COST 299: Second technical committee
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WG3 : Distributed and nonlinear optics

Report

Marc Wuilpart (FPMS) and Hervé Maillotte (LOPMD)

I. Technical presentation

The technical presentation of WG3 has been dedicated to a review of existing POTDR-based distributed measurement techniques. In the frame of SG3, a round robin for comparing PODTR measurement set-up developed in the COST 299 community has been set up and it therefore appeared interesting to address a partial review of existing techniques to the entire COST community. The talk entitled “Distributed measurements of the polarization properties in optical fibres using a Polarization-OTDR” has been presented by Marc Wuilpart (FPMS). The abstract can be found hereafter:

Abstract -- We review some Polarization-OTDR techniques for the distributed measurement of the beat length, the coupling length and the polarization mode dispersion in telecommunications optical fibres. After explaining the generic POTDR set-up, various configurations proposed in the literature are detailed. Some of them only allow beat length measurement whereas the others enable the measurement of the coupling or the PMD. The presentation then focus on the two measurement techniques developed in the COST 299 community: the photon counting POTDR developed in GAP and the FPMS technique based on the statistical properties of the POTDR trace. Advantages and drawback of each technique are presented.

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

1. Talks presented in the technical session

Three talks have been presented in the frame of SG1:

1. *Presentation of a new partner*: Optoelectronics Research Center (ORC), University of Southampton, N. Broderick

Abstract -- Neil Broderick introduced the Optoelectronics Research Centre, which is a part of the University of Southampton. The ORC has a 35 year history of developing new devices for telecommunications from low loss silica fibres to the erbium doped fibre amplifiers and is among the leading centres for research in the UK. The ORC is able to bring fibre fabrication (doped fibres, photonic crystal fibres, non-silica fibres …), grating writing and device testing to the COST 299 network as well as having experience in modelling PCFs. Neil Broderick stated that the ORC is keen to engage with as many people as possible and looks forward to being a full member of the COST action.

2. *Measurement of nonlinear effects*: “Measurement techniques for SBS Stimulated Brillouin Scattering”, Anne Andersson (SP).

Abstract -- The Brillouin scattering, BS, can involve either the generation of waves (Stokes process) or annihilation of waves (anti-Stokes process) in the material. BS can be used to characterise thin film, bulk material and fibres. In fibres it also has a limiting effect of the fibre performance. BS is a nonlinear scattering effect from acoustic waves (phonons). The incident photon converts to a scattered photon (- 10 to 20 GHz below the incident radiation frequency) and a phonon (travelling at a speed of 5,6 km/s in standard single mode fibres). The BS Shift in fibres depends much on the GeOx doping within the core. BS can be described theoretically by the ultrafast third-order susceptibility $\chi(3)$ where the real part leads to SPM, XPM, and FWM and the imaginary part leads to SBS and SRS. Spontaneous BS at low powers when stimulated the effect can be very strong Stimulated BS (up to 90 dB) at powers above a threshold Pth. Threshold Pth = Aeff*21/(gain* Leff). Pth is low (< 5 mW) for long telecom fibres (>20 km), Pth can be high (20 W) for highly Yb-doped Fibre Lasers and Amplifiers (1 m fibre), and becomes a limiting factor at 1 kW. Typical bandwidth of the backscattered Brillouin shifted signal is 50 – 100 MHz. Reduction or control of BS can be achieved by fibre nonuniformities, large Aeff, small Leff, phase mismatching/matching. Phase matching is a group of techniques for achieving efficient nonlinear interactions to enhance the effect. Using Fibre Gratings is an other example of technique for controlling the BS (Lee and Agrawal, Opt.Exp.11.3467 (2003)). ITU study group is working with the subject and has done a comparison between 6 methods for a couple of standard single mode fibres. They call the effect SB critical power since the SB threshold lacks a clear definition. In all methods the input and backscattered power are recorded. Two groups of methods are reported on. Methods that need power referencing of the backscattered signal and methods that use some analyses of the backscattered power like moving window 2nd derivative. First group reports a SB critical power of 7.8 mW and the second group reports on a value around 7.0 mW. Both methods where measured ten times with a similar standard deviation with a value below 0.08 mW. A new technique for automated fibre testing is proposed by SP, quantifying the SBS critical power. The technique differs from previously presented work through the modulation of the input signal, and is easy to automate. The estimated reported critical power was about 17 mW for a standard single mode fibre of 25 km. SP is interested to compare the technique and discuss theory and results from other techniques.

