COST 299: Third technical committee
Ecole de Physique des Houches, Les Houches, France, 31/01/07 – 02/02/07

WG3 : Distributed and nonlinear optics

Report

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I. Overview

In the frame of WG3, the "Les Houches" meeting included:

- 2 reports of Short Term Scientific Missions
- 4 reports of collaboration works involving 9 partners
- 2 proposal for new activities
- 2 reports of new results from partners in order to initiate collaborations

II. Technical presentation

The technical presentation of WG3 entitled "*Stimulated Brillouin scattering and optical phase conjugation in multimode optical fibers*" has been presented by Dr Andréi Fotiadi (FPMs). This topic is part of SG1 which is dedicated to the fundamentals and modelling of nonlinear effects in optical fibres.

Abstract -- Stimulated Brillouin scattering (SBS) and optical phase conjugation (OPC) in multimode optical fibers is of great interest for many high power laser applications, including laser beam combining. The quantitative estimation of the SBS gain factors and the OPC fidelities in fibers should be based on accurate solution of the SBS stationary problem that necessarily takes into account the hypersound propagation effects. In this report we present the OPC-SBS theory specifically developed for optical fibers with a cylindrical symmetry. There are two stages of our analysis. First, we consider SBS interaction between one pump and one Stokes spatial modes and derive an analytical expression for the SBS gain spectrum in this case. Then this solution is applied for description of multimode pump-Stokes interaction in two general SBS configurations: SBS generator and SBS amplifier. In particular, we report a significant improvement of the OPC fidelity achieved with the SBS amplifier by the use of an external Stokes signal with a narrow spectral line. The results of numerical simulations are in good agreement with our experiments.

III. SG1 : Nonlinear effects in optical fibres: fundamentals and modelling (chair: T. Sylvestre, LOPMD)

1. Talks presented in the technical session

Two talks have been presented in the frame of SG1:

1. *Ultrashort pulse propagation*: "Nonlinear pulse compression to sub-30 fs regime in highly nonlinear fiber", B. Kibler, FEMTO, c*ollaboration FEMTO/CUDOS*

Abstract -- Nonlinear pulse compression techniques are of course very well-known, exploiting the initial spectral broadening and temporal compression phase of higher-order soliton evolution in the anomalous dispersion regime of an optical fiber. Here we focus on providing a series of our own experiments around 1550 nm, where we have used sub-10 cm lengths of highly nonlinear fiber directly spliced to the output pigtail of a commercial femtosecond source, in order to obtain nonlinearly compressed pulses to the sub-30 fs regime using controlled compression. The objective is to concentrate specifically on the simpler configuration using only one step of nonlinear soliton compression. The accurate FROG characterisation of the input pulses is a crucial step that facilitates the use of numerical simulations to accurately determine the compressor fiber length without the need for time consuming (and sometimes expensive) trial and error. In addition, we also describe recent results where a non-phasematched third harmonic generation have been obtained during these compression experiments. This process has been also observed in less than 1 mm of HNLF using only commercial femtosecond fiber laser.

2. *Report of activities (Measurement of nonlinear effects)*: "Brillouin threshold measurement", Anne Andersson, SP.

Abstract -- At previous meetings i.e. Mons and Nice it was agreed to do a co-operation and possible comparison of SBS threshold alternatively called SBS critical power. One of the first tasks would be to decide what to define as the measurable SBS-quantity.
Anne Andersson presented SP efforts to do SBS measurements at the COST 299 meeting in Les Houches. SP are developing a power calibrated SBS set-up. The first method suggested by SP was pulsed at 100 kHz and presented at the COST299 in Mons May 2006. The reported threshold of about 17 mW seamed high compared to results presented in the literature for standard sm fibres. The method needed to be improved in power referencing to know the precise power of the SBS onset. With this intension CW methods are investigated. The power is measured with an Ophir thermocouple high power instrument calibrated traceable to national standards at SP. The power was calibrated direct out from EDFA source and at three locations on the circulator used. The EDFA has a 5 % monitor output which was tested to be very repeatable and linear related to the output power. One problem was that the power stability was only about 10 % of signal. Not moving the set-up the measurements could be repeated within 0,2 dB. Removing and reproduce the set-up the value for SBS onset changed from about 9,7 dBm to 8,8 dBm. Suggested at the meeting was that backscattering from contacts and polarisation effects might not be fully avoided or controlled in the set-up. The next SP efforts will be to try to minimize backscattering and to scramble polarisation to get more repeatable and reproducible SBS measurements. Also it was suggested to measure the Gain factor from which one should be able to calculate the SBS. At the meeting it was agreed to start a sub-working group SG4 in WG3 to deal with SBS threshold measurements. Anne

