## Cover Page

1. Project title (up to 200 characters): **Tailoring light-matter interaction: from topological and quantum phenomena to new functional materials**
2. Acronym, which consists of up to 20 uppercase or lowercase letters of the English alphabet, decimal digits 0−9, hyphen (-) and underscore (\_), which is used throughout the Project Proposal: **LIGHTMat**
3. Sub-program (Natural sciences and mathematics, Engineering and technological sciences, (Bio)medical sciences, and Social sciences and humanities): Natural sciences and mathematics
4. Participating Scientific and Research Organizations (SROs) and their acronyms: Vinča Institute of nuclear Sciences, National Institute of the Republic of Serbia, University of Belgrade (INNV); Faculty of Sciences and Mathematics, University of Niš (UNFSM); School of Electrical Engineering, University of Belgrade (ETF); Faculty of Electronic Engineering, University of Niš (FEE-UNI)
5. Principal Investigator (PI): Aleksandra Maluckov
6. Abstract (up to 2000 characters) including:

Photonics provoked a breakthrough in physics offering a flexible and easy-manageable playground for investigating and testing the fundamental processes in the condensed matter physics, quantum informatics and computation, which inevitably leads to the development of new materials, new generation computers and deeper understandings of fundamental science. LIGHTMat is aimed at probing the light-matter interaction to achieve an effective route to perform tasks such as effective storage and transmission of light/information and developing of new functional material and devices. Regarding this, the efficient light propagation control is a central point of all tasks in the project. We investigate particularities of the classical and quantum light localization, along with thermalization processes in atomic and photonic systems, such as photonic topological lattices, optical fibers and metamaterials, accounting inevitably present disorder and/or nonlinear effects. Results from fundamentally oriented investigations will be further directed towards their application exploitation accompanied by analytical and numerical modeling to provide platforms for practical realization of optical switching, lasing, amplification, modulation and sensing operations. The LIGHTMat project gathers experts from Nonlinear photonics, Quantum optics and Micro- and Nano- photonic structures, with a common goal: paving new routes towards efficient information manipulation and development of new optical materials and devices. The project will have a strong societal impact in securing future generations of experts in photonics, quantum informatics and numerical modeling.

Total requested budget in EUR: **297,511.13**

## Project Description − Part A

## 1. Excellence

Data transfer, storage, manipulation and detection via pure all-optical networks are still a great challenge. Basic sciences have shown how one might radically enhance all these aspects of technology separately, but deeper understanding of background processes is crucial for further advancements in integration towards application-relevant structures. LIGHTMat will address these challenges. By combining fundamental science ideas from quantum, topological and micro- and nano-scale structure photonics, we will establish theoretical background and address relevant interconnects that lead to platforms offering major advances in sensing, communications, and information processing, as outlined below.

The ability to manipulate quantum information enables researchers to perform tasks, such as unconditionally secure transmission of information, which would be unachievable in a classical context. The storage and transfer of information appear as significant issues. Storage of a quantum state implies that it is effectively decoupled from the rest of the system and not affected by its environment.

Recently, a great potential for developing quantum computers and efficient information transfer has been found in the topological photonics which do not require strong magnetic fields, feature intrinsically high-coherence, room-temperature operation and easy manipulation [1-3] [san3,san4,san5]. The topological effects, such as those found in crystals whose surfaces conduct electricity while their bulk does not (topological insulators), have been an exciting topic of physics research in recent years and were the subject of the 2016 Nobel Prize in physics [4] [san6]. This could lead to the development of new materials, new generation computers and deeper understandings of fundamental science.

Artiﬁcial photonic structures can provide a controllable platform to explore physical phenomena that are difﬁcult to achieve in real materials [5][san1]. In particular, photonic lattices have proven to be an extremely effective platform for investigating fundamental physics in simple optical settings [6] [san2]. The underlying physics relies on the analogy between the paraxial equation for electromagnetic waves and the Schrödinger equation describing quantum phenomena. Photonic lattices offer exquisite control of initial conditions and allow for monitoring the actual wave functions (including phase). The localization of light and control of light propagation through the photonic media (topological lattices, optical fibers, metamaterials, waveguides) became a paradigm for interpreting, and understanding transport and localization phenomena in condensed matter physics, and complex systems in nature [1] [san3].

Although undesirable, due to reduction of the speed of transmission and degradation of the signal/noise ratio at long distances, nonlinear effects can be used to design and produce ultrafast passive and active optical components in which signal control is determined by light, thus eliminating the need for conversion into an electrical signal [7] [11-PB]. Localized waves known as optical solitons are shown to be potential candidates as signal carriers to overcome these limitations [8] [22-PB].

Bearing this in mind, we aim to interface diverse effects from three related areas: Topological photonics, Quantum optics and New functional materials in order to propose photonic platforms capable of efficient control of light-matter interaction. We will perform comparative theoretical-numerical research of the abilities of quantum interference effects, nonlinear and topological effects to control the laser light/photon propagation through atomic systems, semiconductor heterostructures and topological photonic insulators, respectively. We will focus on the reduction of the group velocity, storage, retrieval and controlled propagation of light pulses, as a basis for applications in quantum technologies and functional photonic devices. This will trace a route for future collaboration of all three groups of researchers in nonlinear photonics, quantum optics and nanomaterials forming LIGHTMat’s team in combining the interference and nonlinear effects in topological heterostructured metamaterials.

# The key point in the physical realization of quantum information processing is the coherent manipulation of light. The potential breakthrough will be achieved by electromagnetically induced transparency (EIT) [9,10][1-LjS], [2-LjS]. Due to the destructive interference between the excitation pathways in the interaction of the probe and control lasers with the medium, the probe light can be transmitted through the medium without losses, meaning that the information is transferred unchanged. EIT is an efficient tool to control the probe laser light resulting in its slowing and storage in the medium, as well as its retrieval on demand. By combining the EIT and laser without inversion (LWI) technique the phase shift and amplification of optical pulses can provide efficient control of power losses and efficiency of reading process in quantum memory [11,12] [LJS n1, n2]. On the other hand, the tuning of topological photonic structures to the presence of nonlinearity opens an intriguing route towards enhancing the storage and optimal light control properties of photonic topological insulators.

We will provide new theoretical solutions directed towards enhancing the storage capacity and robustness of quantum memories by finding the optimized parameters and conditions for establishing the EIT and LWI in nanostructured and atomic media and the efficient synergy between the topological and nonlinear effects in photonic lattices.

Theoretical findings on relaxation, localization and light propagation control in different nonlinear topological structures, as well as the ultrashort light pulsed control by quantum cascade based structures will provide numerical design of the artificial metamataterial and metasurfacies based devices for optical switching, modulation, and sensing. We will develop a new topological switch device based on the active multicore fibers which could provide design of integrated optical elements for coding information over power, phase, frequency and topological charge.

The development of the efficient deep learning based algorithm for the prediction of huge intensity events will enhance the efficiency of photonic structures by selecting optimal experimental conditions free from devastating effects. This is of critical significance for design of future funcional photonic devices.

To achieve established aims which will trace the routes to future collaborations, the project will connect three teams with expertise in the quantum optics (UNFSM), nonlinear photonics (INNV, FEE-UNI) and quantum materials (ETF). The implementation of this project will enlighten and interface fundamental processes from three related areas: Topological photonics, Quantum optics and New functional materials in order to propose photonic platforms capable for efficient control of light-matter interaction. The LIGHTMat will provide a new solution for efficient light storage, neural networks (NN) based algorithm for extreme events prediction and topological charge switch based on multicore fiber platform in three years’ activity. It will also initialize the long-term collaboration of the team members on the problems in the intriguing fields of the nonlinear photonics and beyond.

### 1.1. Objectives

Probing the light-matter interaction from the viewpoint of efficient light control in order to provide the new routines for designing functional optical materials and devices is the cornerstone of the LIGHTMat. It will result in one of the first studies which treats together the quantum interference, topological and nonlinear effects in photonic structures based on metamaterial platforms which will provide efficient transmission, coding, storage and retrieval of information by managing light properties.

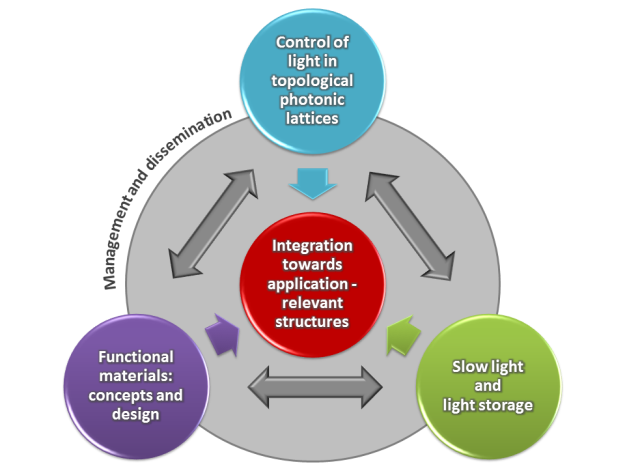
The main scientific goals of the Project are to

* investigate the possibility to slow and trap light by different quantum interference effects, nonlinear and topological effects;
* investigate the light localization and relaxation phenomena in photonic structures and accordingly provide models for efficient light control in different photonic active/passive configurations (topological insulators, two-dimensional semiconductor layers, quantum metamaterials);
* provide new numerical algorithms for prediction of extreme localized events in the photonic media and automatic design of photonic components implementing the machine learning and deep learning approaches
* Propose design of multicore fibers and THz metamaterials as platforms for practical implementation of optical topological structures and EIT, respectively, in building multifunctional structures and devices.

