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Spatio-temporal Dynamics of Broad Area Semiconductor Lasers and its Characterization

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Abstract—We present experiments giving evidence for the onset of irregular spatio-temporal dynamics on picosecond timescales in broad area lasers and characterize the dynamical complexity. In particular, we present single shot streak camera measurements of the nearfield dynamics of a broad area laser with a 100 μm wide active area and successfully apply Karhunen–Loève Decomposition (KLD) directly to the experimental data. Only a limited number of KLD modes is necessary to recover all essential features of the dynamical behavior. This fact allows the estimation of the system's number of degrees of freedom. © 1999 Elsevier Science Ltd. All rights reserved

1. INTRODUCTION

Broad area lasers are technologically very important devices. Their high optical output power makes them interesting for many applications, e.g. in telecommunication, manufacturing, pumping of solid state lasers and of fiber amplifiers. However, their applicability is restricted to conditions where good beam quality and good coherence properties are not required. The large aperture of the devices, which allows many transverse modes to oscillate simultaneously and a strong interaction of the light with the semiconductor material, leads to spatio-temporal structure formation in the nearfield. A few nanoseconds after current injection and still within the relaxation oscillations the light field breaks up into optical filaments that migrate in the transverse direction. This behavior has been predicted by numerical simulations [1–3] and experimentally observed recently [4]. The relevant physical mechanisms that lead to irregular pulsing and migrating optical filaments are local carrier induced changes of the refractive index (self-focussing), diffraction, carrier diffusion and spatial hole burning. Additionally, thermally induced changes of the refractive index can also contribute to the spatio-temporal behavior, however, this influence has been minimized in our investigations.

Methods based on concepts of nonlinear dynamics appear to be indispensable to gain insight into the dynamical complexity and to characterize the spatio-temporal behavior of broad area lasers. In particular the Karhunen–Loève Decomposition promises to be a valuable tool. The time dependence of the amplitudes of KLD modes has been studied in the context of chaos control in order to characterize the influence of a control signal for the stabilization of unstable orbits [6,7]. Furthermore, the KLD modes have been demonstrated to obey the same scaling laws with respect to the system size as the fractal dimension. Thus, the number of relevant KLD modes provides a measure to investigate the system size dependence of the spatio-temporal complexity [8,9]. KLD has already been applied to modelling results of the nearfield dynamics of multi-stripe and broad area semiconductor lasers in order to obtain intensity eigenmodes [5,1]. In

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this paper, we successfully apply Karhunen–Loève Decomposition directly to our experimental data, in particular to the nearfield traces of a broad area semiconductor laser. We find that only a relative small number of modes—in the actual case 15 modes—contains the essential dynamical features despite of the restricted time window and the existence of noise in the data.

This paper is organized as follows. First we shortly review the method of KLD which we apply directly to our experimental data. After the description of our experimental technique we present a measured nearfield trace which demonstrates the complex spatio-temporal dynamics of the emission of these devices. Finally, we apply the KLD onto this experimental nearfield trace, as a representative example, and discuss the results and the conclusions, which can be drawn from this analysis.

2. KARHUNEN–LOÈVE DECOMPOSITION (KLD)

Karhunen–Loève Decomposition is a useful tool for the characterization of spatio-temporal complexity in the sense that it yields dynamical eigenmodes which are directly extracted from the dynamical behavior and include a maximum of the dynamical variance. The aim of its application to our experimental data is the estimation of the system's number of degrees of freedom. The data $I(x,t)$, in our case the spatio-temporal nearfield traces, are decomposed into a basis of orthonormal eigenmodes. Thus, it can be written as follows:

$$I(x,t) = \sum_{n=0}^{\infty} A_n(t) i_n(x) \tag{1}$$

where $A_n(t)$ are the time dependent amplitudes of the eigenmodes (KLD modes) $i_n(x)$. The eigenmodes are obtained by solving a variational problem such that for each mode the intensity variance is maximized within the given time window. They are the eigenfunctions of the integral equation

$$\int_0^L K(x,x') i_n(x') dx' = \lambda_n i_n(x), \tag{2}$$

where $K(x,x')$ is the two point correlation function (covariance matrix)

$$K(x,x') = \langle I(x,t) I(x',t) \rangle_t \tag{3}$$

and $\langle\,\rangle_t$ denotes the temporal average over the time window. The eigenvalues λ_n are proportional to the probability of the appearance of the corresponding eigenvectors $i_n(x)$ in the nearfield trace. This method appears to be well suited to obtain a minimal set of relevant dynamical eigenmodes.

Before presenting the results of the application of KLD to our experimental data we give a short description of the experimental method.