Andersson was elected to be the group leader. SG4 full intention has to be further discussed. A questionnaire will be sent to interested partners.

2. Status of the study group

The following collaborations, defined before the "Les Houches" meeting are still in progress:

- *Next generation PCF, XLIM / IRCICA / MUL / INESC.* NextGenPCF is an Integrated Project of the "Information Society Technologies" (IST) priority of the 6th Framework Program (FP6). It is part of the "Photonic Components" IST Strategic Objective. NextGenPCF brings together an international consortium of 18 partners including 4 COST 299 members, integrating key European industrial and academic groups, from raw material developers to final users. It aims to incubate key devices in three fields of applications:
  - ⇒ Biomedical: Raman laser for photodynamic therapy and wideband sources for cytology,
  - ⇒ Telecom: easy-to-install, low-cost fibre for indoor wiring, and high performance discrete Raman amplifiers
  - ⇒ Sensors for environment: methane detection in mining and landfill monitoring.

- *Raman amplification in nonlinear holey fibres for telecom applications, FOTON/ PERFOS.* This collaboration between several partners, notably PERFOS and FOTON is concerned with the development of low-loss and highly nonlinear holey fibres (NLHF) and their use in telecommunications applications. The recent demonstration of an extremely low water nonlinear holey fibre has allowed the first demonstration of Raman amplification in the C Band using NLHF. We have also developed a method for the measurement of dispersion based on higher order soliton compression. Future research work is concerned with the demonstration of efficient all-optical regeneration (project FUTUR, financed by the French National Research Agency).

Two new common works have bee defined during the "Les Houches" meeting:

- *Brillouin threshold measurement, SP, GTF, FPMS, EPFL, TAU, IREE.* This activity and the next step are summarized in point III.1.2.

- *Brillouin measurement, EPFL, LOPMD.* At the beginning of the Action, *a c*ollaboration between EPFL and LOPMD has been reported (*Brillouin optical time domain analysis of fiber optic parametric amplifiers*, A. Vedadi STSM). A potential continuation of this topic is now under investigation.

IV. SG2 : Nonlinear effects in optical fibres: applications (chair: T. Sylvestre replacing J. Dudley, LOPMD)

1. Talks presented in the technical session

Five talks have been presented in the frame of SG2:

1. *STSM report (Supercontinuum generation)*: "Demonstration of a compact low-threshold Supercontinuum fiber laser source in the range 1.1-2.1 μm", A. Boucon, LOPMD, c*ollaboration LOPMD-FPMS*.

