Multi-scale fibre-based optical frequency combs: science, technology and applications (MEFISTA)

Deliverables D5.1

6 ESRs trained to advanced PhD level

Project details

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Document details

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Confidential, only for members of the consortium (including Commission Services)	

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Contents

1 EXECUTIVE SUMMARY

The deliverable D5.1, titled ‘Six ESRs trained to advanced PhD level’, is part of Work Package 5, which focuses on ‘Recruitment, Management and Implementation’ within the European Training Network, MEFISTA, Multi-scale fibre-based optical frequency combs: science, technology and applications.

This project is funded through the Horizon 2020 Marie Skłodowska-Curie scheme under Grant Agreement (GA) 861152.

The purpose of this document is to provide details about the graduation of recruited ESRs within the MEFISTA project, their enrollment in PhD programs and the progress of their respective PhD theses as of the submission date of this deliverable.

In summary, one PhD thesis has been successfully completed and defended, while four PhD theses are currently still in progress (section 2). It is important to note that the information provided for the ongoing PhD theses, including titles, abstracts, and submission dates, may be subject to modifications and amendments.

It should be noted that, as a deviation from the initial plan outlined in the GA, ESR4 did not enrol onto a PhD programme (see section 3).

In addition, because the project started during the height of COVID, the start dates of three ESRs were delayed, impacting the end date of PhD completion.

- ESR2 Mohammad Nayeem Akhter started at UPC in June 2021, M17
- ESR4 Qing Wang started at Aston in May 2021, M16
- ESR5 Alberto Cuevas Rodriguez started at Aston in April 2021, M15

Consequently, a 6-month project extension was granted by the Project Officer, making MEFISTA’s end date 31 July 2024, not 31 January 2024.

ESR Contract dates

ESR	Name	Recruiting Beneficiary	Contract start date	Contract end date
ESR 1	Stefano Negrini	ULille	01-10-2020	30-09-2023
ESR 2	Mohammad Nayeem Akhter	UPC	01-06-2021	31-05-2024
ESR 3	Moritz Bartnick	EPFL	15-05-2020	14-05-2023
ESR 4	Qing Wang	Aston	01-05-2021	30-04-2024
ESR 5	Alberto Rodriguez Cuevas	Aston	01-04-2021	31-03-2024
ESR 6	Anamika Nair Karunakaran	NKT (PhD awarding body, DTU)	15-07-2020	14-07-2023

2 PhD THESES COMPLETION AND DEFENCE

2.1 Stefano Negrini, ESR1

Host beneficiary:	Université de Lille (ULille)
PhD Enrolment:	Université de Lille (ULille)
Supervisors:	Professor Arnaud Mussot
Co Supervisor	Dr Matteo Conforti
PhD thesis title:	Gain Through Filtering in fiber cavity resonator
PhD defence date:	28 November 2023
Access to Full Text (Open Access)	https://theses.fr/2023ULILR049?domaine=theses https://pepite-depot.univ-lille.fr/LIBRE/EDSMRE/2023/2023ULILR049.pdf

PhD Thesis Abstract

In this work, we study the phenomenon of modulation instability (IM) in fiber ring resonators, induced by asymmetric spectral losses in the form of a filter. The phenomenon, known as gain through filtering (GTF), consists in the modification of the phase matching condition of the resonator, given by the phase signature of the filter. We first characterised this phenomenon theoretically and experimentally in a passive fibre resonator for both normal and anomalous dispersion regimes, highlighting the relationship between GTF instabilities and parametric MI.

We then developed a theoretical model to describe the formation of GTFs in a polarisation-maintaining (PM) cavity. Using this model, we have shown how it is theoretically possible to obtain two MI spectra with detuned spectral peaks. This is made possible by using a PM filter with a different loss profile in the two polarisation axes. In the more general context of fibre cavities, we have studied the effect of a synchronisation mismatch between the repetition rate of the pulse train driving the cavity and the natural repetition rate of the cavity. The mismatch results in a shift of the sideband of the MI spectra due to the competition between two MI regimes: absolute and convective.

