COST 299: Fourth technical meeting
Conference Center, Naples, Italy, 02/07/07 – 03/07/07

WG3 : Distributed and nonlinear optics

Report

Marc Wuilpart (FPMS) and Hervé Maillotte (LOPMD)

I. Overview

In the frame of WG3, the Naples meeting included:

- 2 reports of Short Term Scientific Missions
- 4 reports of collaboration works involving 11 partners

II. Technical presentation

The technical presentation of WG3 entitled *"Overview of coherent-OFDR technique: characterization of components and small systems"* has been presented by Dr Matthieu Legré (GAP). This topic is part of SG3 which is dedicated to distributed measurement techniques.

Abstract -- Coherent reflectometry techniques have important advantages over direct detection techniques: larger sensitivity, larger dynamic range, better resolution, and spurious light suppression. The measurement range is typically limited to<~1km for CoherentOptical Frequency Domain Reflectometry. It is therefore well suited for measurements of optical modules with extended components and for small systems.

III. SG-FU : Nonlinear effects in optical fibres: fundamentals and modelling (chair: H. Maillotte replacing T.Sylvestre, LOPMD)

1. Talk presented in the technical session

"Raman generation in liquid filled photonic crystal fiber", P. Delhaye, LCFIO, France, c*ollaboration LCFIO/XLIM*

Abstract -- Stimulated Raman scattering is widely used in different areas of optics, such as the regeneration of signals in telecommunications or the realization of new tunable laser sources. To obtain efficient Raman scattering, and more generally efficient nonlinearities, three parameters have to be optimized: the interaction length, the pump power density and the active medium that has to be a material with a high Raman gain. Conventional optical fibers present the two first properties but are limited by silica that present a poor Raman gain. The use of capillaries filled with liquids having a high non linear efficiency has soon been proposed. However, as the guidance is obtained by total internal reflection, this solution is limited to the use of liquids with a refractive index higher than the one of silica which limits the number of usable liquids and forbids the use of gases. Photonic crystal fibers offer new solutions by using hollow core fibers filled with high efficient Raman low index liquids or gases. We present here results of stimulated Raman scattering obtained in hollow core photonic crystal fibers filled with ethanol that show that high efficiency with high spatial quality of the emitted beam can be obtained in these new fiber structures.

2. Status of the study group

It has been stated during the meeting that some papers have been published in the frame of the study group :

- The STSM work (LOPMD/EPFL/UAH) about distributed measurements of parametric gain in DSF and HNLF (also with SG-DM) has been published in IEEE Photonics Technology Letters, and presented in ECOC'06, JNOG'06 and EOS'06.

- The collaboration work between LOPMD and CUDOS entitled "extreme pulse propagation phenomena in PCS, such as a few cycle compression and frequency conversion" has been presented in Photonic West'07 as an invited paper and in CLEO-Europe'07. A related tutorial has also been presented in ECOC'07.

Current collaborations

Six collaborations are under progress:

- *Next generation PCF, XLIM / IRCICA / MUL / INESC.* NextGenPCF is an Integrated Project of the "Information Society Technologies" (IST) priority of the 6^{th} 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.

  A presentation in Berlin is foreseen.

- *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). A presentation in Berlin is foreseen.

- LCFIO/LIEKKI: Liekki Yb-fiber for parabolic amplification of femtosecond pulses .

- FOTON/IFRES/PERFOS/LVC: Highly NL PCF for higher-order soliton compression and efficient all-optical regeneration.

- An STSM work (LOPMD/EPFL/PERFOS) will be presented in the next meeting. It concerns the measurement of SBS in PCFs (also with SG-DM). Let us note that the work has already been presented in JNOG'07.

- LCFIO/XLIM: Raman generation in liquid filled PCF

Forthcoming collaborations

Two future collaborations are planned:

- A new collaboration between LOPMD and COM is planned about Raman gain in HNLF.
- A STSM request between LOPMD and ORC is foreseen about experimental tests of generalised nonlinear envelope equation modelling for extreme pulse propagation phenomena.

