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REVIEW
of Anupamaa Rampur's doctoral dissertation entitled "Coherently seeded broadband ultrafast fiber amplifiers"

The subject of the review is Anupamaa Rampur's doctoral dissertation entitled "Coherently seeded broadband ultrafast fiber amplifiers", advised by Dr. hab. Mariusz Klimczak and co-advised by Dr. Tomasz Stefaniuk. The review was prepared at the request of the prof. dr hab. Zygmunt Lalak, the Chairman of the Scientific Discipline for Physical Sciences, University of Warsaw in Poland.

1. Introduction

Photonics in the last century was clearly indicated as one of the main directions of development of our civilization. This conviction resulted from the features of the photon as the fastest way of transmitting and unique shaping possibility of coherent propagation. There were honored with the Nobel Prizes: C. Kao in 2009 for "groundbreaking achievements relating to light in fibers for optical communication", N. G. Basow, A. M. Prochorow, C. H. Townes in 1964 for "invention of the maser and the laser" and G. Mourou, D. Strickland in 2018 for "chirped pulse amplification". The last one opened in 1985 a way to build new fiber laser and amplifier systems. Particular interest concerns amplifying pulsed radiation in the femtosecond range, where typical MOFPA system in limited by strong non-linear effects resulting from the high power density of the amplified pulse in the fiber's core. Here the Chirped Pulse Amplification (CPA) is widely used, where the radiation pulse is first expanded (chirped), amplified in the active medium and finally compressed in anomalous dispersion medium. CPA technique was extended in many bulk and optical fiber systems for laser power scaling and amplifiers. This area includes the subject of Anupamaa Rampur's doctoral dissertation.

2. Layout and evaluation

Numbering 134 pages, the work is divided into two parts: theoretical (chapters 1-2) and experimental (chapters 3-7). Additionally, the following parts of the dissertation as: abstract, acknowledgements, list of acronyms, Author's publications were exposed.

In the theoretical part, which is less than 25% of the volume of work, the subject area was characterized, justifying the purpose and indicating the analytical and experimental aspects of coherently seeded ultrafast RE doped fiber amplifiers. In the first chapter we can find a clear

description of the Author's thesis as she presented based on the last references a clear motivation for the proposed research chain to obtain broadband ultrafast amplifiers using coherent seeding of polarisation maintaining (PM) all normal dispersion (ANDi) supercontinuum SC pulses. Extended justification of the conducted experimental and computational works can be found in chapter 2, where apart from the basic issues, Author presents aspects of supercontinuum generation in PCF, femtosecond laser pulse characterization techniques and pulse retrieval methods. The latter are particular important as the frequency-resolved optical gating (FROG) techniques helped in coherent supercontinuum seed pulses and amplified output pulses optimisation. The 3rd chapter covers measurements and discussion about dispersion and birefringence measurements of different fibres from commercially available ultra-high numerical aperture (UHNA, PM2000D) to ANDi PCF from high-nonlinear soft glasses (NL38, NL48, NL46). Analysis allowed to proof all-normal dispersion non-PM and weakly-PM photonic crystal fibers which finally benefited building Tm/Er amplifiers with improvement of noise performance. In the Chapter 4 the spectro-temporal characterization of coherent supercontinuum pulses obtained in microstructured PM and non-PM ANDi PCFs using FROG technique have been analysed. It is a key analysis which showed that SC pulses emitted from PM and non-PM fibers pumped by a ultrafast Er:fiber laser had a complex structures. Besides it opens discussion that it is possible to obtain fine linear pulses form soft glasses including all-fiber architecture. The results obtained in this chapter supplemented the knowledge on optical fiber dispersion (including new PCF designs) and clearly determined the choice of PM fibers in constructing high quality all-normal dispersion SC sources. Proposed ANDi SC source was used for development of thulium-doped all-fiber chirped-pulse amplifier presented in the next 5th chapter. Author realised here SC generation in PM ANDi fiber and amplification in a PM fiber system composed with: Er:fiber laser - the ANDi SC - and the Tm-doped fiber. Detail analysis of noise reasons at each stage of the system allowed to eliminate anomalous dispersion which directed to the nonlinear limitations like soliton formation. In results for the output of 96 fs pulses (350 mW, 100 MHz, 1900 nm) the final RIN value of 0.04% was achieved. In the Chapter 6 the works relied on simultaneously pumping of two amplifiers i.e. Tm:fiber and Er:fiber in a CPA scheme and merging outputs of their signals. Here, Author at the beginning, modified the SC source by using high birefringent tellurite ANDi PM photonic crystal fiber in order to achieve higher average power (307 mW). The broadband emission of SC spectrum which extended from 1200 nm to 2200 nm was stretched due to different lengths of PM fibers (PM2000D) to compensate a anomalous dispersion of used fibers. In the next steps the optimisation of Tm and Er doped fibers excitations and compressing were performed to achieve emission average power output of 580