3. EXPERIMENTAL METHOD

Broad area semiconductor lasers are unique model systems for the investigation of spatio-temporal complexity with respect to the timescales as well as to the spatial dimension. A temporal resolution in the sub-ns range is required to detect their irregular emission behavior. Furthermore, one spatial dimension has to be resolved with an accuracy of a few μm. For this reason we perform single shot streak camera measurements which enable at the same time high temporal resolution of $\sim$ 10 ps and the required spatial resolution. The experimental setup is shown in

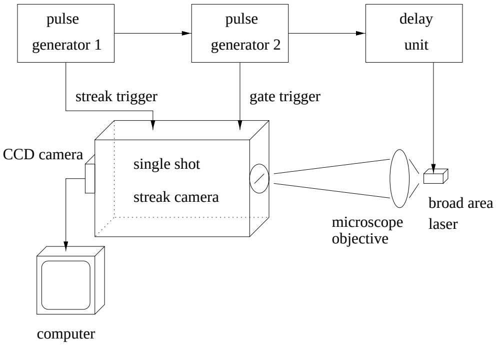

Fig. 1. Experimental setup for the measurement of the nearfield dynamics. The output facet of the laser is projected onto the entrance slit of the single shot streak camera. The delay unit allows to measure the turn-on dynamics as well as the dynamics several ns after the relaxation oscillations. The CCD camera is read out by a computer for further processing.

Fig. 1. The output facet of the semiconductor laser is projected onto the entrance slit of the streak camera. Nearfield traces of a length of up to 10 ns can be obtained. The delay unit allows to measure the laser's turn-on dynamics as well as the dynamical behavior several ns after the relaxation oscillations. In order to avoid thermal effects on the refractive index (i.e. thermal lensing) the laser is driven with current pulses with a length of less than 100 ns at a repetition rate of $\approx$ 100 Hz. The streak traces are detected by a high sensitivity CCD camera which can be read out by a computer for subsequent analysis. The two synchronized pulse generators deliver the gate trigger as well as the streak trigger allowing an improvement of the signal-to-noise ratio by opening the gate for the shortest necessary time. In our measurements we use a quantum well laser based on GaAs/AlGaAs material with an emission wavelength of $\lambda = 814$ nm and a width of the active area of $w = 100\ \mu$m. Wave guiding is achieved by the cladding layers confining the light in the direction perpendicular to the active area and by gain guiding in the lateral direction.

4. EXPERIMENTS AND KLD EIGENMODE ANALYSIS

A nearfield trace with a temporal length of $\Delta t = 4.1$ ns of the broad area laser is depicted in Fig. 2. The space coordinate in the lateral direction is given by the horizontal axis while the vertical axis shows the temporal evolution. The emitted intensity is linearly coded via greyscales such that light shading corresponds to high intensities and dark shading to low intensities. This nearfield trace has been obtained 8 ns after turning on the injection current to $I \approx 2 \cdot I_{th}$. This represents the post-relaxation-oscillation regime as it prevails for later times [4]. The nearfield exhibits a nearly static spatial modulation of the intensity with seven maxima. This spatial modulation which can also be observed in time-integrating measurements is well known and has been called multi-filamentation or higher nonlinear modes [10–12]. Underlying these time-independent behavior, the laser exhibits irregular spatio-temporal dynamics on sub-ns timescales and a striking phenomenon, so-called migrating optical filaments which have also been found in numerical modelling [4,1]. The migrating filaments manifest themselves in spots of high (or low) intensity which change their position of emission on timescales of a few hundred picoseconds. They migrate from one boundary of the laser to the opposite one at the boundaries seemingly being reflected and thus bouncing back and forth a few times. Typical dimensions of these migrating filaments are lateral widths of 5–15 μm and temporal pulse durations of 50–100 ps.

We apply the KLD as it has been presented above onto this experimental streak trace. The results of this analysis are depicted in Fig. 3 showing a semi-log plot of the so obtained eigen-

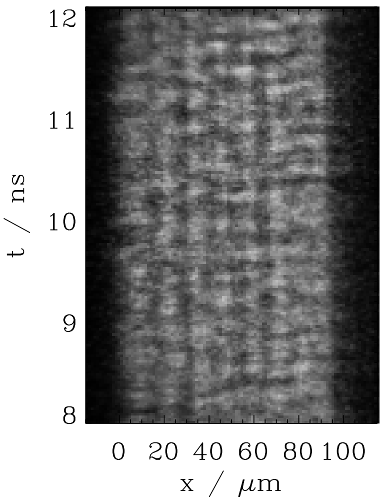

Fig. 2. A 4.1 ns long nearfield trace of a broad area laser with $w = 100$ μm at $I = 2 \cdot I_{th}$.

