Allegato 9

BANDO PUBBLICO PER LA SELEZIONE DI PROPOSTE PROGETTUALI, FINALIZZATE ALLA CONCESSIONE DI FINANZIAMENTI PER ATTIVITA' COERENTI CON QUELLE DELLO SPOKE 1 "PERVASIVE AND PHOTONIC NETWORK TECHNOLOGIES AND INFRASTRUCTURES" DELL'INIZIATIVA "RESEARCH AND INNOVATION ON FUTURE TELECOMMUNICATIONS SYSTEMS AND NETWORKS, TO MAKE ITALY MORE SMART (RESTART)" A VALERE SULLE RISORSE DEL PIANO NAZIONALE DI RIPRESA E RESILIENZA (DI SEGUITO PNRR), IN ATTUAZIONE DELL'INVESTIMENTO 1.3 – CREAZIONE DI "PARTENARIATI ESTESI ALLE UNIVERSITÀ, AI CENTRI DI RICERCA, ALLE AZIENDE PER IL FINANZIAMENTO DI PROGETTI DI RICERCA DI BASE" NELL' AMBITO DELLA MISSIONE 4 "ISTRUZIONE E RICERCA" – COMPONENTE 2 "DALLA RICERCA ALL' IMPRESA", (PE 0000001), DI CUI ALL'ART. 5, DELL'AVVISO PUBBLICO NR. 341.2022 - CUP B53C22003970001

CODICE BANDO: IEIIT-RESTART-SP1-01

Titolo del Progetto: Graphene/a-Si:H Photonic Integrated Circuit Switch

Acronimo: GrapHICS

Tipologia di progetto: Focused

Area di ricerca di riferimento: Green / autonomic optical networks, systems and integrated devices

Breakdown by intervention fields - (022, 023, 006)

Green (25%)	Economia circolare (25%)	Altro restante (50%)
40%	20%	40%

Synergy of the research program with programs financed under the other Investments envisaged by the NRRP (Mission 4, Component 2), (1.3 Partenariati allargati estesi, 1.4 Potenziamento strutture di ricerca e creazione di "campioni nazionali di R&S", 1.5 Creazione e rafforzamento di "ecosistemi dell'innovazione", 3.1 Fondo per la realizzazione di un sistema integrato di infrastrutture di ricerca e di innovazione).

The NRRP gives priority to the National Research Program (PNR) 2021-2027 to ensure implementation of the strategic research initiatives. The device targeted by GrapHICS Project finds in fact perfect place in the context of the initiatives promoted by the PNR 2021-2027. The concept of "***integrated photonics***" is a cornerstone of the PNR, which finds its declination in countless contexts mentioned in the document, and in particular in quantum applications. In Section 5.4 (Digital, Industry and Aerospace), Section 4, the Program promotes the transition to digital through the so-called ***Moore-then-Moore technological development model***, in the microelectronics field, which consists in the "development of scientific and technologies for the integration of new materials and functions and for the heterogeneous packaging of devices". **The optical switch on a silicon chip** proposed here, which monolithically integrates electronic and photonic functionalities, perfectly **represents this approach**. Moreover, it responds to the PNR addresses relating to the opening towards "*energy autonomous systems*" and "*photonics*".

Annex 4.1 (Digital transition I4.0) of the same Program attributes to ***silicon photonics*** "the potential to be considered an enabling technology for the interconnection of data between chips in advanced integrated systems made with the most advanced heterogeneous integration technologies. Research must therefore be directed increasingly towards the reduction of the size of photonic components and the heterogeneous integration of advanced electronic systems ".

Again, in connection with the PNRT 2021-2027 directive, although GrapHICS do not directly aim at exploiting quantum effects, it is worthwhile highlighting that Graphene is a leading candidate material for realizing quantum computing devices. In particular, it has been recently shown a new way to use Graphene in quantum electronics. In a layered capacitor structure, very similar to the one GrapHICS will rely on, where Graphene forms the capacitor parallel plates, quantum capacitance gives rise to novel nonlinear electronic phenomena. In this system small changes in, for example, the intensity of an incident laser beam, give rise to large changes in the measured capacitance of the device.

Starting "Technology Readiness Level" (TRL) and the TRL to be reached at the end of the research program

TRL 2 - TRL 4

Attraction from other EU and non-EU countries, based on the quality of their scientific curriculum

Europe currently produces only 9% of the chips distributed on the global market. The new European Chips Act, recently presented by the European Commission, aims to more than double this share within seven years, i.e. by 2030. Plenty of investments in research initiatives are programmed, that will no doubt boost innovation in silicon photonics. Many European Universities and Research Centres are research leaders in the field of Silicon photonics, and the attraction and involvement of highly skilled researchers will be key for GrapHICS success. By the way, all participants have already taken part in European Projects and are included in research networks on the same topic.

Abstract

The project will exploit the low-cost and low-thermal-budget technology of hydrogenated amorphous Silicon (a-Si:H) in conjunction with the excellent electro-optical properties of Graphene to demonstrate a novel and fully CMOS-compatible photonic platform that can be realized with a back-end technological process. The main advantage of this approach regards the independency of the two fabrication steps, namely the microelectronic and photonic ones, that may virtually take place in two separate facilities. The demonstrator target device is an active 1xN switch intended as a replacement of passive splitters used in passive optical networks (PON). The device brings the advantage of fixed insertion loss, that is lower in comparison to a corresponding 1xN optical power splitter. This will allow to significantly extend the network power budget, *i.e.* the network reach, while enhancing data security. The successful demonstration of the 1xN switch will pave the way to highly desirable NxN switches.

Keywords

innovative materials;

new generation optical access/metro/transport technologies;
device-level optical, photonic, and integrated technologies

Context and Motivation

Due to their technological simplicity, Passive Optical Networks (PONs) are today the most successful broadband access architecture being deployed worldwide for Fiber-To-The-Home (FTTH). PONs would highly benefit, in terms *e.g.* of distance, quality of service and data security, from the deployment of active optical switches instead of passive splitters. Classical switches are, however, expensive and power-hungry devices. Through the GrapHICS project, the partners, with a strong expertise in the fields of photonics, microelectronics and deployment/management of fiber optical networks, will develop and test an innovative low-cost and low-power optical switch, compliant with actual standards, enabling the widest diffusion possible of PONs for FTTH applications.

The overall objective of the project is to develop a new technology and an Active Optical Switch that will be based on the concept of the **monolithic integration of photonic and electronic functions within the same Photonic Integrated Circuit (PIC)** by means of a fully back-end, CMOS-friendly, clean room process. In particular, the GrapHICS members aim to develop the first-time-ever monolithic convergence between an all-optical switch for 10/40 Gbps Hybrid Optical Networks, and a low-power microchip performing all the necessary control functions.

Such a device can replace passive splitters in PONs, and will be "optically transparent", in the sense that it will perform optical switching without optical-electrical-optical conversion, a power-hungry and costly process. The device will require just a few mW for its operation and will not use copper-wiring for power supply. For this goal, a power-over-fibre technology will be developed.

Beside the specific and similar application in fibre-based telecommunications, the new technology, based on the low cost thin-film of graphene as an active layer between silicon on CMOS, will also enable the conceiving of new optoelectronic devices deployable in other fields, like aerospace, biomedicine, or for on-chip communications.

Context and Motivation

The fast development of new broadband telecommunication services makes the upgrading of the access infrastructure a demanding research goal. Advanced Internet and explosive IoT applications will rapidly lead to channel capacity saturation even for residential customers.

In Passive Optical Networks (PON's) a group of Optical Network Terminals (ONT's) is connected to the central office (CO) by a series of optical links. **The communication link on the CO side is shared by all the**

ONT's and, therefore, passive optical devices must perform, in a transparent way, the separation of downstream (from the network to the end user) optical channels as well as the multiplexing of upstream (from the user to the network) optical data. More advanced schemes allow to realize virtual point-to-point PONs, however the implementation of such technologies induces an increase of operational expenses, which is a major obstacle to wider implementation of PONs.

An active optical network (AON) relies, instead, on some sort of electrically powered equipment in the optical distribution network (ODN) to distribute the signal, such as a switch or a router. Normally, optical signals need Optical-Electrical-Optical (O-E-O) conversion in the ODNs. **Among the advantages of an AON is the data security, because at any time the information is sent just to one specific ONT.**

PON's, when compared to networks with active components, offer several advantages: low cost, high reliability, no need for maintenance. These characteristics have led to the worldwide deployment of the Fiber-To-The-Home (FTTH) broadband access architecture and the time-division-multiplexed PON (TDM-PON) is the best-known solution protocol for such networks where the optical carrier is shared by means of a spatial splitter among all the subscribers.

However, in this fully passive approach, **the number of users is limited by the splitting attenuation** and by the working bit-rate of the transceivers in the CO and in the ONTs. If we take the Gigabit PON (GPON) as an example, the optical power splitter used in GPON is defined to have a maximum split ratio of 1×128, hence **the maximum allowed number of users is limited by the link budget, which basically depends on the amount of optical losses introduced by the power splitter.**

Moreover, the ONT at the customer's end must perform some special functions which would not be otherwise required using a powered router: encryption/decryption e.g., **must be used to warrant data security and prevent eavesdropping**.

It is also worth noting that, out of the total Internet power consumption, access networks consume about 60 to 80% of power, and an ONT, installed at a customer's premises, accounts for about 60% of the energy consumed in current FTTH technologies. Thus, significant energy savings can be attained by low energy consuming architectures.

In this context, in order to bring the desired broadband access to everyone, new opto-electronic devices that can handle light more effectively, with lower manufacturing and maintenance costs, should be designed and experimentally validated. The prerequisite for a low-cost mass fabrication of such robust devices is the full monolithic integration on a single microchip of the required electronic and optical functions.

This Project deals with overcoming the economic and technological constraints limiting the full development of low-cost optical switches for PONs by exploiting compatibility between the "CMOS" and the "photonics" worlds by means of a "back-end" process. The main advantage of this approach regards the **independency** of the two fabrication steps, microelectronic and photonic, that may virtually take place in two separate facilities, a most welcome target by IC manufacturers.

We propose the design, fabrication and test of a demonstrator **photonic microchip** working as an all-optical switch for Hybrid Optical Network (HON). It will be the building block for a large active optical switch deployable to replace 1:1 the actual passive splitters in PONs. Moreover, such "passive-and- active" device will be optically transparent, in the sense that, unlike conventional switches, the data travelling onto the optical carrier will not undergo an Optical-Electrical-Optical (OEO) conversion, further lowering costs and power consumption.

We will pursue an ultra-low-power design to target a self-energization approach, by means of a power- over-fiber concept, so that the switch will maintain the advantages of passive splitters since it does not require to be energized at the network nodes and is essentially maintenance free.

Goals

An active 1xN optical switch will be developed, with an innovative optical design, based on integrated Silicon Photonics (SP) technology, allowing to increase the port count while keeping a low insertion loss. In order to develop the proposed technology, and make results concretely useful for the photonic industry, a series of intermediate scientific goals have been defined, focused around the scientific, technical and integration challenges central in the GrapHICS project:

Goal 1: Design, fabrication and test of high-quality a-Si:H-on-SOI and Gr/a-Si:H/SOI, or variants of them, passive waveguides and splitters, the main passive components for guiding light through an integrated optical circuit. Also standard Silicon substrates (non SOI) can be explored.
Goal 2: Design, fabrication and test of electro-optically controlled Gr/a-Si:H/SOI, or variants, switching integrated matrix structures. They will be based on the electric control of refractive index variation to influence light propagation.
Goal 3: Design, fabrication and test of a powered-over-the-fiber microelectronic driver for the optical switch matrix elements. It is aimed at minimizing the overall power consumption in the switch, and testing a power harvesting technology based on the photovoltaic conversion of a light beam, at an appropriate wavelength, travelling along the fibres.
Goal 4: Demonstration of the technical feasibility of the proposed optical switch by experiments in a test access optical network: the operation of the switch will be experimented in a test optical network. System testing will include variable bit-rate transmission as well as transmission with ONTs operating at different signaling rates to investigate inter-operability among different communication standards.

