Master in Photonics – "PHOTONICS BCN"
Master ERASMUS Mundus "EuroPhotonics"

MASTER THESIS PROPOSAL

Full time from April 2026 (it can start part time from February 2026)
Presentation date to be chosen: end of July or beginning of September 2026

Note: The main Master Thesis supervisor has to be a professor of the Master in Photonics program. One co-supervisor (internal or external) can be defined. Main Supervisor is responsible for the subject of the proposal and has to give continuous support to the student (research development, Report writing and presentation preparation). For external proposals a co-supervisor from the Master program and a collaboration agreement with UPC are needed. You can find all information about the Master Thesis process in our webpage.

Laboratory: Quantum Nano-optoelectronics group
Institution: ICFO
City, Country: Castelldefels (Barcelona), Spain

Title of the master thesis: Learned sampling for rapid Fourier-transform spectroscopy

Name and affiliation of the master thesis supervisor: Prof. Dr. Frank Koppens
Name and affiliation of the co-supervisor (if any): Dr. Ediz Herkert
(for external proposals a co-supervisor chose among the Master Program professors and a collaboration agreement with UPC is needed)
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Keywords: Neural networks, spectroscopy, chemical analysis

1. **Summary of the subject (maximum 1 page):**

Fourier-transform spectroscopy (FTS) is a powerful and flexible method for obtaining spectra from time-domain measurements. It provides detailed spectral information with a high signal-to-noise ratio, which makes it useful for applications such as chemical analysis. However, this level of spectral detail comes at the cost of longer measurement times compared to more specialized techniques that focus on a narrow spectral range.

As a result, specialized techniques are often preferred for time-critical applications like real-time gas sensing. The drawback is that they can only detect a limited number of chemical analytes because they lack the broad chemical specificity that FTS offers. Developing methods to significantly speed up FTS could make it possible to perform rapid chemical

analyses with high specificity, greatly expanding the range of applications where FTS can be used.

The acquisition speed of FTS is fundamentally limited by the Nyquist–Shannon sampling theorem. This theorem defines a limit for the number of time-domain measurements required to obtain an artifact-free spectrum. However, this limit only applies when the measurements are taken at uniform time intervals. It has been shown that methods like compressed sensing can reconstruct spectra with fewer measurements if the time intervals are chosen non-uniformly [1-4]. However, these approaches rely on assumptions that often do not apply to FTS.

This project explores how neural networks (NNs) can be used to learn optimal sampling strategies for time-domain signals in FTS and reconstruct artifact-free spectra from substantially fewer measurements than required by the Nyquist–Shannon limit. The core idea is that NNs can learn the specific assumptions that apply to FTS signals, rather than relying on predefined assumptions as in existing approaches like compressed sensing. Encoder-decoder architectures are promising candidates for this task because they are designed to learn efficient representations of input signals and reconstruct them with minimal error.

In this project, the student will design, implement, and evaluate different NN architectures to determine which models most effectively reduce the number of time-domain measurements while minimizing spectral artifacts. An emphasis will be placed on understanding why certain architectures perform better than others in this context. Ultimately, this project contributes to establishing FTS as a rapid and specific technique for chemical analysis in time-critical applications.

2. **Objectives (maximum 1 page):**
   - **Develop and compare neural network architectures** for learning optimal time-domain sampling strategies and spectrum reconstruction.
   - **Quantitatively evaluate performance** in terms of spectra reconstruction quality, reduction in required measurement number, and robustness to noise and other experimental artifacts.
   - **Analyze learned sampling patterns** to gain physical and conceptual insight into how different network architectures exploit signal characteristics in FTS.
   - **Benchmark against existing methods** such as compressed sensing and traditional uniform sampling to assess the advantages and limitations of NN-based approaches.

Additional information:

Required skills:

- **Programming proficiency:** Intermediate or higher skills in Python (alternatively MATLAB or Julia).
- **Machine learning experience:** Ideally, some experience in working with neural networks and frameworks such as Scikit-Learn, PyTorch, or TensorFlow.
- **Knowledge of Fourier-transform spectroscopy (FTS):** Understanding of time-domain signal acquisition and spectral reconstruction principles (e.g., FTIR techniques).
- **Background in photonics:** Familiarity with optical measurement systems
- **Analytical skills:** Ability to evaluate model performance using quantitative metrics

References:

[1] Bolzonello L., van Hulst N. F. & Jakobsson A. Fisher information for smart sampling in time-domain spectroscopy. *J. Chem. Phys.* **160**, 214110 (2024).
[2] Candès, E. J. & Tao, T. Near-optimal signal recovery from random projections: universal encoding strategies? *IEEE Trans. Inf. Theory* **52**, 5406-5425 (2006).
[3] Kästner B., Schmähling F., Hornemann A., Ulrich G., Hoehl A., Kruskop M., Pierz K., Raschke M. B., Wübbeler G. & Elster C. Compressed-sensing FTIR nano-spectroscopy and nano-imaging. *Opt. Express* **26**, 18115–18124 (2018).
[4] Marschall M., Hornemann A., Wübbeler G., Hoehl A., Rühl E., Kästner B. & Elster C. Compressed FTIR spectroscopy using low-rank matrix reconstruction. *Opt. Express* **28**, 38762–38772 (2020).