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| To reach this goals we will complete the following objectives:   * *provide a new theoretical model for efficient light storage and transmission – quantum memory by confronting the quantum interference effects and topological effects in the nonlinear photonic structures* * *provide the results of the probe of bulk-surface correspondence in topological photonic lattices by nonlinearity* * *provide new numerical algorithm for prediction of extreme localized events in the photonic media by implementing the neural networks algorithms* * *conduct analysis of numerical models of efficient photonic systems and materials for light control (optical switching, amplification, absorption, modulation, sensing)* |

### 1.2. Concept and methodology

Methodology of this project will be explained through scientific research described via four interrelated WPs as shown in Fig.1: **WP1 – Slow light and light storage, WP2 – Control of light in nonlinear topological photonic lattices, WP3 – Functional materials: concepts and designs** and **WP4 – Integration towards application-relevant structures.** Last WP, **WP5**, is devoted to **managing the activities and dissemination** of project results.

We are probing the light-matter interaction to achieve a route towards performing tasks, such as effective storage and transmission of information which are fundamental issues of quantum informatics, quantum computing and efficient functional optical devices. Regarding this, the control of light is a central point of all tasks in the project which will correlate three teams of researchers from fundamental quantum optics (WP1), nonlinear photonics (WP2) and quantum materials (WP3). The project will be a synergy of the theoretical attempts to enlighten the genesis and properties of localized modes in nonlinear and disordered photonic media, the potentials of light control, slowing and trapping light by topological effects and quantum interference, all conflating in tasks of WP4 devoted to design of the efficient functional materials and optical devices.

We investigate the particularities of the classical and quantum light relaxation and localization in topological lattices including inevitable present disorder and nonlinear effects to achieve the efficient functional materials for light control. The mechanisms of energy and particle exchange and the approach to thermal equilibrium in different systems are issues of central importance in statistical mechanics in which root is the ergodicity. A natural way to break it is to find systems which are insulating. The absence of diffusion is closely related with Anderson localization in non-interacting static disordered systems [13] [san10], whose essence is complete change of the single-particle eigenstate’s nature in a crystal: propagating Bloch state ‘converts’ to the exponentially localized state. The interplay of interactions and disorder inevitably appeared at the scene, since the non-interacting insulator is not a true phase of matter [14][san11]. Moreover, recently the existence of the localized phase at non-zero temperature, as a dynamic phase of matter, introduced the many-body localization which is robust to a range of interactions [15][san12]. The interplay between light and photonic lattices has been providing the testbed for localization and relaxation/thermalization phenomena in general.

**Figure . Scheme of the project's concept.**

The nonlinear response of the topologically non-trivial media to light propagating through them is inevitably related to/reflected on the topological properties. This topic is not fully investigated in spite of the intriguing finding that topological lattices support edge states even in the low-amplitude limit and do not require any threshold perturbation to exist. We aim to provide answers on the topology – nonlinearity synergy by investigating the relaxation in the non-trivial topological structures. We will start by probing the statistical approach based on the grand-Gibbsian ensemble and consider the new approach based on the extensive entropy measures. The prototypical topological models: Haldane, Bernevig–Hughes–Zhang, staggered graphen, Dirac lattice [16][san17] will be tested. The relaxation in the framework of the bulk topological invariants, will be studied, regarding the recently proven possibility to capture the topological invariants by the modulation instability [17][san13]. We will provide one of the first studies of the signatures of relaxation in periodically driven topological system (Floquet topological lattice) [18][san14] and probe by nonlinearity the properties of topological invariants such as Chern number of quasienergy bands and winding numbers associated with the gaps. This will be preparatory study for a future joint project on the thermodynamics properties of the nonlinear topological lattices in contact with nontrivial topological baths.

Simultaneously, we will provide new information regarding the robustness of the topologically protected states on the presence of time evolving irregularities [19][san16] and influence of the bulk nonlinearity of the short and long range. Regarding this, we will explore novel mechanisms for formation of topological and embedded solitons, and the zero-mode dynamics. The main tools will be analytical and numerical methods based on the coupled mode and tight-binding lattice models. The project activities related to the nonlinear topological photonics will be the continuation of the collaboration with the group of Dr D. Leykam from Centre for Quantum Technologies, National University of Singapore, Singapore.

Within the scope of WP1, LIGHTMat will be simultaneously focused on the phenomena of slow light and light storage which are closely related to the realization of quantum memories and basic quantum computation operations. They will be probed by the interaction between the light/photon and topological photonic isolators’ [16,20][san17,san18] investigated in WP2, and by emergent quantum interference phenomena. Regarding this, the topologically protected states have shown that they can add robustness to quantum communication, decreasing noise and defects prevalent in quantum technology. We will study the possibility to enhance the storage abilities by nonlinearity and to provide a framework for nonlinear topological photonic based quantum memory.

Simultaneously, the slow light and light storage by the quantum interference effects, such as EIT and LWI, in atomic ensembles and heterostructures such as quantum dots will be investigated. The new type of all-optical memory cell will be designed by using EIT, for reading out the stored data and LWI to compensate the loss. The complete quantum approach to these phenomena will demand on the entropy and entanglement measures. The model of quantum memory will be based on different types of three-, four- and multilevel model configurations (like ladder, Λ, V, diamond, tripod, double tripod and other configurations) and their interaction with pulse probed and continuous wave or pulsed control lasers. We will investigate how the probe and control laser pulse shapes, moment of the control laser turning on and off and some external electromagnetic fields affect the efficiency of memory cell. We will provide polariton picture of our investigation for reason of better understanding the underlying physical processes. In our study we will use analytical and numerical methods based on appropriate methods for solving the emergent Maxwell-Bloch equations.

Relying on the information obtained in WP2 upon remarkable light field robustness of topological properties to various external perturbations; in WP4 we will investigate dynamics of optical vortices to address the problem of opto-electronic conversion of signal in switching nodes of data traffic [21] [1-PB]. Recently, technology of multi-core fibers emerged as a possible platform for practical implementation of vortex optical topological objects [22,23] [2-PB, 3-PB]. Having this in mind, we will demonstrate through numerical modeling, design of the device based on active MCF that can change topological charge of the state of light. The concept is based on the nonlinear dynamics of optical vortices in active MCF with linearly coupled cores, saturated gain and constant linear losses [24][4-PB]. We will demonstrate that the proposed system can provide change of the topological charge of vortices and provide a model of MCF for efficient disorder protected coherent light propagation [25][5-PB]. Our output results will make necessary theoretical background for its practical realization via on-going collaboration with researchers from Aston University in Birmingham, UK [22][2-PB2]. Additional advantages of our results will be reflected through other operating regimes of MCF serving as a platform for high-power fiber lasers or for coherent beam combining.

Tracing a route towards the design of functional photonic materials which is the subject of WP3, the project will explore the quantum metamaterials efficiency for controlling light propagation. In this context, the quantum cascade lasers’ (QCL) based structures will be investigated. The aim is to numerically design the functional devices for generation and exploration of ultra-short large amplitude light pulses which benefit from sub-picosecond carrier relaxation dynamics in cascaded intraband transitions. The ultra-short pulses will be probed to capture snapshots of molecular dynamics and drive high-speed communications. The next procedure, which will be provided by the project, is related to employing unipolar the mid-infra red and the THz range intrasubband transition devices based on ZnO and nitride heterostructures. In addition, the different designs of metamaterial absorbers composed of periodically distributed metal resonators with chiral geometry will be examined. The other type of metamaterial structures which will be investigated will be based on graphene and liquid crystals [26,27] [3,4]. The focus will be on adjusting the geometry of this type of structures to be applicable for efficient dynamically tunable light modulators.

The information from investigations of EIT in WP1 and graphene based metamaterial structures in WP3 will be combined to utilize the electromagnetically induced transparency like effects in THz metamaterials in the scope of WP4. We intend to provide an efficient theoretical approach for the realization of THz modulators whose artificial optical resonances can lead to high optical field concentrations and enhancement of the light–matter interaction. We will propose new models for frequency modulator [29][5] and electrically tunable polarization modulator [30] [6] based on integrated metal resonators - graphene and the chiral metamaterial arrays with graphene, respectively.

Finally, the development of proper statistical and numerical methods will be crucial for all WPs. We plan to test and incorporate existing methods, as well as to develop new according to the requirements of proposed research. The statistical, entropy and probability based measures (Shannon entropy, probability distances, entanglement entropy, concurrence, conditional quantum entropy), and methods of nonlinear dynamics (bifurcation analysis, linear-stability analysis) will be the governing ones in interpreting the light properties. The numerical methods for modeling the light-propagation through different atomic and photonic media will be based on the Runga-Kutta method, Pseudo-spectral methods, split-step Fourier method, finite element method (FEM) and finite difference time domain method (FDTD) [28][1]. The program package Comsol Multiphysics will be used for performing numerical simulations in frequency domain, while numerical simulations in time domain will be provided by both, Comsol Multiphysics and Lumerical software. Both packages will be applied in order to obtain a proper design of application relevant photonic structures. Comsol is preferable for models with more complicated geometry when a finer mesh is required. On the other hand, simulation results of structures with simpler designs can be obtained for a very short time by using Lumerical software. In addition, the machine learning and deep learning platforms will be used to enlighten the genesis of the extreme events in photonic structures (WP2 and WP4), light propagation through metamaterials [29][2] and to automatize the design process of quantum metamaterials (WP3).