mW (1880 nm, 3 dB bandwidth of 100 nm, 120 fs) and 220 mW (1555 nm, 3 dB bandwidth of 64 nm, 56 fs) respectively. Finally the sum frequency signal between simultaneously seeded Er and Tm amplifiers has been generated. The RIN values were also characterised.

Summarising it should be emphasized that theoretical background, is strictly related to the subject of the conducted research. The analysis of the state of knowledge was made on properly selected, up-to-date literature covering 202 positions (among them 6 of A. Rampur), which allows to conclude that Author has a deep knowledge of the subject. PhD thesis ends well written chapter 7 "Conclusions and future developments".

The dissertation layout is transparent and makes it possible to evaluate the Author's achievements.

2.1 The choice of the research topic and the quality of the formulation of the research target and methodological approach applied

Broadband sources in the eye safe range have long been proposed in a variety of lanthanide doped fiber configurations. The obvious advantage, but also limitation, are the specific emission transitions, in particular of Tm, Er and Ho ions. They allow for conventional materials to obtain wide emission from 1.46 to 2.2 μm, but a typical problem is getting a flat spectrum and high gain which is important for applications in spectroscopy, sensing and medical applications. Alternative solution is based on photonics crystal fibres which allow to generate a broad emission (supercontinuum - SC) in wide spectrum with single mode propagation in the long range of wavelengths in NIR spectrum. However under CW pumping they suffer of low threshold limit and problems with spectrum stability. As mentioned before a new possibilities in construction of laser and amplifiers opened after invention of fiber chirped pulse amplification in particular amplifying pulsed radiation in the femtosecond range. It allowed to overcome the problem with damage threshold of the fiber core which is in particular important in the small core diameters of PCFs. Merging the advantages of broadband SC emission of PCFs, RE doped optical fibres and CPA technique significantly expanded the design possibilities. Anupamaa Rampur in the first two chapters presented clearly analysis of the last directions and proposed to use coherent supercontinuum pulses as a seed signals in thulium-doped or/and erbium-doped amplifier systems and realise two main objectives:

1. Design and development of fiber-based setups for amplification of coherent polarized seed signals in the 2 μm spectral window and its temporal recompression to below 100 fs.
2. Design and development of fiberized platform enabling simultaneous coherent seeding of erbium and thulium fiber amplifiers and their output pulse compression and nonlinear mixing.

It should be noted that the implementation of the work required the development and analysis of the propagation and emission parameters of individual elements, i.e. SC sources, chirp management and amplified signal compression. Moreover, it was assumed that the RIN parameter should be low, which was related to the theoretical analysis of the planned experimental studies. Author was aware of these dependencies, which is clearly visible in the detailed objectives explained on page 5 and confirmed by the sequence of chapters. Author proposed spectro-temporal characteristics of coherent SC pulses generated in several all-normal dispersion fibres using frequency resolved optical gating techniques, chirp management with chosen PCFs, development of polarization-maintaining, ultrafast erbium and thulium-doped amplifiers and simultaneous seeding of the Tm and Er-doped fiber amplifiers.

It is worth to underline that realization of above advanced photonic devices undoubtedly required a systematic experimental research combined with deep structural dispersion analysis. The aim of the work is unambiguously directed at projecting a specific FCPA advanced photonics system by using implementation of different type of optical fibres and techniques.

