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Review of the PhD dissertation entitled
'Nonlinearity Shaping in Specialty Tellurite Glass Optical Fibers'
submitted by Tanvi Karpate

Introduction

This review was prepared at the request of the Chair of the Council of the Scientific Discipline 'Physical Sciences' at the University of Warsaw, Prof. Wojciech Satuła, based on delivered hardcopy of the PhD dissertation. The research presented in this dissertation was carried out by Tanvi Karpate, MSc, at the Department of Photonics of the Faculty of Physics under the supervision of Dr. hab. Mariusz Klimczak and Dr. Adam Filipkowski.

Aim of the thesis and rational for the topic

Generally, the thesis is devoted to the development of novel microstructured and nanostructured optical fibers to shape non-linear pulse propagation in the shortwave-infrared wavelength range. Four specialty tellurite glass fibers have been demonstrated to enable engineering of the properties like dispersion, confinement or mode field area. Those properties facilitate the applications such as supercontinuum generation, amplification, pulse compression etc.

In this context, the research presented in the thesis responds to a strong demand for infrared light sources. Development of compact and stable wide-band low-noise sources in infrared wavelength range is currently of great interest of science and industry due to the emerging technologies such as optical frequency metrology, LIDAR, spectroscopy, hyperspectral imaging or bio-medical imaging.

The Author formulated the main goal of the presented study in Introduction. The Author stated in a general way that '*this dissertation aims at expanding the current state-of-the-art in non-oxide fibers for nonlinear optics applications* (…)'. Later on, more detailed description of the objectives was given: (1) *to shape the nonlinear response of tellurite fibers with structure (i.e. mode confinement and anomalous chromatic dispersion) for isolated* *soliton propagation*; (2) *to assess the feasibility for shaping nonlinear response of fiber designed for efficient spectral broadening of femtosecond pulses exploiting non-soliton dynamics*; and (3) *to explore spatial and temporal complexity of femtosecond pulse propagation in conditions of strong nonlinear response and support of multiple guided modes of the fiber*. It has to be mentioned that those three aims correspond to three research hypotheses to be tested in the proposed research program. Although the Author follows rigorous scientific approach leading to provide the research aims, all hypotheses should be given prior the aims in Section 1.1. In my opinion, the research problem has been proposed correctly, and the title of the dissertation matches the assumed goals.

Structure of the thesis

The main part of the doctoral thesis presented for review contains 133 pages. This was preceded by 23-page initial part including abstracts (in English ad in Polish), a table of contents, a list of figures and a list of tables. The main part of the dissertation has been divided into 7 chapters, 2 appendixes and a bibliography. The thesis contains 46 figures, 7 tables and 43 equations. The thesis is characterized by a regular and logical structure, which makes it easy to read and follow. It is important to mention here that by introducing the most relevant information, Mrs. Karpate successfully balanced the fundamentals of non-linear fiber optics (Chapters 2-3) and the research details (Chapters 4-6). Therefore, the information given in all chapters are also appropriately linked with no redundancy or unrelated material.

The structure of the thesis directly refers to the tested hypotheses and specific goals given at the beginning of the dissertation. The thesis under review starts with Introduction that presents the motivation, main objectives and hypotheses of the dissertation. Chapter 1 demonstrates also a brief summary of the outline of the PhD thesis. An interesting and very useful part of this chapter is the last section devoted to contributions and acknowledgements. In particular, the Author lists all completed research tasks precisely as well as contribution of her lab mates that enabled execution of the project. In my opinion, this is a really important and valuable section of the thesis, which ensures that the candidate is aware of the aspect related to research integrity.

Chapter 2 describes the fundamentals of light propagation in optical fibers and it is crucial to understand the phenomena observed in the experiments. The effects of dispersion, attenuation and birefringence are introduced here theoretically, and experimental methods and set-ups allowing for the measurement of chromatic dispersion, attenuation and fiber birefringence are demonstrated. The second part of this section is devoted to non-linear light pulse propagation in fibers. The non-linear phenomena such as soliton self-frequency shift, optical wave-breaking and self-phase modulation and supercontinuum generation. The Author introduces also the details of the experimental procedures to determine pulse parameters like frequency-resolved optical gating, (FROG) and its variants, dispersive Fourier transformation. Generally, Chapter 2 serves as a theoretical background for the study, it covers some aspects of methodology section but it also presents the state-of-the-art, to which the Author refers in subsequent chapters. I value this chapter very high since all information has been written in a synthetic way and has provided with accurate recognition of the current advances in the field. It also proves that the Author is able to select the most important facts that are crucial to understand the topic.