Finally, we built two active cavity devices. They consist of a fibre cavity in which a section of doped fibre (erbium or thulium dopant) is embedded in the coil to act as an amplifier. By carefully adjusting the gain of the amplifier, it's possible to compensate for the losses and still remain in a passive regime (below the lasing threshold). By using erbium-doped fiber as active media we were able to obtain GTF at very low power, while by using thulium-doped fiber we were able to generate MI at a wavelength of 2μm.

2.2 Mohammad Nayeem Akhter, ESR2

Host beneficiary:	Universitat Politècnica de Catalunya (UPC)
PhD Enrolment:	Universitat Politècnica de Catalunya (UPC)
Supervisors:	Prof Kestutis Staliunas
Co Supervisor	Dr Muriel Botey and Dr Ramon Herrero
PhD thesis title:	Mode control in optical fibers and waveguides by non-Hermitian potentials
PhD defence date:	December 2024
Access to Full Text (Open Access)	Not yet known.

PhD Thesis Abstract

Non-Hermitian photonics has emerged as a powerful new platform for the control of light. In particular, we propose non-Hermitan graded index optical fibres and waveguides offering a control over the output mode profile. We show that the simultaneous modulation of the propagation constant and of the gain/loss coefficient along GRIN multimode fibers and waveguides results in unidirectional coupling among the modes. Depending on the modulation parameters, it possible to control either the enhancement or the reduction of higher order transverse modes. In the latter case, effective mode-cleaning is predicted, ideally resulting in single-mode spatially coherent output.

The effect is semi-analytically predicted on a simplified Gaussian beam approximation and numerically proven by solving the wave propagation equation introducing the non-Hermitian modulated potential for a linear system.

Therefore, in the following work, we proposed the introduction of antisymmetric non-Hermitian modulations in one- and two-dimensional (2D) waveguides as a mechanism to affect all helicities, and control all modes. This results in an effective mode-cleaning, for any arbitrary initial field distribution. The proposal is supported by analytical predictions based on a coupled-mode theory for 1D waveguides, which is numerically proven solving the wave propagation equation. The scheme can be generalized to the more involved case of 2D waveguides, for different geometries controlling the unidirectional mode-coupling and final beam shape.

In the final and current work, we apply this antisymmetric non-Hermitian potential in active multimode fiber amplifiers, including nonlinearity, in order to shape the beam profiles which leads to different types of mode management for different values in the parameter space of the applied potential.

2.3 Moritz Bartnick, ESR3

Host beneficiary:	EPFL
PhD Enrolment:	EPFL, Doctoral School of Photonics
Supervisors: **Co Supervisor**	Prof Camille-Sophie Brès
PhD thesis title:	Design and experimental characterization of frequency comb sources in the short-wave infrared
PhD defence date:	October/November 2024
Access to Full Text (Open Access)	Not yet known, general url is: https://infoscience.epfl.ch/?ln=en

PhD Thesis Abstract

The invention of the laser in the 1960s heralded a new era in photonics. Owed to both academic and industrial research, photonics technologies have long become part of our everyday life. This thesis is located at the intersection of two subfields of laser technologies: Frequency combs, and fiber lasers.
A frequency comb can be defined as an optical spectrum consisting of many equidistant lines. A pair of them, a dual frequency comb, is a powerful tool which can be used to measure optical frequencies and distances with unprecedented precision. This work focusses on frequency comb technology at 2 micron wavelength, since this spectral region overlaps with the fingerprint of several atmospheric molecules, such as CH_2, NH_3 and NO_2, but also contains a good atmospheric transmission window for potential ranging applications. All-fiber setups were investigated in order to implement sources that are portable and resilient against ambient disturbances. A key component present in all of our studies is thulium-doped active fiber which provides substantial gain within the 2 micron band.