Themes for future development

The following themes have been proposed for future interactions:

- PCF design and fabrication
- PCF post-processing
- Nonlinear properties of PCF
- Properties of non-PCF highly nonlinear fibres

which all require a strong interaction with WG1

IV. SG-SC : Supercontinuum generation (chair: H. Maillotte replacing J. Dudley, LOPMD)

1. Talk presented in the technical session

STSM report: "Modulation instability of a tunable CW Ytterbium fiber laser in a PERFOS microstructured fiber: application to chromatic dispersion measurement and high-power Supercontinuum generation", L. Abradi, UAH, Spain, c*ollaboration UAH/LOPMD/PERFOS*.

Abstract – The objective of this work was to generate a supercontinuum source by pumping a microstructured PERFOS fibre with a tunable cw Ytterbium-fibre laser emitting in the spectral region of 1060-1104 nm, where the fibre presents large anomalous dispersion. The spectral broadening was lower than expected, compared to older results obtained with similar fibres. We tried to measure the zero-dispersion wavelength $\lambda 0$ and the nonlinear coefficient γ of the fibre by using a method based on modulation instability to investigate the reason of such a low SC spectral broadening. The results show that, on one hand, the nonlinear coefficient of the fibre is much lower than expected, and, on the other hand, that the method based on MI, which up to now has been applied only in the region of small anomalous dispersion of optical fibres, can be also used in large anomalous dispersion regimes to give a rough estimation of λ_0 and γ.

2. Status of the study group

It has been stated during the meeting that some papers have been published in the frame of the study group :

- The STSM work (FPMS/LOPMD) about low-threshold all-fiber SC IR pulsed source has been presented in RFL'07 as an invited talk, in JNOG'07 and ECOC'07. A paper in Photonics Technology Letters has also been submitted.

- The collaboration work between PHLAM and LOPMD entitled "CW controlled tunable SC generation in PCF exhibiting two zero-dispersion wavelengths" has been presented in IPSSO'07 and CLEO-Europe'07. A journal paper in Optics Express will also be published soon.

Current collaborations

Three collaborations are under progress:

- UAH/LOPMD/PERFOS: CW MI for dispersion measurements and SC generation around 1300 nm for OCT. A STSM has been accomplished but the results still need to be improved.
- POLIMI/IPHT/FPMS: Efficient generation of tunable visible ultrashort pulse for biomedical applications. A presentation should be done in the next meeting.
- XLIM/LOPMD: short-wavelength enhanced SC generation under dual wavelength microchip-laser-pumping for spectroscopic OCT. A presentation will also be done in the next meeting.

Forthcoming collaborations

Two future collaborations are planned:

- A STSM between PHLAM and UAH is foreseen: CW controlled tunable SC generation in a PCF with two zero dispersion wavelengths.
- A STSM between WUT and XLIM is also foreseen: FWM in tellurium-oxide PCF for 2 μm to 4.1 μm efficient generation (also with WG1).

V. SG-BM : Measurement of Brillouin threshold (chair: A. Andersson, SP)

1. Talk presented in the technical session

Report of measurements, A. Andersson, SP, Sweden, *collaboration SP / LOPMD / FPMS / IREE / GTF*.

The measurement report can be found in appendix 1

2. Status of the study group

The status of the SG can be found in appendix 1.

VI. SG-DB : Distributed Brillouin measurement (chair: L. Zeni, DII-SUN)

1. Talk presented in the technical session

"Progress on characterization of specialty fibres from a Brillouin point of view", A. Minardo, DII-SUN, Italy, c*ollaboration DII-SUN/UMCS/CNR-IREA/WRUT*.

Abstract – We presented our recent progress on characterization of specialty fiber from a Brillouin point of view. In particular, we presented some results related to the so-called "core-suspended" fibers, provided by UMCS. We performed some FEM numerical simulations, according to which the Brillouin frequency of these fibers is very strongly dependent of the refractive index of the material filling the fiber holes. In particular, we estimated a sensitivity of about 1MHz/2·10-4 in terms of Brillouin frequency shift. Such a high sensitivity to refractive index can be exploited in several ways. For example, we proposed the use of a negative thermo-optic liquid to fill the holes. In this way, the increase of Young modulus with temperature can be compensated by reduction of the effective refractive index of the fiber, hence reducing the overall sensitivity of Brillouin frequency shift to temperature. This property can be useful is distributed SBS-based strain sensing.