Chapter 3 is the key methodology section to get acquainted with the fiber designing, which is based on numerical solving of Generalized Nonlinear Schrödinger Equation to model light propagation. Then the Author concentrates on selection of glass types of particular properties and fiber fabrication process used in the study. This section includes also information on the geometry of four types of fibers developed for this study. This gives an overview on the novelty of the achieved goals.

The next three chapters include the results of the experiments completed the PhD candidate. Each chapter corresponds to the specific research question (hypothesis) raised in Introduction. Therefore, the structure of Chapters 4-6 is similar and has the details of fiber development and manufacturing (task-specific methodology). Later on, the above-mentioned chapters present the simulated or / and measured properties of the fiber and demonstrate experimental results, which are followed by discussion and aim-specific conclusions. In particular, in Chapter4 the Author presents Raman soliton detuning in a tellurite suspended core PCF fiber with pumping at 1560 nm and 1900 nm. The spectra at the fiber output were also analyzed with dispersive Fourier transform. In Chapter 5, two all-normal dispersion tellurite photonic crystal fibers (polarization maintaining and non-polarization-maintaining) were used. Generation of supercontinuum was studied, and noise of supercontinuum was assessed for different input polarization states. In Chapter 6, a graded-index fiber fabricated from two types of rods is utilized to study spatial, spectral and temporal characteristics of the output pulse under femtosecond pulse pumping. This fiber was later used for supercontinuum generation.

Final seventh chapter of the dissertation summarizes the most important facts and discusses the obtained results with respect to the stated hypotheses. The novelty, originality and significance of the achievements are pointed out. The reader is also informed how the results for each part of the study were disseminated and published. The thesis includes also two Appendixes which show the codes of implemented algorithms (in MATLAB): (A) to determine chromatic dispersion of the fiber and (B) to reconstruct a FROG / XGROG pulse. The Author made also significant efforts to do accurate literature search during editing the text as the bibliography contains 175 references.

Editorial (technical) comments

The dissertation is written in English in a style meeting the standards of scientific publications. This makes the thesis easy to read and follow. A strong point of the composition of the thesis is the fact that each chapter showing the results refers to the aim and tested hypothesis, which is also underlined in the discussion. On one hand, this provides with a very specific style of the whole dissertation and increases links between the sections (allowing for a better understanding of the implementation of the PhD project). On the other hand, it may generate the impression of repetitions throughout the text. Although few minor editing errors were detected during reading the thesis (listed below) but they do not affect my positive opinion.

Visual content of the dissertation increases data readability. The artwork consisting of 46 figures was prepared correctly but some plots could have been larger to enable readers with poorer vision to see the details. The quality proves that the Author took care on that technical aspect of the dissertation, which I value very much.

Critical analysis & questions

In this section, I would like to raise the issues and questions that arose during reading the manuscript. The list below can be addressed by the Candidate during the defense:

1) **Typographical errors**: p. 6 (two fiberS, theor ??); p. 11 (Eq.2.6 typed twice); p. 14, line 2 (‘then’ repeated twice); p. 15 (Ai does not correspond to coefficients in eq. 2.11); p. 21 (in-line equation for soliton number does not include β_2); p. 26 (‘sech’ ??); p. 43 ($Na2_O$); p. 45 (‘100C’ and ‘131,5C’); p. 65 (‘seed to for’ ??); p. 67 (‘case of 1560

pumping'); p. 78 ('all the while ensuring' ??); p. 80 (is 'slow is axis spanned', should be 'slow axis is spanned'); p. 82 (a range of wavelengthS); p. 92 (pulSE pumping).