In my opinion the assumptions proposed by the Author are correct, the aims and methodology of the work have been formulated correctly.

2.2 The significance, originality and novelty of the research conducted by the student and the international quality of the results within the research field

Rampur proposed the study on the ultrafast pulsed amplifiers in the 1.5-2 mm region based on the FCPA technique indicating clearly new challenges:

a) post-amplification temporal compression close to 100 fs using available single mode/ polarization maintaining fibers,

b) reduction of relative intensity noise characteristics, compared to state-of-the-art soliton-driven ultrafast fiber amplifier systems,

c) nonlinear mixing of ultrafast both developed fiber amplifiers seeded from a common coherent signal, with the relative intensity noise of the mixing product not exceeding the level of state-of-the-art ultrafast fiber amplifiers.

The significance of the work relates not only to the indicated parameters, but also applies to several aspects, such as: characterization and selection of optical fibers for the optimization of the SC source and spectro-temporal analysis of the emission output in the aspect of system delivered fs pulses, power and frequency taking into account low RIN values. Important novelty of the constructed amplifiers include: use of broadband, coherent seed signal with linear polarization, thulium-doped all-fiber chirped-pulse amplifier with RIN value order of magnitude lower than last reported systems seeded with Raman solitons, simultaneous seeding

of the Tm and Er fiber amplifiers with improved parameters of Tm and unique attempt to sum-frequency signal generation outputs of the two amplifiers.

In this respect, the work undoubtedly include original elements in the field all-fiber photonics i.e. knowledge about non-linear and dispersion of PCFs and FCPA in all-PM amplifiers.

2.3 The contribution of the student's own achievements

Strong side of the dissertation is the impact analysis of various variables (PM fibers and output characterisation form each section of the FCPA systems) on the emission properties (<100fs, low NIR) which allowed to obtain a significant approach in the field. The important Author's contribution includes:

- Broadband dispersion measurements in commercial Ultra-high numerical aperture (UHNA) fibers and all solid PM ANDi PCFs with analysis of their usage in broadband emission. These results extended the state of knowledge for the ultrafast fiber optics community, because up to date, dispersion of these fibers was available only for single wavelengths and this is insufficient for femtosecond laser pulse applications, because such pulses usually span tens of nanometers.
- Spectro-temporal characteristics of coherent SC pulses generated in several implementations of silica and soft-glass PM and non-PM ANDi PCFs. Analysis of relation of femtosecond pump pulse characteristics to sub-25 fs fine structure of coherent supercontinuum pulses. These results had a practical dimension, because they emphasized the influence of pre- and post-pulse structure of the pump pulse – typical to real, commercial femtosecond lasers - on the nonlinear broadening characteristics related supercontinuum pulse. On the basis of these results, the Author established the most important assumptions for developing amplifiers in the doctoral dissertation, including the motivation for use of a polarization maintaining version of the nonlinear fiber for obtaining of the supercontinuum seed signal.
- Developing Tm-doped fiber amplifier @1900nm (96 fs pulses, 350 mW output power) seeded with coherent superkontinuum, achieving low RIN (0.04%, 10 Hz - 1 MHz) value. Improved pulse amplification in the next setup achieving values @1880nm (120 fs, 580mW av. power, RIN 0.035%).
- Demonstration for the first time simultaneous seeding of the Tm and Er-doped fiber amplifiers synchronized by common, wavelength-demultiplexed seed signal, subsequent sum-frequency signal generation, and confirmation of low relative intensity noise level inherent to highly coherent operation.

2.4 Coherence of the published articles and the research topic of the dissertation

There is no doubt that publications and conference presentations (p.vi) are coherent and in line with the doctoral thesis as they presents convergent subjects. Besides their high scientific

quality and the dissertation simultaneously have been evaluated by well-recognizable publications and photonics conferences. Doctoral thesis was verified by 4 JCR journals (Opt. Express (2), J. Opt. Soc. Am and J. Opt., 2018-2019) – 36 citations (related to the thesis), *h*-index 3 (acc. Scopus) and presentations during photonics conferences (8th EPS-QEOD, OSA Technical Digest - 2018-2019). I am convinced that the presented dissertation meets with excess the usual requirements for this type of scientific studies.

