Załącznik nr 3 do wniosku o wszczęcie postępowania habilitacyjnego - autoreferat w języku angielskim

Scientific Curriculum Vitae

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Brief CV

Rafał Zdzisław Kotyński

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Education and scientific degrees

May 1989	maturity exam at the XIV high school in Warsaw (formerly named after K. Gottwald, currently named after S. Staszic) in an experimental mathematical class
27 June 1994	M.Sc. in Physics with the specialisation in Fourier Optics and Information Processing, from the Faculty of Physics UW, received after completing the five-year physics curriculum in the years 1989-1994; the master thesis on “Dual nonlinear optical correlator” (written in Polish) was supervised by Prof. Katarzyna Chałasińska-Macukow and was rewarded with the Dean's award named after J.J Glazer for the best thesis of the year
30 October 2000	Ph.D. in Physical Sciences (in the domain of physics), received from the Faculty of Physics UW, after completing the Ph.D. studies in between 1994-1999; the Promoter of the thesis entitled “Pattern recognition algorithms for coherent optical correlators,” (written in English) was Prof. Katarzyna Chałasińska-Macukow

Employment

October 1999 - till now	Positions at the Faculty of Physics UW: - a technical position (October 1999 - February 2001) - Assist. Prof., fixed-term, (adiunkt), (March 2001- March 2005) - post-doctoral leave (2002-2004) - Assist. Prof., indefinite-term, (adiunkt, mianowanie) (since April 2005)
October 2001- Decembre 2004	3-year post-doctoral scholarship at the Department of Applied Physics and Photonics, Vrije Universiteit Brussel, Belgium – 2 yearly contracts, and one indefinite time contract, funded by the Belgian IAP V-18 Photon Network program

Foreign visits and scholarships

1995-1996	Tempus Individual Mobility Grant in the Laboratoire de Signal et Image, Ecole Nationale Superieure de Physique de Marseille (ENSPM), Marseille, France, 6 months
2001-2004	post-doctoral scholarship (aforementioned), at the Department of Applied Physics and Photonics, Vrije Universiteit Brussel (VUB), Brussels, Belgium
after 2005	four 1-2-week visits to the Department of Applied Physics and Photonics, Vrije Universiteit Brussel (VUB), in September 2005, in June 2006, in June 2007 and in September 2008 – short term scientific missions funded from COST P11, and MP 0702 programs

Functions and positions

Since March 2006	Head of the Information Optics Laboratory at the Faculty of Physics UW (the second term will last until March 2013)
Since 2008	Member of the Scientific Council of the Institute of Geophysics at the Faculty of Physics UW
Since 2008	Member of the Electors Collegium of UW

Scientific publications included in the Web of Science database

(data for September 30, 2011 for Kotynski* R*)

#H Index	9
Number of publications	54, including 22 papers in JCR journals, out of which 16 have been published after receiving the Ph.D. degree and which have not been related to the subject of the Ph.D.
Number of citations	208 citations in 168 citing articles, 148 citations without auto-citations

Rewards

2007	Scientific grant (stypendium naukowe) of the Rector of the University of Warsaw
2007, 2010	Reward of the Rector of the University of Warsaw (twice)

Scientific Career

My research track may be subdivided into three chronologically and thematically distinct periods. These are – the period prior to receiving the Ph.D. degree (1994-2000), the period of the first five years after receiving the Ph.D. (2001-2005) and of the following five years (2006- until now).

The first period begins with the final year of my master studies and lasts through the Ph.D. studies at the Faculty of Physics, University of Warsaw (UW), and is related to the research on optical pattern recognition.

The second period includes the research on photonic crystals in general, and photonic crystal fibres in particular, and mainly overlaps with my three-year post-doctoral scholarship spent at Vrije Universitetit Brussel.

The third period comprises research in the domains of plasmonics and of optical metamaterials, conducted at the Faculty of Physics at UW.

For the purpose of this application for the *habilitation* degree (Doctor of Science), the scientific output of both latter periods is used, respectively, to define my *research score*, in the case of the second period, and the *significant scientific achievement* consisting of a series of seven thematically linked publications, in the case of the third period. The two elements are required by Polish law for a person to apply for the habilitation degree.

I will present each of the three periods of my scientific life in separate sections of this CV.