Abstract – I present here my short-term scientific mission, which took place in the Faculté Polytechnique de Mons (FPMs) for one week with Dr. Andréi Fotiadi. The supercontinuum (SC) sources have already been studied extensively because of their numerous applications. Usually they are available from solid-state or microchip Q-switched laser with the drawback of integrating bulk laser and fiber components. That's why we aimed at building and studying a compact low-threshold SC all-fiber source. For that purpose we used a passively self-Q-switched Er-Brillouin fiber laser developed by the FPMs Belgian team (supplied by a 120mW pump diode), a highly nonlinear dispersion fiber (HNLF) provided by FEMTO-ST French group (with a low dispersion slope and a high nonlinear coefficient) and a long-wavelength InGaAs photodiode using to make an extended spectrometer. We also inserted a loss section in order to analyze the SC dynamics. On the spectra recorded by OSA at low power we can see two sidelobes close to the pump wavelength generated by modulation instability in the anomalous dispersion regime. This phenomenon leads to sub-pulse generation in the temporal domain and these soliton-like pulses undergo self-frequency red shift through both third-order dispersion and stimulated Raman scattering. Simultaneously these pulses shed blue-shifted dispersive waves at shorter wavelength. The SC extends from to the cut-off wavelength for the fundamental mode up to the upper limit of the OSA. That's why it was interesting to make measures at longer wavelengths. We then compared our results with these obtained with a dispersion-shifted fiber (DSF) and we observed that our SC is more flat and wide than the other. We can conclude that the HNLF is appropriate fiber to generate beautiful supercontinua because of its low dispersion slope and its high nonlinear coefficient.

Remark : Submissions to ECOC and PTL have been done.

2. *Supercontinuum generation*: "Tailoring CW supercontinuum generation in microstructures fibers with two-zero dispersion wavelength", A. Mussot, PHLAM, *collaboration FEMTO/PHLAM.*

Abstract - We theoretically study broadband supercontinuum generation in photonic crystal fibers exhibiting two zero dispersion wavelengths and under continuous-wave pumping. We show that when the pump wavelength is located in between the zero-dispersion wavelengths, a wide and uniform spectral broadening is achieved through modulation instability, generation of both blue-shifted and red-shifted dispersive waves and subsequently through soliton self-frequency shift. This supercontinuum is therefore bounded by these two dispersive waves which allow the control of its bandwidth by a suitable tuning of the fiber dispersion. As a relevant example, we predict that broadband (900-1600 nm) continuous-wave light can be generated in short lengths of microstructured fibers pumped by use of a 10-W Ytterbium fiber laser.

3. "All-fiber frequency doubled Er/Brillouin laser", A. Fotiadi, FPMS, *"collaboration FPMS/ORC*.

Abstract – We propose a low-cost solution for all-fiber frequency-doubled laser sources by combining two ingredients: 1) a self-Q-switched erbium/SBS fiber laser that generates ~5 ns pulses with a bandwidth of ~0.25 nm and a peak/average power contrast up to ~1000 W/25 mW; 2) a periodically poled fiber with QPM resonance around ~1556 nm. We demonstrate

that, in spite of the low average power (~250 μW) associated with the random nature of erbium/SBS laser pulsation, the peak power of second-harmonic pulses at ~778 nm lies within the ten-Watts-scale and is high enough to generate the fourth harmonic at ~389 nm in a cascade process. In practice, simple bending of fiber allowed us to completely suppress the residual pump and to select the second and fourth harmonic signals. The advantage of the proposed solution relies in the specific suitability of the nanosecond pulses generated through the multi-cascade SBS process for nonlinear interaction. Since the optical spectrum of the pulses contains several SBS components (the SBS shift is ~11 GHz) locking between them could considerably enhance values of peak power available for SHG.

4. *Results of partners*: "Control and removing of modulational instabilities in low dispersion photonic crystal fibre cavities", Eric Louvergneaux, PHLAM.

Abstract – Taking up to fourth order dispersion effects into account, we show that fiber resonators become stable for large intensity regime. The range of pump intensities leading to modulational instability becomes finite and controllable. Moreover, by computing analytically the thresholds and frequencies of these instabilities, we demonstrate the existence of a new unstable frequency at the primary threshold. This frequency exists for arbitrary small but nonzero fourth order dispersion coefficient. Numerical simulations for a low and flattened dispersion photonic crystal fiber resonator confirm analytical predictions and opens the way to experimental implementation.

5. *Results of partners*: "Third-order spectral phase compensation in parabolic pulse compression", Marc Hanna, IOTA.