Goals General description of the goals

We will research and develop a microchip system with integrated photonic capabilities that can replace a 1xN passive splitter and act instead as an active switch in a splitting node of Short Reach Optical Networks, i.e., Access/Metro environments and in Data-Centres.
The device will be optically transparent, in the sense that the traveling information will not undergo an optical-electrical-optical (O-E-O) conversion. Therefore, it will not require buffering and will avoid power-hungry O-E-O stages, as is the case for conventional switches. In addition, the optical transparency will allow for “bit-rate and modulation-format” transparent switching, opening new possibilities for implementation of QoS policies, and for the distribution of heterogeneous services. Our switch will simply configure an optical path for each address.
Nowadays active optical switch solutions are based on three different technologies: Micro Electro Mechanical Systems, Liquid Crystal on Silicon, and Integrated Photonics.
MEMS is a mature technology which allows latching operations. Commercially available devices have small port count and high power consumption. Liquid Crystal on Silicon technology is used in optical networks to implement Wavelength Selective Switches (WSS). A complete new optical design is required to adapt WSS operations to an optical switch matrix, and wideband operation (may be an issue. We will pursue our goal by exploiting the integration of photonic and electronic functions by means of a back-end, CMOS-friendly, process.
As a distinctive and highly innovative approach, the research will take advantage of Graphene (Gr) layers laid in such a way that the maximum of the propagating mode effectively overlaps the thin Gr layer, a smart option that reduces the device footprint which normally limits the integration density. In addition, a shrinking of the device length allows reducing the insertion losses, the parasitic capacitance and consequently the device bandwidth. The outstanding electro-optical properties of Gr and the technological versatility of amorphous-silicon, which can be easily deposited at temperatures as low as 200°C by a plasma enhanced chemical vapor deposition (PECVD) system, will converge to give life to the first-time-ever Graphene/amorphous-silicon/silicon switch.
We will develop short-term proof-of-concept prototypes of active switches whose overall design may not be market-ready yet. The pursued technology can therefore be positioned as “experimental proof of concept” (TRL 3) both for the active optical switches on CMOS and for micro system validation in the lab. We define the prototype as the microchip-integrated sample switch.

Goal 1: Design, fabrication and test of high-quality a-Si:H-on-SOI and Gr/a-Si:H/SOI, or variants of them, passive waveguides and splitters.

The Goal is the design of the waveguides, the main passive components for guiding light through an integrated optical circuit. Two-dimensional waveguides will be taken into account. In particular, low propagation loss waveguides (single-mode and multi-mode), fabricated using a-Si:H deposited by PECVD at low temperature over a standard Silicon-on-insulator (SOI) substrate, will form the basic optical structure of the PIC. To make the active switches, an insulator/Graphene/insulator stack needs to be embedded in the waveguide to form a capacitor. Various effects which may influence the propagation behavior need to be studied, including the waveguide shape, the cladding layers, the deposition condition (*e.g.*, substrate temperature, RF power, annealing process, ...). The wavelength and polarization dependence in the C-band (1520–1620 nm) of the waveguides need to be minimized. The Goal is reached with the design of a sub-micrometric waveguides with propagation losses below 3 dB/cm and as low as possible birefringence effects.

Goal 2: Design, fabrication and test of electro-optically controlled Gr/a-Si:H/SOI switching integrated matrix structures.

This Goal deals with the design of the basic element enabling optical switching. Waveguide switches are based on a controlled refractive index variation in order to influence the light propagation. In particular, the splitting function will be obtained through a field-induced change of the Graphene refractive index obtained by applying an electrical bias. Different configurations will be analyzed: adiabatic mode couplers (Digital Optical Switches (DOS)) and interferometric devices (directional coupler, Mach-Zehnder interferometer, MultiMode Interference (MMI)).
The DOS configuration is characterized by low sensitivity to wavelength and polarization, large fabrication tolerance, and no precise control of the driving electrical power. MMI couplers have many advantages, such as compactness, tolerance for the fabrication parameters, wide bandwidth, and significant reductions in the waveguide propagation losses because S-bends and Y-branches are not used.
For each optical switch the main figures of merit need to be studied and optimized in the newly proposed multistack structure: the crosstalk, the electrical power consumption, the switching time, optical losses, polarization dependence. The Goal is reached with the demonstration of an optical switch with on-off ratio of 25 dB or higher.

Goal 3: Design, fabrication and test of a powered-over-the-fiber microelectronic driver for the optical switch matrix elements.
The Goal is the development of a low-power microelectronic circuit that will drive the integrated optical switches to direct the optical signal to the right output. To do so, it needs to decode the address information from the output of a C-band photo-detector. The circuit is powered from optical energy harvested from the fibre, in the visible. Challenges include the design of a readout circuit for the photo-detector, a driver for the optical switches and an address decoder and switch selector that can operate at the limited optical power harvested from the fibre. Including the expected power needed to drive the optical switches, a total power consumption lower than 5 mW is the target to consider that the Goal is reached.

Goal 4: Test of the device in a real optical network
The Goal is the experimental implementation of the proposed architecture in a test-bed comprising the realized Photonic Integrated switch, integrating the new technical solutions that are needed in the GrapHICS architecture in a unified demonstrator in a single location.

Work plan

Work organization

An overview of the division in work packages (WPs) and related tasks (Ts) is summarized in the following:

WP1: Specification, architecture and network definition

T1.1 Architecture definition

T1.2 Communication Layer Protocol Extension

WP2: Photonic Integrated Circuit passive elements

T2.1 Low loss integrated a-Si:H/SOI waveguides

T2.2 Low loss integrated Graphene/Nitride/a-Si:H/c-Si waveguides T2.3 Efficient optical couplers

WP3: Photonic Integrated Circuit active elements and integration

T3.1 Design of the basic switch

T3.2 Design of the optical switch matrix

T3.3 Fabrication and test of the basic switch and optical matrix

WP4: Low Power electronic driving circuit

T4.1 Research and development of switch drivers

T4.2 Research and development of energy management circuitry

WP5: Switch validation in an actual PON

T5.1 Design and construction of a laboratory test facility

T5.2 Device characterization in an existing PON infrastructure

WP6: Training and Dissemination

T6.1 Transfer of knowledge and scientific results T6.2 GrapHICS life after the end of project

Work plan

Work organization:

We have designed a comprehensive project work plan to ensure that all of the scientific and technological objectives of the project are achieved in the most efficient way.

WP1: Specification, architecture and network definition

WP1 delivers a list of functional requirements as well as the specifications of nodes and network in the form of a concise technical document. Application scenarios and market drivers shall be provided.

T1.1 Architecture definition

This task will analyse the proposed active optical network from a system perspective. The goal of this task is to produce direct inputs for the active switch design. Optical switch architectures required for next-generation FTTH networks will be devised with a clear focus on the technological feasibility for the GrapHICS technology.

T1.2 Communication Layer Protocol Extension

This task will specify the communication layer protocol in the proposed active optical network. The target is to maintain the widest compatibility with available standards.

WP2: Photonic Integrated Circuit passive element

This WP will define the detailed optical and electronic characteristics of the PIC and will pursue the final design of the device. It will also address the fibre-to-PIC coupling issues, and provide results on the power-over-fibre approach for energisation.

T2.1 Low loss integrated a-Si:H/SOI waveguides

Two-dimensional waveguides will be taken into account. In particular, low propagation loss waveguides (single-mode and multi-mode) using a-Si:H deposited by PECVD at low temperature as guiding layer will be analysed. Various effects which may influence the propagation behavior will be studied, including the waveguide shape, the cladding layers, the deposition condition (e.g., substrate temperature, RF power, annealing process, ...). This will be useful to address all the possible origins of propagation loss. The wavelength and polarization dependence in the C-band (1520–1620 nm) of the waveguides will be also minimized. The targets of this task will be the design of sub-micrometric waveguides with propagation losses below 3 dB/cm and as lower as possible birefringence effects. Physical characterization techniques will be exploited throughout (Field Emission Scanning Microscopy, Atomic Force Microscopy, Spectroscopic Ellipsometry, C-V-f.)

T2.2 Low loss integrated Graphene/Nitride/a-Si:H/c-Si waveguide

Starting from results of T2.1, the aim of this task is the fabrication of submicron single-mode waveguides where the core is based on the Gr/insulator/a-Si:H/SOI multi-stack.

A first fabrication milestone of the project will be the realization of waveguides with propagation losses below 4 dB/cm.

T2.3 Efficient optical couplers

In this task useful optical fibre coupling to connect optical fibers to optical planar circuits will be designed. Fibre pigtailing concept will depend on the chosen coupling approaches. In particular, in order to avoid active alignment process between the optical core fibre and the integrated coupler, several alignment techniques will be explored. Inverted tapers and grating couplers (out-of-plane coupling) will be considered.

WP3: Photonic Integrated Circuit active elements and integration

T3.1 Design of the basic switch and matrix

This task will be focused on the design of the building-block element to enable optical switching. Waveguide switches are based on a controlled refractive index variation in order to influence the light propagation. In particular, the splitting function will be obtained through a field-induced change of Graphene refractive index. Different configurations will be analyzed, such as: adiabatic mode couplers (Digital Optical Switches (DOS)) and interferometric devices (directional coupler, Mach-Zehnder interferometer, MultiMode Interference). By cascading the basic device, 1xN switches can be obtained. The most commonly used DOS is a linear Y-junction branch, consisting of an input-tapered waveguide, which adiabatically adapts (i.e., slowly varying) the launched fundamental mode in the bimodal input region, followed by two single-mode symmetric output branches. The 1×2 DOS operation principle is based on the modal effective index variation induced by a bias applied to the Gr layer, which can modify the beam propagation pattern inside the structure itself. Interferometer structures are based on mode interference effect and the Mach–Zehnder interferometer (MZI) is perhaps the most extensively studied thermo-optic switch thus far. The conventional and simplest form of the switch is made up of one 3-dB splitter and one 3-dB combiner connected by two channels, with an electro-optic phase shifter placed in one arm of the interferometer. Often, multimode interference (MMI) is employed. An MMI waveguide employs the self-imaging principle, a property by which an input-field profile is reproduced in single or multiple images at periodic intervals along the propagation direction of the MMI waveguide. MMI couplers have many advantages, such as compactness, tolerance for the fabrication parameters, wide bandwidth, and significant reductions in the waveguide propagation losses because S-bends and Y-branches are not used.

T3.2 Fabrication and test of the basic switch and optical matrix

We will pursue in this Task the fabrication of passive and active photonic devices on the same CMOS-compatible platform, namely the low loss micron-sizes waveguides and 1x2 switches. Both coupling schemes (in- and out-of-plane coupling) will be investigated. The latter will provide fast access points for testing of the integrated photonic circuits. First basic characterizations will follow in a laboratory test setup.

WP4: Low Power electronic driving circuit

T4.1 Research and development of switch drivers

A low power and very efficient digital selector in order to generate the appropriate digital signals to drive all three cascaded optical switches and configure the optical route relevant to the detected ONT address will be designed.

T4.2 Research and development of energy management circuitry

Including the expected power needed to drive the optical switches, a total power consumption lower of the order of mW is expected. At this power level, we expect it will be feasible to power the device from optical energy harvested from the fibre. For this purpose, a detector for 830-850 nm or visible will be selected and operated in photo-voltaic mode.

WP5: Switch validation in an actual PON

T5.1 Design and construction of a laboratory test facility

The purpose of the test bed is to provide a smooth way towards deployments. In this sense, it is the intention to start the demonstrator in early phases of the project and populate it with the separate prototypes/PICs that will be developed within the project. The test environment will be located at the industrial partner laboratories, based on ONLs, splitters and ONTs actually used in PONs, although slightly modified to allow the launch of power-over-fiber.

T5.2 Device characterization in an existing PON infrastructure

The objective of this task is the characterization of the PIC within an existing PON. The test-bed will evaluate experimentally both the validity of the network protocol and the photonic integrated optical router. The photonic integrated optical switch will be characterized and inserted in the system test-bed for the overall concept assessment.

WP6: Training and Dissemination

T6.1 Transfer of knowledge and scientific results

The scientific advances in technology and application results of the Project will be disseminated by all partners. Topic seminars will be organized for Master Program students and PhD students by the academic partners. Intermediate results and proposed basic principles, supported by analysis and simulated data, will be presented at international conferences. The creation of a Special Session centered on Gr/a-Si devices for photonics will be proposed to one or more conference organizing committees. Research results will be submitted for publication in top class international journals. A project website will be created, with dedicated contents, to enable the entire community to find out about the project.

T6.2 GrapHICS life after the end of project

This task aims to sustain impact of GrapHICS results after its end, by tackling the causes of loss of new competences common to many funded projects. It will also keep partners engaged in promoting the participation in new research calls.