The period prior to receiving Ph.D. – research on optical image processing

The research I have conducted in the years from 1994 to 2000, in the course of preparing the doctoral thesis at the Faculty of Physics UW, dealt with optical pattern recognition methods, and in particula with the development of pattern recognition algorithms for coherent optical correlators. Some of the algorithms have been implemented in experimental correlator set-ups.

My work has been dedicated to several topics. The first, has been nonlinear matched filtering, with the power-law nonlinearities applied in the spatial spectral domain [A1-1, A1-3, A1-5], independently to the spectrum of the analysed image and to the spectrum of a reference object. Such an operation makes it possible to control the discrimination capability of pattern recognition, as well as its robustness to the presence of realistic e.g. non-additive noise. I have also analysed the performance of nonlinear matched filters applied for pattern recognition in the presence of additive and correlated noise that is not ergodic [A1-4], showing the advantages of using nonlinear filters, as compared to using classical matched filtering. Moreover, I have been involved in research on the so called pure phase correlation [A1-5, A1-6], which is a pattern recognition method that can be realised optically using spatial filters with a high diffraction efficiency, and which is characterised by high discrimination efficiency. Another subject that I have been working on, was numerical optimisation of pattern recognition filters for image classification, with use of genetic algorithms [A1-2]. The last topic that I would like to mention is the intensity invariant pattern recognition in complex images composed of multiple objects differing in intensity. I have introduced and tested a correlation-based recognition method that involves the normalisation of the optical signal with use of the Hölder's inequality. The method allows for correct recognition of objects that match a reference shape, in the presence of neighbouring objects resembling the correct target and having larger intensities [A2-4, A2-6].

I have conducted these works with the supervisor of my doctoral, and also master, theses - Prof. Katarzyna Chałasińska-Macukow. I have also worked with Prof. Phillippe Réfrégier, and with François Goudail from Laboratoire de Signal et Image at Ecole Nationale Superieure de Physique de Marseille. I have collaborated with them during a six-month scholarship in ENSPM the framework of the Tempus individual mobility grant in 1995 and later in the framework of the bilateral Polonium project with France. I have also collaborated with Dr. Maria Sagrario-Millan and with Elisabét Perez(-Cabre) from the University of Terrassa in Spain. The collaboration with Spain has been based on a Spanish networking program allowing for short bilateral visits, and has been focused on experimental realisation of pattern recognition. Finally, I have also built, programmed and tested a simple optical correlator at the Faculty of Physics, UW.

In this period I have co-authored the following 6 scientific papers published in JCR journals, as well as 7 conference papers in SPIE volumes. I have presented my research at several international conferences, and I have presented one invited talk.

A1-1 Millán, M. S., Pérez, E., **Kotyński, R.**, Chałasińska-Macukow, K.: "Optical correlator with variable discrimination capability - Experimental results," **Optica Applicata** Vol. 30(2-3), pp. 301–302, PWr&IOP **2000**.

A1-2 **Kotyński, R.**, Chałasińska-Macukow, K.: "BPOF composite filter optimized with a genetic algorithm, **Optica Applicata** Vol. 30(2-3)," pp. 303–316, PWr&IOP **2000**.

A1-3 Pérez, E., Chałasińska-Macukow, K., Styczyński, K., **Kotyński, R.**, Millán, M. S.: "Dual nonlinear correlator based on computer controlled joint transform processor: Digital analysis and optical results," **Journal of Modern Optics** Vol. 44(8), pp. 1535–1552, Taylor & Francis **1997**.

A1-4 **Kotyński, R.,** Goudail, F., Réfrégier, P.: "Comparison of the performance of linear and nonlinear filters in the presence of nonergodic noise," **Journal of the Optical Society of America A**: Optics and Image Science, and Vision Vol. 14(9), pp. 2162–2167, OSA **1997**.

A1-5 **Kotyński, R.**, Chałasińska-Macukow, K.: "Optical correlator with dual nonlinearity," **Journal of Modern Optics** Vol. 43(2), pp. 295–310, Taylor & Francis **1996.**

A1-6 Styczyński, K., **Kotyński, R.**, Chałasińska-Macukow, K.: "Phase Encoded Binary Phase-Only Filter Recorded in the Epson Liquid-Crystal Screen," **Optica Applicata** Vol. 25(2), pp. 81–92, PWr&IOP **1995**.