Abstract – We have reported on the use of a hybrid compressor system consisting in a set of prisms embedded in a sequence of gratings specifically designed to optimize the compression of amplified parabolic pulses. Parabolic amplification has been demonstrated to be an elegant and efficient way to amplify femtosecond pulses in positive dispersion fibers. Since high-order dispersion effects -especially the third-order dispersion (TOD)- are particularly important for broad spectra, it is crucial to take them into account to understand and predict energy scaling limitations of parabolic amplifiers. Spectral phase measurements confirm that, as opposed to traditional gratings compressors, the third-order spectral phase is efficiently compensated in our system. We demonstrate that prisms embedded gratings compressors assert itself as a simple and efficient solution to third-order dispersion compensation as this issue grows rapidly with the scaling of the performance in energy and bandwidth of parabolic fiber amplifiers.

2. Status of the study group

Ongoing collaborations

The following collaborations, defined before the "Les Houches" meeting are still in progress:

- *Supercontinuum generation for OCT, XLIM / LOPMD.* Optical Coherence Tomography is an emerging technique for biomedical diagnostic help. This is a non-invasive, high resolution, non-destructive mean for some optical biopsy. Since a few years new developments have been undergone in the field of OCT trying to functionalize OCT measurements. One of them is Spectroscopic OCT where simultaneous accesses to depth resolution as well as spectral features depth resolved in the media are obtained. These

spectroscopic OCT system are mainly based on post processing of classical OCT signals what is time consuming and which add numerical noise. An 'all optical' system is proposed for real-time direct display of depth-frequency analysis of media.

- *CW supercontinuum generation with an Yb- fiber laser and a highly-nonlinear PCF, LOPMD/UAH.* This study is aimed at characterizing numerically and experimentally the dynamics of continuous-wave supercontinuum generation in the regime of large anomalous dispersion. Emphasis is put on the limiting role of fiber dispersion and the absorption peaks present in the fiber.

- *Generation of tunable visible light for biomedical applications*, *IPHT/POLIMI.* The goal of this study is to evaluate the possibility to generate visible ultrashort pulse in a microstructured fibre using a Ti:Sapphire femtosecond laser. The technique consists in exploiting high-order propagation to generate peaks in the visible part of the spectrum and would overcome limits of standard techniques. In fact spectrum slicing of supercontinuum spectrum generated in standard microstructured fibres suffers from limits in visible light generation due to high dispersion in the fundamental mode propagation. Meanwhile, frequency doubling does not allow for wavelength tuning and is upper limited by Ti:Sapphire longest achievable wavelength. IPHT sent a set of microstructured fibre to POLIMI. All fibres were tested and the best one was used for experiments. In a preliminary set of experiments, peaks from 440 nm to 610 nm could be tuned by carefully adjusting the laser power. This phenomenon is already investigated theoretically in the literature but was never investigated for real applications, in particular in biomedicine. We already demonstrated that this technique is potentially alternative to spectrum slicing of supercontinuum spectrum. In fact we obtained similar output power in the visible and, as a further advantage, generation of lower wavelength. During third week of September a final set of experiment has been scheduled recently for measuring induced fluorescence in a cancer-like substance by using yellow and red light. In addition IPHT will deliver a new set of microsctructured fibre that could enhance performances. We believe that this simple approach would be beneficial to extend sensing applications of Ti:Sapphire femtosecond lasers.

  A new partner (FPMS) joined the group during the "Les Houches meeting".

- *Realization of fibre sheat for embedding into concrete, LCPC-IDIL.* It has been decided during the "Les Houches" management committee meeting to move this topic to WG4.

- *Brillouin effect in special fibres for sensing purposes , LCPC-ENST-EDF.*

A new common work has been defined during the "Les Houches" meeting:

- "Control and removing of modulational instabilities in low dispersion photonic crystal fibre cavities": following the presentation of Eric Louvergneaux (see point IV.1.4), a collaboration between PHLAM and UAH.

Nonlinear effects for signal processing

Two groups (LOPMD, IRCICA) aim to develop a mode-locked Raman Fiber Laser. They are currently sharing their vision and discussion for a common project is in progress.