2. Status of the study group

Three collaborations are under progress:

- DII-SUN/WRUT/UMCS/CNR-IREA: Experimental characterization of specialty fibre from a Brillouin point of view.
- DII-SUN/BAM/CNR-IREA: Comparison of BOFDA distributed SBS technique.

Let us note that a FP7 joint project will be submitted. The tentative project title is "Monitoring of hydroelectric and nuclear plants by distributed optical fibre sensors". Six teams of our COST action are involved : LCPC, BAM, WRUT, UMCS, DII-SUN and CNR-IREA.

VII. SG-DP : Distributed measurement of polarization properties (chair: M. Wuilpart, FPMS)

1. Talks presented in the technical session

1. "High dynamic distributed measurement of PMD", M. Wuilpart, FPMS, Belgium, c*ollaboration GAP/FOTON/MUL/FPMS.*

Abstract – A first round robin has been organized between GAP, FPMS, FOTON and MUL and the results presented in Nice. The goal was to compare the POTDR techniques developed in FPMS and GAP with comparison with classical PMD measurements performed in all teams. A good agreement was observed except for a low beat length fibre for which the FPMS technique was not appropriate. A second round robin has been organized in order to evaluate the possible association of the GAP technique and a modified FPMS technique. The modification basically consists in adapting the algorithm to allow longer OTDR pulses which results in an increase of the dynamics. The GAP technique is used to extract the fibre beat length while the FPMS technique is used the measure the coupling length obtained by a POTDR measurement and the beat length value provided by GAP. The measurements have been performed on a 45 km concatenation of 5 fibres including small length of high PMD values. The obtained PMD were in good agreement with classical techniques.

2. *STSM report*: "Study of Rayleigh backscattered evolution as a function of temperature", C. Crunelle, FPMS, Belgium, c*ollaboration GAP/FPMS.*

Abstract – The aim of the 2 weeks Short Term Scientific Mission was to start a collaboration between the Group of Applied Physics (GAP-Optique) in Geneva (Switzerland) and the Electromagnetism and Telecommunications Department of the Faculté Polytechnique de Mons (FPMS) in Mons (Belgium) within the scope of distributed sensing methods. More precisely, the goal of this mission was to study the evolution of the Rayleigh backscattered signal for different types of fibres subject to different temperature conditions. The linear dependence of the beat length on temperature has been investigated on a 26 meters long fibre with elliptical core, and a beat length of about 5-6 cm. For that purpose, the fibre was either entirely, or partly, placed into a temperature controlled environment, and analysed with a coherent polarisation-sensitive reflection measurement (P-OFDR). Results demonstrated the possible achievement of a distributed temperature sensor based on that beat length dependence. Other measurements were also carried out on 5 meters long HiBi fibres that also exhibit a linear dependence of the beat length on temperature. Another type of measurement consisted in measuring the attenuation of standard optical fibre with respect to temperature while the fibre is immerged into liquid nitrogen. These measurements showed, for standard patchcords, a linear variation of the transmitted power with temperature between -10°C and -70°C. This temperature range is interesting for sensing applications. For a standard single mode fibre (without loose tube), no dependence was observed.

2. Status of the study group

Current collaborations

Three collaborations are still under progress. They are the continuation of the two collaboration works presented during the meeting:

- GAP/FPMS/FOTON/MUL: The second round robin showed that it is possible to associate the GAP and FPMS POTDR techniques for measuring PMD distribution even if the beat length is quite low. The activities will now focus on studying the possibility to apply the FPMS algorithm for the determination of the coupling length directly from the POTDR trace provided by GAP photon counting POTDR signal. In case of success, it will mean that all the trace processing can be done with a single experimental set-up which will make the technique practical.
- GAP/FPMS: “Analysis of the attenuation of standard optical fibres with respect to temperature while the fibre is immerged into liquid nitrogen”. This study investigates the potential use of fibres for low temperature distributed sensing. The effort will now focus on the analysis of the repeatability, the bending effect and the coating effect.
- GAP/FPMS: The measurements undertaken within the STSM at GAP-Optique did exhibit the linear variation of the beat length with temperature (see talk 2). That property was exploited to show a distributed temperature analysis of different types of fibre. In particular, the possibility to detect hot and cold zones on an optical fibre was demonstrated. The goal of the collaboration between GAP-Optique and FPMs is now to work on improving the accuracy of the detected temperatures.