The period of the first five years after receiving Ph.D. – research on photonic crystal fibres and photonic crystals

My research conducted in the years 2001-2005, right after receiving the Ph.D., during my post-doctoral scholarship at the Department of Applied Physics and Photonics at the (Flemish) Free University of Brussels, and afterwards, continued in Poland, has been related to modelling and development of novel photonic elements [B1-8 to B1-16]. In particular, my work has been focused on photonic crystal fibres (PCF), which as opposed to classical optical fibres, contain a periodic microstructure cladding that forms a two-dimensional photonic crystal. Photonic crystals, also known as electromagnetic crystals, are periodic dielectric structures with modes of the Bloch-form that form a complicated band-structure, which in various terms resembles that of ordinary crystals.

The photonic crystal cladding of PCFs usually consists of silica and air, although PCFs made of various glasses, or of polymers are also known, while the gaps in between the capillaries may be also filled with e.g. rare earth vapours or with liquid crystals.

The size of an elementary cell of a photonic crystal is in the same order as the wavelength. For technological reasons, the PCFs often contain a microstructure cladding, which only approximately satisfies the condition of periodicity. Among the properties of PCFs, which decide upon their importance, first comes the novel mechanism of light guidance in a low-refractive-index core, resulting from the existence of a partial photonic band-gap in the photonic crystal cladding. Following, are the possibilities of tailoring dispersion and birefringence, and therefore of controlling optical nonlinear effects. Let me also mention, the possibilities of achieving single-mode guidance in a broad spectral range, or of tailoring the surface of the guided mode to a large degree.

In my work, I have focused on birefringent PCFs for polarimetric sensing applications [B1-8, B1-13]. I have also studied PCFs with Bragg gratings [B1-11], and with Kerr-type nonlinear Bragg gratings [B1-9]. I have also investigated the polarisation properties of vertical cavity surface emitting lasers (VCSELs) with a surface relief [B1-15]. My research interests also encompassed the development and improvement of novel numerical methods for determining the modal structure of these photonic elements [B1-10, B1-12, B1-16].

Finally, the paper [B1-8] on temperature sensitivity of PCFs, presents a critical comment to another paper authored by a research group from Sapporo (Hokkaido Univ.). That paper published in 2006 in IEEE Phot. Technol. Lett., borrowed without citation a significant part of text from an earlier ICTON conference paper co-authored by myself and other authors from VUB, and contained surprisingly similar numerical results and conclusions. It should be emphasized that our original conference paper from 2002 contained preliminary and in some part completely wrong results, which have been later fully repeated in IEEE PTL. Therefore, in the comment [B1-8] we have taken the opportunity to clarify the results presented previously in both coincidentally similar papers.

For the purpose of my research on PCFs, I have developed, written and used the software based on the Fourier decomposition method. It is capable of calculating the modal structure of arbitrarily-shaped two-dimensional photonic elements, in general consisting of materials described with complex-valued uniaxially anisotropic electric permittivity and magnetic permeability tensors. The Fourier decomposition method, also known as the plane-wave expansion method is a classical and general computational technique, which I have adjusted and extended for calculations of the modal structure in PCF and in other photonic components with a similar composition.

The software that I have developed, allows for the analysis of modal dispersion, of propagation losses, of dispersion of phase and group birefringence, and for determination of the vectorial mode profile. It may also be used for finding the photonic band-structure of two-dimensional photonic crystals, and for determining the location of a partial or full photonic band-gap. It is particularly useful for the analysis of microstructure optical fibres, but also for investigating two-dimensional metallic or metamaterial structures with negative (effective) permittivities and permeabilities.

Within the same material model, it is possible to implement a uni-axial perfectly matched layer (UPML) i.e. an artificial electromagnetic absorber with non-reflective properties independent of the angle of incidence and polarisation. UPML materials are used in numerical simulations for reducing the computational mesh to the actual region of interest. UPML used in conjunction with the plane-wave expansion method makes it possible to account for radiation losses in PCF modal calculations [B1-10].

Moreover, since the method is valid for optically anisotropic materials, it gives the possibility of finding polarimetric sensitivities of PCFs to temperature, pressure, and to some forms of mechanical stress, as well as of investigating PCFs with holes filled with a liquid crystal (with a constraint of the LC director being parallel to the optical axis). I have presented such calculations in conference publications.

