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EUROPEAN UNION ACTS PROJECT MIDAS: OBJECTIVES AND PROGRESS TO DATE.

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1. Introduction to the ACTS program

Advanced Communications and Technology and Services, known simply as ACTS, is one of the specific programmes of the "Fourth Framework Programme of European Community activities in the field of research and technological development and demonstration (1994-1998)" [1]. It provides the main focus of the European Unions research effort to accelerate deployment of advanced communications infrastructures and services, and is complemented by extensive European research in the areas of information technology and telematics. The stated objectives of ACTS are to "develop advanced communication systems and services for economic development and social cohesion within Europe, taking account of the rapid evolution of technologies, the changing regulatory situation and opportunities for development of advanced transeuropean networks and services". Within ACTS, the emphasis of the work has shifted from the exploration of fundamental concepts and detailed system engineering, as it had been in earlier programs such as RACE (Research and development in Advanced Communication technologies for Europe), to issues relating to implementation of advanced systems and generic services, and applications which demonstrate the potential use of advanced communications in Europe. A key feature of the ACTS program is that the research be undertaken in the context of real-world trials. Work within the program is divided into six technical areas: Interactive digital multimedia services, photonic technologies, high speed networking, mobility and personal communication networks, intelligence in networks and services and quality, safety and security of communication systems and services. The total EU budget for the ACTS program is approximately 670 MECU, covering around 160 projects, with over 1000 individual organisations participating within the program, thereby illustrating the scale of the activities.

MIDAS is one of five projects in the technical area of photonic technologies concerned with high speed transmission, the others being ESTHER, UPGRADE, HIGHWAY and SPEED, each concerned with various aspects or approaches to the development of 40 GBit/s transmission systems within the European arena. A full list of project descriptions and objectives, as well as those of the ACTS program as a whole, are to be found in Ref [1]. The MIDAS consortium consists of the following organisations: Chalmers University of Technology (Sweden), CSELT (Italy), Thomson LCR (France), United Monolithic Semiconductor (France), Telia (Sweden), Kings College London (UK), University of Athens (Greece), ORC University of Southampton (UK). The project started in September 1995 and is currently scheduled to finish in September 1998.

2. MIDAS Project Objectives

MIDAS is primarily concerned with the field demonstration of transmission techniques suitable for the upgrade of existing fibre lines to 40 GBit/s over length scales relevant to European requirements (~1000 km). The ultimate project objectives are the realisation of two field trials over installed fibre lines, one a full 40 GBit/s soliton field trial over dispersion shifted lines, and the other a 40 GBit/s linear transmission experiment over high dispersion standard fibres using Mid Span Spectral Inversion (MSSI) to combat dispersion. Both field trials are fully supported by appropriate component development and system studies. In addition, the project has a small research element looking at advanced concepts and techniques which go beyond the demands of the current field trials and are targeted, mostly with a view to soliton transmission, at capacities between 40-100 GBit/s.

3. Technical scope and status of the MIDAS project

3.1. SOLITON FIELD TRIAL

The major field trial within the project is concerned with the upgrade of installed dispersion shifted fibres within the existing European fibre base to 40 GBit/s through the use of soliton techniques. The soliton field trial is being undertaken principally by Chalmers University, and is to be performed over installed fibre lines belonging to the Swedish operator Telia. The trials are to use a fibre based approach within the transmitter and demultiplexer design. Considerable component development has been required to bring laboratory grade devices up to a standard suitable for field trial validation.

The installed dispersion-shifted fibres to be used in the trial have been identified and are located near the town of Jönköping, Sweden (see Fig. 1). The fibres, which were acquired by Telia from Sumitomo, Japan, consist of ribbons with four fibres in each ribbon, and were and installed in 1991. The total length of installed fibre is 2774 km.

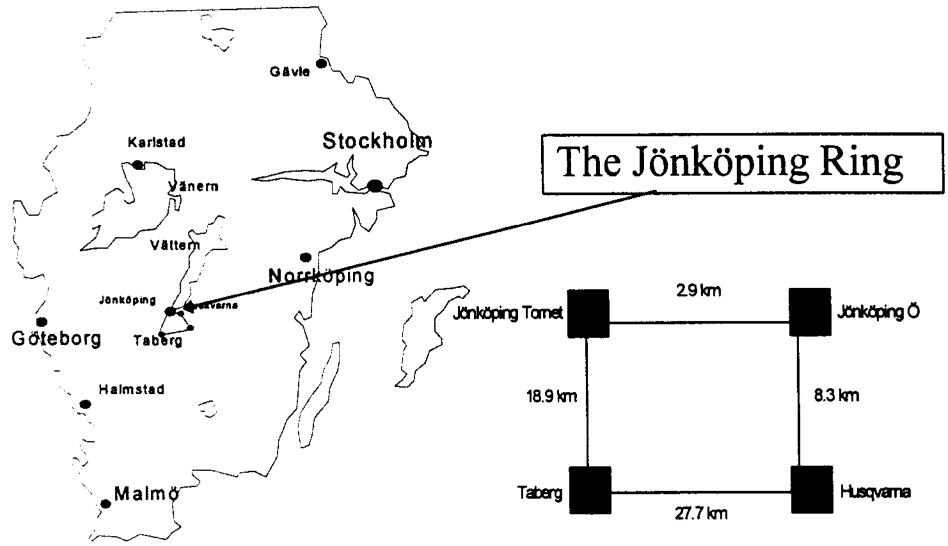

Fig. 1. The geographic location of the installed Swedish dispersion-shifted fibre lines with inset of ring configuration.