3. *Measurement of nonlinear effects*: “Strong Guided Acoustic Wave Brillouin Scattering in photonic crystal fibres”, H. Maillotte, J.C. Beugnot, T. Sylvestre, G. Mélin, V. Laude.

Abstract -- We report on our recent experimental studies of guided acoustic wave Brillouin scattering (GAWBS) in various core-size photonic crystal fibers using the so-called fiber loop mirror technique. We show first an almost complete suppression of the usual low-frequency polarized GAWBS modes due to efficient isolation, by the air-hole microstructure, of the optical guided mode from the acoustic modes guided in the surrounding glass cladding. Meanwhile, a high-frequency sharp optical spectral component reveals the existence of a strong isolated acoustic mode in the small-core fibers. Finite-element-method simulations clearly demonstrate that this acoustic mode is the fundamental phonon mode of the fiber core. Its enhanced generation is due to its strong confinement by the air-hole microstructure and strong overlap with the optical guided mode. We have found that the acoustic fundamental

core-mode frequency and the fiber core diameter are inversely proportional, in quite good agreement with the experimental measurements.

2. Status of the study group

Ongoing collaborations

- *Nonlinear characterization of irradiated PCF, XLIM / SCK*

- *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).

- *Novel ultrafast pulse propagation phenomena in photonic crystal fiber, CUDOS / LOPMD.* Robert Fischer, a PhD student in the group of Yuri Kivshar and Dragomir Neshev at Australian National University, is spending 10 weeks at LOPMD in the framework of CUDOS's participation in COST 299. He is working with Professor John Dudley on novel pulse propagation phenomena in photonic crystal fiber such as few cycle compression and frequency conversion.

Planned work for SBS threshold measurement

During the technical meeting, Anne Andersson (SP) summarized the ITU work concerning the measurement of SBS threshold. During the discussion, some problems were underlined: problem related to the power meter calibration, problem of reflexion and problem of a clear definition of the Brillouin threshold. A proposal has then been set-up by four interested team (EPFL, SP, IREE, UAH). The group suggested for each participant interested in this measurement to set up a method and try to measure the SBS on standard single mode fibres as well as for other fibres of interest. EPFL will provide a fibre for the round robin. The results and the experimental difficulties will be presented at next meeting in Les Houches in January

2007. Modelling of the effect is also appreciated to help and interpret the results. For doped fibres LIEKKI volunteered and can be contacted. The report of Anne Andersson can be found in appendix 1.

Measurement of Raman and Brillouin effects in PCF.

It resulted from the Mons meeting that a round robin for the PCF characterization would have been proposed. The SG chairman, Thibaut Sylvestre, asked for the facilities, equipment and fibres available in the COST 299 community. The following groups answered:

Users : facilities and equipments

1. Manolia group, LCFIO, P. Delaye
2. DII-SUN, L. Zeni
3. CNR-IREA, R. Bernini
4. FOTON, ENSSAT : T. Chartier
5. LCPC, Sylvie Lesoille, Spontaneous Brillouin scattering, collab. ENST
6. POLIMI, S. Taccheo.

Suppliers

1 expression of interest: Pawel Mergo, UMCS

During the Nice meeting, two additional suppliers, XLIM and PERFOS (to be confirmed) volunteered to make their fibres available.

It was stated by the SG chairman that it will be more efficient if partners make specific propositions about which parameters can be measured. An email will be sent by the chairman to ask for specific propositions from which a common proposal will be defined.

Call for collaboration

In PCF, the measured Brillouin threshold is greater than predicted by the theory. LOPMD is looking for a collaboration work in order to explain this phenomenon.