I have been working on these topics at VUB, and later in collaboration with VUB, and in particular jointly with Prof. Krassimir Panajotov, with Maciej Antkowiak (at that time a Ph.D. student at VUB, de facto under my guidance), with Maciej Dems (at that time, a Ph.D. student at the Łódź Technical University, visiting VUB), and in some cases with scientists from Wrocław University of Technology, in particular with Prof. Wacław Urbańczyk, and his Ph.D. student, Marcin Szpulak, and to a lesser degree with doctoral students from Warsaw University of Technology. In the case of the collaborative work conducted in the framework of the COST P11 programme "Physics of linear, nonlinear and active photonic crystals" (2003-2007), I have also collaborated with partners from Russia (Dr. A. Zheltikov, Dr. E. Serebryannikov from the Lomonosov University in Moscow), and from Israel (Prof. Yehuda Leviatan and Amit Hochman from Technion University of Technology in Haifa). Journal publications have been also traditionally co-authored by persons responsible for organisation of research at VUB.

I have participated in the COST P11 action chaired by Prof. Concita Sibilia from Sapienza - Università di Roma, as well as in the EU Network of Excellence on Micro-Optics (NEMO) led by VUB, firstly from the Belgian side, and since 2005 from the Polish side.

In this period I have co-authored the following 9 JCR journal papers:

B1-8 Antkowiak, M., **Kotynski, R**. Comments on "Thermooptical Sensitivity Analysis of Highly Birefringent Polarimetric Sensing Photonic Crystal Fibers With Elliptically Elongated Veins," **IEEE Photonics Technology Letters**, Vol. 19, pp. 795-796, (IEEE, **2007**);

In this work we clarify the inaccuracies in the results and put in question the original character of an earlier publication (Florous, Varsheney, Saitoh, Koshiba, IEEE PTL vol.18 pp. 1663, 2006), where, without citation, there reappear large parts of text and the major conclusions of our earlier work (Kotyński et al. ICTON, Warsaw, 2003). All three papers are devoted to temperature sensitivity in highly birefringent PCFs.

B1-9 Antkowiak, M., **Kotyński, R.**, Panajotov, K., Berghmans, F., Thienpont, H., "Dynamic characteristics of nonlinear Bragg gratings in photonic crystal fibres," **Optical and Quantum Electronics,** Vol. 39, (4-6), pp. 455-467 (Springer, **2007**);

This paper includes an analysis of time-dynamics for the propagation of the fundamental mode in a PCF with a nonlinear (Kerr) Bragg grating. The analysis involves solving the nonlinear coupled mode equations with coupling coefficients obtained from the PCF modal plane-wave-based calculations. In particular, bi-stability is observed in this system. The paper presents the resulting bifurcation diagrams.

B1-10 **Kotynski**, R., Dems, M., Panajotov, K. "Waveguiding losses of micro-structured fibres - plane wave method revisited," **Optical and Quantum Electronics**, Vol. 39, pp. 469-479, (Springer, **2007**);

Taking PCFs as an example, this work presents a numerical method for calculating the modal structure of two-dimensional photonic elements consisting of materials with complex-valued and anisotropic permittivity and permeability tensors. The method may be used in the modelling of highly dispersive materials, such as metals or optical metamaterials (with negative permittivity and permeability values). It allows for including the non-reflecting boundary conditions realised with a uniaxial perfectly matched layer (UPML) material. Special focus has been put on the calculation of radiation losses in PCFs.

B1-11 Antkowiak, M., **Kotyński, R.**, Panajotov, K., Berghmans, F., Thienpont, H.: Numerical Analysis of Highly Birefringent Photonic Crystal Fibers With Bragg Reflectors, **Optical and Quantum Electronics** 38(4-6), 535–545, Springer **2006** ;

This paper presents a numerical method for calculating the spectral transmission and reflection characteristics of a PCF with a Bragg grating. The proposed method consists of two parts – a plane-wave-based modal solver for PCF which is used to determine the coupling coefficients for the fundamental mode and the grating, and a set of perturbation equations with the synchronous approximation for the coupling process.

B1-12 Szpulak, M., Urbańczyk, W., Serebryannikov, E., Zheltikov, A., Hochman, A., Leviatan, Y., **Kotyński, R.**, Panajotov, K.: Comparison of Different Methods For Rigorous Modeling of Photonic Crystal Fibers, **Optics Express** 14(12), 5699–5714, OSA **2006** ;

This work presents a comparison of accuracy and of the convergence of six numerical methods applied to the calculation of the PCF modal structure (including modal birefringence, group birefringence, propagation losses, second order dispersion, and the vectorial mode profile). The methods compared, include the plane-wave expansion method, the finite element method, the source model technique, localised function method, and a simplified equivalent elliptical-core fibre method. A real fibre with a profile measured using SEM is used for the purpose of this comparison. This joint paper resulted from the collaboration among the participants of the COST P11 programme.