Expected results and impact

The ultimate goal of GrapHICS it to accelerate the route to market for breakthrough innovations, and ultimately to contribute to reaching the ambitious objectives of sustaining industrial competitiveness and leadership in the rapidly growing photonic market of Fiber-to-the-Home (FTTH). It covers the integration of high-speed electronic circuits with photonics by blending both fields with a seamless integration platform. Moreover, by overcoming the limitation of current passive components, solutions developed in this Project will be also well suited for advanced computing and other applications.

The new technology, aimed at substantially increasing bandwidth capability and energy efficiency of PON, will deliver significant benefits to consumers as they will allow the highest possible speeds of internet access, both downstream and upstream, at lower infrastructural costs. These benefits include:

- micro-encapsulation of the photonic functions on a CMOS chip will enable the widest, easiest and cheapest sharing of optical fibre advantages among consumers;
- the pursued technology will foster the development of new microelectronic devices embedding optical functions, a big step forward for the microelectronics industry not only at a European scale;
- the new concept of a hybrid technology (with optical energization) that can be 1:1 introduced in the current passive scheme would significantly overcome the state of the art technologies.

Scientific impact:

In this Project, the Optical Switch will be based on Electro-Optical Switching rather than All-Optical processing. All-optical processing and all-optical packet switching functionalities have been widely demonstrated in the past to provide both fast switching time and complex labeling processing. However, all these solutions are known to have low scalability and serious reconfigurability issues. On the other hand, the choice of an Electro-Optical switch based on a-Si:H and Graphene opens new possibilities. Their physical properties make them compatible with all the switching requirements (switching speed, insertion-loss, etc.). Furthermore, they allow for the realization of circuits integrating the electro-optical switching functionality with electronics. This results in two main advantages:

1. the routing can be controlled remotely, allowing for simplified labeling schemes. With a suitable network protocol design, this could lead to the adoption of label-free switching algorithms.
2. the optical switch can be reconfigured at any time. Reconfigurability is an added value for access networks that can be achieved only in E/O approaches.

The second point the Optical Switch is the unwired-powering capability. In Access and Metro Area optical networks, it is commonly envisioned that the switching elements should be passive, *i.e.*, they should not require to be hard-wired to power sockets. This is an important requirement for operators, because it significantly lowers the operational expenses and out-of-service risks. Within the project we propose instead to provide the needed power by means of a power-over-fibre approach. In particular, the power will be provided in the form of light by the distributed ONTs. This requires additional laser sources at the ONTs and a proper photovoltaic element to be ultimately integrated within the PIC. Power-over-fibre delivery will be operated at a suitable wavelength, differing from that used for data- transmission, most probably visible or 830-850 nm. It should be noted that the active optical elements in the switch are expected to require a very limited energy to be operated. From a solid-state perspective, the core-switch is in fact a thin a-Si/nitride/Gr/nitride/c-Si capacitor. The dynamic power associated to the charge-discharge of the capacitance is therefore the major concern. We have calculated that each element dissipates an energy-per-operation (operation = switch-on or switch-off) lower than 50 pJ. It is evident that the big part of the power necessary to operate the device will be dissipated by the microelectronic circuit. Low-power design techniques, like power gating and low voltage, will be therefore adopted to keep the total power below a few mW.

One additional scientific result of the research consists in the significantly lower insertion losses compared to the counterpart passive optical splitters. This is obtained thanks to the physical properties of thin film silicon and Graphene. This results in a power budget gain, which can be exploited either to increase the network reach, to increase the system baud-rate, or for a combination of them.

Technological impact:

There are several benefits for the future dynamic telecommunication market in studying and implementing a full optical switching system able to be remotely configured and re-configured to interconnect customers, services, sensors networks etc.
This technology will be the key to enable a simplification in interconnecting users and services over optical networks with reduced delivery time and cost-effective operational management.

Several telecommunication operators, already using a common network infrastructure wholesale model, could get improvements in service activation in terms of time, costs and in general service level delivered. In the same way the network devices, that will be involved in this technical evolution, will be interconnected to be the central element housing news services like reconfigurable local and distributed sensor networks and IOT.
Moreover, the optical remote switching technology will be the driver in the next years enabling the implementation and spreading of a smart city set-up leaning on a strong, dynamic, reliable and wholly reconfigurable optical network.

Contributions to sustainability:

The deployment of a telecommunication network is a challenge for the sustainability constraints.

The proposed remote switching technology is meant to improve the sustainability of the network deployment. The introduction of this technology in a quite mature optical network scenario, will strongly reduce the field activity needed to connect new users' services on site. There will be no longer the need for physically operate on site with a technical team to configure and re-configure customer or new services connections. Therefore, technician teams mobility in the field will be strongly reduced. Due to this simplification, the impact on cities livability other than the quicker availability of the services, would be in terms of reduction in traffic jam, pollution etc., too.
Moreover, the re-configuration of the optical network on the customer side would highly reduce the time needed for the customer or service to be connected or even reconnected to the desired service/operator. In a smart-cities scenario the next future will be driven by the need for a fast and reliable service oriented interconnecting optical network.
Besides the sustainability of a PON itself in an energy consumption style, this remote switching and interconnecting device will have a very low power consumption with the goal of near zero power consumption at the operational level as a target of the project.
Furthermore, the reduced need to access to several network cabinets located in the city streets, will give the opportunity to reduce visual and environmental impact of the telecommunication network infrastructures. The remote configuration systems will have less need to be accessible and could even be mostly located in less accessible hidden environments (i.e. underground).

The project is definitively respectful of the *"not significant harm"* principle.

Benefits for the society:

Overall, the project will have an impact on the new digital society, helping to bring economic prosperity and a multitude of business, social and entertainment opportunities to its users. The major societal impacts of GrapHICS include:
substantial cost savings infrastructures: deploying FTTH networks requires a big investment. The actual network deployment is the dominant factor (about 40%), generally insisting on operator's budget. The actives, i.e., both the active electro-optical components in the customer premises equipment (CPE) and the optical network termination (ONT) located at the central office (CO), represent theremaining.
The creation of high quality and high level added-value jobs in the strongly growing field of telecom and

datacom: GrapHICS has potentials to trigger technological advantage to industry in this exploding sector, leading directly to significant increases in numbers of high added-value jobs.

An improvement in the quality and a reduction in the costs of modern communication services could derive from the novel switch, providing an affordable access to the digital world and the information age. This will improve the quality of life and working conditions for the population but also less developed regions, specifically for young people under education, and for elderly and disabled persons.

Possible collaborations and synergies with other projects (

This project takes advantages of the advancements brought by previous research developed within the FP7 Project "HELIOS" (grant agreement 224312), for which in the "Overall results of the Project" it was highlighted that "*With the work on innovative devices, amorphous silicon modulator exhibited performances far beyond the original expectations*", while in the 3rd "Technical Review Report" it was highlighted that *"The main scientific/technological achievements of the project within the 3rd year include: ….. a nanosecond response time a-Si:H based modulator".*
Plenty of research initiatives exist today in the Silicon Photonic area, recently revitalized by the outstanding results brought by the coupling with Graphene. Although GrapHICS stands out from all the others for the fact that it focuses on a-Si:H rather than crystalline Silicon, synergies are possible and indeed certain.

Principal Investigator: [redacted]

List of partners

1. CNR – ISASI
2. Open Fiber
3. University of Naples "Federico II"
4. University of Reggio Calabria "Mediterranea"

Partner 1:

Reference investigator: [redacted]

List of permanent staff

1. [redacted] Reasearcher, 3 man-months/year
2. [redacted] Techologist, 2 man-months/year

Geographical balance (sede e stima della percentuale di budget speso nelle regioni del sud)

The expected percentage of budget to be spent in objective 1 regions is 100%.

Partner 2:

Reference investigator [redacted]

List of permanent staff

1. [redacted] 3 man-months/year
2. [redacted] 3 man-months/year

Geographical balance (sede e stima della percentuale di budget speso nelle regioni del sud)

The expected percentage of budget to be spent in objective 1 regions is 50%.

Gender balance (stima della percentuale di spese di personale relativo a donne

About 50% of man-months/year is related to women

Partner 3:

Reference investigator [redacted]

List of permanent staff

1. [redacted], Full Professor, (ING-INF/01), 2 man-months/year
2. [redacted], Full Professor (ING-INF/01), 3 man-months/year

Geographical balance (sede e stima della percentuale di budget speso nelle regioni del sud)

The expected percentage of budget to be spent in objective 1 regions is 100%.

Partner 4:

Reference investigator: [redacted]

List of permanent staff

1. [redacted], Assistant Professor (FIS/01), 1 man-months/year
2. [redacted], Full Professor (FIS/01), 1 man-months/year
3. [redacted], RTD-B (ING-INF/01), 3 man-months/year

Geographical balance (sede e stima della percentuale di budget speso nelle regioni del sud)

The expected percentage of budget to be spent in objective 1 regions is 100%.

Gender balance

About 30% of man-months/year is related to women

Titolo del Progetto: Lithium niobate on insulator (LNOI) nonlinear photonics for communications
Acronimo: ELENE
Tipologia di progetto: Focused-Theoretical

Area di ricerca di riferimento: **4**

Breakdown by intervention fields - (022, 023, 006)

Green (25%)	Economia circolare (25%)	Altro restante (50%)
25%	25%	50%

Synergy of the research program with programs financed under the other Investments envisaged by the NRRP (Mission 4, Component 2), (1.3 Partenariati allargati estesi,1.4 Potenziamento strutture di ricerca e creazione di "campioni nazionali di R&S", 1.5 Creazione e rafforzamento di "ecosistemi dell'innovazione", 3.1 Fondo per la realizzazione di un sistema integrato di infrastrutture di ricerca e di innovazione).

Starting "Technology Readiness Level" (TRL) and the TRL to be reached at the end of the research program

1	4

Attraction from other EU and non-EU countries, based on the quality of their scientific curriculum

Abstract
The performance of current optical links is limited by the electronic subsystems needed to convert the carrier wavelengths and relocate the channels. All-optical wavelength conversion enables easily reconfigurable wavelength-division multiplexing (WDM) optical systems, thus boosting the aggregate system capacity. ELENE aims at implementing all-optical wavelength conversion by exploiting the optical quadratic nonlinearity of Lithium Niobate. Although this approach has been introduced in the literature before, reported conversion efficiencies are still far from the performance level that is required for a practical WDM network. Thanks to the recent development of Lithium Niobate on Insulator (LNOI) wafers, and related nano-fabrication technologies, we will design, fabricate and test wavelength converters in LNOI waveguides. In order to control the flow of power among the different wavelengths, LNOI must undergo the process of poling, which periodically reverses the sign of the quadratic nonlinearity. ELENE will experimentally demonstrate all-optical frequency conversion by two methods: 1) difference frequency generation (DFG) starting from a signal channel in the C-band (i.e. around 1550 nm) and a pump at around half the signal wavelength; 2) parametric conversion based on cascaded quadratic effects, starting from both signal and pump in the C-band. The impact of the proposed wavelength converters on the performance of optical networks will also be thoroughly evaluated.

Context and Motivation
All-optical signal processing techniques have the potential to make current electronic based routing systems obsolete, paving the way towards WDM optical links that are transparent to the modulation scheme, and easily reconfigurable. The key building block at the heart of any optical processing scheme for WDM systems is the wavelength converter, which must be able to shift an optical channel over a span of at least 50 nm, without affecting the information carried by the signal phase. A very promising solution based on quadratic nonlinear interactions in Lithium Niobate (LN) is already present in the scientific literature. However, so far the reported conversion efficiencies are too low for any real-world telecom application. The low conversion efficiency stems from the fact that traditional LN waveguides, fabricated starting from thick LN wafers, exhibit quite wide area guided modes in the near-infrared, so that the resulting weak effective nonlinear coefficients hamper the conversion efficiency. In recent years, standard

wafers with a LN thickness of at least 5 microns have begun to be replaced by Lithium Niobate on Insulator (LNOI) wafers, where the top LN layer can be as thin as 0.3 micron (over a silicon dioxide substrate). Waveguides operating in the telecom C-band can be fabricated on these substrates and, due to the sub-micron thickness of the LN layer, the effective area of the fundamental mode can be one order of magnitude smaller than that of traditional LN waveguides. This project aims to leverage this predicted one-order magnitude increase in conversion efficiency, as well as the yet unexplored potential of cascaded quadratic nonlinearity in poled LNOI waveguides, in order to experimentally demonstrate a new class of efficient wavelength converters, outperforming any previously studied all-optical converter, and leading to the development of new switching architectures for optical networks.

