Summary of Professional Accomplishments

1. **Name**
   Karol Tarnowski

2. **Diplomas, degrees conferred in specific areas of science, including the name of the institution which conferred the degree, year of degree conferment, title of the PhD dissertation**

   - **master's degree** in **Physics** (speciality Physical Foundations of Computer Science), **06.07.2007** (Faculty of Fundamental Problems of Technology, Wroclaw University of Science and Technology)|,
   - **master's degree** in **Computer Science** (speciality Algorithms and Computer Systems), **25.02.2010** (Faculty of Fundamental Problems of Technology, Wroclaw University of Science and Technology),
   - **degree of Doctor of Physical Sciences** in the field of **Physics** conferred upon the resolution of the Scientific Board of the Institute of Physics, Wrocław University of Science and Technology, on the basis of the thesis „The selected frequency conversion processes in structured optical fibers", the thesis was **awarded**.

3. **Information on employment in research institutes or faculties/departments or school of arts**

from 01.10.2012 till 30.09.2014	research assistant, Faculty of Fundamental Problems of Technology, Wrocław University of Science and Technology
from 01.10.2014	assistant professor, Faculty of Fundamental Problems of Technology, Wroclaw University of Science and Technology

4. Description of the achievements, set out in art. 219 para 1 point 2 of the Act.

A series of thematically related scientific articles published in scientific journals, entitled "*The use of linear and nonlinear phenomena to control light properties in specialty optical fibers*."

The series consists of the following publications (listed in chronological order):

[1] K. Tarnowski, W. Urbańczyk, *Origin of Bragg reflection peaks splitting in gratings fabricated using a multiple order phase mask*, Optics Express, vol. 21(19), pp. 21800-21810 (2013) DOI: 10.1364/OE.21.021800;

[2] K. Tarnowski, A. Anuszkiewicz, J. Olszewski, P. Mergo, B. Kibler, W. Urbańczyk, *Nonlinear frequency conversion in a birefringent microstructured fiber tuned by externally applied hydrostatic pressure*, Optics Letters, vol. 38(24), pp. 5260-5263 (2013) DOI: 10.1364/OL.38.005260;

[3] K. Tarnowski, A. Anuszkiewicz, K. Poturaj, P. Mergo, W. Urbańczyk, *Birefringent optical fiber with dispersive orientation of polarization axes*, Optics Express, vol. 22(21), pp. 25347-25353 (2014) DOI: 10.1364/OE.22.025347;

[4] K. Tarnowski, A. Anuszkiewicz, P. Mergo, B. Frisquet, B. Kibler, W. Urbanczyk, *Nonlinear mode coupling in a birefringent microstructured fiber tuned by externally applied hydrostatic pressure*, Journal of Optics, vol. 17(3), 035506 (2015) DOI: 10.1088/2040-8978/17/3/035506;

[5] K. Tarnowski, W. Urbanczyk, *All-normal dispersion hole-assisted silica fibers for generation of supercontinuum reaching midinfrared*, IEEE Photonics Journal, vol. 8(1), 7100311 (2016) DOI: 10.1109/JPHOT.2016.2524550;

[6] K. Tarnowski, T. Martynkien, P. Mergo, K. Poturaj, G. Soboń, W. Urbańczyk, *Coherent supercontinuum generation up to 2.2 μm in an all-normal dispersion microstructured silica fiber*, Optics Express, vol. 24(26), pp. 30523-30536 (2016) DOI: 10.1364/OE.24.030523;

[7] K. Tarnowski, T. Martynkien, P. Mergo, K. Poturaj, A. Anuszkiewicz, P. Béjot, F. Billard, O. Faucher, B. Kibler, W. Urbanczyk, *Polarized all-normal dispersion supercontinuum reaching 2.5 μm generated in a birefringent microstructured silica fiber*, Optics Express, vol. 25(22), pp. 27452-27463 (2017) DOI: 10.1364/OE.25.027452;

[8] J. Biedrzycki, K. Tarnowski, W. Urbańczyk, *Optimization of microstructured fibers with germanium-doped core for broad normal dispersion range*, Opto-Electronics Review, vol. 26(1), pp. 57-62 (2018) DOI: 10.1016/j.opelre.2018.01.004;

[9] G. Statkiewicz-Barabach, K. Tarnowski, D. Kowal, P. Mergo, *Experimental analysis of Bragg reflection peak splitting in gratings fabricated using a multiple order phase mask*, Sensors, vol. 19(2), 433 (2019) DOI: 10.3390/s19020433;

[10] K. Tarnowski, T. Martynkien, P. Mergo, J. Sotor, G. Soboń, *Compact all-fiber source of coherent linearly polarized octave-spanning supercontinuum based on normal dispersion silica fiber*, Scientific Reports, vol. 9, 12313 (2019) DOI: 10.1038/s41598-019-48726-9.

Telecommunication optical fibers now entwine the entire world with a dense network, without which the modern information society could not exist. Simultaneously, telecommunication applications are not the only area where optical fibers are used. Specialty optical fibers are used in medicine, metrology and optoelectronics. Many new applications have emerged in the last decade as a result of the development of microstructured optical fiber fabrication technology[1]. In this type of optical fibers, the light-guiding is achieved due to the presence of structural elements which are micrometer-sized (e.g. air holes of such diameter). The large difference of the refractive indices of glass and air enables flexible shaping of the properties of the optical fibers and, consequently, allows to control the properties of the light propagating in them. Moreover, thanks to the high concentration of optical power on a small area and the long propagation distance, not only linear but also nonlinear phenomena can occur in the optical fibers. The use of these phenomena to control the properties of light was the subject of my research, the results of which were presented in the series of scientific publications entitled *"The use of linear and nonlinear phenomena to control light properties in specialty optical fibers."*

The theoretical description of light propagation in optical fibers is based on Maxwell's equations from which the Helmholtz equation and the nonlinear Schrödinger equation are derived. The Helmholtz equation allows to determine the guided modes of the optical fiber, while the nonlinear Schrödinger equation allows to describe the propagation of light including nonlinear effects[2]. Within my research, I used advanced numerical tools to solve these two equations. In the case of the Helmholtz equation, it was the commercial Comsol Multiphysics software implementing the finite element method, and in the case of the Schrödinger equation, I developed my own numerical implementations in the Matlab environment to solve the generalized nonlinear Schrödinger equation and the coupled nonlinear Schrödinger equation system for polarization modes. The use of these numerical tools allowed me to propose innovative designs of specialty optical fibers that exhibit previously unattainable properties or extend the range of applicability of already known phenomena.