B1-13 Antkowiak, M., **Kotyński, R.**, Nasiłowski, T., Lesiak, P., Wójcik, J., Urbańczyk, W., Berghmans, F., Thienpont, H.: Phase and Group Modal Birefringence of Triple-Defect Photonic Crystal Fibres, **Journal of Optics A**-Pure And Applied Optics 7(12), 763–766, IOP **2005** ;

This work presents the experimental measurements and numerical modelling results of the dispersion of phase and group birefringence in a PCF with an elliptical core. It is shown that the two birefringencies are highly dispersive, may differ in sign, and in the order of magnitude. This finding contrasts with the properties of classical birefringent optical fibres, where usually the two birefringencies are considered to be equal. In particular, the relation between polarisation mode dispersion (PMD) and the group birefringence allows to predict that for some wavelength, the PCF may exhibit a huge phase birefringence combined with a vanishing PMD.

B1-14 **Kotyński, R.**, Antkowiak, M., Berghmans, F., Thienpont, H., Panajotov, K.: Photonic Crystal Fibers With Material Anisotropy, **Optical and Quantum Electronics** 37(1-3), 253–264, Springer **2005**;

This paper introduces a plane-wave-based numerical method formulated for the modal analysis of PCFs consisting of piecewise uniform materials with an anisotropic permittivity, where the permittivity-tensor has a diagonal form. An iterative method is used to solve the large-scale eigenvalue problem. No scalar approximation is assumed. The method accounts for material dispersion and absorption.

B1-15 Panajotov, K., **Kotyński, R.**, Camarena, M., Thienpont, H.: Modeling of the Polarization Behavior Of Elliptical Surface-Relief Vcsels, **Optical and Quantum Electronics** 37(1-3), 241–252, Springer **2005** ;

This paper presents an analysis of the influence of a surface-relief put on top of a vertical cavity surface emitting laser (VCSEL) on the operation of the laser. The elliptical relief stabilises the single-mode operation of the laser. The relative orientation of the principal directions of the permittivity tensor of the semiconductor, and of the axes of the ellipse have been discussed. Experimental results that confirm this analysis have been presented.

B1-16 Dems, M., **Kotyński, R.,** Panajotov, K.: Plane Wave Admittance Method - A Novel Approach for Determining the Electromagnetic Modes in Photonic Structures, **Optics Express** 13(9), 3196–3207, OSA **2005**;

This paper introduces a novel numerical method for the calculation of the modal structure of three-dimensional photonic elements. The method couples the plane-wave expansion method applied in two dimensions with the generalised transmission line equations (the admittance transfer method) applied in the third dimension. Materials with complex and anisotropic permittivity and permeability may be included in the calculations, therefore UPML termination of the simulation area is possible. The proposed method is particularly useful for the modal calculations in periodic or partly regular structures, such as based on photonic crystal components.

The period of the second five years after receiving Ph.D. – research on plasmonics and on optical metamaterials

Since 2005, after my return to the University of Warsaw from the post-doc. at VUB, my research has been focused on photonic crystals, optical metamaterials and on plasmonics. The work in these fascinating domains have been initiated at the Faculty of Physics UW by Prof. Tomasz Szoplik with participation of other members of the Information Optics Laboratory, who became involved in the Network of Excellence "Metamorphose - MetaMaterials Organized for radio, millimetre wave, and PHOtonic Super-lattice Engineering" (2004-2008, 6th Framework Program of the EC) and in the COST P11 program "Physics of linear, nonlinear and active photonic crystals" (2003-2007) which was later continued with COST action MP0702: "Towards Functional Wavelength Photonic Structures" (2008-2012) and with the COST action MP0803: "Plasmonic components and devices" (2008-2012). I have been participating in these networking programs, as well as in the realisation of several national grants on related subjects.