### The development of the recurrent neural network approach to prediction of huge intensity events in photonic lattices is continuation of our attempt to enlighten the EE phenomena using the advances of deep learning and machine learning [30][san19]. This will require the preparation of a large set of experimental data and search for optimal recurrent neural network algorithms. We will provide one of the first NN based procedures for the prediction of the huge intensity events in photonic media and beyond which we attempt to be upgraded in accordance with the future experimental requests.

#### 1.2.1. Data usage[[1]](#footnote-1)

We will collect experimental data sets and data sets from numerical simulations regarding the development of the deep learning based algorithm for the prediction of EE in WP2. The experimental data will be collected in laboratory for nonlinear optics at Departamento de Física – FCFM, Universidad de Chile,by team of our collaborators, while the numerical sets will be collected by P5 and P8 on personal computers and cluster machine in laboratory of atomic physics at INNV. The estimated time for collection of data is one year from the start of the project. The preferable type of data files are .png and .csv. The data will be analyzed and used for preparation of prediction EEs’ algorithm. P5 and P8 as well as our collaborators from Chile will store data sets. We will provide open access to data via link on the project website and webpage of our collaborators in Chile. The access will be provided during the project and after it.

### 1.3. Ambition

The topological matter provides a challenge to the concepts of thermodynamics. This originates from inability to use standard thermodynamics in describing topological-phase changes, owing the generic thermodynamic concept about infinitely large systems, whereas topological-phase changes involve finite-size systems due to the presence of edge states. Regardless the solution is offered in the framework of so-called Hill’s thermodynamics the things are far from being determined. Provoked by this, we will study the relaxation phenomena in different nonlinear topological lattices attempting to trace a route towards the description of thermodynamics in driven and open topological photonic structures. This will be the preparatory phase of a future joint project on this topic.

The relaxation phenomena are in a root of different aspects of light matter interaction. Related to this the investigation of the localized mode dynamics in different photonic topological structures in the presence of irregularity (disorder), different types of nonlinearities (short and long range interactions) will give new information regarding the possibility of light (classical and quantum) manipulation. The ambition is to enlighten the topologically protected states properties, as well as the bulk-surface correspondence in the presence of different types of nonlinearity. In addition, we will study the robustness of the properties of the topological insulators to the presence of the time-evolving disorder which has not been enlightened before. We will provide one of the first full analyses of the properties of light dynamics in the nonlinear Floquet topological lattices.

By probing the robustness of protected topological states we will trace new solutions for light storage and control of light. We will provide a skeleton for highly efficient and robust light memory which utilizes the nonlinearity in topological photonic structures. The results will be submitted to international journals as PRL, PRB, PRA.

The investigation of the quantum interference effects, as EIT and LWI will result in new discoveries related to the process of slowing and trapping light. The LIGHTMat is an attempt to design a new theoretical model of quantum memory based on the quantum interference effect. The findings will be published in an international journal. We attempt to attract experimental groups in quantum optics and photonics and correlate our theoretical investigations with experiments.

The significant achievement of the project will be the deep learning based algorithm for prediction of the extreme events in photonic media which will be the first fully developed route towards the control of the devastating effects in the photonic devices and beyond. By making the collected data set and algorithms open to the research community we will accelerate the investigations related with EEs.

One of the LIGHTMat attempts is to provide a solution for surpassing the opto-electronic conversion of signals in switching nodes which breaks the optical domain of data traffic. Our design of an all-optical fiber nonlinear system capable of changing the topological charge of optical vortices, paves the way for development of a topological charge switching device. If shown to be possible, such a system would provide topological charge switch function between non-counterpart vortices by appropriate adjustment of the system's parameters. To the best of our knowledge, this phenomenon has not been observed in nonlinear media, yet. On the top of this, switch function could be realized between high-power modes giving additional benefit in comparison to linear media based switchers.

Metamaterials have a strong ability to manipulate electromagnetic waves which enables many application opportunities. We will design 2D and 3D metamaterial structures with advanced sensing and modulation abilities in the THz regime [26,31,32][3-6]. The other direction of research will result in ultrashort pulse production in QCL which benefits from sub-picosecond carrier relaxation dynamics in cascaded intraband transitions. The ambition of this project is to design new optical devices for sensing and light modulation in THz frequency range which are based on metamaterial designs attractive for the experimental groups from the leading international laboratories which would realize them. This will open the opportunities for new collaborations and projects.

The project is mainly focused on enlightening the fundamental concepts and providing proof-of-principle of the designing of new functional photonic materials and devices. Since the experimental checking and realizations surpass the scope and time frame of the project, the aim is to extend our collaborations with experimental groups from Aston University and Leads (UK), Singapore, Chile, Lithuania. On the other hand, our plan to design the machine and deep learning algorithms to automate the optical device design and simulate certain aspects of the light-matter interaction will increase interest in the project findings and open a new door to international collaborations.

## 2. Impact

### 2.1. Expected impact

Photonics provides a unique platform for probing different quantum informatics and phenomena in condensed matter physics. In that sense the ability to manipulate light properties by topology is around to lead to a wave of new solutions in quantum computing and emergent materials.

The impact of findings related with the nonlinear bulk effect in the topological photonic insulators will give a tool to sense the topological properties and topological phases of matter in a novel optical context. On the other hand, topologically protected states’ robustness which is of the crucial significance for optical quantum information processing will be tested by nonlinearity. The achievements of these tasks will be interesting for a broad photonic community.

Significance of the results from the theoretical study of the particularities of relaxation and dynamical properties of driven and open nonlinear topological photonic structures related to protected states and localized topological bulk modes extends beyond the frameworks of photonics.

Important impact will be on the study of slow light and light storage by the EIT and other quantum interference related effects in the nanostructures and ensembles of atoms. Another impact is related to the photon entanglement which comes into or out from the atomic ensemble on demand by using EIT. This will be a step ahead in the context of quantum informatics.

The impact of the study of vortex and localized mode dynamics in passive and active photonic media, metamaterials and metasurfaces will yield a route towards the design of more efficient schemes for optical signal switching, amplification, polarization modulation, sensing and filtering.

For example, investigations oriented towards exploitation of vortex dynamics in MCFs are significant for telecom where pulses with orbital angular momentum are considered for transmission of information. Switching topological charge is important for signal processing. Proposed system can be also significant for high power lasers and power delivery systems, where optical vortices can transport high power through MCF. Control of coherent optical power is important for coherent beam combining applications. We expect that our results will meet experimental verifications in the experimental group led by Prof. Sergei Turitsyn from Aston University, Birmingham, UK, with whom we have established collaboration.

The impact of the realization of ultrashort pulse production in QCL, which benefits from sub-picosecond carrier relaxation dynamics in cascaded intraband transitions will lead further stringent tests of the quantum phenomena of nanoscale structures. This will initiate design of new materials, concepts and effects that can be efficiently employed in novel devices.

Another very important scientific impact will be the implementation of machine learning and neural networks based techniques which are nowadays the standard tools in diverse sciences. These activities will be a starting point for collaboration with nonlinear optics group at University of Chile. The implementation of the recurrent neural network platform will result in the algorithm for prediction of the EE at the final stage of the project. The long-term benefit will be seen in the area of telecommunication and optical devices. Moreover, the impact is not limited to photonics because the extreme events are in the focus of research in many diverse fields such as biology, economics, oceanography, etc.

The project will have a strong social impact in securing future generations of experts in photonics, quantum informatics and numerical modeling. In the unfavorable economic situation in the country, it is particularly important to show that research and inventions are the main cost of innovation and the economy of knowledge. Here, we will use an excellent ground formed by 2 universities in consortium to transform the role of the innovative Vinca group from leading-by-example into leading-and-teaching-by-example. We will inform the general public of research results through media, Open days, Festival of science, public lectures, and appropriate material on websites of participants.

### 2.2. Dissemination of results

Dissemination will be conducted all-round to inform the scientific audience on the new achievements, methods and design tools. Reflecting the nature of the Project, it will be interesting across photonics, quantum informatics, material science.

*Dissemination of the project results to scientific community, young researchers and students*

Results will be published in high-level professional journals/conferences. To ensure our research is disseminated to a broad academic audience, we will target open access publications. The costs for providing open access publications are predicted in the project budget. We will organize a topical meeting at PHOTONICA2023 conference (<http://www.photonica.ac.rs/>), where the results will be presented to a wide audience.

*Transfer of knowledge to young future researchers*

During the project, we will organize lectures targeting young doctoral and master students in order to familiarize future researchers with current perspectives and ideas within LIGHTMat investigations and progress. We will organize regular OpenLab events in INNV aimed at students and interested high-school pupils. Outreach activities will include participation at Petnica National Scientific Centre, where talented young primary and high-school pupils are gathered and provided with guided science and technology training.

*Project web-site creation and maintenance.*

Results and ideas of the LIGHTMat will be shared via the project website, hosted by Vinca Institute and cross-linked to the University of Belgrade and University of Nis websites. It will contain a description of the project, motivation, scientific background, project results, references to our scientific publications and coverage, project reports. Internally accessible web site will act as a forum for discussions and for sharing data and calculations. The website will be active for at least 5 years after the end of the project.