Context and Motivation

All-optical signal processing techniques have the potential to make current electronic based routing systems obsolete, thus paving the way towards WDM optical links which are fully transparent to the modulation format [1,2]. As a matter of fact, current WDM systems implement wavelength conversion by means of electronic subsystems that do not preserve the phase information and can add distortion and noise, thus posing a stringent upper limit on the overall throughput. Moreover, it remains challenging to upgrade routers to new modulation formats. The wavelength converter must be able to relocate any optical channel over a span of at least 50 nm, without affecting the information carried by the signal phase. As widely discussed in the literature, the same wavelength converter can also perform all-optical digital processing operations. Frequency conversion can be obtained in Lithium Niobate (LN) thanks to its optical quadratic nonlinearity; however, the reported conversion efficiencies are too low for telecom applications, where bulky high-peak power lasers cannot be easily integrated. In a quadratic nonlinear conversion process, the conversion efficiency is related to the square of input power (when two wavelengths are involved), or to the product of signal and pump powers (when three wavelengths are involved), and it is inversely proportional to the overlap among the modes at the different wavelengths. Low conversion efficiencies stem from the fact that traditional LN waveguides (i.e., fabricated starting from thick LN wafers) exhibit wide area fundamental modes, so that the resulting weak effective nonlinear coefficient limits the conversion efficiency. The experimental results reported in the literature are based on reverse proton-exchange (RPE) waveguides, whose fundamental mode area can be of the order of 10 micron squared or even larger. The RPE technology works on wafers where a thick layer of LN (in 5-50 microns range) is grown on a silicon dioxide substrate: as a consequence, the area of the fundamental mode cannot be smaller than about 10 micron squared. This leads to the conclusion that this well-established technology is not suitable for boosting the wavelength conversion efficiency. In recent years, Lithium Niobate on Insulator (LNOI) wafers have become commercially available, and have started a fast-paced resumption of studies on quadratic effects in LN waveguides [3]. In fact, in LNOI wafers the LN layer has a typical thickness of 0.3 micron, and the layer below LN is made of silicon dioxide: the thin LN layer, combined with the large refractive index difference between LN and silicon dioxide, guarantee a tight confinement in the vertical direction. This results in an effective area of the fundamental mode which is at least one order of magnitude smaller than that of LN waveguides used in wavelength conversion experiments based on legacy fabrication technologies. Waveguides and basic components, such as couplers and Y-junctions, can be fabricated on LNOI substrates by titanium diffusion or by etching, but these technologies are not widely commercially available for those substrates. Nevertheless, research laboratories at Italian universities and foundries operating in Italy are capable of periodically poling the LNOI wafers, and of manufacturing LNOI waveguides. In our approach we will also explore the potential of permanent and transient waveguides due to self-guiding and photorefractive effects [4]. ELENE aims to explore wavelength converters based on two physical mechanisms that can be exploited in LNOI waveguides: 1) difference frequency generation (DFG); 2) parametric conversion by means of cascaded quadratic nonlinearity. In order to use DFG for translating a channel in the C-band, the fundamental frequency (FF) wavelength must be around half the C-band wavelengths, and the corresponding quasi-phase matching condition must be fulfilled by choosing the appropriate poling period. In the case of cascaded quadratic interactions, the poling period is chosen in such a way that there is a residual phase mismatch which prevents DFG and also the build-up of second harmonic (SH) power but, owing to the reiterated forth and back conversion between the FF and its SH, a nonlinear phase is accumulated by the FF. It can be proved that the cascaded quadratic nonlinearity is equivalent to a cubic nonlinearity: in fact, in presence of a strong pump a parametric conversion similar to four-wave mixing is observed. Alternatively, the poling period can be chosen to phase match internal SH generation in the LNOI waveguide. Next, mixing of the SH and the signal around the FF will generate the idler by DFG. Devices based on cascaded quadratic nonlinearity have a twofold advantage: the required pump wavelength is within the C-band, and the theoretically predicted efficiency is greater than that achievable by resorting to the LN Kerr nonlinearity, or the DFG process. ELENE will also confirm that the proposed all-optical converters can be beneficial in exploiting spectral and fiber core switching capabilities [5].

References

[1] C. Langrock et al., All-optical signal processing using $\chi(2)$ nonlinearities in guided-wave devices, J. Lightwave Technol., 24, 2579-2592 (2006)
[2] M.H. Chou et al., 1.5-μm-band wavelength conversion based on difference-frequency generation in LiNbO3 waveguides with integrated coupling structures, Opt. Lett., 23, 1004-1006 (1998)
[3] Y. Qi et al., Integrated lithium niobate photonics, Nanophotonics, 9, 1287-1320 (2020)
[4] E. Fazio et al., Screening-photovoltaic bright solitons in lithium niobate and associated single-mode waveguides, Appl. Phys. Lett., 85, 2193-2195 (2004)
[5] G. M. Saridis et al., Survey and evaluation of Space Division Multiplexing: from technologies to optical networks, IEEE Communication Surveys & Tutorials, 17, 2136-2156 (2015)

Goals

The aim of the project is to experimentally prove the feasibility of all-optical conversion using LNOI waveguides, and theoretically evaluate the beneficial effects that such converters can have for optical networks.

Goal 1: develop new skills for LNOI waveguides
Goal 2: develop new ideas and devices for wavelength conversion
Goal 3: prove a disruptive prototype for telecom of the future
Goal 4: envision a step forward for optical networks

General description of the goals:

The aim of the project is to experimentally prove the feasibility of all-optical conversion using LNOI waveguides, and theoretically evaluate the beneficial effects that such converters can have for optical networks.

Goal 1: develop new skills for LNOI waveguides

Acquire all the skills to design and test waveguides to be fabricated on LNOI by means of different technologies (titanium diffusion, etching, self-guiding).

Goal 2: develop new ideas and devices for wavelength conversion

Find the most efficient method for wavelength conversion in LNOI waveguides by exploring the degrees of freedom offered by waveguide geometries and poling engineering.

Goal 3: prove a disruptive prototype for telecom of the future

Successfully test at least one wavelength converter prototype working with pump and signal wavelengths in the C-band, at power levels compatible with telecom applications.

Goal 4: envision a step forward for optical networks

Prove by means of simulations that LNOI wavelength converters, properly inserted in the switching architecture, allow for an increase in the number of connections accepted by each node.

Work plan

Work organization:

The consortium will be composed of three Units: Sapienza Università di Roma (Sapienza-Unit1), and two additional Units, to be selected via open calls. Sapienza brings expertise on nonlinear optical signal processing and optical networks. Additional skills in integrated photonics, including component and mask design, support for fabrication and characterization of waveguides and optical frequency converters will be provided by Unit2 and Unit3, respectively.

WP1: Design and characterization of waveguides on LNOI substrates

The aim of this work package (WP1) is the design and characterization of the structures needed for the development of the project activities. The first task is focused on the identification of the optimal design of the waveguides and of other optical components. The aims of the second and of the third task are the fabrication and experimental characterization of those waveguides.

Task 1.1: Design of waveguides and nanostructures on LNOI substrates (all Units)
Task 1.2: Characterization of the fabricated structures and related optimization issues (Sapienza, Unit2)
Task 1.3: Design and manufacture of ultralow-loss self-induced waveguides on LNOI (Sapienza)

WP2: Nonlinear properties of waveguides fabricated on LNOI substrates

This WP deals with analyzing and optimizing the nonlinear optical properties of the waveguides that can be fabricated on LNOI substrates. In particular, the small thickness of the LN layer leads to unprecedented high effective nonlinearities. The poling of the LNOI substrates is instrumental in harnessing the quadratic nonlinearity, on which the function of the wavelength converter is based. In the first task, the correctness of the poling procedure is tested by SH generation measurements, whereas the conversion processes are experimentally verified in the second task. In the third task, the role of the competing Raman effect is assessed, and in a fourth task the possibility of exploiting all-optical, nonlinearity-induced waveguides is explored.

Task 2.1: Test of the poling efficiency by second-harmonic generation measurements (Unit3)
Task 2.2: Test of the cascaded quadratic nonlinearity by means of four-wave mixing and supercontinuum generation (Unit2, Unit3)
Task 2.3: Investigation of the Raman effect and Raman induced pump depletion at high input intensities (Sapienza)
Task 2.4: Analysis of the ability to recognize and store information in solitonic waveguides in both a supervised and unsupervised way at ultralow optical fluences (Sapienza)

WP3: All-optical signal processing by means of wavelength conversion

This WP aims at the design and experimental characterization of the wavelength converters: these converters must be capable of shifting a C-band channel by at least 50 nm, while preserving its bandwidth and the information carried by its phase. The converter is the analog of a RF mixer when working with a CW pump, and the same converter behaves as a gated mixer when the pump consists of a train of pulses. The low propagation and insertion losses achieved in WP1, and the optimization of quadratic and cascaded quadratic processes performed in WP2 will lead to converters requiring pump power levels that are compatible with a practical device, to be integrated into a router.

Task 3.1: Design of the wavelength converter based on nonlinear effects in LNOI waveguides (all Units)
Task 3.2: Testing of the wavelength converter in the C-band (all Units)

WP4: Performance evaluation of a network implementing the proposed wavelength converter

The WP4 will propose and investigate new switching architectures equipped with LNOI wavelength converters. In particular, three tasks will be carried out. Task 4.1 will define the switching architectures. The resource allocation problem in elastic optical networks with multicore fibers (MCFs) and equipped with LNOI wavelength converters will be formulated in Task 4.2. Finally, the proposed switching architectures will be evaluated in Task 4.3, in the context of a real network and traffic scenario.

Task 4.1: Definition of switching architectures equipped with LNOI wavelength converters (Sapienza)
Task 4.2: The spectrum and core allocation problem in elastic optical networks with Multi Core Fibers (MCFs) and equipped with LNOI wavelength converters (Sapienza)
Task 4.3: Performance evaluation of the switching architectures with LNOI wavelength converters (Sapienza)

Work plan

The consortium will be composed of three Units: Sapienza Università di Roma (Sapienza, Unit1), Unit2, and Unit3, to be selected via open calls. The researchers of the 3 Units need to have the skills and experience necessary to demonstrate all-optical wavelength converters based on LNOI waveguides: theoretical and numerical modeling of nonlinear effects in waveguides (all Units), experimental characterization of spatio-temporal effects (Sapienza, Unit3), testing of optical chips (Unit2), design and optimization of optical networks (Sapienza).
The laboratories at the 3 Units need to be equipped with all basic instruments necessary for the experimental activities: optical benches, optical spectrum analyzers, visible and infrared cameras, high peak power lasers. We plan to use part of the project budget to purchase some equipment that is necessary to complete the measurement setups: two CW lasers emitting in the C-band, two amplifiers working in the C-band, one piezoelectric stage, several diodes in the visible and near-infrared range, two electro-optic modulators, one RF signal generator.
Optical chips will be either manufactured thanks to a scientific collaboration with the Università degli Studi di Padova (wafer poling and waveguides/components fabrication by titanium diffusion), or purchased from the Italian foundry Inphotec (waveguides fabricated by etching). ELENE's budget will cover the cost of wafers and manufacturing consumables, and the purchase from Inphotec of chips from 2 separate "runs".

WP1: Design and characterization of waveguides and nanostructures on LNOI substrates

Task 1.1: Design of waveguides and nanostructures on LNOI substrates (All Units)

This task aims at designing the waveguides and other optical structures which are needed for the development of the project activities. Approaches based on numerical tools will be mainly used. In particular, modal solvers will assist the waveguide design, by the identification of geometries supporting low loss propagation. Solutions based on etching and on titanium diffusion on a single-crystal lithium niobate thin film on an insulator (silicon dioxide) will be considered.

Task 1.2: Characterization of the fabricated structures and related optimization issues (Sapienza)

In this task, the fabricated components will be experimentally characterized, in order to verify the correspondence of the design parameters with those obtained after manufacturing, with the aim of highlighting fabrication issues, and identifying possible parameter optimizations for further fabrication runs. Coupling efficiencies of the input/output sections, waveguide losses and the performance of functional structures (WDM couplers, rings, cavities, etc.) will be measured by using conventional approaches, such as the cut-back method, interferometry (Fabry-Pérot technique), or the evaluation of the quality factor of rings made with similar cross section of the waveguides. Measurements will be performed in the linear regime, by using low-power signals. The outcomes of these measurements will be used for tuning the fabrication process, and for driving nonlinear experiments.