In the further part of the summary, I discussed the obtained results in details, describing my contribution to the published articles. I divided the published in series articles into two groups containing the results concerning:

- linear phenomena, including:
  - spectral filtering with fiber Bragg gratings (articles [1], [9]),
  - light propagation in birefringent optical fibers with dispersive orientation of polarization axes (article [3]),
- nonlinear phenomena, including:
  - frequency conversion and polarization mode coupling in birefringent optical fibers (articles [2], [4])
  - generation of coherent supercontinuum in normal dispersion optical fibers (articles [5-8], [10]).

[1] J. C. Knight, T. A. Birks, P. S. J. Russell, D. M. Atkin, "All-silica single-mode optical fiber with photonic crystal cladding," *Optics Letters* **21**(19): 1547 (1996)
[2] G. P. Agrawal, *Nonlinear fiber optics*, 5th edition, Academic Press (2013).

Linear phenomena

Spectral filtering with fiber Bragg gratings

Fiber Bragg gratings allow spectral filtering of light propagating in the optical fiber. The Bragg grating is an axial modulation of the properties of the fiber with a fixed period (Λ), which causes the reflection of light with a wavelength ($\lambda^{(p)}$) meeting the condition[3]:

$$\lambda^{(p)} = \frac{2}{p} n\left(\lambda^{(p)}\right)\Lambda , \tag{1}$$

where $n(\lambda)$ describes the dependence of the effective refractive index of the mode on the wavelength, and p is the order of reflection. The most popular method of Bragg gratings fabrication is the phase mask method[4] in which the optical fiber is illuminated laterally through a phase mask (diffraction grating) with electromagnetic radiation in the ultraviolet range. The interference pattern created behind the phase mask translates into axial modulation of the refractive index in the fiber core due to the photosensitivity of GeO_2-doped silica glass. In the ideal case, the optical fiber is aligned parallel to a phase mask with the period Λ_d that generates two orders of diffraction: first and minus first. The periodic modulation of the refractive index with the period $\Lambda = \Lambda_d/2$ is produced in the fiber core. The actual phase masks generate several diffraction orders of a UV inscribing beam. Consequently, the interference pattern created behind the phase mask is complex. In this case, the relative tilt of the fiber from the phase mask causes the splitting of the Bragg peaks. The connection between the fiber tilt angle, the presence of several orders of diffraction, and the separation of Bragg peaks was known[5]. However, the quantitative description and the physical explanation of this phenomenon were not given. The explanation of the physical reason of an experimentally-observed Bragg peaks splitting is the original result presented in the article:

[1] K. Tarnowski, W. Urbańczyk, *Origin of Bragg reflection peaks splitting in gratings fabricated using a multiple order phase mask*, Optics Express, vol. 21(19), pp. 21800-21810 (2013).

I showed that this splitting is caused by the overlapping of Bragg gratings with different periods which arise due to the interference of the UV beams diffracted on the phase mask into different diffraction orders (the tilt of the fiber differentiates the periods of the gratings formed in the fiber core as a result of the interference of distinct pairs of beams). For example, the phase mask with period Λ_d diffracting the UV beam into diffraction orders: −2, −1, 0, +1, +2, allows to inscribe many different Bragg gratings in the tilted fiber. They are: four different Bragg gratings with periods close to Λ_d related to the interference of following pairs of beams: (−2, −1), (−1, 0), (0, +1), (+1,+2); three different Bragg gratings

[3] K. O. Hill, G. Meltz, "Fiber Bragg grating technology fundamentals and overview," *J. Light. Technol.* **15**(8): 1263–1276 (1997).
[4] ibid
[5] S. A. Wade, W. G. A. Brown, H. K. Bal, F. Sidiroglou, G. W. Baxter, S. F. Collins, "Effect of phase mask alignment on fiber Bragg grating spectra at harmonics of the Bragg wavelength," *J. Opt. Soc. Am. A* **29**(8): 1597-1605 (2012).

with periods close to $\Lambda_d/2$ related to the interference of following pairs of beams: (−2, 0), (−1, +1), (0,+2); two different gratings with periods close to $\Lambda_d/3$ related to the interference of pairs of beams: (−2, +1), (−1, +2) and grating with a period close to $\Lambda_d/4$ related to the interference of pair of beams: (−2, +2). In general, the interference of beams diffracted into orders (*m*, *q*) contributes to Bragg grating with period close to $\Lambda_d / |m-q|$.

The theoretical description, that I had formulated, allowed predicting the wavelengths for which resonance reflections from the overlapping Bragg gratings inscribed in the tilted fiber appear. The parameters of the model are as follows (according to [1]):

- the angle between the inscribing UV beam and the normal to the phase mask (α),
- the angle between the incidence plane and the plane determined by the normal to the phase mask and its inverse vector (β),
- the tilt angle of the fiber with respect to the phase mask (φ),
- the rotation angle of the fiber around normal to the phase mask (θ).

Using this description, I explained quantitatively the Bragg peaks splitting reported in earlier works[6]. It results from different periods of gratings created by interferences of pairs of beams: (−1, 0) and (0, +1) in the tilted fiber. In addition, I predicted the possibility of obtaining additional Bragg peaks related to the interference of UV pairs of beams diffracted into higher diffraction orders. For example, close to the Bragg peak of grating created by the interference of the beams pair (−1, 1), two side peaks related to the interference of the pairs of beams (−2, 0) and (0, +2) may be present.

Theoretical predictions regarding the possibility of the formation of multiple Bragg peaks (going beyond the previously known splitting in two) as a result of the fiber tilt have been confirmed experimentally in the article:

[9] G. Statkiewicz-Barabach, K. Tarnowski, D. Kowal, P. Mergo, *Experimental analysis of Bragg reflection peak splitting in gratings fabricated using a multiple order phase mask*, Sensors, vol. 19(2), 433 (2019).

The assumptions of this work were formulated by me together with Gabriela Statkiewicz-Barabach, PhD. Additionally, my contribution included the theoretical analysis of experimental data. The measurements revealed the separation of the Bragg peak observed at the wavelength of 1560 nm into five peaks. The spectral separation of those peaks depends linearly on the angle of the fiber tilt. Using the developed theoretical model, I indicated the origin of individual Bragg peaks: the main peak is related to the first-order reflection from the grating inscribed by the interference of orders (−1, +1); and two pairs of peaks located symmetrically to the main peak are related to: (i) second-order reflection from the gratings created by the interference of diffraction orders (0, +1) and (−1, 0); (ii) the reflection of the first order from the gratings created by the interference of orders (0, +2) and (−2, 0).