*Actions toward exploitation of the project results*

The activities on quantum memories will be followed by active collaboration with colleagues from the Institute of Theoretical Physics and Astronomy at Vilnius University, Lithuania, while the topological photonics related studies (WP2) will be provided in close collaboration with collaborators at the Centre for Quantum Technologies, National University of Singapore. The datasets for establishing the efficient deep learning algorithm for prediction of huge amplitude events in photonic lattices will be provided by our collaborators from the Department of optics at University of Chile. Results obtained from WP4 and related to particular device designs will be discussed with colleagues from the Aston University, Birmingham and University of Leeds, UK about directions of the future experimental realization and technological development.

*Creation and expansion of the ecosystem*

An ecosystem comprising all interested parties (participants and their institutions, research leaders in the field, young upcoming researchers, industry representatives, interest groups and initiatives) will be created, nurtured and structured. We will create a database of interesting parties and regularly inform them of the project results, OpenLab events, conferences and other events via news-letters and website. Dissemination to the non-scientific community will take place via clear and understandable reports on the project web-page, media and social networks (Facebook, Twitter and LinkedIn) as well as through collaborations with the Center for Promotion of Science and the National Committee for Celebration of International Day of Light.

## 3. Implementation Plan

### 3.1. Credentials of PI and members of Project team

The LIGHTMat team represents a well-balanced group of competent, experienced researchers with a diverse fields of expertise (nonlinear photonics, quantum optics, quantum materials, telecommunications) necessary for the success of the project. The members are well balanced with respect to gender, i.e. 58. 3% of the project team is women. Three of four WPs are led by female members together with the PI.

Dr. Aleksandra Maluckov (PI) is a principal research fellow at Vinca Institute of Nuclear Sciences, University of Belgrade. Her research interests include nonlinear dynamics, nonlinear and quantum optics and physics of complex systems. She has participated in 2 international projects (1 trilateral (Sweden-Chile-Serbia) and 1 H2020 RISE), 2 national projects and 1 COST action (MC). She has co-authored 80 scientific articles in refereed international journals, more than 20 conference papers and two university textbooks. Aleksandra is a member of the Optical Society of Serbia and reviewer to the Physical Review group of journals. On the Web of Sciences her Hirsh index is 20 with over 500 citations.

Dr. Goran Gligorić (P1) completed his PhD thesis in 2010 in which he studied dynamics of localized modes in Bose-Einstein condensates in optical lattices. After his Ph. D, from 2010 till 2012, he continued to study different localization phenomena in the more general complex systems (including photonic lattices and nonlinear fibres) as a postdoc at the Max Planck Institute for the Physics of Complex Systems in Dresden, Germany. His research of interest is in studying nonlinear dynamics and localization phenomena in photonic and other complex systems. Until now, he participated at 3 national, 2 bilateral, 1 trilateral and 2 COST actions. He is a reviewer to the Physical Review group of journals, and lead guest editor in Optical and Quantum Electronics.

Dr. Petra Beličev (P2) is Senior Research Associate with strong scientific background in modelling and simulations of various linear and nonlinear photonic systems for light beam propagation control. She has published 30 SCI papers and participated in 2 national and 6 international projects (2 bilateral (Germany-Serbia), 1 trilateral (Sweden-Chile-Serbia), 1 Danube region programme, 1 Central European Initiative and 1 H2020 RISE). As a Management Committee Substitute Member, she participated at two COST actions and cooperated with PI, P1, P3 and P9 on several projects. She was chairperson of the 7th International School and Conference on Photonics - PHOTONICA2019.

Dr. D. B. Stojanović (P3) completed her PhD thesis in 2018 on modelling electromagnetic wave propagation through THz chiral metamaterials. Her research interests are in the field of metasurfaces and metamaterials for diverse applications, ranging from light modulators and sensing at THz and IR frequencies, to structures in visible range applicable for solar cell technology. Until now, she participated in 2 bilateral projects and currently, she takes part in 1 COST action. She has served as a reviewer to 3 international journals and is recognised as an outstanding reviewer for Journal of Physics D: Applied Physics in 2019.

Dr. Ljiljana Stevanović (P4) is a full professor at the Department of Physics, Faculty of Sciences and Mathematics, University of Niš, Serbia. She is an experienced researcher in the field of atomic and molecular physics, theory of quantum confined systems and the field of quantum optics. Her results have been published in 15 papers in international scientific journals, 3 papers in national scientific journals and 9 contributed papers published at international conferences and were cited 120 times. She has participated in 2 national projects and one international COST project.

Dr. Ana Mančić (P5) is an associate professor at the Faculty of Sciences and Mathematics, University of Niš. She is an experienced researcher in fields of nonlinear dynamics and optics. Her research resulted in 24 publications at journals and 19 conferences and her Hirsch index is 10. She participated in 3 national projects and she has a successful cooperation with the PI.

Dr. Vladan Pavlović (P6) is an experienced researcher and an assistant professor at the Faculty of Sciences and Mathematics, University of Niš. He holds a PhD degree in Physics from the same faculty. His research interest is in the fields of quantum optics, particularly in the coherent effects, and quantum confined systems. He participates in one national project and he is a management committee substitute for one international COST project.

Nikola Filipović (P7) is a promising young researcher and a PhD student at the Faculty of Sciences and Mathematics, University of Niš. He already has a solid experience in the fields of quantum and nonlinear optics, and the quantum mechanics of confined systems. He participates in one national and one COST project. The topic of his future PhD thesis is closely related to the scope of LIGHTMat. He had fruitful cooperation with the PI on several recent projects as well.

Dr. Daniela Milovic (P8) is a full professor at the Faculty of Electronic Engineering, Department of Telecommunications, University of Niš, Serbia. She received Ph.D. degrees at the University of Nis, Serbia, in 2003. Her interests include nonlinear fiber optics and solitons, photonic crystal fibers, free-space optical communications, as well as wireless communications and wireless sensor networks. She participated in a few international and national projects. She is a co-author in more than 60 SCI indexed journal papers, more than 20 papers at international conferences and textbook [san20]. On the Web of Sciences her Hirsh index is 22 with over 1500 citations.

Dr. Jelena Radovanovic (P9) is a full professor at the School of Electrical Engineering, University of Belgrade. Her research interests include optical properties of semiconductor nanostructures, optical metamaterials, terahertz quantum cascade lasers, tunneling properties of complex photonic heterostructures. She has participated in more than 10 international projects, in many of them as PI/Project Co-director, including FastIQ - Swiss National Science Foundation), Trace-Gas Sensor Monitoring (NATO SFP), and 3 COST. She has co-authored more than 200 scientific articles, out of which 95 articles in refereed international journals, 115 conference papers, two monographs, one book chapter, and two university textbooks. Prof. Radovanovic is one of the founders and currently the President of the Optical Society of Serbia and a member of the Scientific Society of Serbia.

Dr Nikola N. Vukovic (P10) obtained his Ph.D. degree in Electrical Engineering in 2018. from School of Electrical Engineering, University of Belgrade, Serbia where he is currently employed as a teaching assistant. His research interests include electronic structure and optical properties of semiconductor nanostructures, quantum cascade laser, semiconductor metamaterials, ultrafast nonlinear optics, instabilities, and chaos. He is co-author of 8 papers published in international peer-reviewed journals and 19 papers at academic conferences. He has been involved in a few international and national projects.

Aleksandar Atic (P11) is currently enrolled in PhD studies at School of Electrical Engineering, and is working as a Junior Researcher at Vinca Institute of Nuclear Sciences. His research interests include electronic structure and optical properties of semiconductor nanostructures, quantum cascade lasers, devices operating in the THz range and Bose-Einstein condensates. He has been involved in 1 Ministry of Education, Science and Technological Development (Republic of Serbia) project.

***Table 3.1. Members of the Project team***

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ID[[2]](#footnote-2) | Name and family name | SRO | Person-months[[3]](#footnote-3) | Effective person-months[[4]](#footnote-4) |
| PI | Aleksandra Maluckov | INNV | 36 | 10.8 |
| P1 | Goran Gligoric | INNV | 36 | 9 |
| P2 | Petra Belicev | INNV | 36 | 9 |
| P3 | Danka Stojanovic | INNV | 36 | 10.8 |
| P4 | Ljiljana Stevanovic | UNFSM | 36 | 9 |
| P5 | Ana Mancic | UNFSM | 36 | 7.2 |
| P6 | Vladan Pavlovic | UNFSM | 36 | 10.8 |
| P7 | Nikola Filipovic | UNFSM | 36 | 10.8 |
| P8 | Daniela Milovic | FEE-UNI | 36 | 7.2 |
| P9 | Jelena Radovanovic | ETF | 36 | 9 |
| P10 | Nikola Vukovic | ETF | 36 | 10.8 |
| P11 | Aleksandar Atic | INNV | 36 | 10.8 |
|  |  |  | Total Person-months: | Total Effective person- months: |
|  |  |  | 432 | 115.2 |