The first part of this thesis is about the generation of a free-running dual comb from a thulium-doped fiber laser. While a mode-locked laser emits a single frequency comb, our objective is to generate two frequency combs in one oscillator by simultaneously mode-locking at orthogonal polarizations. In such a free-running dual comb, both combs share common noise and thus do not require stabilization for spectroscopic or ranging applications. Several fiber laser cavity designs have been investigated to identify the best design for this purpose. This involves, among others, different cavity lay outs (linear, circular, figure-of-9), different mode-locking mechanisms (material saturable absorbers, nonlinear amplifying loop mirror, hybrid), and the incorporation of chirped-fiber Bragg gratings (CFBGs) as wavelength-stabilizing elements.

Throughout the investigations, a mode-locked thulium-doped fiber laser with a broad tunability from 2022.1 nm to 2042.2 nm was implemented. This was achieved by applying mechanical tension or compression to a CFBG, was implemented. Moreover, a figure-of-9 all-fiber thulium-doped laser was demonstrated, generating 560 fs long pulses at 1948. Self-starting passive-mode-locking was achieved through the utilization of an in-fiber Faraday rotator, inducing a nonreciprocal phase shift.
Concerning the free-running dual comb, a hybrid cavity layout combining a nonlinear amplifying loop mirror with a saturable absorber mirror turned out to be a promising approach. A pulsed emission occurred at two repetition rates, corresponding to simultaneous mode-locking at two polarization axes. Yet, the two pulse trains could not be separated. Nevertheless, the demonstration underscores the potential feasibility of the dual-comb at 2 microns.

In the second part of the thesis, active fiber resonators incorporating thulium-doped active fiber, while operating below the lasing threshold were investigated. These resonators have the potential to

generate cavity solitons serving as frequency combs. While active fiber resonators have been demonstrated at telecom wavelength, they have never been investigated at 2 micron wavelength. Given the higher fiber propagation losses at 2 micron, employing an active fiber is a good approach to mitigate these losses. The cavity resonances were characterized and the system was modelled using numeric simulations. Ultimately, the use of an active fiber for loss compensation enabled the attainment of a sufficiently high finesse to observe modulation instability. Overall, this exploration lays the groundwork to generate cavity solitons and consequently frequency combs at 2 micron wavelength.

In conclusion, different avenues towards frequency comb generation at 2 micron were explored. Within these investigations, systems incorporating thulium-doped fiber were examined and comprehended, assessing their potential as optical frequency comb sources.

2.4 See Section 3 regarding ESR4

2.5 Alberto Rodriguez Cuevas, ESR5

Host beneficiary:	Aston University (Aston)
PhD Enrolment:	Aston University (Aston)
Supervisors:	Dr Sergey Sergeyev
Co Supervisor	Dr Hani Kbashi
PhD thesis title:	Polarization-multiplexing ring-cavity fibre laser for dual-comb generation – study, dynamics and application
PhD defence date:	July 2024
Access to Full Text (Open Access)	Not yet known.

PhD Thesis Abstract

This thesis investigates the development and characterization of a polarization-multiplexing ring-cavity fiber laser designed for dual-comb generation. It explores the underlying physics, practical implementation, and potential applications of this innovative laser system in fields such as LIDAR.
The primary challenge addressed is generating a dual-frequency comb system for metrology applications, overcoming the drawbacks of current methods. Traditional approaches using two synchronized lasers are complex and prone to phase-locking issues. Single-cavity dual-combs can reduce complexity by generating two combs with slightly different repetition rates in the same cavity, ensuring mutual coherence and shared noise. However, these systems often generate unstable regimes and are typically only demonstrated in laboratories.

The objective is to design, build, characterize, optimize, and demonstrate a single-cavity polarization-multiplexed fiber laser capable of producing dual optical frequency combs with sufficient stability and precision for dual-comb LIDAR. This system aims to simplify the generation process while enhancing the practical applicability of dual-comb technology. Secondary objectives include studying the laser's intensity dynamics and collaborating with a company to understand commercial needs and challenges in LIDAR technology, particularly under harsh environmental conditions.