In summary, the theoretical model enabling the design of Bragg gratings with several reflection peaks was provided and experimentally verified in [1, 9]. The positions of the peaks are controlled by tilting the fiber with respect to the phase mask. In this way, the

[6] S. A. Wade, W. G. A. Brown, H. K. Bal, F. Sidiroglou, G. W. Baxter, S. F. Collins, "Effect of phase mask alignment on fiber Bragg grating spectra at harmonics of the Bragg wavelength," *J. Opt. Soc. Am. A* **29**(8): 1597-1605 (2012).

reflection spectrum of the Bragg gratings can be shaped and the wavelength of the light propagating in the optical fiber can be controlled.

Propagation of light in birefringent optical fibers with dispersive orientation of polarization axes

Next property of light that can be controlled in optical fibers is the polarization state. Birefringent[7] and polarizing[8] optical fibers are used for this purpose. The first designs of birefringent fibers were developed on the turn of the seventies and eighties of the last century. In general, the observation and application of phenomena that were occurring in volumetric systems were enabled by the development of specialty optical fibers technology.

In order to obtain birefringence, it is necessary to break the cylindrical symmetry typical in telecommunication optical fibers. This can be achieved by fabricating an elliptical core, placing stressing elements in the cladding or introducing microstructural elements close to the core (e.g., side air channels in side-hole optical fibers). All the above-mentioned methods break the circular symmetry of the optical fiber, however they maintain the plane symmetry. In this way, a linear birefringence is obtained, and the directions of the polarization axes agree with the symmetry planes of the optical fiber and do not depend on the light wavelength. The birefringence in many optical bulk media has a similar character; i.e., a constant orientation of the polarization axes as a function of wavelength. Simultaneously, in optical crystals with monoclinic and triclinic systems, the dependence of the orientation of the polarization axes on the wavelength is known as “the dispersion of the axes”. The possibility of obtaining such effect in an optical fiber was an interesting research problem. My original result is the project of a birefringent optical fiber with dispersive polarization axes presented in the article:

[3] K. Tarnowski, A. Anuszkiewicz, K. Poturaj, P. Mergo, W. Urbańczyk, *Birefringent optical fiber with dispersive orientation of polarization axes*, Optics Express, vol. 22(21), pp. 25347-25353 (2014).

In this work, I proposed the design of a side-hole optical fiber with an elliptical core, in which the core symmetry axes do not overlap with the cladding symmetry axes. Such construction allows to obtain the dependence of the orientation of the polarization axes on the wavelength. In the short wavelength range, the fiber mode is well-confined in the core. In this case, the polarization axes of the fiber are determined by the symmetry axes of the core ellipse. As the wavelength increases, the contribution of air holes to the mode guidance increases. For this reason, the polarization axes of the optical fiber gradually rotate towards the cladding symmetry axes. This results in a dispersive orientation of the polarization axes.

Additionally, I contributed to this work with calculations of the linear properties of idealized optical fibers (phase birefringence, group birefringence, orientation of polarization axes). Using numerical tools, I analysed the effect of a thermal stress related to

[7] R. B. Dyott, J. R. Cozens, D. G. Morris, “Preservation of polarisation in optical-fibre waveguides with elliptical core,” *Electron. Lett.* **15**(13): 380–382 (1979).

[8] M. P. Varnham, D. N. Payne, R. D. Birch, E. J. Tarbox, “Single-polarisation operation of highly birefringent bow-tie optical fibres,” *Electron. Lett.* **19**(7): 246–247 (1989).

a difference in thermal expansion coefficients of pure silica glass (cladding) and doped glass (core) on the properties of the fibers. Calculations have shown that the thermal stress gives a significant contribution to the phase birefringence. It should be highlighted that the change of the material refractive indices induced by the stress was calculated in the reference frame determined by the local principal stress directions, and then the dielectric tensor was transformed to the Cartesian reference frame for the electromagnetic calculations.

Finally, the fiber with dispersive polarization axes was fabricated in the Laboratory of Optical Fibers Technology of Maria Curie-Skłodowska University in Lublin and characterized experimentally and numerically. I performed numerical calculations using the fiber cross-section image obtained in a scanning electron microscope. The measurements and simulations gave consistent results, confirming the desired effect – the change in the orientation of the polarization axes by 14.5° in the spectral range of 500 nm – 1100 nm.

This type of the optical fibers can be used to control the polarization state of the light. Change of the polarization state of the light can be used in metrology. For example, the orientation of the polarization axes can be changed by an external factor (e.g., hydrostatic pressure), which will induce local coupling of polarization modes that can be measured using the polarization optical time-domain reflectometry (p-OTDR).

Summarizing, I proposed the experimentally verified concept of the birefringent fiber with the dispersive orientation of the polarization axis [3], which can be used to control the polarization state of propagating light and distributed measurements using the polarization reflectometry method.

Nonlinear phenomena

Frequency conversion and polarization modes coupling in birefringent optical fibers

As mentioned earlier, the high intensity of light propagating in the optical fibers enhances the nonlinear phenomena leading to the generation of new frequencies. In general, the linear and the nonlinear processes depend on the properties of the optical fibers, therefore, by designing the optical fiber appropriately, one can influence these phenomena. Additionally, it is possible to make the phenomena occurring in optical fibers sensitive to external factors. On the one hand, it allows to control the properties of the light propagating in the optical fiber with the external factor, and on the other hand, it allows to infer the value of the external factor from the measured properties of the light. Such dependences underlie the operation of fiber optic sensors. Typically, the linear phenomena are used in the fiber optic sensors, while the use of nonlinear phenomena has been shown in a limited scope, e.g. to the detection of biological substances[9] and the measurement of the refractive index of liquids[10]. In my research, I presented the method of using the

[9] J. R. Ott, M. Heuck, C. Agger, P. D. Rasmussen, O. Bang, "Label-free and selective nonlinear fiber-optical biosensing," *Opt. Express* **16**(25): 20834 (2008).
[10] M. H. Frosz, A. Stefani, O. Bang, "Highly sensitive and simple method for refractive index sensing of liquids in microstructured optical fibers using four-wave mixing," *Opt. Express* **19**(11): 10471 (2011).

phenomenon of modulation instability in a specialty optical fiber for hydrostatic pressure measurement. The results of this work were published in the article:

[2] K. Tarnowski, A. Anuszkiewicz, J. Olszewski, P. Mergo, B. Kibler, W. Urbańczyk, *Nonlinear frequency conversion in a birefringent microstructured fiber tuned by externally applied hydrostatic pressure*, Optics Letters, vol. 38(24), pp. 5260-5263 (2013).