The PI will, according to her research competences, coordinate the research at the whole project (as stated in WP5) and directly participate and lead activities in working packages WP1 and WP2 which are closely related with her field of expertise (A1.2,A2.1). These activities deal with theoretical research on synergy of nonlinear and topological effects in increasing the light storage efficiency and enlighten the fundamentals of localization and relaxation phenomena in topological photonic media. She will participate in all activities in WP2 and A.4.1 in WP4. PI will be responsible for coordinating the progress of the project and ensuring that the project objectives (deliverables and milestones) are completed according to the project work plan, for monitoring the overall resource utilization and project spending and for preparing quartile and final reports . P1 and P2, who have been collaborating with PI from their PhD studies, are expertized in theoretical nonlinear photonics. The research competencies of P1, particularly numerical skills, will be of crucial significance in activities related to light control. Thus he will lead WP2 and participate in A.1.2, and A4.1. Within the project, P2 will lead and coordinate research in WP4 which will correlate activities on control of light by quantum interference effects (WP1), synergy between the nonlinear and topological effects (WP2) and effects included in micro- and nano-scale structures (WP3). Also, she will be engaged in A2.2 and A3.3 due to her expertise in theoretical modeling and simulations of light interaction with metamaterials and nonlinear photonic lattices. Experienced in conference organization and disseminating activities and manifestations, P2 will actively participate in all tasks related to WP5. P3 will be involved in numerical modelling of metamaterials and metasurfaces for sensing applications. She will lead A3.3 and A3.4 in WP3. The competencies of P3 clarified her for leading role in the joint activity of all three groups (INNV,UNFSM,ETF) on probing the metamaterial structures based on graphene which exhibit electromagnetically induced transparency in THz regime and provide new light modulators (A.4.2). P3 will commit 30% of her working time on the project. P4 expertise in quantum optics clarified her for leading WP1 and participating in A4.2. Recently started collaboration with PI will be utilized in searching for the most efficient mechanism for efficient quantum memory confronting the quantum interference effects and topologically/geometrically related ones in atomic and photonic systems. P5 work on the project will mostly contribute to development machine learning procedure for prediction of the huge intensity events in photonic media which will be the finalization of the joint project started with PI, P8 and collaborators at Department of optics, University of Chile. She will lead A2.3 and participate in activity in A2.1. P6 is an experienced team member in quantum optics related phenomena and numerical modeling. Thus he will lead subactivity 1.4. He will commit 30% of his working time to LIGHTMat project. Research competencies of P8 are closely related to WP2 implying her involvement in designing machine learning algorithms and studies of extreme events in photonic structures. This will be continuation of her joint research with PI and P5 on creation of huge amplitude events in optical fiber systems. A wide and profound experience of P9 will be dominantly utilized in leading WP3 and consulting on fundamental problems such as problem statement, model development and analysis, and integration strategy in WP4 A4.2. She has a fruitful collaboration with Vinca’s team (PI, P1, P2, P3) which will be continued by joint research of light control in metamaterial configurations with different topology properties. P10 has experience in quantum cascade laser based physics and he will give contributions in WP3 and WP4. He will commit 30% of his working time on the project. P7 and P11 work on the project will contribute to realization of their PhD thesis. They will commit 30% of their working time to LIGHTMat project. P7 will join studies of quantum interference effects for increasing the ability of quantum memories in WP1. P11 will participate in realization of issues in A3.1 related to modeling and design of semiconductor quantum nanostructures which is closely related to the topic of his thesis.

### 3.2. Implementation plan

***Table 3.2a: List of work packages (WP)***

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| WP No | WP title | WP Lead SRO’s acronym | WP Coordinator - team member’s ID | Start month[[5]](#footnote-5) | End month[[6]](#footnote-6) | Total calendar months of WP duration[[7]](#footnote-7) |
| 1 | Storage and slow light: quantum interference and topological effects | UNFSM | P4 | 1 | 36 | 36 |
| 2 | Control of light: the dynamics of localized structures | INNV | P1 | 1 | 36 | 36 |
| 3 | Functional materials: concepts and design | ETF | P9 | 1 | 36 | 36 |
| 4 | Integration towards application-relevant structures | INNV | P2 | 1 | 36 | 36 |
| 5 | Management and dissemination | INNV | PI | 1 | 36 | 36 |

***Table 3.2b: Work package description****[[8]](#footnote-8)*

|  |  |  |  |
| --- | --- | --- | --- |
| Work package number | I | Work package title | Slow light and light storage |
| Lead SRO’s acronym | UNFSM (INNV) | | |
| WP Coordinator - team member’s ID | P4 | | |
| Team member ID | P6 ,P7,PI,P1 | | |
| Objective:  In this work package we develop theoretical models for efficient light storage in photonic structures by confronting the quantum interference and topological effects. | | | |
| **Activity 1.1. Light storage by quantum interference effects**  We will perform theoretical – numerical research of the influence of quantum interference effects on control of laser light propagation through the medium - reducing the group velocity, storage and retrieval of the light pulses, as the basis for applications in quantum technologies. We will focus on EIT and LWI and their realization in atomic systems and semiconductor heterostructures. The EIT effect will be used to read out stored data by using three level quantum dots in cascade configuration, while LWI effect will be realized by using four level quantum dots, and it will be used to compensate energy loss in a memory cell. We will determine the influence of some parameters like laser light intensity, laser detuning, external electromagnetic fields and the degeneracy or quasi-degeneracy of energy levels on slowing and storing light. The adiabatic approximation for light propagation, as well as its violation, will also be discussed.  *Subactivity 1.1.1* *Semi-classical model*  We will use a semi-classical model (medium is represented by multilevel quantum system and laser light by classical electromagnetic fields) to investigate the slowing, storing and retrieving the laser light under EIT conditions. The Maxwell-Bloch equations will be obtained and solved numerically applying the combination of Runge-Kutta and pseudospectral or Lax-Wendorf method. Also, the approximate analytical solution will be found in order to explain the numerical results and provide insight into the process. In order to describe the storing and retrieval of light, we will introduce the concept of polaritons, quasi particles composed from photonic and atomic parts. P4 and P6 will lead activity, P7 will perform the numerical calculations and PI will be involved through the discussions.  *Subactivity 1.1.2* *Full quantum mechanical model*  We will perform a full quantum mechanical approach (medium is modeled by multilevel quantum system and laser light is by quantum light) to study EIT-based slow and stored light. Also, the study of entropy and entanglement in the EIT system, as the basic for implementation of quantum information processes like long-distance quantum communication, will be performed. The quantum information measures, like Shannon entropy and Fisher information, will be proposed in order to describe the efficiency of the control of light propagation and EIT-based quantum memory. The concept of polariton will also be used here. P4 and P6 will lead this activity, involving discussion with PI and numerical simulation performed by P7.  *Subactivity 1.1.3* *Lasing without inversion*  We will propose the theoretical model to study LWI in quantum dots in THz domain along with the investigation of slowing light. The different multilevel configurations will be tested for efficiency. The obtained Maxwell-Bloch equations will be solved numerically by the aforementioned methods and their perturbative analytical solution will be found. P6 and P7 will lead activity involving P4. Discussions with PI.  **Activity 1.2 Light storage by topological effects and nonlinearity**  Photonic topological insulators provide a reconfigurable platform for coherent light control. We probe the nonlinearity’s efficiency to enhance their light storage abilities. We will focus on study of the physics of edge modes formed at boundaries between domains with different topology and vortex-bound ‘zero’ modes formed at midgap at zero energy in two-dimensional photonic materials (waveguides arrays accessible in experiments). The prototypical Bose-Hubbard and Dirac like lattices models will be considered analytically and numerically. We will provide an efficient solution for light storage by managing nonlinearity response.  PI and P1 will lead all activities. Discussions with P4 and P6 | | | |
| Deliverables of the work package (brief description and month of delivery)  D1.1.1 Reports (M12 and M24); conference presentation (M26); manuscript on EIT-based control of light (M18)  D1.1.2 Information measures for the efficiency of EIT-based slow and stored light (EIT-based quantum memory) manuscript (M36).  D1.1.3 Manuscript delivery on LWI and slow light, (M20)  D1.2. Nonlinearity enhanced efficiency of topological quantum memory-manuscript (M31) | | | |
| Work package number | II | Work package title | Control of light in topological photonic lattices |
| Responsible SRO | INNV (FNS,FEE-UNI) | | |
| WP Coordinator − team member’s ID | P1 | | |
| Team member ID | PI,P2,P5,P8 | | |
| Objectives: This work package is devoted to the investigation of the synergy between the local/nonlocal nonlinearity, time-evolving disorder, geometry effects and topological properties in photonic topological lattices via characterization of links between the relaxation, topological invariants and bulk-surface correspondence, probing of the protected mode’s robustness and detection of extreme events. | | | |
| **Activity 2.1** **Relaxation processes in nonlinear photonic lattices**  We will investigate the relaxation / thermalization processes in nonlinear topological lattices (prototypes: Haldane, Bernevig–Hughes–Zhang, staggered graphen, Dirac) and Floquet lattices and correlate it with the bulk-edge properties. The proper system observable will be defined and extensive statistical analysis based on standard Gibbs approach and extensive entropy measures will be provided. This is a necessary preparatory step for light control. Investigation will be divided in two activities.  *Subactivity 2.1.1* *Ergodization in topologically nontrivial phases*  We aim to enlighten the ergodization with regards to the presence of nonlinearity and irregularities in topological lattices. We will study the light/photon ensemble behavior in the neighborhood of Dirac points which are generically related to the topological phase transitions in the system. To discard the relaxation signatures in Floquet lattices we will search for and establish a new suitable statistical approach. The characteristic relaxation times in different topological lattices will be determined.  *Subactivity 2.1.2* Thermodynamics of *topological photonic insulators*  The aim is to answer the fundamental question regarding the thermodynamics of nonlinear topological photonic insulators interacting with topologically trivial and nontrivial thermal baths. We will start from the corresponding master equation and solve it numerically. We will study the contributions of edge states and phase transitions on thermodynamic potential. Thermodynamic properties will be considered with respect to bulk-surface correspondence and type of bath in prototypical 2D lattice models.  PI will lead activity, P1 and P5 will work in numerical simulations.  **Activity 2.2** **Robustness of topologically protected states**  Boundaries between two materials, with distinct topology, host gapless protected states. We will challenge their robustness to the long-range nonlinear effects and time-evolving disorder to afford new insights into the control of light in nonlinear photonic lattices. The prototypical two-dimensional topological lattices will be basic structures for numerical investigation. Dynamical simulations based on the Runge-Kutta and pseudo spectral methods will be applied. Simultaneously we will check the topological properties and the bulk-surface correspondence. This will be provided by studying:  *Subactivity* 2.2.1 *Nonlocal nonlinearity effect vs. protected states*  Determination of the dynamics of protected modes vs. the effects of nonlocal nonlinearities on topological phases and edge states, and vice versa.  *Subactivity* 2.2.2 *Time evolving disorder effect vs. protected states*  Probe of robustness of topologically protected states to time evolving disorder. Time periodic and nonquenched disorder will be numerically modeled and the semi-analytical treatment of the time-evolving disorder will be advanced.  *Subactivity* 2.2.3 *Self-trapping in nontrivial topological phase*  Self-trapping mechanisms in the topological models with preserved and broken time-reversal symmetry will be investigated. We will give a comparative analysis of the efficiency of self-trapping in these media and properties of different localized mode families: topological gap solitons, embedded and semi-vortex in these two types of topological structures. P1, PI will lead activities. P8 and P2 will help in numeric.  **Activity 2.3 Extreme events in nonlinear topological lattices**  The extreme (huge) amplitude events are inevitable in photonic devices and usually have a deteriorated effect regarding their functionality . We will investigate occurrence, properties and possibility to control these events in the topological lattices. The main method of investigation will be numerical one. Extensive statistical analysis and machine learning approach will be applied.  *Subactivity 2.3.1* *EEs in nonlinear topological lattices*  We will prove the existence of EEs in photonic systems with nontrivial topology. This will be achieved by numerical modeling of light propagation in 2D photonic lattices with manageable flatness and topological properties. We will define the threshold for EEs and statistical measures based on the height probability and the return time distribution.  *Subactivity 2.3.2.* *Prediction of EEs*  We will develop the machine learning procedure based on the recurrent neural networks for prediction of the EEs. Crucial point in this attempt will be the preparation of huge experimental data sets, which will be realized by collaboration with the group at the Department of optics at University of Chile. The second step will be checking and establishing an algorithm based on RNN. The next issue will be the selection of proper decision procedures. P5 and P8 will lead activities; PI will contribute in method development, interpretation of results and will coordinate activity. | | | |
| Deliverables of the work package (brief description and month of delivery)  D2.1.1 Manuscript on ergodic properties of topologically nontrivial phases in photonic lattices (M14)  D2.1.2 Report on thermodynamics of nonlinear topological photonic insulators interacting with topologically trivial and nontrivial thermal bath (M35)  D2.2.1 Manuscript on influences of nonlocal nonlinearity on topologically protected states in photonic lattices (M13)  D2.2.2 MS on robustness of topologically protected states on different types of disorder in photonic lattices (M23)  D2.2.3a Manuscript on different localized modes in topological structures with broken and preserved time-reversal symmetry. (M22)  D2.2.3.bManuscript on light control in optical devices via topological protected states (M33)  D2.3.1 Manuscript on Geometry and topology effects vs EEs(M13)  D2.3.2 Report/manuscript: RNN based algorithm for EE manuscript (M36) | | | |

