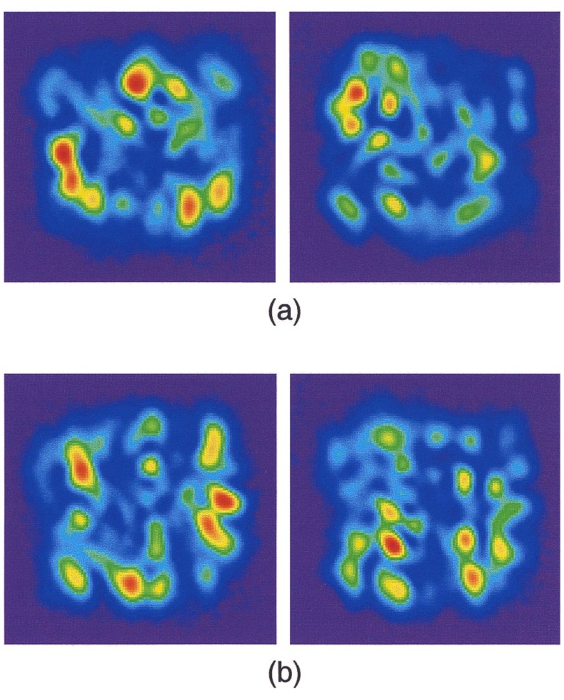

FIG. 3 (color online). Representative pairs of consecutive instantaneous patterns separated by a time delay of (a) $t_d = 4.3$ ns and (b) $t_d = 6.8$ ns. The transmitted pattern (left) is recorded a time t_d before than the reflected pattern (right). Experimental pattern dimension 20×20 mm. The color scale is the same as in Fig. 2.

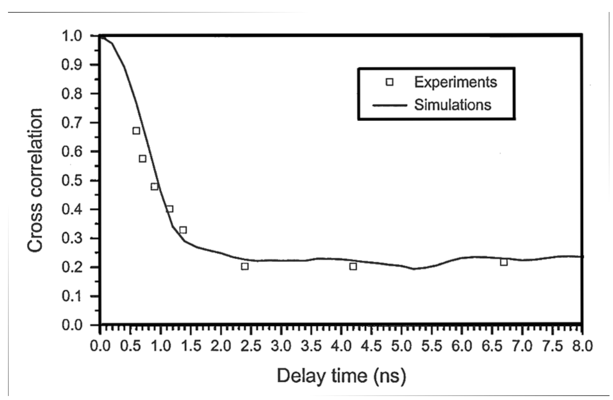

FIG. 4. The maximum value of the cross correlation function between consecutive patterns versus the time delay t_d. Each point corresponds to an average over approximately 200 laser pulses. The solid curve corresponds to the numerical simulations.

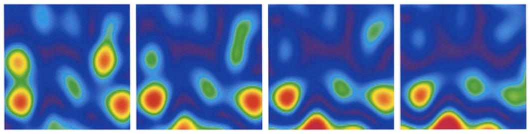

FIG. 5 (color online). Four consecutive frames of a movie showing the numerically simulated patterns with a temporal separation of 0.5 ns. In order to focus on a few optical filaments a small section (7 × 7 mm) of the pattern is shown.

$$\frac{\partial E}{\partial t} = -\kappa\left[(1 - i\delta) - i\frac{a}{2}\Delta_\perp\right]E - \kappa r P, \quad (1)$$

$$\frac{\partial P}{\partial t} = -\gamma_\perp[(1 + i\delta)P + ED], \quad (2)$$

$$\frac{\partial D}{\partial t} = -\gamma_\parallel\left[D - 1 - \frac{1}{2}(E^* P + E P^*)\right]. \quad (3)$$

Here E, P, and D are the dimensionless envelopes of the electric field, the electric polarization, and the population inversion, respectively. $\gamma_\parallel = 10^7\ \mathrm{s}^{-1}$, $\kappa = 9 \times 10^7\ \mathrm{s}^{-1}$, and $\gamma_\perp = 3 \times 10^9\ \mathrm{s}^{-1}$ are the population inversion decay rate, the cavity losses, and the polarization decay rate, respectively [21]. $\delta = (\omega_{21} - \omega)/(\gamma_\perp + \kappa)$ is the rescaled detuning which is chosen to be 0.25, in agreement with our previous work [21]. $\Delta_\perp = \partial_x^2 + \partial_y^2$ is the transverse Laplacian where x and y are normalized with the transverse size $2b$, and $a = c\lambda/[2\pi\kappa(2b)^2]$ is a diffraction coefficient. r represents the pumping. In order to reproduce the experimental pumping conditions, the transversal pumping profile is taken to be homogeneous along one transverse axis and Gaussian in the other one [7,21]. Likewise, the temporal form of the pumping was simulated by a function approximating the pulse excitation, with a maximum value of $r_{\max} = 25$.

Figure 5 shows a sequence of four consecutive frames (each one separated by 0.5 ns) of the simulated intensity patterns. The simulations allow us to follow in detail the complex temporal evolution of these 2D patterns. We have obtained that the randomly distributed optical filaments flash in a nanosecond time scale during which they do not appreciably move along the cross section pattern as observed in the experiment. The cross correlation obtained through the simulations agrees with the experimental one, as can be seen in Fig. 4. These simulations results reproduce our experimental findings with outstanding agreement.

In conclusion, we have directly observed for the first time the complex dynamical behavior of two-dimensional transverse patterns in broad area lasers. In order to do that, we have developed a new experimental setup that allows the consecutive measurement of 2D instantaneous patterns separated by a controlled short-time delay. A continuous creation and vanishing of filamentary structures has been found. These optical filaments are aperiodically flashing in time with different growing rates and they do not move along the pattern cross section. By measuring the cross correlation function between consecutive patterns, we have found a filament lifetime of approximately 2 ns. The numerical integration of the Maxwell-Bloch equations shows outstanding agreement with our experimental results.

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