2) **Grammar errors**: p. 16 (is 'drift', should be 'drifts'); p. 19 (is 'SPM and XPM, leads …', should be 'SPM and XPM lead …'); p. 22 (is 'work', should be 'works'); p. 29 (is 'the dynamics behind SC generation are self-seeded …', should be 'the dynamics behind SC generation IS self-seeded …'); p. 33 (is 'spectral broadened', should be 'spectrally broadened'); p. 37, line 1 (is 'have been', should be 'has been'); p. 37 (is 'Use of PCF increase', should be 'use of PCF increases'); p. 64 (is 'the output spectra GIVES', should be 'the output spectra GIVE'); p. 64 (is 'the output spectra ACCOUNTS', should be 'the output spectra account'); p. 67 (is 'was then observed', should be 'were then observed'); p. 69 (is 'obtain', should be 'obtained'); p. 72 (is 'this result is evidence', should be 'this result is an evidence'); p. 73 (is 'red shifts on increasing the number', should be 'red shifts with increasing number'); p. 75 (is 'design fiber', should be 'designed fiber'); p. 79 (is 'a octave spanning continuum', should be 'an octave spanning continuum'); p. 97 (is 'additional verifies', should be 'additionally verifies'), p. 101 ('pulse reshaping ariseS'); p. 102 ('impactS the characteristic'); p. 102 ('dynamicS leadS').
3) When the sentence finishes with **Equation**, a full stop should be used after the equation. When the equation is followed by further explanations (starting usually with 'which' or 'where'), a comma should be used after the equation.
4) It would be good to include a list of **symbols**. There are few places, where the symbols were either not explained or are not used consistently:
   – p. 13 – Pulse duration t0 is given in the text whereas T_0 is used in the in-line equation for dispersion length.
   – p. 18 – What does gamma mean in section 2.3.1 and 2.3.2? It is rather explained in p. 40.
   – p. 22 – Equation 2.22 does not explain τ_{shock}.
   – p. 26 – The text mentions Ω_s but Eq. 2.23 has ω_s.
   – p. 27 – We have SC in section 2.3.7 while the explanation appears in section 2.3.8.
   – p. 35 – $\tilde{A}$ depending on $t/\beta_{2s}z$ should be indicated in Eq. 2.31 (lack of bracket).
   – p. 39 – D_g not explained in Fig. 3.1. Where is d/Λ in that figure? The legend shows rather 'a'.
   – p. 40 – Equation 3.4 does not explain l_m.

5) The **abbreviations** should be explained at the first use. Some abbreviations are not explained at all or explained at the next use, e.g. p. 21 (GNLSE not explained in section 2.3.3. The explanation is given later in section 2.3.4, and the inconsistency appeared probably due to the rearranging the sections during the text editing); p. 17 (PANDA); p. 26 (FWM process); p. 32, Fig. 2.6 (SFG wavelength); p. 68 (Norm. PSD in Fig. 4.10).
6) **Stylistic errors**. There are some sentences that require rewriting like: p. 17 (sentence starting with 'PM fibers are widely used … in various …'), p. 18 ('A chirp is …'), p. 29 ('A great example of using … is that of …'), p. 37 ('While single-mode fiber (SMF) based systems …' – too complex and the second part of the sentence not clear), p. 41 ('From Kerr nonlinearity …'), p. 67 ('Dispersive Fourier transform (DFT) theory states…'), p. 68 ('This is in agreement with the earlier reports …'), p. 73 ('One such way to achieve high confinement of guided modes …'), p. 91 ('Measurement of dispersion of such fiber…'), p. 103 ('This in turn controls …').
7) Please, do not use **contractions** in the formal text like dissertation, e.g. p. 18 (I'll should be 'I will…'), p. 48 (doesn't, should be 'does not').
8) p. 19, sentence 'In a spectrogram, SPM is identified by a characteristic S-shape relating to the oscillatory structure' – it would be good to either refer to fig. 2.4 or to show the S-shape in a separate figure.
9) p. 33 – Noise reduction methods in the FROG software are described using **jargon** language, e.g. lowest pixel.
10) p. 34 – sentence 'A detailed methodology of spectral analysis using DFT was presented by Goda and Jalali in 2013'. I would expect reference here.
11) Please, pay more attention to units in Table 3.2.
12) Either American or British English should be used consistently through the entire manuscript ('fibre' or 'fiber').
13) p. 58, section 4.3 – comments to Fig. 4.3 'Beyond the ZDWs, the fibers show flat dispersion profiles in the anomalous dispersion region'. What is the condition that allows to describe the fiber as the one with flat dispersion?
14) p. 59, section 4.4 – 'This fiber sample was chosen as it showed the flattest dispersion profile in the anomalous dispersion wavelength range.' – How did you assess the flatness of dispersion profile? The same question refers to fiber type NL50C1 mentioned on p. 62.
15) Fig. 4.5 – Intensity has logarithmic scale. What is the normalization factor here?