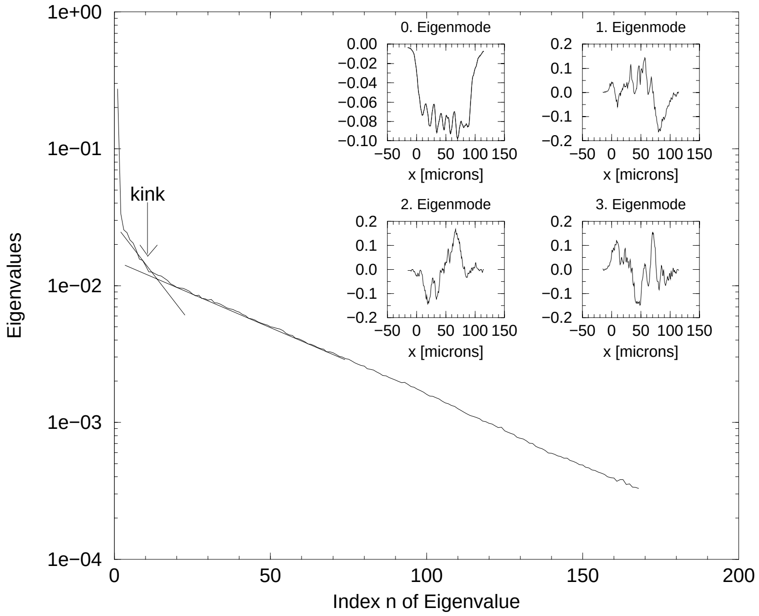

Fig. 3. Semi-log plot of the eigenvalues. The kink indicates the number of relevant modes. The inset shows the lateral profiles of the four most relevant KLD modes.

values. The inset in Fig. 3 shows the first four extracted dynamical eigenmodes. The dominant KLD mode $n = 0$ exhibits nearly no temporal dependence, thus incorporating the static nearfield information. In particular, this mode shows a spatial modulation with seven maxima, as they have already been discussed for the streak trace. The dynamical changes of the nearfield are contained in the higher KLD modes. We find that one of the next three dominant KLD modes is a mode with a spatial profile that is nearly anti-symmetrical with respect to the center of the active area. In this example this symmetry-breaking mode is KLD mode $n = 2$. It exhibits a temporal dependence being determined by the typical timescales of the migrating filaments. Therefore, this mode contains relevant information of the migration of the dynamical filaments across the lateral width of the active area. Also nearly symmetrical modes can be found for many nearfield traces under these experimental conditions in good qualitative agreement to the findings of the modelling [1]. However, the limited time window and the signal-to-noise ratio prevent a more detailed physical interpretation of the different KLD modes. Although the interpretation of the individual modes is difficult, the estimation of the number of dynamically relevant modes appears to be possible, as will be discussed in the following. Fig. 3 shows the eigenvalues corresponding to the KLD modes versus the index n of the eigenmodes in a semi-log plot. Two separate scaling regions can be recognized, both showing a linear scaling corresponding to exponential decays. The transition point between these two regions is indicated by a distinct kink at an index of $n_k \approx 15$ which is visualized by a crossing point of two fitted lines. We interpret this index n_k as the one denoting the highest relevant mode. The modes above this index contain mainly noise information. This can be supported by recomposing the dynamics only considering the modes with indices $n = 0 \ldots n_k - 1$. This recomposition is depicted in Fig. 4. It contains all essential dynamics, in particular the static and dynamical filamentation and the details of the irregular spatio-temporal pulsing behavior. Furthermore, the pixel noise from the experimental data is significantly reduced which might also be attractive for noise filtering purposes.

5. CONCLUSIONS

In conclusion, we have presented spatially and temporally high-resolved nearfield measurements of a broad area semiconductor laser demonstrating that it shows complex spatio-temporal dynamics on picosecond timescales. In order to characterize the complexity we have performed a Karhunen–Loève Decomposition demonstrating that it allows the estimation of the number of relevant dynamical degrees of freedom from a distinct kink in the eigenvalue spectrum. The validity of this observation is supported by recomposing the nearfield trace, only considering the relevant modes. Some of the individual spatial eigenmodes can be interpreted as the static part of the nearfield profile or as a symmetry-breaking mode. The noise in our experimental data so far prevents a more detailed physical interpretation of the higher modes which seem to contain dynamical information on even faster timescales. Nevertheless, we demonstrated KLD

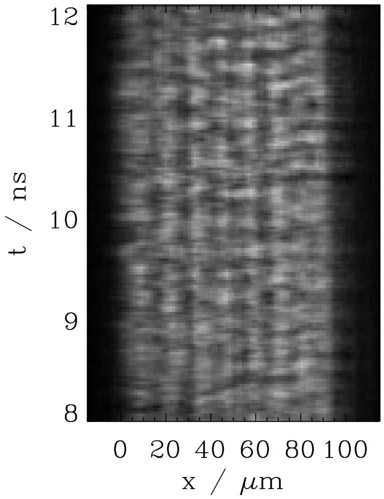

Fig. 4. Recomposition of the nearfield dynamics considering only the relevant number (n_k = 15) of KLD modes.

to be a promising tool for the experimental investigation of the spatio-temporal complexity of broad area semiconductor lasers with the perspective to study the parameter dependence, e.g. the pumping conditions and the system size, i.e. the width of the active area.

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