HYPHa project: a low-cost alternative for integrated photonics

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Abstract—In this paper, a brief introduction is presented to the Hybrid sensor platforms of integrated photonic systems based on ceramic and polymer materials (HYPHa). The project's goal is to establish a collaborative effort of institutes specialized in integrated optics. A newly formed group of professionals will be founded on research groups' experience, collaboration, and devotion. We intend to develop a method for combining competencies and a universal material platform for integrated photonics, based on newly validated hybrid materials as part of the project. Silica compounds with additions including TiO_2, SnO_2, used as structural matrices, polymer coatings with dopants (active or protective layers), organic dyes, and active two-dimensional materials such as transition metal dichalcogenides, graphene hybrids, and boron nitride will be the foundation for these materials.

The Foundation for Polish Science is funding the project "Hybrid sensor platforms of integrated photonic systems based on ceramic and polymer materials." The goal of the project is to create a new, low-cost technological platform for photonic integrated circuits based on Silica-Titania (SiO_2:TiO_2) waveguide films generated from sol-gel. The investigated platform has several notable features, including: (i) the ability to operate in both the visible and near-infrared wavelength ranges, (ii) the ability to tailor refractive index contrast, (iii) high chemical resistivity, and (iv) the ability to use direct nanoimprint for low-cost fabrication.

The project's major objective is to provide a full manufacturing process for both passive and active integrated photonic devices and circuits. The waveguide film production technology will be refined during the project's execution, resulting in even lower-loss waveguide films. Furthermore, if at all feasible, a low-cost patterning approach will be created without the use of costly techniques like electron-beam lithography or plasma etching. Passive photonic elements such as straight and curved waveguides, multimode and directional couplers, optical filters, and multiplexers, as well as active photonic components such as optical amplifiers and lasers, will be created. The project will be concluded with the creation of two integrated optical systems demonstrators: a multichannel optical sensor and integrated lasers. The project is being carried out by a consortium of Polish research centers leading in the field of integrated photonics. The paper is split up into two parts: the contributing partners, research activities and the skills offered by each group are discussed in the first part of the paper. In the second part, the initial findings on the SiO_2:TiO_2 based optical elements are investigated within the consortium. Figure 1 reveals the consortium working on the HYPHa project.

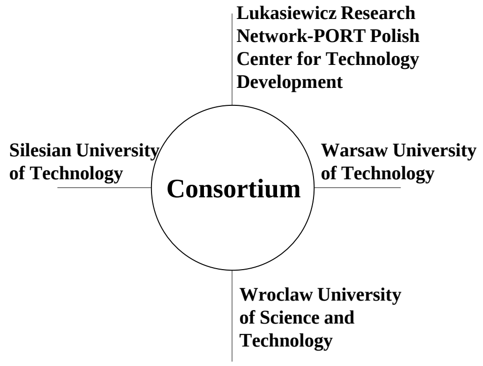

Fig. 1. Research teams involved in the HYPHa project.

The *Advanced Materials Synthesis Group at Lukasiewicz- PORT* is the leader of the consortium and focuses on the design and formulation of inorganic compounds (phosphors, metallic or oxide nanoparticles) along with organic compounds with specific Physico-chemical characteristics, such as luminescence, thermochromic, thermal, mechanical, antibacterial, electrical, or sensor attributes. The group is focusing on hybrid systems that have been enhanced and/or doped with dyes and nanoparticles for photonics purposes and

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laser action. Also created are biodegradable polymers and composite materials with functional features. Intelligent transport systems of active compounds for use in medicine and cosmetics are one example.

Research is undertaken on solid-state chemistry as well as phenomena that occur at the interface between the solid, liquid, and gas phases. It also involves studies of adsorption and catalysis using porous materials, primarily layered minerals and miscible layered hydroxides, as well as the manipulation of these materials to effectively remove dangerous compounds from the air and water. Furthermore, research is being done on using a concentrated electron beam to modify different materials to get adequate physicochemical characteristics for possible applications in photonics and electronics. These investigations focus on the micro- and nanostructuring of ionic liquids, as well as their combinations with other substances (e.g., metal salts) [1, 2].

The research team from the Department of Optics and Photonics at the Wroclaw University of Science and Technology is a part of the Optical Fiber Optics group. The Group has the tools and expertise for testing standard and special optical fibers (including photonic optical fibers) and optical fiber components and devices. These include broad spectral range measurements of phase and group mode birefringence, polarization mode dispersion, chromatic dispersion, as well as transmission, bending, and polarization-dependent losses. Measurements of the interferometric and polarimetric sensitivities of optical fibers to different physical factors such as temperature, hydrostatic pressure, axial and transverse load, and measurements of the metrological characteristics of fiber Bragg gratings are also carried out. Long-period gratings in different types of optical fibers may also be manufactured and characterized by the group. Design and simulations of photonic components utilizing modern numerical tools are essential parts of the group's capabilities, including modelling linear and nonlinear propagation and sensing properties in classical and microstructured optical fibers, fiber Bragg gratings, long-period gratings, or integrated optic elements [3, 4].

The *Silesian University of Technology's* Photonics and Nanotechnology Team is an intergenerational multidisciplinary group of scientists that includes physicists, chemists, mechatronics, and biotechnologists. The Team's research work in the HYPHa project is focused on designing, fabrication, and characterization of integrated optics elements, primarily for use in planar optical sensors. The SiO_x:TiO_y composite waveguide layers with a high refractive index (1.8) discovered by the Group and generated by the sol-gel process and dip-coating technique provide the basis for this field of research. Theoretical analyses carried out using commercial software and custom programs by Team members enable the design of integrated optical systems. Optical techniques and commercial instruments, as well as customized measurement systems, are used to characterize the structures generated.