16) Figs. 4.8 & 4.9 – What does vertical axis show? What are the units?
17) p. 64 – The description of energy efficiency is not clear. It would be good to present the integrated area graphically in Fig. 4.8. There is also inconsistency between energy efficiency (%) indicated in Fig. 4.8, data in Table 4.2 and information in the text.
18) p. 74 – Plots in Fig. 5.1 are extremely small. It is hard to distinguish the text in the axes. The same applies to the plots in Fig. 6.8.
19) Fig. 5.5a – What is the Intensity unit?
20) It is advised to include explanation of abbreviations used in all figures with experimental schemes in the corresponding captions.
21) How were the lengths of fibers selected for each study?
22) Fig. 5.9 – Why were not the same input power levels presented in both plots?
23) p. 80 – description of Fig. 5.10 – This figure does not show polarization extinction ratio but SC generated for two orthogonal polarization states. PER can be calculated from those data.
24) Figure 5.10 – The text says that minimum optical power is 8.3 mW but the legend indicates 8.6 mW.
25) Fig. 5.13 – It would be good if the candidate proposes a way to quantify the SC noise suppression.
26) p. 90 – The description of the optimization process of the GRIN fiber design could have been illustrated with a figure.
27) p. 108 – reference of the candidate to Optics Letter paper was not correctly listed.

Evaluation of the dissertation

The PhD thesis is the result of numerical simulations and experimental work that has a direct impact on future photonic technologies. **The PhD candidate had to acquire several skills necessary to complete the research tasks and to achieve the goals**, from numerical simulations of light propagation in the fibers, fiber design, fabrication and optimization to performing the measurements to characterize the fibers, data processing and advanced modelling of speckle phenomena. Comprehensive, integrated and adequate research methodology was applied to problems solved in this thesis.

In my opinion, a unique achievement of the PhD student is the **demonstration of proof-of-concept methodology for shaping the nonlinearity of the fiber made of tellurite glass**. I particularly value the applications presented in the thesis, i.e. the research open new paths toward new light source technologies for wide-band imaging or optical pulse control systems. Therefore, the results obtained by Mrs. Karpate form a basis for future advances in both fundamental and applied science.

In spite of my comments and raised questions, I have to admit that the proposed research constitute the **Author's original contribution to the development of field of fiber and nonlinear optics**. Furthermore, the outcome of the PhD project is significant at the international level as three articles in peer-reviewed journals and two conference proceeding have been already published, with first-authorship or co-authorship of the Candidate. Conference proceedings also show that the material included in the dissertation was presented at the Conference on Lasers and Electro-Optics (CLEO). T. Karpate, MSc, has also authored / co-authored other 3 papers in the field. The articles were already cited 34 times. During realization of her PhD project, Tanvi Karpate had the chance to develop soft skills like team work since her research was carried out within the Marie Skłodowska Curie Actions and TEAM-NET projects.

Final conclusions

In conclusion, all achievements demonstrated in this thesis by Mrs. Karpate represent consistent set of studies. The research problems addressed in this thesis demonstrate not only general knowledge of the candidate in the discipline ‘Physical Sciences’ but also a high level of skills and expertise acquired by the candidate. The original results and completed tasks indicate the candidate’s ability to do research independently and within the team. All defined aims have been achieved.

I do declare that the PhD dissertation of Tanvi Karpate, MSc meets the requirements for doctoral dissertations specified in Art. 190 of the Act on Higher Education and Science of July 20, 2018 (Dz.U. 2021 it. 478; as amended) and in other relevant regulations. Accordingly, I do recommend that Mrs. Karpate’s PhD thesis proceeds to the next stage of the procedure and be admitted for public defense.

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