Experiments on Random Lasers

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Outline

• Complexity and spin glasses
• Lasers and Random lasers
• Observation of a Photonic Spin Glass
Complexity
Many years ago…

• My first meeting with complexity

The physical Meaning of Replica Symmetry Breaking

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( Dirac medal talk, arXiv:cond-mat/0205387v1 )
The Landscape

\[ w_\alpha \propto \exp(-\beta F_\alpha) \]

Figure 1: An artistic view of the free energy of a complex system as function of the configuration space.

(Parisi, arXiv:cond-mat/0205387v1)
The overlap and the $P(q)$

$$q[\sigma, \tau] = \frac{1}{N} \sum_{i=1,N} \sigma(i) \tau(i).$$

We define $P_J(q)$ as probability distribution of the overlap $q$ at given $J$, i.e. the histogram of $q[\sigma, \tau]$ where $\sigma$ and $\tau$ are two equilibrium configurations. Using eq. (2), one finds that

$$P_J(q) = \sum_{\alpha,\gamma} w_\alpha w_\gamma \delta(q - q_{\alpha,\gamma}),$$

where in a finite volume system the delta functions are smoothed. If there is more than one state, $P_J(q)$ is not a single delta function

$$P_J(q) \neq \delta(q - q_{EA}).$$

If this happens we say that the replica symmetry is broken: two identical replicas of the same system may stay in a quite different state.

(Parisi, arXiv:cond-mat/0205387v1)
P(q) for different J

Figure 2: The function $P(q)$ for four different samples (i.e. different choices of J) for $D = 3$, $L = 16$ ($16^3$ spins).

(Parisi, arXiv:cond-mat/0205387v1)
Disorder average $P(q)$

$$P(q) = \overline{P_j(q)}.$$ 

Figure 3: The function $P(q) = \overline{P_j(q)}$ after average over many samples (D=4, L=3...10).

(Parisi, arXiv:cond-mat/0205387v1)
Experimental evidence

\[ \chi_{eq} = \beta \int dq \ P(q)(1 - q) \]
Questions

• Photonic spin-glass?

• Direct measurement of $P(q)$?

• Replica Symmetry Breaking?
Why lasers?

- Lasers are known for being thermodynamic systems
  - Black body radiation
  - Negative temperature

- «Random lasers» are disordered systems

Maiman, 1960
Lasers

• Light amplification by stimulated emission of radiation

• The original laser model:
  • Gould, Prokhorov, Schawlow, Townes
  • Invented the open cavity design (1957)
Random lasers

- A new design for lasers, dating back to 1966
- The photonic bomb

VS Letokhov
Several different random lasers

Ambartsumyam, Basov, Kryukov, Lethokov (ABKL) experiment, 1966

The first one

The most famous

Laser action in strongly scattering media

N. M. Lawandy, R. M. Balachandran, A. S. L. Gomes & E. Sauvain

Our first one

CC et al,
PRL 101, 143901 (2008)
Shaken granular lasers

PRL 2012,
Scientific Reports 2013
Laser with soft matter

• Colloidal dye
Experimental results
Paper-based microchannels

Fabrication by I. Viola, A. Zacheo, V. Arima and G. Gigli from Nano-CNR in Lecce
Experimental results 
Paper-based microchannels

The lasing circuits are realized by using, firstly standard soft-lithography techniques to define the channel geometry, then imbibing with a lasing dye (RhB) through the channel inlet and, finally, fulfilling the channels by capillary processes.
Experimental results
Paper-based microchannels

J. Mater. Chem. C, 2013, 1, 8128–8133
Experimental results
Bio-templated titanium

$\text{TiO}_2$ from cellulose templates:
Titanium with the structure of paper

http://www.professoren.tum.de/en/zollfrank-cordt/
Disorder Vs Size

Disorder versus Size


Astrophysics

Astronomical

Fiber lasers

Random

Shaken granular lasers

size

km

meters

cm

mm

micron

Single atom

Add TiO2

Single cluster laser

disorder
First hints about a possible RSB
The Hamiltonian for Random Lasers

\[ \mathcal{H} = -\mathcal{R} \left[ \sum_{j<k} G^{(2)}_{jk} a_j a_k^* + \sum_{\omega_j + \omega_k = \omega_l + \omega_m} G^{(4)}_{jklm} a_j a_k a_l a_m^* \right] \]