APPENDIX 1 : Measurements of SBS in SMF, DSF and DCF type of fibres. Results reported in Naples June 2007 for WG3 SG2.

Anne Andersson, anne.andersson@sp.se

SBS, Stimulated Brillouin Scattering
SMF Single Mode Fibres
DSF, Dispersion Shifted Fibres
DCF, Dispersion Compensating Fibre

Result contributions from;
Anne Andersson SP, Marc Wuilpart and Priscilla Nankoua at FPM and Hervé Maillotte LOPMD.
Other interested and/or contributive persons are Jesus Subias, Thibaut Silvestre, Luc Thevenaz and Jiri Kanka.

Abstract
Measurements of Psbs threshold, Pth, have been done on three types of fibres, SMF, DSF and DCF. The results reported here are power threshold Pth is when backscattered power over Rayleigh level equals one percent of inserted power (Psbs=1% of Pin=Pth1%).
Three labs have reported results, SP, FPM and LOPMD.
SMF Pth1% results differ between FPM (4,4 mW) and SP(6,3 mW), LOPMD had no report on SMF. All three labs agree (if assumptions is correct for LOPMD results) DSF fibres(6 ± 0,5 mW). Latter is also in agreement with the theoretical estimation for a 13 km DSF (6,2 mW).
Better understanding of polarisation properties of the set-up is needed.
Depolarisation is suggested at discussion in Naples and also in the NPL report.
Properties of the fibres and the measurement parameters will need to be better defined.

Background
Informal reports from ITU study group work towards the revision of Stimulated Brillouin Scattering Appendix of G.650.2.
Measurements are also appreciated for knowing Brillouin backscattering effects in non-linear fibres and for sensor purposes.Understanding and education of how to measure and understand the Brillouin backreflection is an essential outcome from this study.

Introduction
SBS in single mode optical fibres is characterised by efficient transfer of optical power from wave propagation in one direction to a wave in the opposite direction. The pump wave generates a refractive index fluctuation within the fibre core through the process of electrostriction. Electrostriction is a property of all electrical non-conductors, dielectrics, that causes them to change their shape under the application of an electric field. The refractive index fluctuation acts like a Bragg grating traveling forwards at an acoustic velocity, causing the backscattered Stokes wave to be Doppler shifted to a lower frequency than the pump wave traveling in the forward direction. The frequency shift is in the order of 10 GHz in a single mode optical fibre.The line width of the SBS gain is of the order of 50 MHz

Set-up
Below figure denoted 2.1 is the set-up reported by FPM.
SP set-up differs in using the laser to change power and in using circulator instead of splitter.
LOPMD uses a set-up with an Optical Spectrum Analyzer as power meter.

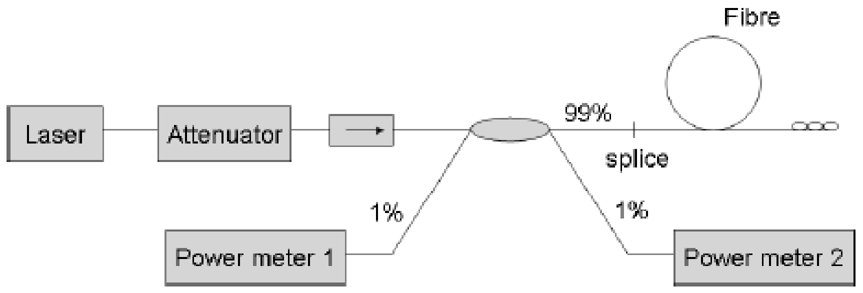

Figure 2.1: Experimental set-up

Demands to be able to compare results;

- CW source that has narrow line width less than Brillouine gain (x10 MHz) (FPM 0,6 MHz and SP 100 kHz).
- The NPL report in agreement with meeting in Naples that the signal most likely should be depolarised to be able to compare results.
- Fibre length over 25 km to saturate the effect i.e. length dependent
- Calibration of the set-up.
- Ksbs=1,5 for completely depolarised and =2 for conventional measurements of SMF