<u>III. SG2 : Nonlinear effects in optical fibres: applications (chair: T. Sylvestre replacing J. Dudley, LOPMD)</u>

1. Talks presented in the technical session

Four talks have been presented in the frame of SG2:

1. *Nonlinear effects for metrology purposes*: "Realization of fibre sheat for embedding into concrete", V. Lanticq and S. Lesoille, LCPC, c*ollaboration LCPC-IDIL.*

Abstract – LCPC developed with IDIL a fiber sheath for embedding into concrete: a composite-made wave-like sensor body enables continuous bonding between optical fibre and concrete and ensures strain and temperature fields transfer from the concrete to the fiber. Laboratory and field tests were performed with 10cm, 20 cm and 70cm long sensors embedded into concrete and interrogated by a low-coherence Michelson interferometer. OFS and reference sensors measurements perfectly agreed.

2. *Nonlinear effects for metrology purposes*: "Brillouin effect in special fibres for sensing purposes", V. Lanticq and S. Lesoille, LCPC, *collaboration LCPC-ENST-EDF.*

Abstract - Temperature and strain distributed Brillouin measurements have been carried out on an instrumented concrete beam during concrete hardening, and during a four-point bending test. It results that the main issue for future Brillouin sensor system is to separate strain and temperature influence. This is the subject of a PhD thesis that links EDF LCPC and ENST. The chosen method is to use special fibers that present multi-Brillouin peaks whose dependence with strain and temperature would be decorrelated. An exact model enabling calculation of acoustic and optical modes, thus spontaneous Brillouin spectrum has been developed for any arbitrary several-dopant-ring optical fibres. Several commercially available fibers (SMF28, DSF, and LEAF) were measured with an operational laboratory setup (spont. + non distributed) and showed multi-Brillouin peak spectra. Meanwhile, modelling of the thermal and strain dependence of Brillouin peaks is progressing; thermal and strain experimental setup for measurement of Brillouin spectra is almost operational.
We look forward to collaborate, especially on two subjects:
1. The choice of the fiber: to validate the model, dopants profile knowledge is required. Moreover, there is a need for other fibers to test, such as PCF.
2. The distributed optoelectronic part: BOTDR versus BOFDR, spontaneous versus stimulated Brillouin scattering.

3. *Supercontinuum generation*: "Supercontinuum generation in holey fibres", P. Leproux, XLIM.

Abstract – In last meeting in Nice have been presented some developments made at XLIM laboratory in the field of supercontinuum generation in holey fibres. Three examples of nonlinear structures fabricated at XLIM were mentioned:
- a common microstructured fibre with a π/3 symmetry (1),
- a highly birefringent fibre with two bigger holes around the core (2),
- a Yb-doped fibre with an air-clad structure (3).

Below are the main results obtained in these three types of fibres.
(1) Dual wavelength pumping (532 / 1064 nm) allows generating both visible and infrared broadenings. Thanks to the XPM process involved from the infrared spectrum onto the green pump, it is possible to tune the visible continuum towards the blue or the red wavelengths. Single pumping can also be used to obtain very wide spectral broadening (350 -> 1750 nm).
(2) Very high group birefringence has been measured in this fibre (close to 10^{-2}), as well as evidence of second harmonic generation. Supercontinuum generation is also improved thanks to a better control of polarization.
(3) This innovative fibre permits to regenerate the pump wave during the propagation, resulting in an increase of the power spectral density of the visible continuum (gain ~ 10 dB).

4. *Supercontinuum generation*: "Application of Er/Brillouin laser for generation of nanosecond supercontinuum in a standard dispersion shifted fiber", A. Fotiadi and P. Mégret, FPMS.