I contributed to this work by developing the assumptions of the research and simulating nonlinear light propagation in a birefringent optical fiber using my own implementation of the coupled nonlinear Schrödinger equation system solver for polarization modes. In optical fibers with anomalous chromatic dispersion, modulation instability is observed when pumping with a continuous wave. The modulation instability relies on the conversion of the energy of the pumping wave (with the absolute angular frequency ω_0) to two bands. The bands of the scalar modulation instability are located symmetrically with respect to the angular frequency of the pumping wave, and the maximum gain is observed for the frequency $\omega_0 \pm \Omega_S$. The relative angular frequency Ω_S depends on the nonlinearity of the fiber (γ), the power of the pumping wave (P_0) and the chromatic dispersion (β_2, the second derivative of the propagation constant versus angular frequency)[11]:

$$\Omega_S = \sqrt{\frac{2\gamma P_0}{|\beta_2|}}. \tag{2}$$

The vector modulation instability is observed in birefringent optical fibers. In this case, the gain maxima of the generated bands appear for the angular frequency $\omega_0 \pm \Omega_V$. The relative angular frequency Ω_V depends on the group birefringence (G) and the chromatic dispersion (β_2) of the fiber[12]

$$\Omega_V = \frac{G}{c|\beta_2|}. \tag{3}$$

I noticed that the process of the vector modulation instability can be controlled by the hydrostatic pressure in the earlier developed specialty optical fiber with the high sensitivity of the birefringence to a hydrostatic pressure[13]. In this fiber, the hydrostatic pressure influences the group birefringence value without significant modification of the group velocity dispersion. Consequently, the hydrostatic pressure tunes the vector modulation instability bands without modifying the scalar modulation instability bands.

The above predictions have been confirmed experimentally, and the results were presented in [2]. In the piece of the specialty optical fiber (80 cm long), bands of scalar and vector modulation instability were generated while pumping with a quasi-continuous laser at 1.064 µm. The central section of the fiber (38 cm long) was placed in an oil-filled pressure chamber. In the range of pressure from 0.1 MPa to 5 MPa, a shift of the anti-

[11] G. P. Agrawal, *Nonlinear fiber optics*, 5th edition, Academic Press, (2013).
[12] ibid
[13] T. Martynkien, G. Statkiewicz-Barabach, J. Olszewski, J. Wojcik, P. Mergo, T. Geernaert, C. Sonnenfeld, A. Anuszkiewicz, M. Szczurowski, K. Tarnowski, M. Makara, K. Skorupski, J. Klimek, K. Poturaj, W. Urbańczyk, T. Nasiłowski, F. Berghmans, H. Thienpont, "Highly birefringent microstructured fibers with enhanced sensitivity to hydrostatic pressure," *Opt. Express* **18**(14): 15113 (2010).

Stokes (Stokes) band of vector modulation instability by 324 GHz/MPa (−341 GHz/MPa) was observed. I performed the simulations of nonlinear light propagation and obtained similar results. Additionally, the performed simulations allowed to gain an insight into the evolution of the position of the gain maxima along the propagation distance.

The proposed operational scheme of a hydrostatic pressure sensor using the phenomena of nonlinear optics does not require additional fiber structuring, unlike the operational schemes of pressure fiber optic sensors using Bragg gratings or rocking-filters. However, the operating range of this sensor is limited to pressure for which the phase birefringence is non-zero.

When the phase birefringence is high, the effects of nonlinear coupling of polarization are negligible. However, when the phase birefringence at the pump wavelength approaches zero, the effects of nonlinear coupling of polarization modes become significant. Therefore, I proposed to conduct research on the phenomenon of nonlinear coupling of polarization modes in a wider range of pressures than in the previous work. The range of the pressure was selected to cover the pressure for which the phase birefringence crosses zero. The results of this research were published in the next work of the series:

[4] K. Tarnowski, A. Anuszkiewicz, P. Mergo, B. Frisquet, B. Kibler, W. Urbanczyk, *Nonlinear mode coupling in a birefringent microstructured fiber tuned by externally applied hydrostatic pressure*, Journal of Optics, vol. 17(3), 035506 (2015).

Additionally, I contributed to this work with simulations of nonlinear propagation of a continuous wave in the optical fiber with birefringence tuned with pressure. I was solving the following differential equation:

$$\frac{d\mathbf{S}}{dz} = \mathbf{W} \times \mathbf{S}, \tag{4}$$

which describes the evolution of polarization state of light along propagation distance (z) with the Stokes vector $\mathbf{S} = [S_1, S_2, S_3]$. The vector $\mathbf{W} = \mathbf{W}_\mathrm{L} + \mathbf{W}_\mathrm{NL}$ represents combined contribution of linear effects – expressed with the vector $\mathbf{W}_\mathrm{L} = \left[\frac{2\pi}{\lambda}B, 0, 0\right]$, where B denotes the phase birefringence – and nonlinear effects expressed with the vector $\mathbf{W}_\mathrm{NL} = \left[0, 0, -\frac{2}{3}\gamma S_3\right]$. The performed simulations showed that when the phase birefringence of the fiber under hydrostatic pressure is close to zero, the coupling period of polarization modes increases. Thus, by appropriately selecting the length of the section of the optical fiber subjected to pressure, the power of the pumping wave and the value of the pressure, one can control the state of polarization at the exit of the fiber or infer the pressure by characterizing the state of light polarization. The advantage of this solution is the simplified measurement of the properties of light. One can measure only the optical power, instead of the spectrum (e.g. recorded with an optical spectrum analyser).

In the performed measurements, no dependence of the polarization modes coupling on the pumping wave power was observed. I proposed an explanation of this observation, which allowed to obtain a good agreement of the experimental and calculation results. The effect of nonlinear energy conversion between polarization modes was undetectable in the power range available in the experiment due to linear coupling of polarization modes in the leadthroughs to the pressure chamber. The mode coupling is related to the local stress induced at the points where the fiber is mounted in the pressure chamber with the epoxy glue.

Summarizing, I proposed to apply the conversion energy phenomena in the birefringent fiber, namely: vector modulation instability [2] and nonlinear mode coupling for polarization modes [4], to pressure measurements. I performed numerical simulations which results were referred to experimental data and revealed advantages and limitations of proposed schemes.

Generation of coherent supercontinuum in normal dispersion optical fibers

The numerical tools developed for modelling nonlinear light propagation in the optical fibers, in particular my own software for solving the system of coupled nonlinear Schrödinger equations for polarization modes, was used in the following studies. Using this software, I performed research on a supercontinuum generation in optical fibers.