Task 1.3: Design and manufacture of ultralow-loss self-induced waveguides on LNOI (Sapienza)

Lithium niobate has been shown to be an excellent candidate for soliton formation and for the application of soliton channels as ultra-low-loss waveguide. In the past, soliton waveguides have already been produced in both bulk lithium niobate and thin films. We will use LNOI samples to create soliton waveguides: in particular we will study both transient and permanent waveguides, for verifying their propagative characteristics.

WP2: Nonlinear properties of waveguides fabricated on LNOI substrates

Task 2.1: Test of the poling efficiency by second-harmonic generation measurements (Unit3)

The first step is the selection of the wafers to be poled, or the design of custom wafers. Both z-cut and x-cut LN layers have to be considered; moreover, the shape and position of the electrodes used to apply the high voltage pulses have to be designed. In particular, z-cut requires a poling field perpendicular to the wafer, and thus electrodes on the wafer top and bottom faces; whereas x-cut requires electrodes on top of the LN layer. Waveguides will be fabricated by means of titanium diffusion or etching, according to the designs of Task 1.1.

The effectiveness of the poling will be verified by means of SH generation measurements. The poling period must satisfy the quasi-phase matching condition, and the tuning curve is measured by using a tunable laser in the C-band. To make the conversion insensitive to small environmental variations, the device must operate at a constant temperature of at least 40 degrees: for this reason, the device must be mounted on a Peltier cell. The effective nonlinearity can be extracted from the measured efficiency, and compared with the numerically calculated value.

Task 2.2: Test of the cascaded quadratic nonlinearity by means of four-wave mixing and supercontinuum generation (Unit2, Unit3)

In this task, poling periods which do not satisfy the phase-matching condition for a C-band pump are considered: in such a case, the quadratic nonlinearity is equivalent to a cubic nonlinearity, whose value can be larger than the intrinsic Kerr effect of LN. This cascaded quadratic nonlinearity will be exploited for the wavelength conversion device of WP3. The present task is devoted to a thorough experimental analysis of the cascaded nonlinearity as a function of poling period and input power. Two types of experiments are considered: 1) unseeded four-wave mixing where an intense (CW or pulsed) pump generates two sidebands; 2) supercontinuum generation, where an intense input (pulsed) pump experiences a spectral broadening over a spectral range of more than a few hundreds of nm. The position of the generated spectral peaks, and the phenomena leading to spectral broadening depend on phase and group velocities. Therefore, the waveguide dispersion has to be optimized during the design in WP1. In order to widen the explorable mismatch range, or to be able to use more powerful laser sources, we could also use lasers that emit in the infrared but not in the C-band, for instance around 1064 nm.

Task 2.3: Investigation of Raman effect and Raman induced pump depletion at high input intensities (Sapienza)

Raman scattering in LN is characterized by a strong gain peak, red-shifted by about 55 nm from the pump. We will study both numerically, by using the generalized nonlinear envelope equation approach, and experimentally by means of a femtosecond optical parametric amplifier laser system, the effect of Raman gain on ultrashort pulse propagation in LNOI waveguides. Since the zero-dispersion wavelength of LN is at about 1900 nm, we will use as a signal a 100-fs soliton pulse train, centered at 2000 nm. By studying the associated Raman-induced soliton self-frequency shift, we will determine the corresponding Raman gain coefficient and response time. On the other hand, the effect of Raman pump depletion on frequency conversion will be studied by pumping the LNOI waveguides with a laser diode at 1550 nm, and by tuning around 1600 nm the wavelength of a pulse train with temporal durations in the range of 0.1-10 ps. A numerical and experimental study will be carried out on Raman-induced tunable wavelength shift at telecom wavelengths.

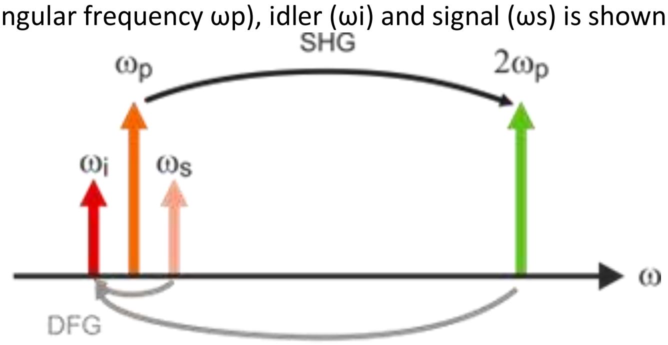
Task 2.4: Analysis of the ability to recognize and store information in solitonic waveguides in both a supervised and unsupervised way at ultralow optical fluences (Sapienza)

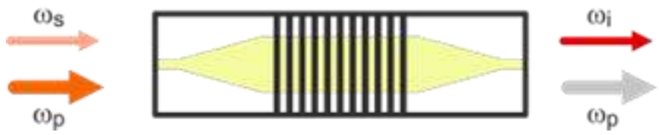
The photorefractive modification of the refractive index of lithium niobate is the basis of plastic systems, capable of learning and memorizing information, behaving as neural systems. In this way it is possible to create neuromorphic circuits, where the memory and data processing areas coincide, eliminating the dichotomy typical of traditional computer systems. In the project we will study specific geometries for LNOI systems, capable of performing both supervised and unsupervised machine learning with very low optical fluences, and therefore interesting for applications in complex optical networks.

WP3: All-optical signal processing by means of wavelength conversion

Task 3.1: Design of the wavelength converter based on nonlinear effects in LNOI waveguides (all Units)

Two types of wavelength converters will be designed and numerically simulated: 1) converters based on DFG; 2) converters based on cascaded quadratic parametric generation. In the DFG converter, a signal in the C-band (and thus around 1550 nm) is shifted to a longer wavelength by DFG with an intense pump at a wavelength around half the signal wavelength (for instance, 775 nm); this DFG process is enabled by the quadratic nonlinearity, and the poling period must fulfill the corresponding quasi-phase matching condition. Alternatively, the poling period can be chosen to phase-match internal SH generation from an intense C-band FF pump in the LNOI waveguide. Next, mixing of the SH and the signal around the FF will generate the idler by DFG. Also for the cascaded converter, the poling period must be carefully tuned, since the equivalent cubic nonlinearity is critically dependent on the phase mismatch. A schematic drawing of the wavelength converter and of the DFG process involving pump (at angular frequency ωp), idler (ωi) and signal (ωs) is shown in the figure below.





Task 3.2: Testing of the wavelength converter in the C-band (all Units)

The experimental verification of the performance of the different converters is very complex and poses challenges: for instance, both pump and signal have to be coupled into the waveguide section where the nonlinear conversion takes place, and the experimental setup must be built in such a way as to easily vary the temperature of the optical chip, for a fine tuning of the nonlinear processes. The measured conversion efficiencies have to be critically compared with the theoretical predictions of Task 3.1 for a large set of waveguide parameters and poling periods. Both DFG and cascaded converters can be tested by using a pulsed pump and a CW signal, since high peak power pulsed lasers are already available in our laboratories. In the case of the cascaded converter, the expected conversion efficiency is so high that the signal shift can also be achieved by using a CW pump, obtained by amplifying by 20-30 dB the output of a standard tunable laser operating in the C-band. The last part of this Task will be devoted to performing a switching experiment, where the conversion of a CW or pulsed signal is gated by controlling the pump (for instance, by modulating the output of the CW laser by means of an electro-optic modulator).

WP4: Performance evaluation of a network implementing the proposed wavelength converter

Task 4.1: Definition of switching architectures equipped with LNOI wavelength converters (all Units)

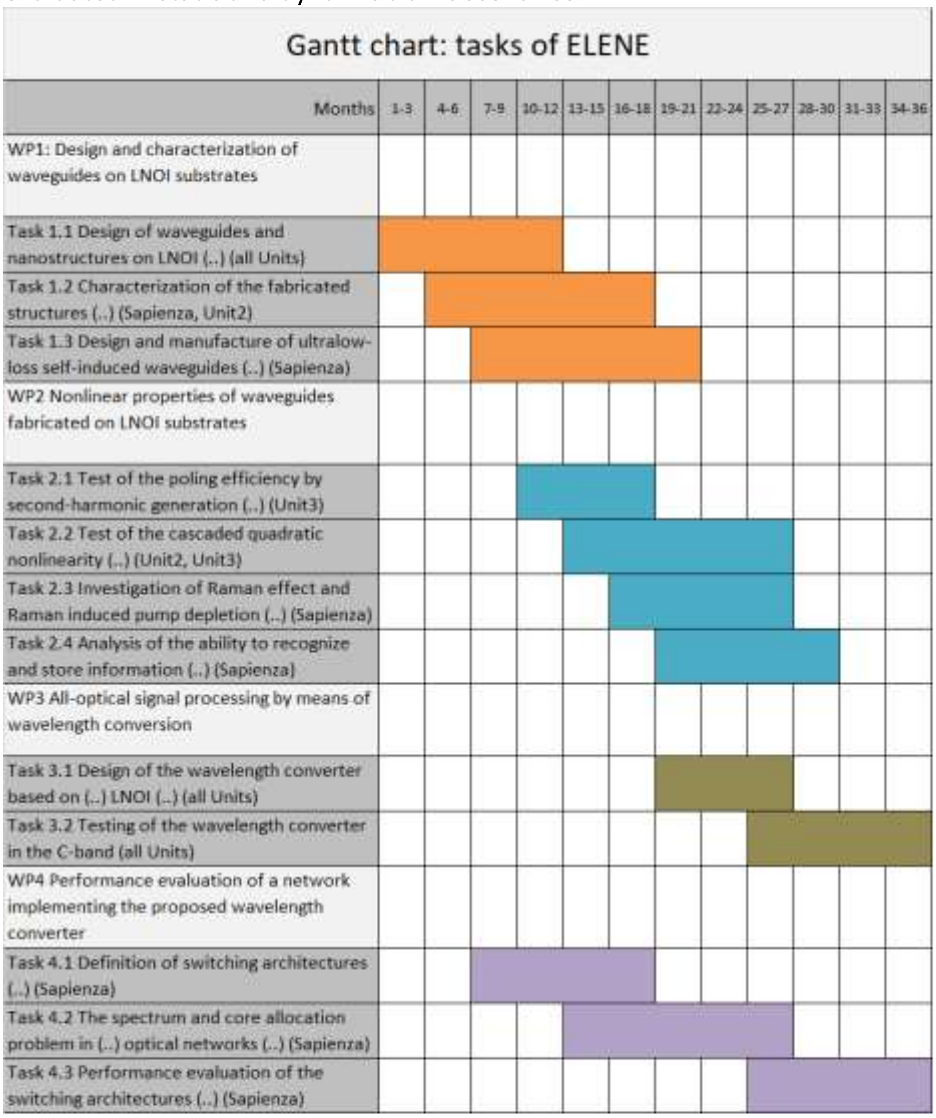
The switching architecture will be based on nodes with spectrum bands and fiber core switching capability. LNOI wavelength converters are inserted to allow wavelength conversion of spectrum bands and to avoid fragmentation problems. To reduce the number of LNOI wavelength converters and the node cost, architectures with shared LNOI wavelength converters will be defined.

Task 4.2: The spectrum and core allocation problem in elastic optical networks with Multi Core Fibers (MCFs) and equipped with LNOI wavelength converters (Sapienza)

For a static traffic demand an optimization problem will be defined and studied; its outputs are: the optical path in which each connection of the traffic demand is routed; ii) the cores to be allocated in the MCFs of the network path; iii) the wavelength spectrums occupied in each MCF without the wavelength constraint, consequence of the use of wavelength converters; iv) the adopted modulation system. The objective of the problem is to maximize the number of connections accepted, with the constraint of guaranteeing adequate Optical Signal Noise Ratio (OSNR) or Q factor. The NP-hard complexity of the problem will lead to defining low computational complexity heuristics, able to solve the problem in a large network scenario.

Task 4.3: Performance evaluation of the switching architectures with LNOI wavelength converters (Sapienza)

We will solve the optimization problem with the CPLEX solver, and the heuristic will be implemented in C language. The effectiveness of the heuristics will be proved by comparing their performance with the results of the optimization problem in a small network scenario. The defined heuristic will be used to evaluate the performance in large network scenarios and prove how the use of LNOI wavelength converters allows for an increase in the number of connections accepted. The performance will be evaluated in static and dynamic traffic scenarios.



Expected results and impact

ELENE aims at tackling the optical network capacity crunch by replacing optical-electrical-optical regeneration with all-optical wavelength conversion and switching. ELENE will develop the first efficient, chip-scale, LNOI based wavelength converter for reconfigurable add-and-drop multiplexers and demultiplexers. By avoiding the electronic subsystems for the optical-electrical-optical regeneration, and by allowing for massive WDM, ELENE contributes to reducing the energy footprint of long-haul optical links and power-hungry data centers, with significant and lasting consequences on the environment.
Researchers and PhD students will be trained as part of the project and the scientific activities of ELENE will equip researchers and students with valuable and transferable technological skills.