Abstract – Brillouin mirrors based on a single-mode optical fiber provide the simplest, completely passive and universal way to produce nanosecond pulses with extensive

wavelength tunability. We propose an all-fiber solution, where a passively Q-switched Er-doped Brillouin fiber laser pumped by a low-power laser diode produces pulses with a peak/average power contrast of 500 W/25 mW, and, in association with a conventional dispersion shifted fiber (DSF) employed as an extra-cavity nonlinear media, causes the generation of a nanosecond supercontinuum extending from 900 to over 1800 nm. Expanding evolution of the spectrum kicked off by multi cascade-Brillouin process is reported.

2. Status of the study group

Ongoing collaborations

- *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.

- *Realization of fibre sheat for embedding into concrete, LCPC-IDIL.*

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

Planned STSM

A short term scientific mission is planned between LOPMD and FPMS team. The aim of this Short-Term Scientific Mission (STSM) is to demonstrate highly-efficient supercontinuum generation (SCG) in nanosecond regime using the home-made self-Q-switched Er-Brillouin fiber source developed by the FPMS Belgian team and highly nonlinear dispersion shifted fibers (HNLFs) provided by the LOPMD French team. Mid-October, Anne Boucon from LOPMD will start this STSM. A detailed work planned can be found in appendix 2.

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.

Supercontinuum Generation: Modelling and Applications

In Mons, several groups (LOPMD (FR), XLIM (FR), FPMS (BE), FOTON (FR), CUDOS (AU), IREE (CZ), WU (PL), UAH (ES), IFN, COM-DTU (DK), ULB (BE), HUT (FI)) were interested for a common project concerning supercontinuum generation. The SG chairman recently sent an email (see appendix 3) presenting a proposal and asking for feedback. Surprisingly little feedback from the consortium about concrete supercontinuum activities have been received and we are far from exploiting the potential synergy of the different members. It has been suggested in Nice to reinforce communication with the SG chairmen such that he has a complete view of what is going on and such that he can introduce new partners that could help with the collaboration proposal.

<u>IV. SG3 : Linear and nonlinear distributed optics (chair: L. Zeni, DII-SUN)</u>

1. Talks presented in the technical session

Four talks have been presented in the frame of SG3:

1. *Sensing application of distributed measurement*: "New configuration for BOFDA measurement", A. Minardo, *collaboration DII-SUN / CNR-IREA*.

Abstract – A novel configuration for Brillouin Optical Frequency Domain Analysis (BOFDA) has been devised and experimentally tested. The proposed technique is based on the use of two counter-propagating intensity-modulated optical signals, with their modulation frequencies differing by a small, fixed quantity. Stimulated Brillouin scattering (SBS) leads to an optical demodulation of the probe signal, generating on its intensity spectrum a low-frequency component which is detected by a lock-in amplifier. As a proof of concept, measurements with a spatial resolution of 6m have been reported on a 230m-long sensing fiber. Work will continue to achieve higher spatial resolution.

2. *Sensing application of distributed measurement*: “SBS in MM fibres”, L. Zeni (DII-SUN), *collaboration DII-SUN / BAM / CNR-IREA*.

Abstract – The basic idea is to exploit multimode (MM) fibers to perform distributed strain and temperature measurements by means of Brillouin scattering. The choice of multimode fibers stems from the fact that they are less sensitive to microbending with respect to single mode fibers, so resulting more suitable for the integration in structures (e.g. geotextiles, etc). In fact, the process of integration often results in a fiber microbending that can severely attenuate pump and stokes light. Preliminary experimental characterizations have been carried out on step-index (at DII-SUN & CNR-IREA) and graded-index (at BAM) MM fibers. The results indicate that MM step-index fibers exhibit a Brillouin spectrum that is well fitted by a double Lorentzian profile. Work on the interpretation of these findings as well as on the spectrum dependence on temperature and strain is in progress. Graded-index MM fibers Brillouin spectrum, on the other hand, exhibits a Lorentzian profile even with a lower gain. The dependence of the Brillouin shift on temperature is similar to the shift observed in single-mode fibers.

3. *Sensing application of distributed measurement*: “Characterization of side-hole fibers from a Brillouin point of view”, L. Zeni (DII-SUN), *collaboration DII-SUN / WRUT / UMCS / CNR-IREA*.