A supercontinuum, i.e. a flat and wide spectrum, is generated due to the interaction of many nonlinear phenomena. The generation of the supercontinuum in optical fibers is very effective due to the long propagation distances and the concentration of optical power on a small area. Depending on the pumping regime (from femtosecond pulses to continuous operation) and on the profile of the chromatic dispersion of the optical fiber, various nonlinear phenomena are important for the generation of the supercontinuum, and the obtained spectrum has different properties[14]. The broadest spectral ranges are obtained when pumping with femtosecond pulses in the vicinity of the zero dispersion wavelength[15]. However, the spectrum generated in such conditions does not maintain spectral coherence, and the pumping pulse breaks up into many pulses during propagation. On the other hand, operating in the normal dispersion regime allows to keep a single pulse, maintain spectral coherence and generate a spectrally flat supercontinuum, although the generated spectrum is not so broad[16]. The advantage of a supercontinuum generated in this way is the possibility of its temporal compression to a very short pulse and its application in ultrafast spectroscopy. For spectroscopic applications, it is useful to achieve the mid-infrared range, where many chemical compounds have characteristic absorption bands. In the first studies on the supercontinuum generation in the normal dispersion (ANDi) regime in silica optical fibers, its range was limited to 1.5 μm[17]. In order to shift the operational range towards longer wavelengths, other multi-component glasses with a transmission window shifted towards the mid-infrared were used.

The transparency window of the silica glass exceeds 2.5 μm, so examining the possibility of shifting the normal dispersion above 1.5 μm in silica optical fibers was important to fully utilize their potential. Moreover, the silica optical fibers can be easily connected with standard optical elements. The development of normal dispersion silica

[14] J. M. Dudley, G. Genty, S. Coen, “Supercontinuum generation in photonic crystal fiber,” *Rev. Mod. Phys.* **78**(4): 1135 (2006).
[15] J. K. Ranka, R. S. Windeler, A. J. Stentz, “Visible continuum generation in air–silica microstructure optical fibers with anomalous dispersion at 800 nm,” *Opt. Lett.* **25**(1): 25 (2000).
[16] A. M. Heidt, “Pulse preserving flat-top supercontinuum generation in all-normal dispersion photonic crystal fibers,” *J. Opt. Soc. Am. B* **27**(3): 550–559 (2010).
[17] A. Hartung, A. M. Heidt, H. Bartelt, “Design of all-normal dispersion microstructured optical fibers for pulse-preserving supercontinuum generation,” *Opt. Express* **19**(8): 7742 (2011).

fibers shifted towards longer wavelengths was the goal of my project "Supercontinuum generation in near infrared range using birefringent all-normal dispersion silica microstructured fibers." The project was financed by the National Science Center under the SONATA 7 program (no. 2014/13/D/ST7/02090). Items [5-8] of the series of articles present the results obtained within this project.

The designs of normal dispersion microstructured silica optical fibers that allow for the generation of a coherent supercontinuum when pumping with pulsed lasers operating at 1.55 μm and 1.97 μm wavelengths are my achievements presented in the article:

[5] K. Tarnowski, W. Urbanczyk, *All-normal dispersion hole-assisted silica fibers for generation of supercontinuum reaching midinfrared*, IEEE Photonics Journal, vol. 8(1), 7100311 (2016),

I proposed the hole-assisted fiber design with six air channels and a core doped with germanium glass. The desired dispersion profile was obtained by selecting appropriately geometric parameters and the level of doping.

Using the numerical tools based on the finite element method, I calculated the properties of optical fibers (chromatic dispersion, effective mode area). Then I simulated nonlinear light propagation in the designed fibers. The calculations showed that it is possible to shift the long wavelength limit of the supercontinuum spectrum generated in silica fibers above 2.5 μm. Additionally, I confirmed the coherence of the generated spectra by conducting a series of simulations taking into account the noise (using the single-photon noise model).

In the next article of the series:

[6] K. Tarnowski, T. Martynkien, P. Mergo, K. Poturaj, G. Soboń, W. Urbańczyk, *Coherent supercontinuum generation up to 2.2 μm in an all-normal dispersion microstructured silica fiber*, Optics Express, vol. 24(26), pp. 30523-30536 (2016),

two normal dispersion silica fibers fabricated in the Laboratory of Optical Fibers Technology of Maria Curie-Skłodowska University in Lublin were presented and the possibility of generating supercontinuum reaching 2.2 μm was confirmed experimentally. I contributed to this work by developing the research concept and performing numerical simulations. The modelling included the calculation of the properties of the real fibers on the basis of images of fiber cross-sections obtained in the scanning electron microscope and simulation of the supercontinuum generation process in both fibers. Supercontinuum was generated in the 80-cm long pieces of fiber by pumping with pulsed lasers operating at 1.56 μm and generating 23-fs and 460-fs pulses (full width at half maximum). In the simulations of nonlinear light propagation, I took into account the wavelength dependence of the effective mode area. Additionally, I performed the analysis of the influence of the non-ideal pulse shape on the characteristics of the registered spectra, pointing to the reason of their non-uniformity.

In the described articles [5-6], the modelling of nonlinear phenomena was based on the scalar nonlinear Schrödinger equation. In the next stage of the research, I performed simulations using the system of coupled nonlinear Schrödinger equations for polarization modes. This allowed to describe the propagation of light and to model the generation of a polarized supercontinuum in a normal dispersion birefringent optical fiber.

I contributed to the next article in the series:

[7] K. Tarnowski, T. Martynkien, P. Mergo, K. Poturaj, A. Anuszkiewicz, P. Béjot, F. Billard, O. Faucher, B. Kibler, W. Urbanczyk, *Polarized all-normal dispersion supercontinuum reaching 2.5 μm generated in a birefringent microstructured silica fiber*, Optics Express, vol. 25(22), pp. 27452-27463 (2017),

by developing its assumptions, designing the birefringent fiber and performing numerical modelling. I designed the birefringent microstructured silica fiber with the germanium doped core. The birefringence of the fiber was induced by squeezing the microstructured lattice in one direction. The designed optical fiber was then manufactured in the Laboratory of Optical Fiber Technology at the Maria Curie-Skłodowska University in Lublin. An excellent agreement was obtained between the measured chromatic dispersion and chromatic dispersion calculated on the basis of the microscopic image of the fiber cross-section. The chromatic dispersion (D [ps/km/nm]) is negative below 2.56 μm, reaching maximum of −2 ps/km/nm at 1.6 μm. Simultaneously, the dispersion is flat in a wide spectral range (the dispersion ranges between −20 ps/km/nm and −2 ps/km/nm in the spectral range from 1.23 μm to 2.56 μm). At the same time, the fiber exhibits the high phase birefringence of the order of 10^{-4}.

In the next step, a supercontinuum was generated in a short section of the fiber (48 mm) by pumping with 70-fs pulses with a wavelength tunable from 1.8 μm to 2.4 μm and a peak power about 400 kW. The dependence of the generated spectra on the pump pulse power and wavelength was investigated. I performed numerical simulations restoring the recorded spectra for all combinations of experimental parameters.