Scientific impact: A major research trend in integrated photonics is the development of technologies that could circumvent limitations posed by TPA in silicon to improve the efficiency of nonlinear interactions and provide a much-needed frequency conversion element. To this aim, the LNOI platform is an excellent candidate, thanks to its strong quadratic nonlinearity and Pockels coefficient. Moreover, LNOI is transparent in the wavelength range 400-5000 nm, which makes it an ideal nonlinear integrated platform for the generation of wavelengths in the mid-infrared, a spectral region of paramount importance for gas sensing and monitoring.

Technological impact: Driven by emerging applications, network traffic has grown exponentially over the past decades. Data traffic has moved from single user connections to machine-to-machine traffic arising from data-centric applications, sensor networks and Internet of Things. Network traffic growth-rates extracted from long-term measurements range between 25% and 80% per year, depending on geographic region, network segment, and traffic type. This trend challenges the fiber-optic communication infrastructure at its foundations and calls for revolutionary solutions to accommodate growing capacity demand. Coherent transmission technologies take advantage of all fiber physical dimensions already, by signaling on both quadratures and orthogonal polarizations of the electric field over the huge bandwidth of fiber systems. Nevertheless, these systems are facing their technological and fundamental limits: a worrying disparity between the exponential growth rates of traffic, and the available capacity of current generation systems is being sensed.
Various approaches to prevent a network capacity crunch have been considered. In current long-haul networks, optical-to-electrical conversion is necessary, and the signal is corrected by DSP techniques. However, optical-electrical-optical (OEO) regeneration is typically customized to a specific optical link and random parameters variation (e.g., polarization) along the link, which limits its efficiency. Moreover, the adaptation of OEO regeneration to dynamic routed networks has proven to be difficult so far.
ELENE aims at tackling these critical issues, by scaling the capacity of coherent fiber-optic systems via massive WDM, and reducing at the same time power consumption. To this end, ELENE will develop the first efficient, chip-scale, low-power generation of wavelength conversion elements for reconfigurable add-and-drop multiplexers and demultiplexers.

Contributions to sustainability:

Even if DSP chips are low cost, they are power hungry, occupy a large footprint, and develop a huge heat to be dissipated. The equipment needed for DSP now accounts for approximately 80% of the cost of setting up new network infrastructures. ELENE will develop an all-optical solution that will enable future fully transparent, energy efficient and sustainable optical networks. In the development of hyper-scale data centers, our energy efficient devices will allow for tighter server deployment, owing to reduced power dissipation of optical interconnects.

Benefits for the society:

The development of all-optical solutions to the network capacity crunch will permit it to keep pace with future bandwidth demand in optical networks and data centers. ELENE proposes a new paradigm on the use of all-optical methods to scale optical transmission capacity via the WDM technique. In terms of social

and economic impact, it should be emphasized that ELENE connects with other National and European initiatives in progress.
ELENE will generate substantial impact beyond the scope of the project in a number of key areas that will support the future growth of photonic integrated technologies: i) hybrid integration; ii) ultrafast and efficient non-linearities and iii) multi-modal integrated components. Hybrid integration has been highlighted as a key requirement to sustain rapid growth of the photonic market not only by large commercial interests, but also by umbrella organizations such as the European Photonics21 body, and the funding priorities of current EU programs. The LNOI devices developed in ELENE will provide very valuable outcomes for the development of hybrid technological platforms and multi-core layer integration.
Last but not the least, all consortium partners recognize that people training constitutes a major impact as it provides a valuable future resource for the country. The early career researchers (ECRs) employed in the project will be exposed to best practice in their career development, and encouraged to take advantage of various opportunities. The ECRs will also be supported in the application of personal fellowships such as Marie-Curie Fellowships and Starting ERC grants. Moreover, several PhD students in the partner institutions will either be directly involved or exposed to ELENE research activities. Because of the interdisciplinary nature of the project, frequent student and staff mobility amongst partners is anticipated, which will further augment the research training opportunities.

Possible collaborations and synergies with other projects

Principal Investigator: [redacted] (Sapienza Università di Roma)
List of partners

1. Sapienza Università di Roma (Sapienza)
2. Unit2 (to be selected via open calls)
3. Unit3 (to be selected via open calls)

Partner 1:
Reference investigator: Prof. [redacted] (Sapienza Università di Roma)
List of permanent staff
Prof. [redacted] (2)
Prof. [redacted] (3)

Geographical balance (sede e stima della percentuale di budget speso nelle regioni del sud)
0

Titolo del Progetto: Introducing SENSING capabilities in deployed TLC fiber NETworks
Acronimo: SENSING NET

Tipologia di progetto: Focused-Industrial

Area di ricerca di riferimento: 8 – 4

Breakdown by intervention fields - (022, 023, 006)

Green (25%)	Economia circolare (25%)	Altro restante (50%)
40%	15%	45%

Synergy of the research program with programs financed under the other Investments envisaged by the NRRP (Mission 4, Component 2), (1.3 Partenariati allargati estesi,1.4 Potenziamento strutture di ricerca e creazione di "campioni nazionali di R&S", 1.5 Creazione e rafforzamento di "ecosistemi dell'innovazione", 3.1 Fondo per la realizzazione di un sistema integrato di infrastrutture diricerca e di innovazione).

Starting "Technology Readiness Level" (TRL) and the TRL to be reached at the end of the research program

TRL2	TRL4

Attraction from other EU and non-EU countries, based on the quality of their scientific curriculum

Abstract
SENSING NET targets to enhance the value of the already deployed optical fiber infrastructure for telecommunications by introducing fiber sensing technologies to explore novel potential applications, assuring additional revenues for networking-service providers, fiber network owners and operators by developing new promising applications and services.
The alternative usage of fiber networks can include not only the control and supervision of the telecom infrastructure integrity, but also the distributed diagnostics and surveillance in smart city scenarios, the monitoring of traffic and facility safety in railways and motorways; the leak detection in pipelines; the detection of large breaches and damages in civil structures.
SENSING NET will exploit TLC-compatible sensing strategies to provide a real-time, pervasive monitoring of mechanical, thermal and electrical phenomena. This sensing strategy will be performed both considering already deployed fiber links and newly installed fibers associated to utilities networks.
The adoption of proper sensing architectures, signal processing techniques and their integration in standard TLC networks will represent a breakthrough innovation providing new tools for real-time study of the status of human activities and infrastructures in populated areas.
The project outcomes could support institutional decision makers in fields ranging from the civilian to the environmental protection, for the prompt detection of structural faults, and hazards.

Context and Motivation
In the last years, the EU H2020 Digital Agenda promoted a huge increase of the amount of deployed fibre in our cities and a further investment is expected in urban fibre infrastructures to improve very high-speed access, new residential and business connectivity services and wireless densification for 5G. This dense metro TLC fibre web can be leveraged also as a distributed optical sensing network providing a real-time monitoring of mechanical perturbations and the detection of the onset of dynamic stress events in civil buildings connected by FTTH access links and in the whole deployed cable infrastructure.

SENSING NET project aims at the advancement of the operation of telecommunication (TLC) optical networks (ONs) to support urban infrastructures surveillance and monitoring through the exploitation of breakthrough fibre optic sensors (FOSs). ONs represent the enabling technology for modern backbone and metro-access networks. They interconnect data centres and users to the Internet across cities, regions, countries, continents, delivering ultra-broad band digital services. Over the last decade, massive traffic growth rates pushed private and public operators to make huge investments to expand the ONs capacity and coverage, while reducing cost and minimizing operational complexity. In this context, the alternative usage of ONs to include also urban infrastructures monitoring features could represent a mean to boost the effectiveness of the made investments, creating also new revenue opportunities.
The already-deployed ONs can be seen as a pervasive fibre-web covering the planet, which can be exploited for monitoring purposes, providing an unprecedented fruitful synergy between TLC and sensing applications. FOSs constituted by the already-deployed fibre cables could be used to monitor physical fields (e. g., strain and temperature) along the fibre and enable their continuous space-time analysis over large areas.

CONTEXT

From '80s early pioneering experiments, fibre optic sensors (FOSs) are nowadays employed in several applications for monitoring critical infrastructures (bridges, tunnels, pipelines), having adopted some advanced technologies borrowed from optical communications, but employing fibres specifically deployed for sensing purposes to assure high sensitivity in detection. Since a few years distributed acoustic sensing (DAS) systems based on phase-resolved time domain reflectometry have been successfully applied to seismic monitoring [Lind19], revealing their potential as research tools, also in urban environment. However, except for very few examples partially working [Aono20], DAS systems are generally not compatible with standard telecommunication (TLC) transmission, requiring a dedicated dark fibre. FOSs have become a very promising technology platform, also for the geomorphological field, where the monitoring of the natural instability processes in the high-elevation mountain environment is a key feature to analyse the impact of the climate change.
The exploitation of the existing fibre network already installed worldwide for TLC purposes (both in the long-haul transport and medium-reach access) could bring a significant added-value to the fibre infrastructure, providing reliable embedded optical systems for surveillance in different urban and regional areas. Fibre sensing strategies fully compatible with the TLC transmission (in terms of wavelength, power, crosstalk, etc.) would enable to take advantage of the pervasive penetration of the TLC networks, from the most remote geographical areas of the planet to the final user home in our cities. Commercial TLC transcontinental submarine cables have been recently exploited to detect seismic waves through the spectral analysis of light polarization [Cant20], but in a very-low environmental noise context. Another very promising sensing approach, fully compliant with the TLC signal transmission, exploits coherent laser interferometry techniques which were first developed in a metrological context to distribute ultrastable laser signals between distant metrological institutes [Lisd16].
Regarding the urban area, the EU H2020 Digital Agenda promoted a huge increase of the amount of deployed fibre and a further investment is expected in urban fibre infrastructures to improve very high-speed access, new residential and business connectivity services and wireless densification for 5G. This dense metro TLC fibre web can be leveraged also as a distributed optical sensing network providing a real-time monitoring of mechanical perturbations and the detection of the onset of dynamic stress events in civil buildings connected by FTTH access links and in the whole deployed cable infrastructure [Hov20]. In a metropolitan environment, few examples have been proposed so far to monitor the vehicle speed and car density in a road through the installed TLC network. In this context, the employed telecom fibre cable is enclosed in standard conduits, demonstrating low detection sensitivity, thus requiring complex and expensive sensing systems such as standard DASs which are not generally compatible with TLC traffic.
The SENSING NET partners POLIMI and POLITO have otherwise preliminarily demonstrated fibre coherent sensing solutions based on interferometric schemes, fully compatible with TLC transmission, specifically tailored for urban area applications, characterized by reduced complexity, cost and power consumption

with respect to other more standard solutions, such as DAS [DiLu21].

[Aono20] Y. Aono, et al."More Than Communications: Environment Monitoring using Existing Optical Fiber Network Infrastructure" Proc OFC 2020
[Cant20] M. Cantono et al., “Sub-Hertz Spectral Analysis of Polarization of Light in a Transcontinental Submarine Cable” Proc ECOC 2020
[DiLu21] I. Di Luch, et al “Vibration sensing for deployed metropolitan fiber infrastructure” J. Lightwave Technol., Early Access, 2021
[Hov20] M. Hovsepyan et al "Fiber Sensing Technology: Challenges for a Service Provider" Proc. ICTON 2020
[Lind19] N. J. Lindsey, et al. ``Illuminating seafloor faults and ocean dynamics with dark fiber distributed acoustic sensing" Science 366, 1103, 2019
[Lisd16] C. Lisdat et al., "A clock network for geodesy and fundamental science" Nature Comm. 7, 12443, 2016

MOTIVATION

The SENSING NET project aims at the advancement of the operation of TLC optical networks (ONs) to support urban infrastructures surveillance and monitoring through the exploitation of breakthrough FOSs. ONs represent the enabling technology for modern backbone and metro-access networks. They interconnect data centres and users to the Internet across cities, regions, countries, continents, delivering ultra-broad band digital services. Over the last decade, massive traffic growth rates pushed private and public operators to make huge investments to expand the ONs capacity and coverage, while reducing cost and minimizing operational complexity. In this context, the alternative usage of ONs to include also urban infrastructures monitoring features could represent a mean to boost the effectiveness of the made investments, creating also new revenue opportunities.