The results demonstrate the successful generation of dual optical frequency combs with minimal drift (1 Hz/hour) and high stability (over 250 hours of operation). The system shows potential for practical applications, achieving sub-millimeter precision in distance measurements and proving its efficacy in LIDAR systems. The findings highlight the robustness of the dual-comb regime and its suitability for high-precision ranging applications.

In conclusion, this thesis presents significant advancements in optical frequency combs, offering a novel single-cavity solution for dual-comb generation and metrology. It opens the way for further optimization, potentially enabling its use for ellipsometric LIDAR and commercial applications.

2.6 Anamika Nair Karunakaran, ESR6

Host beneficiary:	NKT Photonics
PhD Enrolment:	Technical university of Denmark (DTU)
Supervisors:	Prof Kresten Yvind, DTU
Co Supervisor	Dr Minhao Pu, DTU
Industry Supervisor:	Dr Patrick Bowen-Montague
PhD thesis title:	Investigations of microresonator-based frequency combs
PhD defence date:	July 2024
Access to Full Text (Open Access)	Not yet known.

PhD Thesis Abstract

Microresonator-based frequency combs have emerged as a promising technology with diverse applications in fields such as metrology, spectroscopy, and communication systems. This thesis investigates comb generation in silicon nitride microresonators, focussing primarily on minimising noise in the comb lines and enhancing overall performance and stability. The investigation begins by exploring novel methodologies to reduce the noise inherent in comb generation processes. The thesis addresses a critical aspect of noise reduction by utilising a low-noise pump laser to minimise frequency fluctuations of comb lines attributed to pump laser noise. By employing the low frequency noise laser along with temperature stabilisation and packaging of the resonator, highly stable frequency combs are generated in dual ring normal dispersion microresonator.

These combs can operate for several hours without the need for active stabilisation. This thesis also explores an innovative approach to tackle thermo refractive noise, a significant source of instability in microresonator systems, by implementing an all-optical servo loop. Through extensive experimentation and analysis, this technique demonstrates a 50\% reduction in comb line noise over the bandwidth of 10 kHz to 1 MHz of the generated soliton comb. Following this, an in-depth study of the dynamics of solitons produced in a dual ring resonator and their variation as a function of pump resonance detuning is conducted. The thesis reports the experimental demonstration of the variations in spectral envelope, repetition frequency, bandwidth, conversion efficiency and frequency noise of the comb lines with changes in the detuning.

Moreover, our findings with regard to frequency noise and repetition rate stability of microcombs emphasise their great technological potential, especially for applications in the fields of microwave generation. The findings and knowledge acquired from this research are also valuable in the stabilisation of these combs. In addition to the advancements in dual-ring microresonator technology, this thesis explores frequency comb generation in the mid-infrared (IR) spectrum using silicon nitride single ring microresonator. This investigation opens up new avenues for leveraging microresonator-based frequency combs in IR spectroscopy and sensing applications. In summary, this thesis presents significant advancements in microresonator-based frequency comb generation and noise reduction techniques.

By conducting a thorough analysis of dual ring microresonator systems, along with methods to address noise issues and investigating new possibilities for frequency comb generation in the mid-infrared frequencies, this study enhances the development of optical frequency comb technologies, which have broad applications in various scientific and engineering fields.

3 RESEARCH PROJECT WITHOUT A PHD THESIS COMPLETION

ESR4 Qing Wang at Aston University, UK, will not complete a PhD. Her Academic Technology Approval Scheme (ATAS) application was refused by the UK Home Office.

Consequently, Aston could not enroll the ESR onto a PhD. There was a possibility for the ESR to enroll for a PhD at partner UPC, but the researcher declined the offer. The Project Officer was informed of this on 11 November 2022.

This deviation from the project's original Grant Agreement (GA) did not adversely affect the overall implementation or project results.

The researcher successfully finished her research projects and she fulfilled her employment contract, fully contributing to the project's objectives and outcomes.

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