The polarization purity of the generated spectra was also measured for the selected wavelength. In the measurements, light was introduced into the selected polarization mode, and then the spectra were recorded in this mode and in the mode with orthogonal polarization. Experiments have shown that pumping in the fast mode is less favourable for the degree of spectral polarization than pumping in the slow mode. A polarization extinction ratio is higher when pumping in the slow mode, than when pumping in the fast mode, and significantly exceeds 10 dB in the entire spectral range. I performed numerical simulations in which I restored this effect, obtaining a qualitative agreement with experimental results. Based on the obtained results, I formulated an explanation of the observed effect. When pumping in the slow mode, the phase mismatch of the orthogonal modes resulting from the high phase birefringence increases due to the nonlinear contribution to the refractive index. When pumping in the fast mode, the phase mismatch reduces due to the nonlinear change of refractive index what enables the coupling of polarization modes.

The most important results presented in [7] are: (i) shift of the long wavelength limit of the supercontinuum generated in the normal dispersion regime in silica optical fibers to 2.56 μm, (ii) generation of ANDi polarized supercontinuum (PolAND – polarized all-normal dispersion).

The long wavelength limitation of the spectral range of the ANDi supercontinuum in [7] results from the position of the zero dispersion wavelength. Therefore, I proposed to optimize the design of silica microstructured fibers with the doped core with respect to the position of the zero dispersion wavelength. Optimized fibers should be also highly nonlinear. For this reason, I proposed a constrain of keeping the effective mode area below 30 μm^2. Together with Jędrzej Biedrzycki, MSc, we have developed numerical models of microstructured silica optical fibers with the core doped with germanium glass. The results achieved with those models were presented in the next article of the series:

[8] J. Biedrzycki, K. Tarnowski, W. Urbańczyk, *Optimization of microstructured fibers with germanium-doped core for broad normal dispersion range*, Opto-Electronics Review, vol. 26(1), pp. 57-62 (2018).

Additionally, I also contributed to this work with verification of the obtained numerical results. In the discussed work, it was shown that increasing the doping level is beneficial for extending the range of normal dispersion. Finally, several optical fiber designs with different cladding geometries were proposed. The best design is characterized by a normal chromatic dispersion and a low effective mode field for wavelengths below 2.81 μm.

An important feature of all the developed and fabricated silica optical fibers is the possibility of connecting them easily with other optoelectronic elements, e.g. with fiber lasers. The birefringent optical fiber with the normal dispersion described in [7] was spliced to the output of the fiber laser developed at the Faculty of Electronics, Wrocław University of Science and Technology[18]. This resulted in a fully fiberized source of coherent supercontinuum. This source was presented in the last work of the series:

[10] K. Tarnowski, T. Martynkien, P. Mergo, J. Sotor, G. Soboń, *Compact all-fiber source of coherent linearly polarized octave-spanning supercontinuum based on normal dispersion silica fiber*, Scientific Reports, vol. 9, 12313 (2019).

Together with Grzegorz Soboń, PhD, we conceived this study. Additionally, I contributed to this work by designing a nonlinear optical fiber, simulating nonlinear light propagation and processing all the experimental results. The experimental characterization supported with numerical simulations revealed that the developed light source gives a supercontinuum spectrum with a width of one octave (from 1.1 μm to 2.2 μm); with a coherence reaching 1 (based on the interference of successive pulses); signal-to-noise ratio above 10 dB over the entire spectral range, and reaching a maximum of 20 dB; and a linearly polarized spectrum (polarization extinction ratio at the level of 1:57).

Summarizing: (i) I proposed the technologically feasible designs of microstructured silica fibers with a wide range of normal dispersion [5, 8], (ii) I modelled the supercontinuum generation process in the fabricated fibers in direct reference to the experiment, predicting a high spectral coherence [6], (iii) I proposed the design of the optical fiber with the high birefringence and the normal chromatic dispersion [7], (iv) I modelled the generation of the polarized supercontinuum in reference to the experiment, explaining the physical reasons for the different polarization purity (degree of polarization) of the spectra depending on the polarization of the pumped mode [7]. In this way, I showed the possibility of using special fibers to control the coherence and degree of polarization of the generated supercontinuum spectra.

[18] J. Sotor, G. Sobon, "24 fs and 3 nJ pulse generation from a simple, all polarization maintaining Er-doped fiber laser *," Laser Phys. Lett.* **13**(12): 125102 (2016).

Finally, I showed the practical use of the developed birefringent fibers for the construction of the fully fiberized supercontinuum source that emits a coherent and polarized spectrum [10]. Such a light source can be used in spectroscopic studies, gas detection, broadband infrared interferometry, spectral characterization of telecommunications systems and medical diagnostics (OCT).

Summary

The results, presented in the series of scientific publications, show diverse methods to control the properties of light using specialty optical fibers. The common feature of my contribution to the described works are:

- development of the theoretical tools (using analytical and numerical approaches) for modelling light propagation in specialty optical fibers;
- the innovative designs of specialty optical fibers;
- the concepts of the experimental research confirming the effectiveness of the presented methods of controlling the properties of light.

The experimental verification of my predictions certainly increased the significance of the published scientific articles. Obtaining the experimental results would not be possible without my cooperation with the experimenters within the **Fiber Optics Group** (Department of Optics and Photonics, Faculty of Fundamental Problems of Technology, Wrocław University of Science and Technology). Moreover, a substantial contribution in the experimental research presented in the articles in the series was made by collaborators from the **Laboratory of Optical Fiber Technology** (Maria Curie-Skłodowska University in Lublin), the **Laser and Fiber Electronics Group** (Department of Field Theory, Electronic Circuits and Optoelectronics, Faculty of Electronics, Wrocław University of Science and Technology) and **Laboratoire Interdisciplinaire Carnot de Bourgogne** (Université Bourgogne Franche-Comté, Dijon).

Simultaneously, it is worth emphasizing that in all the threads discussed in the series entitled “The use of linear and nonlinear phenomena to control light properties in specialty optical fibers,” the theoretical and numerical results that I obtained, were the motivation for the experimental works. In scope of the linear phenomena:

- the theoretical model allowing to design the Bragg gratings with a few reflectance peaks, which spectral position is controlled by tilting a fiber with respect to a phase mask [1, 9],
- the concept of birefringent fiber with dispersive orientation of polarization axes [3];

and in scope of nonlinear phenomena:

- the concept of using effects of: (i) vector modulation instability [2] and (ii) nonlinear mode coupling for polarization modes in a birefringent fiber [4] to measure the hydrostatic pressure,
- proving feasibility of upshifting a long wavelength limit of coherent supercontinuum spectrum generated in silica fibers with normal dispersion [5, 6, 8] and obtaining polarized coherent supercontinuum spectrum in birefringent silica fibers with normal dispersion [7, 10].