The already-deployed ONs can be seen as a pervasive fibre-web covering the planet, which can be exploited for monitoring purposes, providing an unprecedented fruitful synergy between TLC and sensing applications. FOSs constituted by the already-deployed fibre cables could be used to monitor physical fields (e. g., strain and temperature) along the fibre and enable their continuous space-time analysis over large areas.

SENSING NET multi-disciplinary consortium, including experts in ONs and FOSs (POLIMI, POLITO and CNR), a fiber deployer (OPEN FIBER) and a TLC operator (WIND3) is the right partnership to carry out the project ambitious objectives achieving a real empowerment of the deployed ONs.

Goals

General description of the goals:

GOAL 1: guarantee the coexistence of sensing and TLC signals in the deployed optical networks whose distribution fibre links represent themselves the FOS sensing mean. This goal will be attained in WP2 where the compatibility of the already deployed PONs and MANs networks with the optical sensing techniques proposed in the project will be analysed. The comprehensive analysis of TLC traffic and sensing signal compatibility for multiple FOSs adapted to the different network topologies is a clear advancement with respect to the state of the art (SotA), which seldom has considered one type of FOS and mostly P2P links.

GOAL 2: exploit the passive optical networks (PONs) and the metropolitan area network (MAN) already deployed for TLC purpose in the urban area for real-time and distributed diagnostics and surveillance in a “smart city” context. This goal will be attained in WP3. FOS systems based on tailored coherent interferometric (CI) schemes will be exploited in two different urban network layouts:

- the PON infrastructure, based on a tree topology with power splitters, will be employed for the surveillance of urban buildings in terms of vibrations and deformation modes;
- the typical MAN topology, including rings and network nodes, opens the possibility of new sensing applications for the surveillance monitoring of the infrastructure itself.

GOAL 3: exploit the newly installed fibers associated to utilities networks for the detection of plants, apparata and infrastructures related to the utilities. In this context, the opportunity to improve the value of the new fiber infrastructure suitably deployed to support utilities networks will be considered in WP4. Specific use-cases will be identified, taking in account the monitoring of plants, industrial apparata, power transformers, Industry 4.0 machinery and Internet-of-Things devices. Suitable experimental test will be performed in-field by using the fiber infrastructure made available by OPEN FIBER.

General description of the goals:
Optical networks allow to interconnect people and sites across cities, regions, countries and continents; through modern backbone and metro-access networks ultra-broad band digital services are delivered everywhere connecting data centers and users to the Internet. Over the last decade, massive traffic growth rates pushed private and public operators to make huge investments to expand the optical networks capacity and coverage both in urban and regional areas. In particular a continuous investment in urban fibre infrastructures by telecommunication (TLC) operators, communication service providers and public-private partnerships, is further foreseen to improve very high-speed access, new residential and business connectivity services and wireless densification for 5G. Moreover, the reinforcement of fibre to the home (FTTH) solutions is mandatory to overcome the present "digital divide". In Metropolitan Area Networks (MAN) and backbone (BN) networks, which need to collect this ever-increasing traffic, the investments have been rather focusing in the upgrade of their transport capacity through wavelength and spatial division multiplexing densification and rate increase.
The main goal of SENSING NET is to extend the operation of optical TLC networks with additional services to support urban monitoring and infrastructure surveillance through the exploitation of breakthrough fibre optic sensors (FOSs). This sensing strategy will be performed both considering already deployed fiber links and newly installed fibers associated to utilities networks. With respect to electro-mechanical sensors, the FOSs offer several advantages, such as the immunity to electromagnetic interference, minimal invasiveness and lightweight, multi-parameters sensing, ease of multiplexing, and remote powering/interrogating capabilities over long distances (several kilometres). In most advanced commercial FOSs, the fibre is simultaneously the communication channel and the sensing element.
The goal to exploit optical TLC networks distribution fibres as FOSs will be pursued by attaining the following Objectives.

GOAL 1: guarantee the coexistence of sensing and TLC signals in the deployed optical networks whose distribution fibre links represent themselves the FOS sensing mean. This goal will be attained in work package (WP)2 where the compatibility of the already deployed PONs and MANs networks with the optical sensing techniques proposed in the project will be analysed. The comprehensive analysis of TLC traffic and sensing signal compatibility for multiple FOSs adapted to the different network topologies is a clear advancement with respect to the state of the art (SotA), which seldom has considered one type of FOS and mostly P2P links.

GOAL 2: exploit the passive optical networks (PONs) and MAN already deployed for TLC purpose in the urban area for real-time and distributed diagnostics and surveillance in a "smart city" contest. This goal will be attained in WP3, by experimentally demonstrating the capabilities of fibre sensing systems tailored for the metro/access network architectures in an already deployed urban field-trial. Due to last years investments in the urban area, the deployed fibre infrastructure densely extends over most of the highly populated metropolitan areas. This ubiquitous already-deployed fibre-web will be leveraged for a pervasive and distributed optical sensing, by proving the feasibility of real-time and remote monitoring of mechanical perturbations and the detection of the onset of dynamic stress events in civil buildings connected by FTTH access links and in the whole deployed infrastructure. In particular, FOS systems based on tailored coherent interferometric (CI) schemes will be exploited: preliminary demonstrations proved their effectiveness for optical sensing in the
urban context. In SENSING NET two different urban network layouts will be considered in WP3:

1) In a first layout, the PON infrastructure, based on a tree topology interconnecting multiple optical network units (ONUs) through a common feeding cable (tens of km long) and power splitters, will be employed for the surveillance of urban buildings in terms of vibrations and deformation modes.
2) In a second layout, the typical MAN topologies, including rings and network nodes, open the possibility of new sensing applications carried by dedicated wavelengths in parallel with the dense wavelength division multiplexed (WDM) TLC traffic grid.

GOAL 3: exploit the newly installed fibers associated to utilities networks for the detection of plants, apparata and infrastructures related to the utilities. In this context, the opportunity to improve the value of the new fiber infrastructure suitably deployed to support utilities networks will be considered. Specific use-cases will be identified, taking in account the monitoring of plants, industrial apparata, power transformers, Industry 4.0 machinery and Internet-of-Things devices. Suitable experimental test will be performed in-field by using the fiber infrastructure made available by OPEN FIBER.

Work plan
WP1: Project management and coordination (M1-M36)
Leader: OPEN FIBER
Task 1.1 Project and administrative management
Task 1.2 Communication and dissemination

WP2: Compresence of sensing and TLC transmission in fibre links (M1-M30)
Leader: WIND3
Task 2.1 Standard and requirements
Metro and access networks will be analyzed to determine requirements in terms of physical parameters for the TLC applications.
Task 2.2 Compatibility with the optical data TLC traffic
A theoretical analysis will be performed to study the reciprocal impact between TLC data traffic and optical sensing signals, validated by simulations. Compatibility aspects will be preliminarily tested experimentally in laboratory.

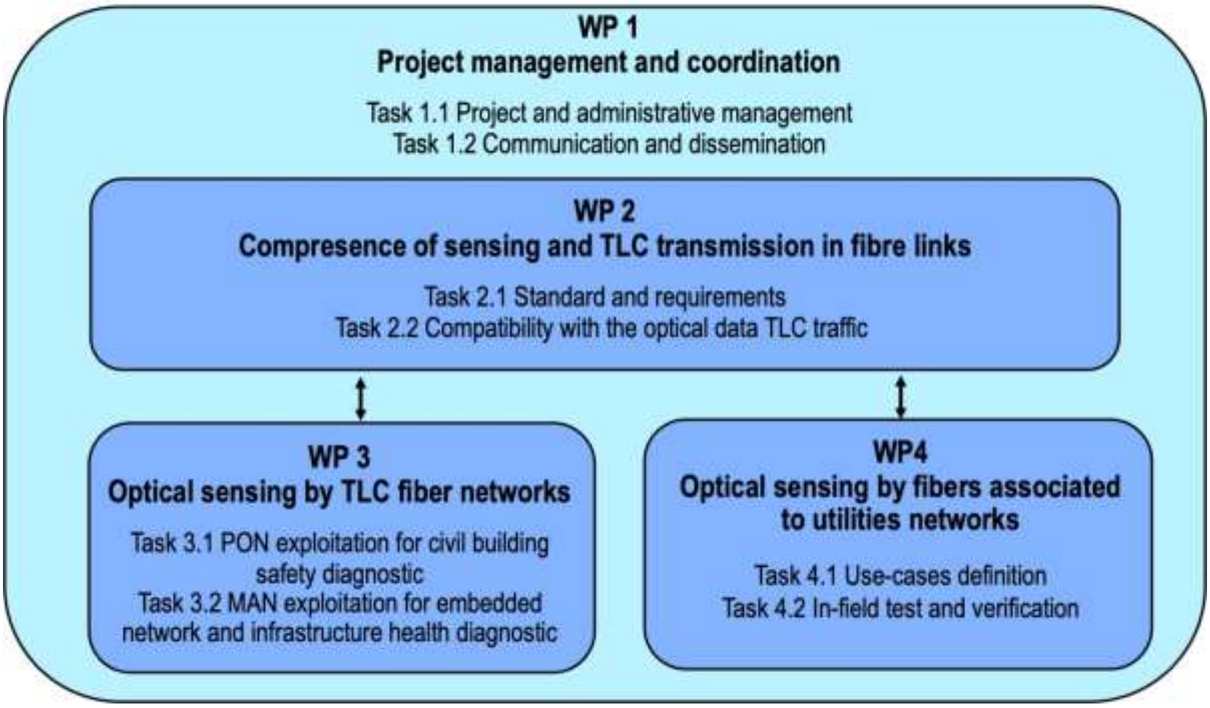
WP3: Optical sensing by TLC fiber networks (M3-M36)
Leader: POLIMI
Task 3.1 PON exploitation for civil building safety diagnostic
SENSING NET partners will develop and test specific CI FOSs architectures to support mechanical strain detection and safety surveillance in the tree-like PON topology with splitters.
Task 3.2 MAN exploitation for embedded network and infrastructure health diagnostic
SENSING NET partners will develop and apply FOS solutions featuring high sensitivity in the diagnostics and localization of mechanical vibrations and acoustic emissions along typical MAN topologies. The exploitation of the digital signal processing already included in the coherent detection of the TLC signals will be analyzed.

WP4 Optical sensing by fibers associated to utilities networks (M3-M36)
Leader: POLITO
Task 4.1 Use-cases definition
SENSING NET partners will identify specific use-cases in case of the exploitation of fibre infrastructures suitably deployed to support utilities networks.
Task 4.2 In-field test and verification
In-field experimentation will be done by exploiting the deployed infrastructures of OPEN FIBER with specific FOSs architectures tailored for the specific kind of fiber infrastructure.

Work plan

Work organization:

SENSING NET is organized in one WP devoted to the project management and coordination and three technical WPs: WP2 evaluating the compresence of sensing and TLC transmission and providing requirements gives and receives feedbacks to/ from WP3 and WP4 which focus on optical sensing in the urban area. The main challenge of demonstrating that the optical TLC networks can be leveraged to support geophysical and civil infrastructure monitoring is carried out by theoretical and experimental activities. The experimental confirmation of the capabilities of the developed FOSs will be performed both in laboratory and in real TLC fibre field trials.



WP1: Project management and coordination (M1-M36)

Leader: OPEN FIBER

Task 1.1 Project and administrative management

Task 1.2 Communication and dissemination

WP1 consists in SENSING NET management and it will take care of SENSING NET administration, partners coordination, control and care of SENSING NET schedule according to the GANTT. After the kick of meeting (KoM) partners will meet every 6 months, possibly in person and yearly deliverables will detail the activities carried out in the three technical WPs. WP1 will also address possible risks and contingencies and it will manage the project communication activities.

WP2: Compresence of sensing and TLC transmission in fibre links (M1-M30)

Leader: WIND3

Task 2.1 Standard and requirements

The Local Access Network already installed are the point to point (P2P) and the Passive Optical Network (PON). The P2P are based on Active Ethernet, the PON uses several standards like GPON, XG-PON working at 1 Gb/s, NG-PON2 (TWDM-PON) working at 2.5 Gb/s with possible extension until 10 Gb/s per wavelength, and finally, the incoming HS-PON with speed at 25 Gb/s and 50 Gb/s per wavelength. For every standard the ITUT specifies, for example, the uplink and downlink wavelength bandwidth, the maximum optical transmitted power in every transmission direction, and the maximum Optical Distribution Network

Loss for every Optical Network Class. For the Metropolitan/Regional Network and the backbone, the Optical links are based on the WDM standards, starting from the baseline 10 gigabit Ethernet to the more advanced DWDM with 400 Gb/s capacity (IEEE standard 802.3bs). The DWDM ITU-T typical standards are G.872, G.692, G.694 (www.itu.int). After the evaluation of the standard and of the requirements in terms of physical parameters for the TLC applications and the innovative optical sensing techniques a key aspect will be to assess the feasibility of the co-presence of sensing application and standard data traffic. The standard taken in account for the access network are up to NG-PON2 and the incoming HS-PON, whereas for the backbone network the ITU-T G 694.1 and G 694.2, and the more recent IEEE 802.3bs DWDM standard will be taken in account.

