Thesis subject

Design and Fabrication of Organic Laser Diode: From transparency to threshold

Context

Organic electronics is an important ~~new~~ area of science that has emerged from the work of A.Heeger, A. MacDiarmid, H. Shirakawa on conductive polymers and has won them the 2000 Nobel Prize in Chemistry. Another milestone is the demonstration in 1987 of efficient light sources made with small organic electroluminescent molecules by Tang and Van Slyke [1]. If the development of organic electronics has given rise to many optoelectronic devices such as organic photovoltaic (OPV), organic photodetector (OPD) and organic transistors (OFETs), the demonstration of the organic laser diode (OLD) remains a major issue despite a very recent publication by the Adachi's Japanese team [2]. Similarly to any other organic semiconductor (OSC)-based optoelectronic devices, the OLD would be feasible with relatively simple, fast, environmentally friendly, low carbon footprint production processes than inorganic semiconductors (III-V). With the almost unlimited availability of these amorphous organic compounds covering the entire visible spectrum and offering hybrid integration on many types of substrate, many new applications in medicine, research, telecommunications, Internet of Things and quantum applications are possible.

Several scientific challenges still need to be overcome for the realization of the OLD. Firstly, the OSCs known as low conductive materials, can only sustain low current density (100-1000mA/cm² in DC regime) while the laser threshold is estimated beyond several kA/cm². Secondly, annihilation losses due to the accumulation of triplet states, which becomes even more important beyond ten nanoseconds, further increases the laser threshold. Without specific materials offering low annihilation rates, lasing can be achieved in another configuration corresponding to a time window shorter than 10ns and to pulsed current density of the order of kA/cm². This is achievable in the most favourable case with an OLED combined with a very high quality factor optical cavity and a resonance specifically tuned to the maximum of the net-gain profile.

Recent scientific advances obtained by the ADOOP (Advanced Devices of Organic Optoelectronics and Photonics) team of LPL (Laboratoire de Physique des Lasers UMR CNRS 7538) show current densities up to 40kA/cm² and light pulses as short as 400ps, which are two world première [3]. Also, recent unpublished results show an optical response 2.9 times more intense when the OLED is combined with a DFB microcavity than the reference OLED without cavity. Using an upgraded laser dynamics model that takes into account electrical excitation, we showed that the transparency threshold has been reached, but the laser threshold is still ahead [4]. Beyond these advances, the design, fabrication and implementation of optimal laser micro-cavities with OLEDs stack including optimal laser gain material to be identified is crucial to exceed the transparency and reach the laser threshold. This is the objective of the proposed thesis.

Objectives:
The objective of the thesis is to demonstrate the laser effect in organic semiconductors under pulsed electrical excitation. The thesis will include modelling, simulations, fabrication and characterization.
At the theoretical level, the objective is about building on an existing model to identify the optimal conditions for lasing. From the model combined with material properties extracted from experimental results, an optimal laser gain material is to be identified and design rules are to be established. The model of laser dynamics can be improved to take into account the accumulation of charges at organic layer interfaces.
At the fabrication level, DFB micro-cavities are to be designed and patterned using e-beam lithography before an organic hetero-structure is to be deposited. One particular effort is to carefully tune the Bragg resonance wavelength to the maximum of the net-gain profile to be identified from the organic material absorption, and electroluminescence spectra.
At the characterization level, the time-resolved electrical, optical and spectral responses of the fabricated device will be measured. An existing measuring bench is to be improved to allow time-resolved measurement of the entire visible spectrum at once.

Collaborations
The thesis will involve leading national collaborations and partnerships as well as other important international collaborations: the CEA LETI (national reference centre for micro and nanotechnologies), the University of Rennes (on laser gain materials), the Technical University of Eindhoven (on an improved dynamic laser model), the NCU University in Taiwan (FDTD 2D Simulations), the Heriot Watt University (Microwave properties of the electrodes), and Université de Tizi Ouzou.

Supervisors
The thesis will be directed by Pr. A. Fischer, and co-directed by Pr. Azzedine Boudrioua. Dr Mahmoud Chakaroun and Quentin Gaimard will supervise providing specific expertise in material sciences, clean room techniques, and instrumentation.
The Ph.D student will be trained in the clean room facilities of CPN2, to acquire expertise in e-beam lithography and OLED deposition with the support of two clean room engineers.

References
[1] Tang, C.W. and Van Slyke, S.A.Organic Electroluminescent Diodes. Applied Physics Letters, (1987) http://dx.doi.org/10.1063/1.98799

[2] S. D. Sandanayaka *et al.*, “Indication of current-injection lasing from an organic semiconductor,” *Appl. Phys. Express*, vol. 12, no. 6, p. 061010, May 2019, doi: 10.7567/1882-0786/ab1b90.

[3] D. Lenstra, A. P. A. Fischer, A. Ouirimi, A. C. Chime, N. Loganathan, and M. Chakaroun, “Ultra-short optical pulse generation in micro OLEDs and the perspective of lasing,” *J. Opt.*, vol. 24, no. 3, p. 034007, Feb. 2022, doi: 10.1088/2040-8986/ac4cd1.

[4] Thesis Amani OUIRIMI, “Modeling, design, fabrication and characterization of organic light emitting diodes with distributed feedback micro-cavity under ultra-short electrical pulsed regime”, defended 28th of September 2022, Université Sorbonne Paris Nord.

[5] A. Ouirimi, A. C. Chime, N. Loganathan, M. Chakaroun, A. P. A. Fischer, and D. Lenstra, “Threshold estimation of an organic laser diode using a rate-equation model validated experimentally with a microcavity OLED submitted to nanosecond electrical pulses,” Organic Electronics, vol. 97, p. 106190, Oct. 2021, doi: 10.1016/j.orgel.2021.106190.