5. Presentation of significant scientific activity carried out at more than one university, scientific or cultural institution, especially at foreign institutions

The Faculty of Fundamental Problems of Technology of the Wrocław University of Science and Technology is the main place of my scientific activity. I have been associated with this institution since the 2002/2003 academic year, in which I started a long-cycle master's degree programme in Physics. From the 2007/2008 academic year, I was a doctoral student of the Faculty, and I was awarded with the doctoral degree on October 23, 2012 by the Council of the Institute of Physics. I am an employee of the Faculty since 1st October, 2012 - initially I was employed as an assistant (Pol. asystent), and from 1st October, 2014 I have been working as an assistant professor (Pol. adiunkt).

Simultaneously, I realized my scientific activity in two foreign research institutions. During the first year of doctoral studies, I did a three-month research internship (February-May 2008) under the Leonardo da Vinci program at the **Fresnel Institute** (Marseille, France) under the supervision of prof. Gilles Renversez. Moreover, I have visited the **Laboratoire Interdisciplinare Carnot de Bourgogne** in Dijon ten times since 2010. These were short scientific internships and consultations carried out as part of Polish-French bilateral cooperation program Polonium. Initially, I participated in two projects coordinated by prof. Wacław Urbańczyk ("Frequency conversion in nonlinear photonic crystal fibers" under the Polonium 2010-2011 program; "From frequency conversion in externally tuned photonic crystal fibers to nonlinear fiber optic sensors" under the Polonium 2013-2014 program), and then I coordinated two further projects ("Towards mid-IR high repetition rate absorption spectroscopy with ANDi fiber-based supercontinuum source" under the Polonium 2016-2017 program; "Nonlinear light propagation in multimode fibers" under the Polonium 2019-2020 program). The described foreign activity resulted in six scientific publications, including: two publications before obtaining a doctoral degree[19] and four publications after obtaining a doctoral degree[20], and in nine conference presentations, including: three oral presentations before obtaining a doctoral degree[21] and three oral presentations and three posters after obtaining a doctoral degree[22].

6. Presentation of teaching and organizational achievements as well as achievements in popularization of science

6.1 Teaching achievements.

Since my employment at the Faculty of Fundamental Problems of Technology, my basic teaching activity relates to conducting classes on numerical methods and introductory programming courses. I have prepared and have been the supervisor and the main teacher for seven classes: *Numerical analysis*, *Numerical methods in physics*, *Introduction to scientific calculations in C language*, *Introduction to programming* (Technical Physcis and Optics), *Procedural programming*, *Introduction to programming* (Quantum engineering), *Programming techniques*.

[19] items [A.8], [A.10] on list pt. II.4.1, attachment 8
[20] items [B.3], [B.7], [B.12], [B.15] on list pt. II.4.2, attachment 8
[21] items [C.9], [C.11], [C.14] on list pt. II.7.1, attachment 8
[22] items [D.1], [D.4], [D.5], [D.12], [D.13], [D.14] on list pt. II.7.2, attachment 8

I have also led other basic classes for students of different Faculties (exercises in Physics) and specialized classes for students of the Faculty of Fundamental Problems of Technology (*Student computational laboratory*, *Numerical methods in optics*). A detailed list of all the classes, I have led, is presented in Table 1.

Table 1. List of classes that I led in academic years from 2012/13 to 2019/20 (names of classes in bold indicate that I was a supervisor of this course).

Classes	form[23]	degree of studyw	faculty [24]
2012/2013 winter semester			
Physics 1.2	C	I	SKP
Physics 1.3A	C	I	IB
Numerical methods in optics	L	II	Opt
2012/2013 summer semester			
Numerical analysis	W, C	I	Fiz, FT, Opt
Student computational laboratory	P	I	Fiz
Physics	C	I	IŚ
Numerical methods in physics	C	II	FT, Opt
2013/2014 winter semester			
Physics 1.1	C	I	Bud
Physics 1.3A	C	I	IB
2013/2014 summer semester			
Numerical analysis	W, C	I	Fiz, FT, Opt
Student computational laboratory	P	I	Fiz
Numerical methods in physics	W, C, L	II	FT, Opt
2014/2015 winter semester			
Physics 1.3A	C	I	IB
Physics F1	C	I	Opt
Numerical methods in optics	L	II	Opt
2014/2015 summer semester			
Numerical analysis	W, C	I	Fiz, FT, Opt
Student computational laboratory	P	I	Fiz
Numerical methods in physics	W, C, L	II	FT, Opt
Introduction to scientific calculations in C language	W, C	I	FT, Opt
2015/2016 winter semester			
Physics 1.3A	C	I	IB
Introduction to programming	L	I	FT, Opt
Numerical methods in optics	L	II	Opt
2015/2016 summer semester			
Numerical methods in physics	W, C, L	II	FT, Opt
Procedural programming	W, L	I	FT, Opt
2016/2017 winter semester			
Introduction to programming	L	I	FT, Opt
Introduction to computer science and programming	C, L	I	IKw

[23] W – lecture, C – exercises, L – laboratory, P - project

[24] Bud – Civil engineering, Fiz – Physics, FT – Technical physics, IB – Biomedical engineering, IKw – Quantum engineering, IŚ – Environmental engineering, Opt – Optics, SKP – Department of Fundamental Education.

2016/2017 summer semester			
Numerical methods in physics	W, C, L	II	FT, Opt
Procedural programming	W, L	I	FT, Opt
2017/2018 winter semester			
Introduction to programming	L	I	FT, Opt
Introduction to programming	W, C, L	I	IKw
2017/2018 summer semester			
Numerical methods in physics	W, C, L	II	FT, Opt
Procedural programming	W, L	I	FT, Opt
Programming techniques	W, L	I	IKw
2018/2019 winter semester			
Introduction to programming	L	I	FT, Opt
Introduction to programming	W, C, L	I	IKw
2018/2019 summer semester			
Numerical methods in physics	W, C, L	II	FT, Opt
Procedural programming	W, L	I	FT, Opt
Programming techniques	W, L	I	IKw
Computer engineering systems	P	I	IKw
2019/2020 winter semester			
Introduction to programming	L	I	FT, Opt
Introduction to programming	W, C, L	I	IKw
2019/2020 summer semester			
Numerical methods in physics	W, C, L	II	FT, Opt
Procedural programming	W, L	I	FT, Opt
Programming techniques	W, L	I	IKw
Computer engineering systems	P	I	IKw

The achievment related with the conducted classes is the **co-authorship of the scirpt** entitled „Student computational laboratory," which was used in the frame work of the course "Student computational laboratory" (J. Olszewski, R. Orlik, G. Pawlik, K. Tarnowski, W. Salejda, *Studenckie laboratorium obliczeniowe*, Wroclaw University of Science and Technology, 2011).