In this period, I have been collaborating with Prof. Tomasz Szoplik on research, on organising the activities of the Information Optics Laboratory and of the plasmonics group, and on seeking funding for these activities. In between 2007-2011, I have led two national grants on plasmonics: N202 015 32/0694 "Nano-optical metamaterial lens as a photonic coupling element" and N N202 033237 "Plasmonic Super-prism". At the same time, I have also been working with the Ph.D. students of Prof. Tomasz Szoplik in some part of their Ph.D. research – with Tomasz Stefaniuk, with Anna Pastuszczak, and with Marcin Stolarek, and I will probably co-promote the Ph.D. of the two latter of them. In 2006, I have been elected the head of the Information Optics Laboratory at the Faculty of Physics UW.

My main research subject in this period has been super-resolution in plasmonic devices and adapting elements of Fourier Optics for the description of propagation with super-resolution in optical layered metal-dielectric metamaterials. This is also the subject of the thematic sequence of seven publications representing my *significant research achievement* – which is the major element, required by law, of an application for the habilitation degree. Their contents will be overviewed more in detail in the following section of my scientific curriculum vitae.
Finally, I should add that in 2005 I have prepared a yearly lecture, accompanied with numerical exercises, on Modelling methods for micro-optics and photonics, and I have given it four times since then. I have also continued my own collaboration with VUB, and in particular with Prof. Krassimir Panajotov, with whom we have been working on modelling methods for photonics. I have visited VUB four times in this period, making use of the short-term-scientific-missions offered by the COST actions. These visits have resulted in several joint journal and conference publications.

Super-resolving flat lenses - an introduction and an overview of the candidate's achievements in the domain

Plasmonics[1] is a novel and intensively developing nano-science forming part of photonics. Its core idea is to make use of surface waves excited at metal-dielectric boundaries for the transmission of optical signals. In particular, such waves accompany the surface plasmon-polariton modes. However the scope of plasmonics interests includes also other solutions to Maxwell's equations with the localisation of electromagnetic field in sub-wavelength areas or volumes, or with modes having a dispersion relation resembling that of surface plasmon-polaritons. One should primarily mention here the spoof plasmons, then the Fabry-Pérot

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[1] The reader interested in a more extended introduction to plasmonics may refer to the first introductory book on this subject by S. Maier, entitled "Plasmonics – fundamentals and applications" (Springer, 2007).

resonances in sub-wavelength-sized cavities, surface waves excited over metallic gratings, and solutions to Maxwell's equations at the micro- or nano-structured metal-dielectric boundaries, and in structured or layered media with effective properties.

The major benefits of prospect plasmonic solutions in photonics include the partial relaxation of the Rayleigh diffraction limit, which gives rise to super-resolving imaging or focusing within the area smaller than half of the wavelength.

Furthermore, plasmonics involves the development, with use of advanced modelling and technology, of novel nano-structured materials, including optical metamaterials i.e. materials with unusual diffractive and refractive properties (this term is also used in a narrower sense, for materials which combine an effective negative permittivity and permeability at the same time). Probable applications of plasmonics range from the improvement of resolution of imaging lithographic and microscopic systems, and SNOM in particular, through novel sensor concepts, including those for biological sensing, up to the use of plasmonic waveguides for optical interconnects in optoelectronic devices.

Finally, plasmonic components are expected to play a role in the increase of sensitivity and selectivity of detectors, e.g. of terahertz radiation, in the increase of efficiency of photovoltaic cells, and in the miniaturization of elementary photonic components to sub-micrometer dimensions owing to the relaxation of the diffraction limit.

In my work, I have focused on the so called superlenses (also known as perfect lenses, or metamaterial lenses), which are in fact metal-dielectric periodic stacks, however with precisely designed layers. They operate at a specific wavelength or within a narrow wavelength range.

These structures allow for an almost diffraction-free propagation of light over distances ranging up to several wavelengths, and the propagated wave-front is preserved up to the resolution in the order of one tenth of the wavelength.

Superlenses are an interesting research topic for at least the following reasons:

- The Rayleigh's diffraction criterion sets the limit on the two-point resolution of an optical system for $\delta_R = 0.61 \cdot \lambda / NA$. Using superlenses, it is possible to reach a tenfold better resolution than expected from the Rayleigh's criterion with $NA = 1$, i.e. $\delta \sim \lambda / 20$. It is necessary to add that neither the Rayleigh's criterion, nor any other common resolution criterion in use, can not be directly applied to measure the resolution of superlenses, and therefore the author's choice is to refer to the resolution defined as the width (FWHM) of the coherent amplitude point spread function, instead. Nonetheless, it clearly appears that the superlenses do have super-resolving properties.