Abstract – A side-hole fiber has been manufactured at Laboratory of Fiber Optic Technology - University of Lublin – Poland and first characterized, at WRUT and UMCS, from a structural point of view. In order to explore the possibility to realize a distributed pressure sensor based on Brillouin scattering, the Brillouin spectrum of a 25 meters long piece of same side-hole fiber has been measured at DII-SUN. The measurements were performed with a spatial resolution of about 66cm and the results indicate a single-Lorentzian spectrum exhibiting a good uniformity along the fiber. Work is in progress to evaluate the sensitivity of the Brillouin spectrum to external pressure changes.

4. *Distributed PMD*: “Polarization-OTDR for the measurement of fibre polarization properties : round robin and comparison”, M. Wuilpart (FPMS), *collaboration GAP / FOTON / MULTITEL / FPMS.*

Abstract – The results of the first round robin within SG1 are reported. Five fibres were involved in the round robin: a G652, a DSF, a NZDSF, a DCF and a high PMD (2ps) fibre. A good agreement has been obtained between the beat length values measured with a GAP photon counting techniqe and the POTDR developed in FPMS. A good agreement, (except for the high PMD fibre) was also observed between the coupling length values measured at FPMS compared to the coupling length obtained from the GAP beat length and the GAP global PMD measurements. The agreement between the PMD measured in FPMS with the global PMD measured in all teams is also satisfactory.

2. Status of the study group

Ongoing collaborations

Production of side-hole fibers and characterization from a Brillouin point of view, *DII-SUN / WRUT / UMCS / CNR-IREA*, in progress

Comparison of BOFDA distributed SBS technique, *DII-SUN / BAM / CNR-IREA, e*xpected start in October 2006

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*, expected start in October 2006

SBS in MM fibres, *DII-SUN, BAM, CNR-IREA*, in progress

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

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

Chromatic dispersion mapping

Several groups developed a bench for the chromatic dispersion mapping in optical fibre links. A round robin has been proposed in Mons with different types of optical fibres. The interested teams were DM-CSIC, EPFL and LOPMD.

Mailing has been done to get more information about the existing techniques within the COST 299 community. A proposal will be soon set up. The fibres will be provided by CSIC team

Polarization properties mapping

A round robin has been organized between GAP-FPMS-FOTON-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. Five fibres were involved in the round robin: a G652, a DSF, a NZDSF, a DCF and a high PMD (2ps) fibre. A good agreement has been obtained between the beat length values measured with a GAP photon counting technique and the POTDR developed in FPMS. A good agreement, (except for the high PMD fibre) was also observed between the coupling length values measured at FPMS compared to the coupling length obtained from the GAP beat length and the GAP global PMD measurements. The agreement between the PMD measured in FPMS with the global PMD measured in all teams is also satisfactory. The next step is to set up a new round robin involving long distance (20km) fibres (expected start : November 2006). It has also been proposed to combine both GAP and FPMS techniques in order to get the ¨PMD distribution with a better accuracy.

APPENDIX 1: SBS THRESHOLD MEASUREMENT

Measurement techniques for SBS Stimulated Brillouin Scattering

Anne Andersson, SP Sweden

This report is a short review of the presentation in Nice, the study group participants and the next action of the group. It motivates continued investigations in COST299 about SBS measurement techniques and summarises the interested parties.

SBS Study group will be

- Marc Wuilpart; FPMS in Mons
- Luc Thevenaz; EPFL in Lausanne
- Anne Andersson;SP in Sweden
- Jesus Subias; UNIZAR Spain
- Mircea Hotoleanu; LIEKKI Finland
- Moche Tur; TAU Israel
- Stefano Taccheo; POLIMI in Italy
- Jiri Kanka;URE in Czeck republic

Next action in SBS study group

The group suggested for each participant interested in measurements to set up a method and try to measure the SBS on standard single mode fibres as well as on other fibres of interest. The results will be presented at next meeting in Les Houches in January 2007. Modelling of the effect is also appreciated to help and interpret the results. We are also working on suppliers of fibres to the group. For doped fibres LIEKKI voluntered and can be contacted.