2.5 Capability of the student to analyse scientific problems and discuss critically his own results

I am impressed of the high level of discussion in fact at each stage of the doctoral dissertation. Author provided a clear summary after each experimental chapter and compared all measured and computational values with the lastest literature. It is clearly visible form the chapter 3 where dispersion characteristics of available fibers and custom nonlinear photonic crystal fibers were measured in the broad spectral range and published in the Journal of Optical Society of America B. Since it was essential for understanding of the SC dynamics so A. Rampur characterized the developed all-solid glass ANDi weakly PM PCFs in terms of dispersion and birefringence. Spectro-temporal analysis (FROG) in chapter 4 allowed to discuss complexity of broadband SC pulses and temporal oscillations at the fs level. It was also confirmed by simulations and reconstructed. Results of this part of her work allowed to anticipate the challenges of pulse amplification (spectral and temporal structure of the amplified pulse) and it also motivated to use a polarized seed signal for improved control of RIN. This results were discussed and published in a paper in Optics Express. Similarly the Author made a clear comparison of developed all-PM Tm-doped fiber amplifier showing RIN value one order of magnitude lower than similar systems previously seeded with Raman solitons – it was also published in Optics Express (vol. 27, 35041, 2019), as well as presented in oral presentations at the CLEO conference in the USA and in Europe in 2019. In particular advanced discussion have been contained during simultaneous seeding of erbium and thulium doped fiber amplifiers. Author are aware of some imperfections in the systems and gives a clear propositions in the conclusions as a future developments.

2.6 Remarks and questions

1. Why did the author limit her work to application of soft glass nonlinear fibers and did not attempt to build a fully fusion-spliced version of the amplifiers, if the silica fibers were available (as compared in the FROG analysis part of dissertation)?

2. The author argues importance of the linear polarization of the supercontinuum pulse of the low noise of her amplifiers. In connection to the previous remark, it is puzzling, that the

polarization maintaining variants of soft glass ANDi fibers produced supercontinuum pulses with lower polarization extinction, than the silica ANDi (or mostly normal dispersion) fibers studied in the dissertation.

3. What was the main limiting factor of compression below 100 fs at the thulium amplifier output compared to the erbium amplifier, which enabled obtaining much shorter pulses? Did this influence the nonlinear mixing performance in the parallel seeding experiments in the dissertation?

4. The work entirely dismissed the 793 nm pumping, which is the most efficient excitation channel for the 1900 nm emission of thulium.

5. While evolution of group delay (FORG) shapes of the Tm:amplifier pulses in chapter 5 is clearly discussed (fig. 5.9 and 5.10), such discussion is missing in chapter 6 relevant to the parallel Er and Tm amplifier seeding.

6. Why was the tellurite fiber used in chapter 6 omitted in the analysis of FROG spectrograms in chapter 4?

3. Conclusion

Summing up, Anupamaa Rampur solved the scientific and research problem which required both a wide range of theoretical knowledge and advanced skills in the field of metrology and constructions of optical fiber photonics systems. The PhD student succeeded in the separation of the noise-sensitive amplification process from the noise-susceptible soliton dynamics involved in seed pulse generation in previously published, boardband-seeded amplifier works, which contributed to very good noise characteristics measured in scope of the dissertation. These results are novel, as confirmed by publication in the renown Optics Express journal, and essentially prove the theses given in the introduction of the dissertation. The achievements presented by Anupamaa Rampur allow me to declare that his work meets the requirements set for doctoral dissertations.

The achievements presented in this thesis allow me to state that, in accordance with the "Act on Scientific Degrees and Titles as well as Degrees and Titles in Art", dated March 14, 2003, as amended, it meets all the requirements doctoral dissertations and I apply for admission to public defence. In addition, on the basis of the scientific achievements indicated in the review I apply for the distinction (justification points 2.3-2.5) of the doctoral dissertation.

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