Glassy behavior of light

L. Angelani, C. Conti, G. Ruocco, F. Zamponi

We study the nonlinear dynamics of a multi-mode random laser using the methods of statistical physics of disordered systems. A replica-symmetry breaking phase transition is predicted as a function of the pump intensity. We thus show that light propagating in a random non-linear medium displays glassy behavior, i.e. the photon gas has a multitude of metastable states and a non-vanishing complexity, corresponding to mode-locking processes in random lasers. The present work reveals the existence of new physical phenomena, and demonstrates how nonlinear optics and random lasers can be a benchmark for the modern theory of complex systems and glasses.
Problems

• Is it true that random lasers have modes?
• Do random laser modes interact?

• What can we measure?
Modes in random lasers?
Experimental results
Random laser from paper cellulose templated Titanium di-oxide

Experiments for the detection of the spatial extension of the RL modes
Modes in random lasers

Nature Photonics, 5, 10: 615—617 (2011)
Mode 2&3:

\[ \lambda_2 = 595.54 \text{nm} \]

\[ \lambda_3 = 596.00 \text{nm} \]
Four modes (peaks) with FWHM = 0.2nm

The fiber moves and scans the emission from the sample with a resolution < 1 micron

Scan over 13.5X13.5 micron
Resolution 0.45 micron
Pump energy 10 μJ
Do random laser modes interact?
Experiment to measure RL interaction

Nat Commun, 4: 1740 (2013)
Which is the interaction length?
Measure of the Overlap?

- The spectra are determined by the amplitude and the phases of the mode.
- The spectra fluctuate.
- The phases determine the fluctuations.
- We measure the overlap of the fluctuations of the spectra.

\[ \Delta_x(k) = I_x(k) - \bar{I}(k) \]

\[ q_{\alpha \beta} = \frac{\sum_{k=1}^{N} \Delta_x(k)\Delta_\beta(k)}{\sqrt{\sum_{k=1}^{N} \Delta_x^2(k)}\sqrt{\sum_{k=1}^{N} \Delta_\beta^2(k)}}. \]
Figure 5 | Distribution function of the overlap in standard and random laser without replica symmetry breaking. (a,b) Emission spectra (a) and $P(q)$ (b) of a Q-switched pulsed Nd-Yag standard ordered laser. The analysis is done on 100 shots. (c-h) Emission spectra (c-e,g) and correspondent $P(q)$ (d,f,h) of a liquid dispersion of titanium dioxide in rhodamine B-ethylene glycol solution at three different pump energy through the threshold.
RSB

**Figure 3**: The function $P(q) = P_{\text{avg}}(q)$ after average over many samples ($D=4$, $L=3 \ldots 10$).

**Figure 4**: Distribution functions of the overlap showing replica symmetry breaking by increasing pump energy. (a-d) Distribution of the overlap $q$ at different pump energy $E$. $q_{\max}$ corresponding to the position of the maximum of $P(q)$ versus pumping.
Replica symmetry breaking: identical systems under identical conditions may reach different states. This effect is revealed by the shape of the probability distribution function of an order parameter named the Parisi overlap. Here we investigate pulse-to-pulse fluctuations in random lasers, we introduce and measure the analogue of the Parisi overlap in independent experimental realizations of the same disordered sample, and we find that the distribution function yields evidence of a transition to a glassy light phase compatible with a replica symmetry breaking.
Open issues

• Direct measurement of phases and amplitude of the modes?

• Direct measurement of the couplings J?

• Accurate measurement of the P(q) to assess a Full RSB

• ………… many publications over the years
The Best Publication: the facebook page of Giorgio!

Thanks!

www.complexlight.org

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