The **Didactic awards (Nagroda dla najlepszego dydaktyka)** are an exceptional honour for me. These awards were conferred by the students of the Faculty of Fundamental Problems of Technology. In the contest, which is organized by Student Government of the Faculty of Fundamental Problems of Technology since 2016, I was awarded four times in the category "*Smile-master*" (Mistrz uśmiechu) (in the editions: 2017, 2018, 2019, 2020).

I was also a supervisor of diploma thesis. 4 students achieved **engineer's degree** under my supervision:

- Wiktor Włodarski (2014/2015),
- Sylwia Majchrowska (2015/2016),
- Barbara Beleć (2018/2019),
- Bartłomiej Bogajewicz (2019/2020),

7 students achieved **master's degree**:

- Wiktor Włodarski (2015/2016),
- Łukasz Łabędź (2016/2017),

- Sylwia Majchrowska (2016/2017),
- Jakub Pabisiak (2016/2017),
- Anna Żelazo (2016/2017),
- Anna Mazurkiewicz (2019/2020),
- Karolina Stefańska (2019/2020).

I am **an assistant supervisor** in the doctoral thesis of Sylwia Majchrowska (supervisor: prof. Wacław Urbańczyk).

6.2 Organizational achievements.

My organizational activity performed at the Faculty of Fundamental Problems of Technology:

- I was a **member of Faculty Council** – a representant of the staff members without a post-doctoral (habilitation) degree group (from 2016 to 2019),
- I was a **delegate** from a group of academic teachers employed in positions other than a professor or university professor for the elections to the University Senate in 2020,
- I was involved in the preparation and service during **accreditation of Technical Physics and Optics** by the Polish Accreditation Committee in the 2016/2017 academic year,
- I performed **visitation** in the framework of the Faculty System for Education Quality (academic years 2016/17, 2017/2018, 2018/2019),
- I was involved in a preparation, conducting, evaluation and analysis of results of **exams in Physics** in years 2007-2020,
- I was involved in the **preparation and service of international conference**: XIX Polish-Slovak-Czech Optical Conference on Wave and Quantum Aspects of Contemporary Optics, Wojanów 2014,
- I was a **member of the scientific committee of the conference**: Nonlinear Optics Applications, XIV International Workshop, Wrocław 2018.

6.3 Achievements in popularization.

- I was **presenting** studies in Technical Physics (specialy Photonics) during the **Open Days** at Wroclaw University of Science and Technology (years 2014 – 2019),
- I was presenting an **invited lecture** on students conference (IV Ogólnopolska Studencka Fizyczno-Optyczna Konferencja FOKA 2019, 07.12.2019),
- I was a guest of Young Explorers Academy (Akademia Młodych Odkrywców) – I co-authored a popularisation class dedicated to children (13.12.2019).

7. Other important information about my professional career

In my opinion, numerous scientific collaborations, which resulted in scientific publications, had a positive impact on the achievements developed during the professional career. I contributed to these publications with the numerical modelling of the light-matter interaction. The scope of these publications often went beyond the fiber optics. Below I listed institutions with which I cooperated, I indicated on the list joint publications with reference to the list of articles published in scientific journals (attachment 8):

- **Maria Curie-Skłodowska University in Lublin** (Lublin, Poland),
  14 joint publications (items: [A.5], [A.6], [B.1], [B.3], [B.6], [B.7], [B.13], [B.14], [B.15], [B.17], [B.18], [B.20], [B.21], [B.22]);
- **Université Bourgogne Franche-Comté** (Dijon, Francja),
  6 joint publications (items: [A.8], [A.10], [B.3], [B.7], [B.12], [B.15]);
- **Wrocław University of Science and Technology, Faculty of Electronics, Laser and Fiber Electronics Group** (Wrocław, Poland),
  5 joint publications (items: [B.10], [B.13], [B.14], [B.17], [B.21]);
- **Wrocław University of Science and Technology, Faculty of Fundamental Problems of Technology, Department of Theoretical Physics** (Wrocław, Poland),
  4 joint publications (items: [A.11], [B.5], [B.8], [B.11]);
- **Wrocław University of Science and Technology, Faculty of Fundamental Problems of Technology, Department of Experimental Physics** (Wrocław, Poland),
  3 joint publications (items: [B.8], [B.11], [B.19]);
- **Pennsylvania State University** (Pennsylvania, USA),
  2 joint publications (items: [A.11], [B.5]);
- **Wrocław University of Science and Technology, Faculty of Microsystem Electronics and Photonics** (Wrocław, Poland),
  2 joint publications (items: [A.7], [A.9]);
- **Vrije Universiteit Brussel** (Brussel, Belgium),
  2 joint publications (items: [A.5], [A.6]);
- **University of Warsaw** (Warsaw, Poland),
  joint publication (item [B.22]);
- **Universität Bern** (Bern, Switzerland),
  joint publication (item [B.22]);
- **Łukasiewicz Research Network - Institute of Electronic Materials Technology** (Warsaw, Poland),
  joint publication (item [B.22]);
- **Universidad de Cantabria** (Santander, Spain)
  joint publication (item [A.4]).

During my professional career, I have been awarded numerous prizes and scholarships. Before obtaining the doctoral degree:

- **scholarship** within the project „Rozwój potencjału dydaktyczno-naukowego młodej kadry akademickiej Politechniki Wrocławskiej" funded by European Social Fund in the 2nd edition (April-September 2010);

- **scholarship** funded by Wrocław University of Science and Technology – 2010/11 academic year summer semester;
- **scholarship** as a part of the professorial subsidy MISTRZ of prof. Wacław Urbańczyk funded by Foundation for Polish Science (FNP), years 2010-12;
- **scholarship** within the project „Rozwój potencjału dydaktyczno-naukowego młodej kadry akademickiej Politechniki Wrocławskiej" funded by European Social Fund in the 4th edition (April-September 2011);
- **scholarship** funded by Wrocław University of Science and Technology – 2011/12 academic year summer semester;

after obtaining the doctoral degree:

- **scholarship Start 2013** funded by Foundation for Polish Science (FNP);
- **award of the Rector** of Wrocław University of Science and Technology 2013;
- **scholarship Start 2014** funded by Foundation for Polish Science (FNP);
- **scholarship of the Ministry of Science and Higher Education** for outstanding young scientist, years 2015-2018;
- **award of the Rector** of Wrocław University of Science and Technology 2017;
- **award of the Rector** of Wrocław University of Science and Technology 2018;
- **award of the Rector** of Wrocław University of Science and Technology 2019;
- **award of the Rector** of Wrocław University of Science and Technology 2020.

Karol Tarnowski

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(Applicant's signature)