Task 2.2 Compatibility with the optical data TLC traffic

A theoretical analysis will be performed to study the reciprocal impact between the optical TLC data traffic and the optical sensing signals and it will be validated by simulations. Compatibility aspects will be preliminarily tested experimentally in laboratory, evaluating the reciprocal impact of sensing and TLC signals on performance for the different developed sensing techniques and network topologies. By using the OPEN FIBER installed fibers with real TLC signals of WIND3, in-field measurements will be finally carried out to demonstrate the complete coexistence between TLC data traffic and the optical sensing applications proposed. To this scope a continuous exchange of information will be performed with WP3 and WP4.

WP3: Optical sensing by TLC fiber networks (M3-M36)

Leader: POLIMI

Task 3.1 PON exploitation for civil building safety diagnostic

SENSING NET partners will develop and test specific CI FOSs architectures to support mechanical strain detection and safety surveillance in the tree-like PON topology with splitters. A sensor configuration based on a Michelson interferometer with the mirrored ONU fibres constituting the interferometer arms can be exploited. The data collected will be also useful for the analysis of local seismologic perturbations in the urban area, where the buildings and skyscrapers, FTTH-connected to the access network, represent "optical sensing antennas". Compliance with the TLC modulation formats and technologies exploited for the next HS-PON will be assured.

Task 3.2 MAN exploitation for embedded network and infrastructure health diagnostic

SENSING NET partners will develop and apply FOS solutions featuring high sensitivity in the diagnostics and localization of mechanical vibrations and acoustic emissions along metro architectures. The typical MAN topologies, including rings and network nodes, open the possibility of new sensing applications carried by dedicated wavelengths in parallel with the dense wavelength division multiplexed (WDM) TLC traffic grid. Mach-Zehnder interferometric schemes arranged in loop configurations are available for this layout. The monitoring of road conditions (street safety, vehicle speed and car density) and of the optical cable health will be achieved by exploiting the MAN itself, providing a real-time warning on the surrounding environment. The exploitation of the digital signal processing already included in the coherent detection of the TLC signals will be analyzed to detect important parameters of the status of the network, such as anomalous vibrations on the fibre path without spatial discrimination. The deployed OPEN FIBER fibre infrastructure will be exploited for WP3 experimentation. With respect to complex solutions as DAS and phase-OTDR schemes, SENSING NET CI FOSs assure not only the necessary requirements (spatial resolution and accuracy in event localisation, event frequency bandwidth), but also the sustainability, in terms of reduced complexity, cost and power consumption, mandatory for urban applications.

WP4 Optical sensing by fibers associated to utilities networks (M3-M36)

Leader: POLITO

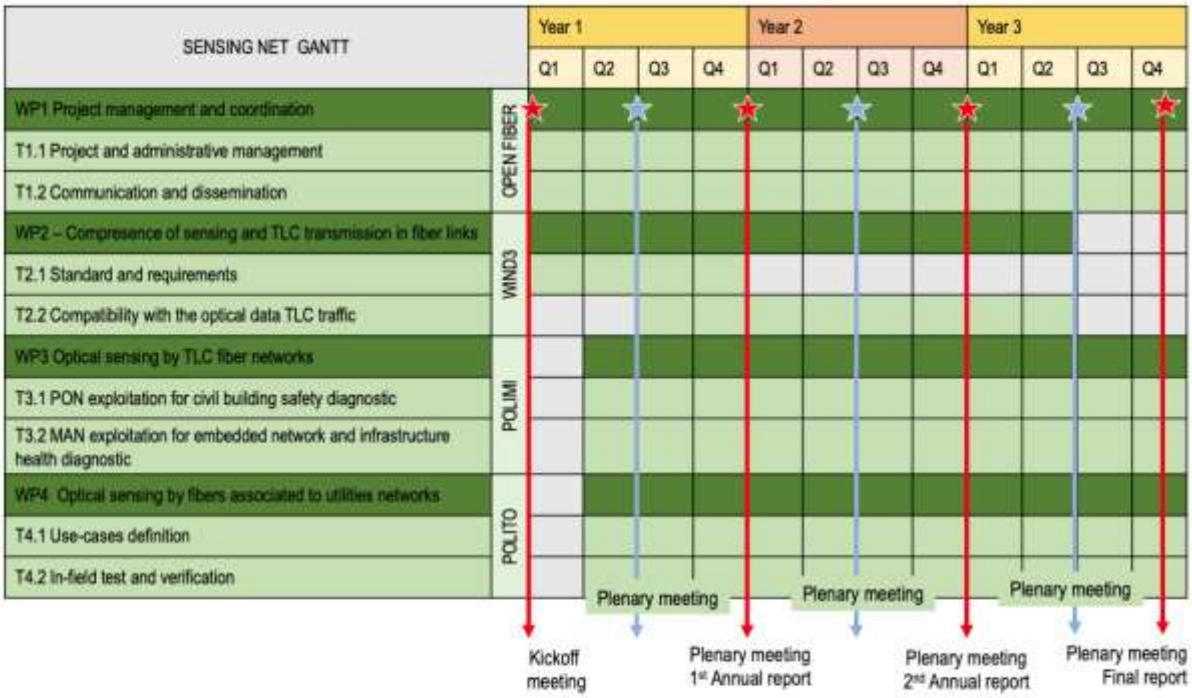
Task 4.1 Use-cases definition

SENSING NET partners will identify specific use-cases in case of the exploitation of fibre infrastructures suitably deployed to support utilities networks. The monitoring of plants, industrial apparata, power transformers, Industry 4.0 machinery and Internet-of-Things devices will be considered, determining requirements and specifications.

Task 4.2 In-field test and verification
SENSING NET partners will develop and test specific FOSs architectures tailored for the specific kind of fiber infrastructure. In-field experimentation will be done by exploiting the deployed infrastructures made available by OPEN FIBER.

SENSING NET consortium collects all the skills needed to fulfil the tasks of the project as the different partners have complementary and multidisciplinary expertise, from the TLC aspects, to the technological demonstration. SENSING NET consortium includes two universities (POLIMI and POLITO) and a research center (CNR) with a large expertise in optical communication networks. POLIMI and CNR master the FOS technology with fibre sensing solution for urban and regional contexts. OPEN FIBER is one of the main fibre deployer in Italy and WIND3 is a big TLC operator.

The foreseen budget allows the collaboration among the partners and supports all the experimental activities. PhotoNext Lab at POLITO, PoliCom Lab at POLIMI in fact are made available with their equipment free of charge, together with the access to OPEN FIBER experimental deployed fibre testbeds.



Expected results and impact
SENSING NET is a pilot project with the aim to obtain an unprecedented increase of capability to monitor, analyse and forecast civil, infrastructural in real-time by exploiting the already deployed TLC fibre networks. The expansion of metro and access networks, mostly in the FTTH version, and dedicated networks is attracting large investments everywhere in the world. SENSING NET impact can thus be huge in the forthcoming years, since the optical sensing solutions developed within the project can be directly applied on these networks. SENSING NET solutions could become the basis for the development of new early warning and maintenance services to diagnose in advance the occurrence of anomalies and critical situations on the optical network itself.
SENSING NET will allow to identify what are the most promising types of signal coming from FOSs that can be monitored systematically in the future in an urban context, using only the pre-existing fibre network, also for prevention, to detect in advance where are the fragilities of the city in terms of ground motion and soil stability. The capillary distributed monitoring of ground motion achievable thanks to the deployed urban fibre network can give in the present COVID-19 pandemic outbreak useful quasi real-time

information about people activities and gathering during quarantine in order to accurately forecast viral infection rates and condition future government decisions.

Scientific impact:
SENSING NET is a pilot project with the aim to obtain an unprecedented increase of capability to monitor, analyse and forecast civil, infrastructural and earth hazards in real-time by exploiting the already deployed TLC fibre networks. The expansion of metro and access networks, mostly in the FTTH version, is attracting large investments everywhere in the world. Focussing on Italy, the Government has invested 5B€ in 2014-2020 (Italian Government portal on UBB: http://bandaultralarga.italia.it/) to meet the EU Broadband agenda (EU H2020 Digital Agenda https://ec.europa.eu/digital-single-market/), and is planning to keep on investing until most of the country is reached by optical fibres. The impact of SENSING NET can thus be huge in the forthcoming years, since the optical sensing solutions developed within the project can be directly applied on these networks. In particular, the civil infrastructure monitoring systems developed in SENSING NET will be completely passive for the outdoor part, since they can be remotely interrogated from the central office. These solutions will be extremely resilient during, for instance, massive urban electricity blackouts (central offices usually have autonomous power supply backup systems that can resist for many hours), and thus may have a huge impact on emergency/protection systems. SENSING NET solutions could become the basis for the development of new early warning and maintenance services to diagnose in advance the occurrence of anomalies and critical situations on the optical network itself. In fact, in urban areas, the probability of damages to installed optical cables is quite high (due for instance to ongoing civil construction work), thus an early warning system that senses anomalous vibrations of an installed cable can be of huge interest for TLC operators.

Tecnological impact:
SENSING NET provides an opportunity to push the use of FOSs for massive monitoring, impacting on the companies involved in FOSs development and production. The analysis of the detected signals recorded in SENSING NET in the deployed TLC networks may provide general guidelines to be applied in future to other FOS use-cases, such as the monitoring of buildings and lifelines safety, of environment stability etc. All these activities are expected to contribute to move FOS-based monitoring from the present stage of early exploitation to a consolidated and reliable technology applicable also in harsh environments.

Contributions to sustainability:
The exploitation of the existing fiber infrastructure for multipurpose applications allows to save CAPEX expenses. On the other hand, the monitoring results can be exploited to reduce OPEX cost, and to obtain early-warnings of apparata failures which can bring to a detrimental extra power consumption.

Benefits for the society:
SENSING NET will allow to identify what are the most promising types of signal coming from FOSs that can be monitored systematically in the future in an urban context, using only the pre-existing fibre network, also to detect in advance where are the fragilities of the city in terms of ground motion and soil stability. The capillary distributed monitoring of ground motion achievable thanks to the deployed urban fibre network can give in the present COVID-19 pandemic outbreak useful quasi real-time information about people activities and gathering during quarantine in order to accurately forecast viral infection rates and condition future government decisions.

Possible collaborations and synergies with other projects
SENSING NET project concerns the application of particular optical sensing solutions (for example interferometric architectures) to the optical fiber infrastructure for telecommunications and to the networks supporting utilities. For this reason, SENSING NET represents a project of strong synergy between Theme 8 "Pervasive, integrated communications and sensing" and Theme 4 "Green / autonomic optical networks, systems and integrated devices". In particular, the research proposed in the focused SENSING

NET project are complementary to the activities relating to telemetry foreseen in WP4 of the structural project of Theme 4.

Principal Investigator
[redacted] **(OPEN FIBER)**
List of partners
1. OPEN FIBER
2. POLITECNICO DI MILANO
3. POLITECNICO DI TORINO
4. CNR IEIIT
5. WIND3

Partner 1:
Reference investigator: OPEN FIBER [redacted]
List of permanent staff
[redacted] 3 m/p/a x 3 anni
[redacted] 2 m/p/a x 2 anni

Partner 2:
Reference investigator: POLITECNICO DI MILANO – [redacted]
List of permanent staff
[redacted] 3 m/p/a x 3 anni
[redacted] 2 m/p/a x 2 anni

Partner 3:
Reference investigator: POLITECNICO DI TORINO – [redacted]
List of permanent staff
[redacted] 3 m/p/a x 3 anni
[redacted] 2 m/p/a x 3 anni

Partner 4:
Reference investigator: CNR – [redacted]
List of permanent staff
[redacted] 2 m/p/a x 3 anni
[redacted] 2 m/p/a x 3 anni

Partner 5:
Reference investigator: WIND 3- [redacted]
List of permanent staff
[redacted] 2 m/p/a x 2 anni