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| --- | --- | --- | --- |
| Work package number | III | Work package title | Functional materials: concepts and design |
| Lead SRO’s acronym |  | | |
| WP Coordinator - team member’s ID | P9 | | |
| Team member ID | P2, P3, P9, P10, P11 | | |
| Objectives: This work package is dedicated to the development of the theoretical and simulation framework for studying relevant phenomena in micro- and nano-scale structures, in order to design new materials with application-relevant functions. One of its important objectives is to provide solid grounds for integration of various effects and structures in WP4. | | | |
| **Activity 3.1** **Modeling and design of semiconductor quantum nanostructures (P9, P10, P11**)  *Subactivity 3.1.1* Quantum cascade emitters (P9, P10)  Reliable models for evaluation of optical properties of QC structures will be developed and implemented by using either rate equation based approach or density matrix method/NEGF method for computations, according to the semiconductor platform and/or spectral region of interest (MIR or THz). Software codes will be developed to fit the needs of the material system used, and introduce physical parameters such as band offset, effective masses, resonant LO phonon energy etc. We will also actively pursue new light emitting schemes and novel semiconductor materials such as non-polar nitrides, ZnO/ZnMgO, GaO/AlGaO and analyze their applicability for QCL realization. The focus will be placed on understanding, modeling, and control of the effects of the nanostructure on optical properties and transport in nitride and oxide-based nanostructures.  *Subactivity 3.1.2* Systematic optimization of optical properties. (P9,P11)  This activity assumes optimization of laser output properties by applying procedures based on global optimization methods (evolutionary algorithms, simulated annealing, particle swarm optimization, or optimal control theory), including analysis of the possibilities to employ machine-learning methods to this type of problems.  *Subactivity 3.1.3* Quantum metamaterials (P10, P11)  Electronic intersubband resonances in conventional semiconductor heterostructure materials could lead to unexpected metamaterial behavior such as optical phase transitions which could be used to further control the photonic response and the dispersion properties of various quantum devices using intersubband transitions, including quantum cascade lasers. We will study the effects of layer thickness and composition, as well as doping levels, on material dispersion and the possibility to achieve negative refraction.  **Activity 3.2 Ultrashort pulse production in QCLs (P9, P10)**  The potential of QCLs as versatile spectroscopic tools can be significantly enhanced if operation in the ultra-short pulses regime is possible. The aim of this task is to study the possibilities of realization of ultra-short pulse production in QCL, explore the origins of extremely broad-band emission of some free-running Mid-IR Fabry-Pérot (FP) quantum cascade lasers and approaches to tailor QCL emission spectrum for specific applications.  This task is related to numerical modeling and linear stability analysis of multimode regimes in quantum cascade laser structures. Input parameters will be upper state lifetime, dephasing time etc. obtained from Task 3.1.  *Subactivity 3.2.1* Linear stability analysis of multimode regimes (P9, P10)  As a starting point, semiclassical Maxwell-Bloch (MB) equations for a two-level system will be used, taking into account the diffusion term in the Schrodinger equation.  *Subactivity 3.2.2* Numerical modeling of multimode regimes (P10)  Numerical simulations with the travelling wave rate equation model will be accomplished by introducing in MB equations two slowly varying amplitudes for the counter propagating waves in the Fabry-Perot cavity and distinguishing the medium’s polarizations associated with the forward and backward traveling waves.  **Activity 3.3 Design of chiral metamaterials for sensing (P2, P3, P9, P10)**  Metamaterial-based sensing technology is expected to provide a wide range of applications in the near future, including electromagnetic absorbers, filters and sensors. Chiral metamaterial absorbers discriminate between the two polarizations of circularly polarized light enabling the identification of chiral molecules.  *Subactivity 3.3.1* Searching for appropriate metamaterial design by using optimization methods (P2, P3, P9, P10)  Optimization techniques will be used in order to find the appropriate geometric parameters of the structures –the goal will be to solve the inverse design problem. In particular, we will test the use of artificial neural networks as promising candidates for modelling the light-matter interaction problems with high degree of precision.  *Subactivity 3.3.2* Numerical investigation of different designs of resonant elements (P3, P10)  Numerical modeling of metamaterial structures will be performed by using finite element method and finite difference time domain method. Different resonator designs and parameters obtained by optimization techniques will be examined in order to find the most suitable geometry for particular application.  **Activity 3.4 Analysis of electromagnetic wave propagation through dynamically tunable THz metamaterials (P3, P10)**  When metamaterials are integrated with active materials (such as graphene or liquid crystals) the manipulation of the THz electromagnetic wave is enabled. Integration of metamaterial with active material causes strong modulation of incident electromagnetic waves and consequently, fine tuning of resonant frequency is achieved.  *Subactivity 3.4.1* Metamaterials integrated with graphene (P3, P10)  Within this activity, we will perform analytical and numerical studies of electromagnetic wave propagation through metamaterial integrated with graphene . The investigation will be directed towards enhancement of electromagnetic response of this gate-tunable meta-device.  *Subactivity 3.4.2* Liquid-crystal loaded chiral metamaterials (P3)  In addition to resonant frequency tuning, circular dichroism values can be modified if chiral metamaterial is integrated with liquid crystal. This study will be done numerically and it is expected that incident circularly polarized wave will be controlled by the alignment of liquid crystal molecules. | | | |
| Deliverables of the work package (brief description and month of delivery)  D3.1.1 Report on the modelling and simulation of optical properties of QC structures (M12)  D3.1.2 Optimized design of QCLs based on novel materials (M24)  D3.1.3 Comparative analysis of QMMs based on conventional and emerging material platforms (M36)  D3.2 Model of multimode regimes in quantum cascade lasers (M24)  D3.3.1. Report on optimal numerical and optimization methods for describing electromagnetic wave propagation in chiral metamaterial absorbers (M18).  D3.3.2 Comparative analysis of different designs of novel chiral structures (M26).  D3.4. Report or manuscript on dynamically tunable THz metamaterials (M36). | | | |