- Superlenses in a large degree consist of a metal. Silver is the preferable choice, as its extinction index in the visible wavelength range is smaller than that of some other metals such as gold or copper. The filling factor of metal is usually large and may even exceed 50%. On the other hand, the skin-depth of silver, i.e. the length at which the amplitude of a wave penetrating a metal perpendicularly to its surface decreases by the factor of the Euler constant, is in the order of only 20nm in the visible wavelength range. However, in the layered structure, the effective penetration depth reaches a value by two orders of magnitude larger than the skin depth of silver. Therefore, it is fully justified to use the term of "transparent metal" for such a stack, as some authors do. At the same time, the structure of a superlens, is an example of an optical metamaterial.

- It is commonly presumed that at distances in the order of single wavelengths, the significance of diffraction for practical applications is marginal. However, an object (a modulation of the wavefront or a light source) with the size in the order of a tenth of the wavelength resembles a point source, and the information about its shape becomes lost after the wave is propagated in free-space for a distance comparable to the actual size of the same object. A possibility of limiting diffraction at this scale opens a potential way for developing more complicated optical components with overall sub-wavelength dimensions.

- Imaging of a sub-wavelength object through a superlens is accompanied with the distribution of electromagnetic field qualitatively resembling a light-ray. The diameter of such a "ray" is in the order of $\lambda/10$ and the principles of geometric optics certainly do not apply at such length-scales, therefore this similarity is apparent. Nevertheless, the geometric simplicity of such an object and the ease in its mathematical description is tempting from an engineering point of view. It might become possible to design sub-micrometer optical components within a theory not more difficult than geometric optics.

- Superlenses, with parallel external layers allow for the realization of linear spatial filtering. This observation enables to describe them with the language of Fourier optics - extended to include polarisation and without neglecting the evanescent waves. Among the achievements of the author is the development of this description and its practical use in the design of superlenses. The point spread function includes a complete information about the imaging properties of a linear isoplanatic system. With its help, one can describe optical layered metamaterials as linear filters with a super-resolving point spread function. The point spread function reflects the effective diffractive properties of the metamaterial, which in turn may be tailored in a large degree through the choice of a specific structure of dielectric and metallic layers.

The materials most commonly chosen as superlenses components are silver and titanium dioxide, although the use of semiconductors such as GaP is also possible.

Experimental production of superlens structures remains at the edge of the current technological possibilities. Indeed, until now, structures with no more than two layers have been reported (transparent metals on the other hand have been experimentally investigated already in the nineties). The actual technological limit is due to the requirement for a sub-nanometre surface roughness of the layer boundaries, and on the precise measurements of the complex permittivities of thin layers. Therefore structures with a total thickness in excess of 100nm are currently subject to intense theoretical and numerical investigations. The seven topical articles co-authored by the applicant and presented below are part of this research.

Currently, the author participates in the realisation of the R&D grant (N R15 0018 06, “Super-resolving flat lens: development, manufacturing, and building demonstrator set-ups,” University of Warsaw, led by Prof. T. Szoplik), where we aim at demonstrating experimentally a superlens with a larger number of layers.

The applicants's input to the development of the theory of super-resolving layered lenses consists in the following seven thematic publications. These articles have been largely written by the applicant, or with his supervision. At the same time, he would like to underline the role of the co-authors which has been considerable, and the collaboration with whom he greatly values. The scientific input of every co-author is specified in a separate certificate attached to this application[2].

A brief description of the publications presented below does not intend to become its summary, but rather aims at pointing the importance of a specific work to the development of metamaterial layered lenses.

B1-1 **Kotyński, R.**, Stefaniuk, T., Pastuszczak, A. "Sub-wavelength diffraction-free imaging with low-loss metal-dielectric multilayers," **Applied Physics A**, Vol. 103, pp. 905-909, (Springer, **2011**);

In this work, a diffraction-free optical metamaterial with a novel composition has been introduced. The metamaterial has an impedance matched to air, it is characterised by low losses, and most importantly its imaging properties show little dependence on its overall length. It is demonstrated, how the metamaterial can be used to construct more involved elements than a simple superlens.