Calculations

Depending on the measurement circumstances the Ksbs can vary between 1 and 2.
Below formulas* for Pth definitions. Psbs = 10%Pin the factor is 19 and a factor 18 for Psbs=1% Pin. Factor 21 for Psbs=Pin.

$$P_{th} \cong 19 \frac{K_{SBS} A_{eff}}{g_{SBS} L_{eff}} \qquad L_{eff} = \frac{1}{\alpha}\left[1 - \exp(-\alpha L)\right],$$

Measurement methods for SBS in Optical Fibres NPL report COEM June 1999
The Pth calculations in below table use a factor of 18 and Ksbs 2 for SMF. One can note a very small shift for fibre length over 25 km. Also depending on polarisation dependency in the set-up the value for the same 25 km fibre can be between 3 mW to 6,5 mW.

Length,km	dB/km	Leff	gsbs	Aeff	Ksbs	Pth, 1%
3	0,18	2,32	5,00E-11	5,00E-11	2	15,53
6	0,18	3,67	5,00E-11	5,00E-11	2	9,81
13	0,18	5,02	5,00E-11	5,00E-11	2	7,17
25	0,18	5,49	5,00E-11	5,00E-11	2	6,55
50	0,18	5,55	5,00E-11	5,00E-11	2	6,48
90	0,18	5,56	5,00E-11	5,00E-11	2	6,48
100	0,18	5,56	5,00E-11	5,00E-11	2	6,48

Length,km	dB/km	Leff	gsbs	Aeff	Ksbs	Pth, 1%
25	0,18	5,49	5,00E-11	5,00E-11	1	3,28
25	0,18	5,49	5,00E-11	5,00E-11	1,5	4,91
25	0,18	5,49	5,00E-11	5,00E-11	2	6,55

Results
FPM
Definition Psbs=1%Pin
25 km SMF Pth=4,4 ±0,3 mW,
13 km DSF Pth=5,7±0,3 mW and
2,5 km DCF 15,7±0,8 mW

LOPMD
DSF Pth= 10,8 mW
α = 0.21 dB/km, Leff = 2965 m corresponds to a 4,64 km long fibre. If Psbs=Pin definition is assumed 10,8 mW corresponds to 7,2 mW for a 13 km fibre and 6,2 mW for Psbs=1%Pin definition. Ksbs factor 2 instead of 1,5 with Pth =8,2 mW is for comparison.

Length,km	dB/km	Leff	gsbs	Aeff	Ksbs	Psbs=1%Pin	Psbs=Pin
4,64	0,21	2,965	5,00E-11	5,10E-11	1,5	9,3	**10,8**
13	0,21	4,451	5,00E-11	5,10E-11	1,5	**6,2**	**7,2**
13	0,21	4,451	5,00E-11	5,10E-11	2	**8,2**	9,6

SP, Sweden
Definition Psbs=1%Pin

Psbs:1%Pin	SMF1,25km mW	SMF2,25km mW	DSF,13 km mW
Ave stdev	6,58 0,97	6,15 0,84	6,41 1,70
no of meas.	7	8	4

Uncertainty
Both SP and FPM reports an uncertainty of 5 % in power recording.
An uncertainty in Pin of ± 5 % corresponds to uncertainty of Psbs ± 0,5 mW for the SP values.SP values also show bad repeatability rising the total uncertainty to about ± 1,2 mW for SMF and ± 2,0 for DSF.
No uncertainty is reported for LOPMD results.

Conclusions and suggestion for future work
Measurements of Psbs threshold, Pth, have been done on three types of fibres, SMF, DSF and DCF. The results reported here are power threshold Pth is when backscattered power over Rayleigh level equals one percent of inserted power (Psbs=1% of Pin=Pth1%).
Three labs have contributed, SP, FPM and LOPMD.
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Better understanding of polarisation properties of the set-up is needed.
Depolarisation is suggested at discussion in Naples and also in the NPL report.
Properties of the fibres and the measurement parameters will need to be better defined.
It might be necessary to measure on the same fibres.