Presentation in Nice

There is a huge benefit if this power level could be easily characterized for a batch of fibres, to enable quality control as well as optimized choice of fibres for an installation.

The Brillouin scattering, BS, can involve either the generation of waves (Stokes process) or annihilation of waves (anti-Stokes process) in the material. BS can be used to characterise thin film, bulk material and fibres. In fibres it also has a limiting effect of the fibre performance. BS is a nonlinear scattering effect from acoustic waves (phonons). The incident photon converts to a scattered photon (- 10 to 20 GHz below the incident radiation frequency) and a phonon (travelling at a speed of 5,6 km/s in standard single mode fibres). The BS Shift in fibres depends much on the GeOx doping within the core. BS can be described theoretically by the ultrafast third-order susceptibility $\chi(3)$ where the real part leads to SPM, XPM, and FWM and the imaginary part leads to SBS and SRS. Spontaneous BS at low powers when stimulated the effect can be very strong Stimulated BS (up to 90 dB) at powers above a threshold Pth. Threshold Pth = Aeff*21/(gain* Leff). Pth is low (< 5 mW) for long telecom fibres (>20 km), Pth can be high (20 W) for highly Yb-doped Fibre Lasers and Amplifiers (1 m fibre), and becomes a limiting factor at 1 kW. Typical bandwidth of the backscattered Brillouin shifted signal is 50 – 100 MHz. Reduction or control of BS can be achieved by fibre nonuniformities, large Aeff, small Leff, phase mismatching/matching. Phase matching is a group of techniques for achieving efficient nonlinear interactions to enhance the effect. Using Fibre Gratings is an other example of technique for controlling the BS (Lee and Agrawal, Opt.Exp.11.3467 (2003)). ITU study group is working with the subject and has done a comparison between 6 methods for a couple of standard single mode fibres. They call the effect SB critical power since the SB threshold lacks a clear definition. In all methods the input and backscattered power are recorded. Two groups of methods are reported on. Methods that need power referencing of the backscattered signal and methods that use some analyses of the backscattered power like moving window 2nd derivative. First group reports a SB critical power of 7.8 mW and the second group reports on a value around 7.0 mW. Both methods where measured ten times with a similar standard deviation with a value below 0.08 mW. A new technique for automated fibre testing is proposed by SP, quantifying the SBS critical power. The technique differs from previously presented work through the modulation of the input signal, and is easy to automate. The estimated reported critical power was about 17 mW for a standard single mode fibre of 25 km. SP is interested to compare the technique and discuss theory and results from other techniques.

References

- http://www.rp-photonics.com/brillouin_scattering.html
- Tutorial ”Nonlinear Effects in Optical Fibres” 2006 by Agrawal
- ITU STUDY GROUP 15 ”Preliminay comparison of SBS critical power definitions for various test fibres” Hanson at Corning
- ITU STUDY GROUP 15 ” Clarification on the fitting method for SBS using second derivative definition
- ”Dynamic Stimulated Brillouin Scattering Analysis”, Djupsjöbacka et al., Journal of Lightwave Technology Vol 18 No 3 March 2000
- “Measurement technique for Stimulated Brillouin Scattering critical power” SOFM in Boulder Sept 2006, Hedekvist and Andersson
- ”Slow light in optical fibres sees fast progress” Optics Communications May 2006 Luc Thévenaz and Miguel Gonzalez-Herraez

APPENDIX 2: STSM LOPMD / FPMS

Detailed Working Plan

The aim of this one week Short-Term Scientific Mission (STSM) at the Faculté Polytechnique de Mons is to demonstrate highly-efficient supercontinuum generation (SCG) using the home-made self-Q-switched Er-Brillouin fiber source developed by the FPMS Belgian team and a concatenation of two highly nonlinear dispersion shifted fibers (HNLFs) provided by the LOPMD French team [1,2]. Our HNLFs have indeed dispersive and nonlinear properties which let us foresee that the spectral extent of the SC generated in the DSF can be significantly enhanced, in particular in the short wavelength region through dispersive wave generation:

- First the nonlinear coefficient γ in the HNLFs is much stronger than in the DSF used in Mons's experiment (about 10-fold increase). It means that the sidebands of FWM will be appeared farther from the pump and then the generated SC spectrum will be wider.