B1-2 Pastuszczak, A., **Kotyński, R.** "Optimised low-loss multilayers for imaging with sub-wavelength resolution in the visible wavelength range," **Journal of Applied Physics**, Vol. 109, 084302, (AIP, **2011**);

In this work a superlens consisting of silver and either TiO_2, or GaP or of $SrTiO_3$ has been optimised numerically in terms of resolution and transmission coefficient. It has been demonstrated that the theory of effective media leads to sub-optimal superlens designs, which differ significantly from the result of numerical optimisation - both with respect to the silver filling fraction, as well as with respect to the field distribution obtained internally within the structure. As an important conclusion, it becomes possible to develop superlenses with relatively thick layers, with the thickness in the order of several dozens of nanometers, for which the effective medium model becomes

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[2] According to these certificates, the respective scientific share of the applicant in the preparation of articles B1-1 to B1-7 is equal to 60%, 50%, 55%, 75%, 100%, 50%, and 75%.

invalid. This observation may play an important role in overcoming the technological obstacles in making thick superlenses.

B1-3 **Kotyński, R.**, Antosiewicz, T. J., Król, K., Panajotov, K. "Two-dimensional point spread matrix of layered metal–dielectric imaging elements," **Journal of the Optical Society of America A**, Vol. 28, pp. 111-117 (OSA, **2011**);
This article has been nominated by the Editor for being published with a review in the OSA Spotlight on Optics and to be published with open-access rights ("Journal Editors identify articles for Spotlight that have excellent scientific quality, are representative of the level of work taking place in a specific area, and put other work in perspective").
This paper presents the description of a layered system, and a layered superlens in particular, as a linear spatial filter. A mathematical polarisation-aware matrix description of this system is proposed, with the point spread function and transfer function taking matrix forms and being interrelated with use of Hankel transforms. The paper shows how the state of polarisation becomes affected by the transmission of an image through the superlens. The proposed formalism is used to design an exemplary imaging element.

B1-4 **Kotyński, R.**, Stefaniuk, T. "Multiscale analysis of subwavelength imaging with metadielectric multilayers," **Optics Letters**, Vol. 35, pp. 1133-1135 (OSA, **2010**);
This paper includes an analysis of the dependence of resolution of a layered superlens on the size of object for imaging with super-resolution. It is demonstrated that in certain circumstances the actual resolution is superior than the width (FWHM) of the point spread function. This apparent paradox origins from the rapid phase modulation of the (coherent) point spread function of the imaging system. Depending, on the size of the object, the same superlens may act as a super-resolving imaging system or as a system with a strong diffraction, even though both situations are described with exactly the same point spread function.

B1-5 **Kotyński, R.** "Fourier Optics approach to imaging with sub-wavelength resolution through metaldielectric multilayers," **Opto-electronics Review**, Vol. 18, pp. 366-375, (Springer, **2010**) - invited paper in a special issue on nanophotonics;
This article presents the possibility of extending the mathematical apparatus of Fourier

optics for the analysis of super-resolving metal-dielectric multilayers. Three different ways of defining the coherent amplitude transfer function are proposed, with respect to a different source model and a different scalar field component.

B1-6 **Kotyński, R.**, Baghdasaryan, H., Stefaniuk, T., Pastuszczak, A., Marciniak, M., Lavrinenko, A., Panajotov, K., Szoplik, T. "Sensitivity of imaging properties of metal-dielectric layered flat lens to fabrication inaccuracies," **Opto-electronics Review**, Vol. 18, pp. 446-457, (Springer, **2010**);

The article presents an assessment of the deterioration of the imaging properties of a superlens, namely of the resolution and of transmission coefficient, resulting from various manufacturing inaccuracies (from the statistical error in the definition of the superlens). The results indicate that the imaging properties are extremely sensitive to the manufacturing tolerances. This joint work has resulted from the collaborative effort in the framework of the COST-MP0702 action.

B1-7 **Kotyński, R.**, Stefaniuk, T. "Comparison of imaging with sub-wavelength resolution in the canalization and resonant tunnelling regimes," **Journal of Optics A**: Pure and Appllied Optics, Vol. 11, 015001, (IOPScience, **2009**);

This work includes an analysis of two distinct propagation mechanisms that may be used in layered superlenses - namely the resonant tunnelling and the canalization. Canalization is a physical mechanism of transmission connected with tuning the effective permittivity of the multilayer in order to satisfy the condition for Fabry-Pérot resonance for any angle of incidence at the same time (!). Both types of superlenses show an acceptable level of losses, which comes in contrast to the majority of other metamaterials.

Warsaw, 10 October 2011

Rafał Kotyński