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| Work package number | IV | Work package title | Integration towards application-relevant structures |
| Responsible SRO | INNV (FNS,FEE-UNI,ETF) | | |
| WP Coordinator − team member’s ID | P2 | | |
| Team member ID | PI,P1,P3, P4, P6, P9, P10 | | |
| Objectives: The work package is focused on combining phenomena and materials investigated in WPs 1-3, for utilization in multifunctional structures and devices. This joint effort will be exemplified via consideration of topological properties of active and passive MCFs for high-power multifunctional devices and utilization of EIT effects in metamaterials-based THz modulators. | | | |
| **Activity 4.1 Investigation on light dynamics in passive and active MCFs**.  Topological properties can make light fields remarkably robust to various external perturbations. By solving difference-differential equations of the generalized Schrödinger type with complex coefficients, passive and active MCF optical switching and amplification properties will be probed.  *Subactivity 4.1.1:* *MCF as optical switcher*  Ability to control and change on demand topological characteristics of light will be theoretically analyzed through numerical modelling and design of the device based on active multi-core fiber that can change topological charge of the state of light. The concept is based on the nonlinear dynamics of optical vortices in active multi-core optical fiber with linearly coupled cores, saturated gain and constant linear losses. Conditions for topological charge/orbital moment transitions of phase vortex beams will be investigated regarding the realization of optical switchers and high-power amplifiers.  *Subactivity* *4.1.2:* *Cross-talk reduction by disorder*  The MCF geometrical/topological properties make it a promising platform for controlled information transfer. Regarding this we will investigate the possibility to reduce the cross-talk between the cores in MCF induced by introduction of disorder. We will provide a model of MCF for efficient disorder protected coherent light propagation.  Activity 4.1 will be led by P2. Subactivities 4.1.1 and 4.1.2 will be numerically covered and interpreted by P1 and P2. Whole task will be monitored and discussed with PI.  **Activity 4.2. Electromagnetically induced transparency in THz graphene metamaterials (P3, P9, P10, P4,P6)**  In this task we intend to exploit the fact that metamaterial-based devices provide a unique, versatile, and efficient approach for the realization of THz modulators; their artificial optical resonances, which are subwavelength in nature, lead to high optical field concentrations, interaction enhancing the light–matter interaction. THz metamaterial-based modulators can be realized by integrating metal resonators with electrically tunable graphene which enables active tuning of resonant frequency. Graphene is an ideal material for modulation as it can be easily integrated into the metamaterial fabrication process and possesses a large conductivity range which can be electrically tuned at high speeds.  *Subactivity 4.2.1*: *Analysis of EIT effects and frequency tuning in metamaterial-based modulator*  By using the integration of metal resonator with graphene, it is possible to obtain electromagnetically induced transparency analog which results in splitting of resonance into coupled hybrid modes. Furthermore, tuning of the resonance frequency achieved by back gating the graphene modulates transmission and group delay through the device.  *Subactivity 4.2.2*: *Modelling of electrically tunable polarization modulator*  Active control of THz radiation polarization is essential for applications such as THz communications, material characterization, probing and characterization of inherently chiral biomolecules, such as DNA, RNA, and proteins. We will analyze the electrically tunable polarization modulator in which modification of the polarization state of the emitted radiation of a standard THz quantum cascade laser is achieved by using chiral metamaterial arrays with graphene.  In both Sub-activities numerical simulations of electromagnetic wave propagation through proposed devices will be performed by implementing finite element method; analytical investigation of graphene metamaterial will be done by using Lorentz oscillator model and equivalent circuit approach. | | | |
| **D4.1.1** Report on High power coherent source with possibility for selective topological charge manipulation of vortex beams (M12)  **D4.1.2** Manuscript draft (M24) on Design of the controllable all-fiber orbital angular momentum mode switch  **D4.2.1** Report on modelling of electromagnetically induced transparency effects in graphene based metamaterials (M26)  **D4.2.2** Report on the possibility of using EIT analogue for active polarization modulation of THz QCL (M36) | | | |

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| --- | --- | --- | --- |
| Work package number | V | Work package title | Management and dissemination |
| Responsible SRO | INNV (ETF, UNFSM, EF) | | |
| WP Coordinator − team member’s ID | PI (Sandra) | | |
| Team member ID | P1,P2,P3,P6 | | |
| Objectives: Activities of this WP will make sure that the progress is maintained within the scheduled timelines, guarantee efficient information flow within the consortium and with the Fund Commission and identify and mitigate risks. Actions toward dissemination of results will be taken accordingly. | | | |
| **T5.1: Scientific and Technical Coordination**  See also Section 3.2. With advice from the Management Board (WP leaders), PI will monitor scientific progress and orient activities so as to achieve the common goals of our collaboration. PI will organize (together with the Management Board), three project meetings (including kick-off) where team members - particularly young researchers - report on their activities. These meetings will be kept in INNV, ETF and UNSFM in order to build collaborations, ensure coherent project development and identify possible future ideas and impacts.  **T5.2: Coordination of Dissemination**  The Coordinator and MB will produce a Plan for Dissemination and Communication within the first year. The Annual Project Reports will list updated plans, completed tasks and future objectives. The coordinator, advised by P2 and P9, will organize a transfer-of-knowledge event during the third project meeting to organize result exploitation. PI, P2 and P3 will organize two-day topical satellite event within PHOTONICA2023 main program.  **T5.3: Conference participation and journal manuscript preparation**  The scientific results from this work will be disseminated to academic researchers in the usual manner, i.e. via high impact factor journal publications and leading international, as well as national conferences. Team members will be encouraged to highlight recent results at meetings and workshops taking place in Serbia and the EU (through COST Action meetings and workshops). Open access journals will be preferred in favor of the Open Data Research initiative.  **T5.4: Project website and Public Engagement Activities**  The project website (hosted by INNV and maintained by P1) will be our main public showcase, presenting explanations for non-experts, links to publications, job opportunities, and press releases. Apart from disseminating project results among the research community, LightMAT team (under the coordination of P6) will also make strong efforts towards communicating project information to the general public in an easy-to-understand, non-technical fashion including key facts, objectives and expected results. | | | |
| D5.1 - Project web site (month 6, INNV)  D5.2 - Organization of the project Kick-off meeting (month 3, INNV)  D5.3 - Dissemination Plan of results and Communication activities (month 12, INNV)  D5.4 - Annual Project Report of Scientific Results (month 12, 24, 36, all)  D5.5 - Organization of a Topical meeting at PHOTONICA2023 (month 27, all)  D5.6 – Seminars in Petnica national research center and OpenLab days in INNV (month 12, 24, 32)  D5.7 – Journal papers | | | |

***Table 3.2c: Major Deliverables***

|  |  |  |  |
| --- | --- | --- | --- |
| Deliverable ID[[9]](#footnote-9) | Deliverable name | WP No | Month[[10]](#footnote-10) of delivery |
| D1.1 | Quantum memory based on the quantum interference effects | 1 | 8 |
| D1.2 | Memory effects by topologically protected states | 1 | 32 |
| D2.1.1 | Manuscript on ergodic properties of topologically nontrivial phases in photonic lattices | 2 | 14 |
| D2.2.3a | Manuscript on different localized modes in topological structures with broken and preserved time-reversal symmetry | 2 | 22 |
| D2.3.2 | Report/manuscript: RNN based algorithm for EE manuscript | 2 | 35 |
| D3.3.2 | Comparative analysis of different designs of novel chiral structures | 3 | 26 |
| D4.1 | Manuscript draft on Design of the controllable all-fiber orbital angular momentum mode switch | 4 | 24 |
| D4.2 | Report on Modelling of electromagnetically induced transparency effects in graphene based metamaterials | 4 | 18 |
| D4.3 | Report on the possibility of using EIT analogue for active polarization modulation of THz QCL | 4 | 36 |
| D5.1 | Project web site | 5 | 6 |
| D5.2 | Organization of the project Kick-off meeting | 5 | 3 |
| D5.5 | Organization of a Topical meeting at PHOTONICA2023 | 5 | 27 |
|  |  |  |  |

* Present a list of milestones which will map the progress in achieving the objectives of each work package.