- Second the zero-dispersion wavelength is around 1550nm in the HNLFs whereas that of the DSF is at 1547nm. As the laser wavelength is at 1556nm we can except that the SCG will be initiated more quickly and more efficiently in the HNLFs.

- More importantly, the dispersion slope of our HNLFs is lower than the one of the DSF (0.03 instead of 0.074 ps/nm^2/km). That's why the supercontinuum might extend more efficiently on the short wavelength side of the pump wave.

By this mission we will have the opportunity to use experimental equipments of both teams: the self-Q-switched fiber source from FPMS and highly nonlinear fibers as well as a long-wavelength-extended photodiode from LOPMD to measure the generated light spectrum above 1.7 µm.

The planed experiments are:

→ To test the highly nonlinear fibers from LOPMD with the Q-switched fiber source from Mons in order to generate a supercontinuum.

→ To characterize this supercontinuum with an optical spectrum analyzer and a long wavelength photodiode which has a spectral sensitivity range from 1.2 µm to 2.6 µm.

The beginning of these experiments is planed on October, the 16th.

[1] A. A. Fotiadi and P. Megret, *"Self-Q-switched Er-Brillouin fiber source with extra-cavity generation of a Raman supercontinuum in a dispersion-shifted fiber"*, Opt. Letters **31**, pp.1621-1623 (2006).
[2] T. Sylvestre, A Vedadi, and H. Maillotte, F. Vanholsbeeck, and S. Coen *" Supercontinuum generation using continuous-wave multiwavelength pumping and dispersion management,"* Optics letters, Vol. 31, N°13, pp-2036-2038 (June 2006).

APPENDIX 3: SUPERCONTINUUM GENERATION

I think that splitting our activities into two broad groups seems reasonable. I have listed these below, together with some ideas of how we could organize ourselves around these. Of course feel free to disagree and make alternative suggestions.
What is important at this stage is that I get a list of names of those interested in actively participating in these activities, and some particular suggestions for related exchanges / collaborations. Please send responses to me, and I will collate and summarize the responses received in a week or so.

1. New Challenges in Modelling
There are a number of new challenges associated with the modelling of SCG, amongst which include new fiber designs and materials, and the possibility to approach the few cycle / ultra broad bandwidth regimes. In order to extend current modelling capacity into these new regimes, a number of things need to be envisaged.

(i) Improvements in modelling code: Several groups already have code for modelling pulse propagation - we could carry out a numerical "round robin" to compare approaches and results, and possibly envisage making the "core code" available to whomever wants it at the end of this.

(ii) Modelling extensions: short term projects (exchanges?) could look at specific numerical aspects involving noise, polarization, ultra-broad bandwidth extensions, Raman inclusion etc...

(iii) Materials Database: we could coordinate a literature database assembling necessary data relating to nonlinear, dispersive and Raman data for a variety of new optical glasses. This could be placed on a webpage for open access. Assembling such information could provide a number of short term "student projects", and would be extremely useful for both the COST consortium and the wider community.

2. Supercontinuum Design and Application
A way to proceed here could be for some groups with modelling expertise to provide "service modelling" to other members of the study group to assist them in the design of supercontinuum sources for particular applications. There are numerous ways to generate a supercontinuum, yet care has to be taken about the particular source/fiber availability as well as cost issues, and it's not always obvious.

At this stage, maybe one way to proceed would be for you to identify yourselves as a "modeller" or a "user" of supercontina (or both!), with 2-3 lines about specific needs and requirements, and then I can try to assemble these data and look for natural linkages.

As I said before, please let me have any feedback at all concerning these ideas, and I will do my best to get this study group moving as soon as possible.

Regards

John