The Team's research focuses largely on technological difficulties, intending to further the establishment of technologies for obtaining SiO_x:TiO_y composite waveguide layers, particularly waveguide layers with a specified refractive index ranging from 1.5 to over 1.9. Waveguide layers with thicknesses adequate for purposes in the NIR spectral region can be made by layering the layers two or three times on one substrate (1550 nm). Active layers, which are created by doping the established waveguide layers with ions of specific lanthanides, are a significant research topic carried out under the HYPHa project. Simultaneously, a technical study is being conducted on the production of silica layers and titanium dioxide TiO_2 layers [5, 6].

The focus of the *Warsaw University of Technology's* Combined Photonics Team's research is on the prototype and characterization of integrated optics systems and components for a wide variety of uses, including structures and sensory systems, as well as optical telecommunications systems using WDM techniques. The Team's research focuses on the design of individual elements (such as individual sensory elements) as well as full integrated photonic systems, as well as the experimental validation of the planned structures' operation. The group also has a lot of expertise in embedding integrated photonics into optical systems.

The team has software for designing and simulating photonic integrated circuits, as well as a measurement set-up that allows for thorough electro-optical characterization of integrated photonic devices in the visible and near-infrared spectral ranges (NIR). As part of the HYPHa project, the team is involved in the design and testing of optical elements and systems built on the SiO_x: TiO_y waveguide layer technology, which includes both passive and active components such as integrated optical filters and optically pumped amplifiers. Based on the technology established in the HYPHa project, the team will also spearhead the effort to build sensory system demonstrations and an integrated optical signal source [7, 8].

Optical ring resonators have gained a lot of interest in recent years as one of the most potent bioactive sensors. The optical ring resonator determines the target molecules by analyzing light behavior variations induced by electromagnetic wave contact with biological molecules such as proteins, bacteria, cells, or DNA samples. The interaction between the evanescent field of the resonating light inside the resonator and bioparticles in the ambient causes this shift in light behavior. The presence of bioparticles in the medium alters the effective refractive index of the surrounding media, causing the resonator's resonance conditions to deviate [9]. The resonant wavelength deflection of the resonator, which is linked to the number of bioparticles in the medium, is a result of such an interaction.

By adopting periodic segmented waveguide constructions at the subwavelength level of the operating wavelength, it is possible to modify the dispersion and nonlinear characteristics of photonic devices without changing the material properties [10]. Many practical devices founded on subwavelength features have become created in recent years thanks to developments in lithographic technology on the semiconductor-on-insulator platform giving sub-100-nm patterning precision. The flexibility to adjust the propagation of the electromagnetic field in these formations on a tiny scale can be used to benefit photonic devices built on photonic crystals (PhCs). Furthermore, systems with compact footprints are possible. Several fascinating devices based on PhCs have been proposed in recent years, including tiny radius bent waveguides, miniaturized resonator cavities, and Y-branches, to name a few. These remarkable characteristics may pave the way for the construction of a dense integrated circuit. However, because PhC technology is still in its infancy, additional research into the subject is required [11].

The polarization beam splitter (PBS) is an essential element for splitting and mixing light having two orthogonal polarizations, namely the transverse electric (TE) and transverse magnetic (TM). The polarization-division multiplexing (PDM) system, which may double the data transmission bandwidth on a single wavelength, uses PBS as one of the key building components [12].

In several material platforms, grating couplers are frequently employed to couple light into and out of the planar photonic system. They may be made in any location on the substrate and are less technologically demanding than horizontal edge couplings, making them especially appealing for the material platform at this initial phase of development. A grating coupler is constructed and composed of a diffraction grating that is commonly shaped like a taper. The light of a specified wavelength can be coupled to the waveguide by properly selecting the grating's period and the angle of the fiber. For improved light coupling, the etch depth and the filling factor should be changed during the optimization process [13]. Consequently, we have numerically demonstrated refractive index sensing devices based on ring resonator [7], subwavelength grating waveguide (SWG) and 1D-Photonic crystal waveguide (PhC) as shown in Fig. 2 (a-c). For increasing the transmission bandwidth on a single waveguide, PBS based on SiO_2:TiO_2 platform is numerically investigated. Several performance-related issues such as crosstalk and polarization extinction ratio will be discussed during the device study. The scheme of the device is shown in Fig. 2d. In the end, an efficient method of fiber-to-chip coupling is proposed by utilizing binary and slanted grating geometries to enhance the directionality and coupling efficiency. The basic scheme of the grating coupler is shown in Fig. 2e.

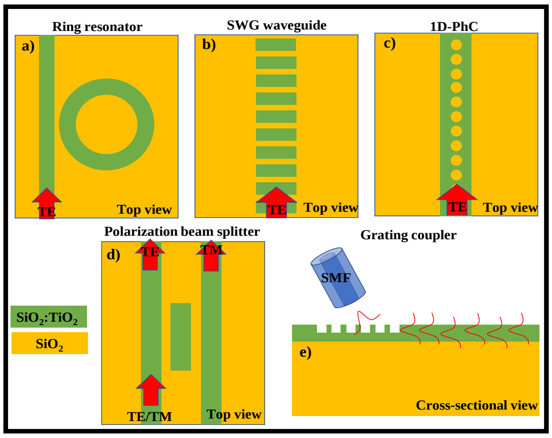

Fig. 2. Schematic representation of optical elements based on SiO_2:TiO_2 platform, a) Ring resonator, b) SWG waveguide, c) 1D-PhC waveguide, d) Polarization beam splitter, e) Grating coupler.

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