V. SG1 - SG2 : Feedback received from the study group chairmen questionnaire.

In order to enhance the collaboration in the frame of SG1 and SG2, feedback from partners has been requested by the study group chairmen on the following topics:

- PCF Design and Fabrication
- PCF Post-Processing
- Nonlinear Properties of PCF
- Properties of non-PCF highly nonlinear fiber

Feedback from COST partners involved only first three points. It therefore appears to be little interest in HNLF for COST collaborations. A summary of the feedback is presented below:

ORC	Collaborations in post-processing and tapering technologies Collaborations in inverse structure design algorithms
EPFL	Measurement facilities for Brillouin and Kerr, possible Raman
XLIM	Collaboration with SC generation modellers for long pulses
IREA-CNR	Offer measurement of Brillouin gain profile, simulations
FOTON	Collaboration with modellers for SC generation Measurements for measuring Raman gain and Kerr effect
COM-DTU	Theory, modelling, Nonlinearities, Raman measurement etc
PHLAM	Nonlinear pulse propagation, SC modelling

VI. SG3 : Linear and nonlinear distributed optics (chair: L. Zeni, DII-SUN)

1. Talks presented in the technical session

Three talks have been presented in the frame of SG3:

1. *STSM report (Sensing application of distributed measurement)*: "Short-term scientific mission UPNA at EPFL, July 1-31, 2006", Sylvia Diaz, UPNA, *collaboration UPNA/EPFL*.

Abstract – The collaboration between the Laboratory of Nanophotonics and Metrology (NAM), EPFL (Lausanne, Switzerland) and the Group Comunicaciones Ópticas y Aplicaciones Electrónicas from Public University of Navarra (Pamplona, Spain), was intended to study different approaches and strategies to extend the range of a Brillouin distributed sensor by using optical schemes reducing the optical noise and through distributed amplification. We propose a novel setup for a Brillouin distributed sensor based on Brillouin optical time domain analysis. This new configuration eliminates many noise problems found in previous schemes. Resolution of about 2 m over a 37-km standard single-mode fibre was achieved.

Remark : A submission to OFS is planned.

2. *Sensing application of distributed measurement*: "Production of side-hole fibers and characterization from a Brillouin point of view", L. Zeni, DII-SUN, *collaboration DII-SUN /WRUT/UMCS/CNR-IREA*.

Abstract – The elliptical-core side-hole fiber, as provided by WRUT, had a too low degree of birefringence to identify two separate Brillouin peaks related to the two polarization eigenmodes. Actually, measurement of the Brillouin gain spectrum at zero pressure (maximum birefringence condition) revealed no splitting of Brillouin peaks, instead we measured a single-Lorentzian peak, similarly to standard single-mode fibers. We made a new proposal in the context of the use of side-hole fiber for Brillouin-based sensing. In particular, we devised the opportunity to produce a side-hole fiber in which the refractive index contrast between the core and cladding regions is so low that a fraction of the guided mode inside the fiber could be accessed by the hole regions. In this way, we could exploit the interaction between the evanescent field inside the hole with a specific fluid infiltrated in the hole itself. This could be useful not only for gas or liquid sensing, but also, perhaps, for temperature/strain simultaneous sensing. Actually, we may argue that the selective filling of one of the two holes by a high thermo-optic coefficient fluid, could break the symmetry between temperature and strain sensitivity, so as to make their discrimination possible within Brillouin sensing.

3. *Proposal of activity*: "Issue related to the definition of the spatial resolution of distributed sensors", L. Thévenaz, EPFL

Abstract – There is a clear need for definitions of resolutions on quantities measured by distributed fibre sensors. Currently resolutions and accuracies are often presented in the best conditions, while they are certainly not evenly distributed along the fibre. This may clearly induce some confusion to the end users and may result in an unfair competition. In particular there is a clear relation between spatial and measurand resolutions, a worse spatial resolution resulting normally in a better resolution for the measured quantity and vice-versa. If clear definitions can be easily found for intensity-based sensors such as those using Rayleigh and Raman scattering, definitions are not so straightforward for frequency-based sensors such as those using Brillouin scattering. Since the COST Action 299 gathers a very credible pool of experts in the field of distributed sensing, it was decided to study definitions in a dedicated Study Group, with the ambition to issue a recommendation.