***Table 3.2.d: Milestones***

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Milestone ID[[11]](#footnote-11) | Milestone name | Means of verification | WP No | Due month[[12]](#footnote-12) |
| M1.1.1 | Models of the influence of system parameters (including the configuration, level degeneracy and external fields) on group velocity, time and efficiency of storage of light | Checking the values of the time and efficiency of light storage in order to choose the optimal system parameters | 1 | 9 |
| M1.1.2 | Calculations of different measures in order to choose the appropriate one | Comparing the values of different measures in order to choose the appropriate one | 1 | 24 |
| M1.1.3 | General model with different system configurations for calculation of gain and group velocity of light | Optimization of the model by checking the configurations with maximum light gain | 1 | 10 |
| M1.2 | Report on nonlinearity effect on storage in model lattice | Checking of storage capacity | 1 | 26 |
| M2.1 | Statistical method for modeling relaxation in topological lattices | Checking of Gibbsian approach applicability | 2 | 6 |
| M2.2.1 | Model of time evolving disorder | Optimization of the models by checking the characteristic times of disorder vs. characteristic times in the system | 2 | 9 |
| M2.2.2 | Model of nonlocal nonlinearity | Optimization of the models by checking the characteristic scales of nonlocal nonlinearity effect vs. characteristic times in the system.  Optimial computing efficiency | 2 | 19 |
| M2.3.2 | Training set with experimental results (M12)  Recurrent NN method (M24) | Checking of set balance. Golden standard (for supervised approach) with respect to standard statistical measures (threshold hight)  checking of different RNNs efficiency via accuracy | 2 | 22 |
| M3.1 | Modeling and optimization of semiconductor quantum nanostructures | Numerical simulations (various methods). | 3 | 12 |
| M3.2 | Exploring Risken-Nummedal-Graham-Haken instability and the potential of self-pulsations in quantum cascade laser | Numerical simulations using traveling wave model and linear stability analysis of multimode regimes in quantum cascade laser structures | 3 | 18 |
| M3.3 | Model of chiral structure obtained by using numerical and optimization methods | Checking the model results by application of different numerical methods | 3 | 24 |
| M.4.1.1 | General model of active MCF  with gain/loss included within fiber cores | Optimization of the model by checking the characteristic parametric regimes where  topological switch is possible. | 4 | 6 |
| M4.1.2 | General model of active MCF  with gain/loss and disorder included | Optimization of the models by checking thecharacteristic times of disorder vs. the other characteristic times in the system. | 4 | 18 |
| M4.2 | Model of EIT effect in metamaterials integrated with graphene | Numerical simulations of electromagnetic wave propagation through metamaterial integrated with graphene and description of obtained effects by analytical model | 4 | 24 |

* Present the costs of all budget categories of the Project.

***Table 3.2.e: Budget***

|  |  |  |
| --- | --- | --- |
| Budget category[[13]](#footnote-13) | Costs in EUR | % of budget |
| Personnel | 205,987.13 | 69.24 |
| Travel | 2,576.28 | 0.86 |
| Conferences and publications | 24,200.00 | 8.13 |
| Equipment | 33,996.61 | 11.43 |
| Consumables | 0 | 0.00 |
| Services and subcontracting | 0 | 0.00 |
| Dissemination | 1000,00 | 0.34 |
| Other costs | 0 | 0.00 |
| SROs overhead | 29,751.11 | 10.00 |
| **Total** | 297,511.13 | 100.00 |

* Provide a short narrative description of all budget categories of the Project as follows.

Personnel: The effective working months are based on the estimated working power for successful project implementation. Personal costs are estimated according to the rules of the Fund and participating SRO’s.

Travel cost: Travels in Serbia are planned in order to realize three project meetings (including kick-off). In the second year of the project two-week scientific visit to the Institute of Theoretical Physics and Astronomy, Vilnius is planned. Costs for each travel are estimated on the base of currently available information about corresponding travel and accommodation expenses plus 50 € per diem (20 € for Serbia) according to the local regulations.

Equipment and consumables: This item within the budget plan assumes purchase of notebook and three desktop computers, necessary for project research. We planned purchase of Matlab basic software package along with 3 year valid license for P6 and P7 and Comsol Multiphysiscs software with necessary modules and license for the whole project period. Comsol Multiphysics is essential for research of P2, P3, P10 and P11. Additionally, six external hard discs will be purchased as well. Expenses have been aligned with currently available information about prices.

Conferences and publications: Plan for conferences is devised with respect to the needs of dissemination of the project results. Costs for each conference are estimated separately per item (travel tickets, conference fee, accommodation expenses, amount per diem…) and formed relying on the currently available information. Costs for publication in open access journals depend on the target journals and paper length; average costs are estimated to be 1700 € per paper.

Dissemination: Organization of the two-day topical meeting within PHOTONICA2023 conference. The cost is based on the local prices and using internal technical and human resources of the SROs.

SROs overhead: 10% according to the internal rules of the participating SROs.

### 3.3. Risk management

The process for identifying team members has been very selective and based on ability to perform the project tasks, personal knowledge and experiences from previous common projects. This provides us with solid grounds for a fruitful collaboration with minimized project risks. Risk management will be used as a means to systematically handle the uncertainties within the project, in order to increase the likelihood of meeting the project objectives. If, during the project, an unforeseen risk is noticed by the PI or any of the team members, solutions will be sought to overcome the risk and/or make the necessary changes at the relevant level.

***Table 3.3. Risk management***

|  |  |  |  |
| --- | --- | --- | --- |
| Risk  assessment | Description  of the risk | Risk mitigation measure to be undertaken by members of the Project team or SRO | Risk level[[14]](#footnote-14) |
| Methodology risk | Description of the risk[[15]](#footnote-15) | Numerical instabilities and convergence issues in modelling of the optical gain of quantum cascade laser | low |
| Actions to be undertaken | Initial conditions for carrier densities will be modified to improve convergence, based on experience and available data. Convergence acceleration schemes based on combining the sheet densities of the previous iterations within self-consistent loops will be tested |
| Description of the risk | Conventional designs and lasing schemes for THz quantum cascade laser cannot work with parameters of novel material platforms | medium |
| Actions to be undertaken | Change in the number of quantum wells per active region, introduction of potential steps, testing of different and combined lasing schemes |
| Work packages, deliverables and milestones | Actions to be undertaken | Delays in the project timeline related to the late completion of a deliverable or milestone achievement. | low |
| Actions to be undertaken | This will be anticipated by a regular work plan monitoring, allowing alternatives. Progress will be reviewed at monthly WP teleconferences and quarterly team meetings |
| Members of the project team and SROs | Description of the risk | A team member leaves the project | medium |
| Actions to be undertaken | A new member with appropriate expertise will be recruited in case the team member leaves. As an inherent preventative measure a regularly updated progress documentation and research diary will be kept. All tasks have more than one participant involved, thus minimizing the risk of sub-activity incompletion. If a team member must take an urgent leave of absence (e.g. for medical reasons), work will be redistributed. |
|  | One project member not performing. | low |
|  | Redistribution of work to other involved task participants and corrective actions. Such risks will be limited by continuous internal communication flow and strict management procedures. |
| Procurement | Description of the risk | Delays in delivery of equipment and software | low |
| Actions to be undertaken | In case of a contract breach by a chosen vendor, new procedure will be initiated and vendor replaced. Existing equipment and software will be put to the best possible use until the problem is resolved. Other institutional resources will be temporarily loaned. Owing to the nature of the proposal (project not dependent on complex or costly experimental equipment), this will not affect the implementation. |
| Budgetary issues | Description of the risk | There is a delay in funding due to administrative or other reasons | low |
| Actions to be undertaken | The work will be resumed until the issue is resolved (if personnel costs are affected). If the delay affects activities with tight payment deadlines (e.g. travel or article processing charge) funds will be temporarily borrowed from other availed resources, upon agreement from the Science Fund and other funding agencies (if applicable) |
| Other risks | Description of the risk | Cancellation of the planned dissemination events (safety reasons, travel restrictions) | medium |
| Actions to be undertaken | If conferences or communication activities are affected, online participation will be considered. Alternative events will be sought. |

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**Višak - na ove reference se nigde ne poziva u tekstu?**

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1. [↑](#footnote-ref-1)
2. PI – Principal investigator, P1 – the first team member, etc. [↑](#footnote-ref-2)
3. Number of calendar months of engagement of the team member on the Project, regardless of the % of working time. [↑](#footnote-ref-3)
4. Number of calendar months of engagement multiplied by average monthly % of engagement on the Project. Effective person-months need to correspond to data in the Gantt chart and the Budget form. [↑](#footnote-ref-4)
5. Month in Project. Starting month should match the data in the Gantt chart. [↑](#footnote-ref-5)
6. Month in Project. Ending month should match the data in the Gantt chart. [↑](#footnote-ref-6)
7. Specify how many calendar months are required for the implementation of each work package, as presented in the Gantt chart. [↑](#footnote-ref-7)
8. For each work package, please add a block, as needed. [↑](#footnote-ref-8)
9. The ID should be composed as D1.1 where the first number represents the number of WP, while the second refers to the number of the particular deliverable. In case you have several deliverables for one WP, please mark them as D1.1, D1.2 etc. [↑](#footnote-ref-9)
10. Month in Project. Month of delivery should match the data in the Gantt chart. [↑](#footnote-ref-10)
11. The ID should be composed as M1.1 where the first number represents the number of WP, while the second refers to the number of the particular milestone. In case you have several milestones for one WP, please mark them as M1.1, M1.2, etc. [↑](#footnote-ref-11)
12. Month in Project. Data should match the Gantt chart. [↑](#footnote-ref-12)
13. Make sure to include any significant items of technical equipment, relevant to the Project proposal, as well as software. [↑](#footnote-ref-13)
14. Indicate risk level as high/medium/low. [↑](#footnote-ref-14)
15. Insert more rows according to the number of detected risks. [↑](#footnote-ref-15)