2. Status of the study group

Ongoing collaborations

The following collaborations, defined before the "Les Houches" meeting are still in progress:

- Comparison of BOFDA distributed SBS technique, DII-SUN / BAM / CNR-IREA.

- Development of signal processing techniques (improvement of systematic errors / power effects polarization effects), DII-SUN, BAM, CNR-IREA, expected start in October 2006

- Design of special fibers for separation of temperature and strain, DII-SUN, BAM, LCPC, CNR-IREA.

- SBS in MM fibres, DII-SUN, BAM, CNR-IREA. A new partner (FPMS) joined this activity during the "les Houches" meeting.

- New configurations for BOFDA measurement, DII-SUN / CNR-IREA

- SBS for distributed vibration measurements, DII-SUN / CNR-IREA

Two new collaboration works have been defined in "les Houches":

- "Issue related to the definition of the spatial resolution of distributed sensors" (see summary in point VI.1.3). The persons listed below have shown their interest to join this new activity

  Moshe Tur (TAU)
  Jose Miguel Lopez-Higuera (UC-GIF)
  Katerina Krebber (BAM)
  Brian Culshaw (USTR)
  Aldo Minardo (DII-SUN)
  Luigi Zeni (DII-SUN)
  Marc Wuilpart (FPMS)
  Andrei Fotiadi (FPMS)
  Krysztof Borycky (NIT)
  Luc Thévenaz (EPFL)

  It has been suggested that this activity could be moved to WG4.

- "Study of the Rayleigh backscattered signal evolution as a function of temperature", collaboration GAP/FPMS. The planned is divided as follows:

  - Measurements on standard optical fibre in FPMS using a POTDR showed a dependent behaviour of the beat length with temperature. The long resolution length associated with the POTDR limits the results analysis $\Rightarrow$ analysis of the temperature dependence of these fibres a Photon Counting POTDR developed in GAP

  - FPMS performed experiments on the linear dependence of PMF beat length with temperature. The SOP evolution is strongly dependent on T $\Rightarrow$ distributed analysis possible with the OFDR developed in GAP

  - Use of OTDR and/or OFDR to analyze the attenuation of standard optical fibres with respect to temperature while the fibre is immerged into liquid nitrogen. GAP has observed a change of the attenuation when the fibre is immerged in liquid nitrogen. The goal of this measurement is to quantify this loss as a function of temperature and also to see its dependence on different physical properties of the fibre (outer coating type, curve radius).

  It has been proposed to start the collaboration with a STSM (FPMS to GAP).

Polarization properties mapping activity (collaboration GAP/FPMS/FOTON)

As already specified during the Nice meeting, the next step of this activity was to set up a new round robin involving long distance (20km) fibres. It has also been proposed to combine both

GAP and FPMS techniques in order to get the PMD distribution with a better accuracy. For a practical reason (difficulty to find high PMD fibres), the round robin did not start right after the Nice meeting. High PMD fibres are now available (from EPFL) such that the round robin could start. Results are expected for the next working group meeting.

VII. New WG3 structure.

According to the proposal of Luc Thévenaz, a new (more dynamic) structure has been proposed. The new study group configuration is as follows:

SG-FU : Nonlinear effects in PCF and HNL optical fibres: fundamentals, modelling and applications (*Chair: T. Sylvestre*)

SG-BM : Measurement of Brillouin threshold (*Chair: A. Andersson*)

SG-SC : Supercontinuum generation (*Chair: J. Dudley*)

SG-DB : Distributed Brillouin measurements (*Chair: L. Zeni*)

SG-DP : Distributed measurements of polarization properties (*Chair: M. Wuilpart*)

SG-SR : Resolution length definition for DOFS (*Chair: L. Thevenaz*). It has been suggested that this activity could be moved to WG4.