The fibre is installed in a 57.8 km long ring structure (Fig.1) with four intermediate but (not equidistant) accessible hubs. Twenty four sections between each of the hubs, totalling in excess of 1200km, have been characterised with respect to attenuation, polarisation-mode dispersion (PAD), and zero-dispersion wavelength using standard techniques and commercial instruments. The average values with maximum variation from these were: loss = 0.27 dB/km +85%/-26%, PMD = 0.40 ps.km$^{-0.5}$+125%/-92%, and zero-dispersion wavelength = 1548 nm +/- 1% respectively.

Critical to the success of the field trial is the simultaneous accommodation of the relatively large variations in zero dispersion wavelength and large values of PMD found within these fibres. The most critical of these parameters for 40 GBit/s transmission is likely to be the PMD. Using numerical simulations to optimise our system configuration, we estimate that by appropriate fibre selection transmission distances in excess of 400 km are possible using orthogonally polarised solitons and a

57km amplifier spacing. We have also briefly investigated other transmission line options and formats e.g. narrowband optical filtering, and dispersion management.

As previously mentioned the project is focused on the use of fibre based componentry. On the source side an environmentally stable, 10 GHz, polarisation maintaining, actively-modelocked erbium doped ring laser has been developed with regenerative feedback to accommodate cavity length drift due to thermal effects thereby maintaining optimal mode-locking conditions [2]. The cavity incorporates sections of dispersion shifted, polarisation maintaining fibre for the generation of soliton pulse shaping effects, thereby allowing the generation of pulses as short as 3.5ps. An intracavity filter is also included within the cavity which, in conjunction with the nonlinear effects within the cavity, leads to passive pulse amplitude stabilisation and the suppression of supermode noise [2]. Suppression of all competing modes to < -80 dB has been achieved. Data is encoded onto the 10 GHz pulse stream using a $LiNbO_3$ modulator and the data sequence multiplexed up to 40 GBit/s using a conventional passive fibre based multiplexer with appropriate delays to generate a true 40 GBit/s psuedo random bit sequence. The multiplexer also facilitates the generation of a sub-multiple clock at 10 GHz.

The laser provides chirp-free $sech^2$ pulses with negligible timing jitter (<1ps) and exhibits excellent long term stability. Fig. 2 shows an eye pattern at 40 GBit/s. A slight intentional time-alteration between consecutive pulses is present and serves to generate a clock signal at 10 GHz. The extracted clock, after narrowband filtering, is also shown in Fig.3. The estimated timing jitter of the extracted clock is 0.9ps.

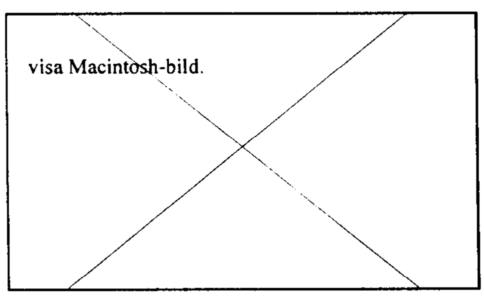

Fig.2 The soliton transmitter 40 GBit/s eye pattern (measured with a 32 GHz detector) and 10 GHz clock extracted from the data.

Demultiplexing of the 40 GBit/s at the receiver data will be achieved using electronic clock recovery and a nonlinear optical loop mirror based scheme, appropriately modified to achieve polarisation insensitive operation. A polarisation dependence of < +/- 0.5 dB over a wavelength range of 3.7 nm has been achieved. Error-free operation at 10 GBit/s has been confirmed with no measurable penalty[3].

The project also has an element of work associated with the development of a direct 40 GBit/s opto-electronic receiver preceded by an appropriate optical pre-amplifier. The design and initial characterisation of a low noise 980nm pumped preamplifier of appropriate characteristics has been undertaken and the design completed for the electronics. The design comprises a side illuminated, multimode structure waveguide PIN photodetector with coplanar electrical access and integrated MMIC preamplifier. The expected performances for the photodetector are an overall sensitivity (including coupling) of at least 0.5 A/W with a 3 dB electrical bandwidth greater than 40 GHz. The amplifier gain is to be ~27dB with 100 KHz to 35 GHz bandwidth.

A full 40 GBit/s test bed incorporating a recirculating loop structure has been constructed at Chalmers University to allow a full simulation of the soliton field trial. The test bed has been designed to readily permit the consortium to perform system measurements on the advanced transmission concepts being developed within the project, thereby enhancing the potential of these aspects of the work.

3.2. 40 GBIT/S STANDARD FIBRE FIELD TRIAL

Most of the installed fibre lines within Europe contain standard step index fibre designs with high dispersion (~17 ps/(nm.km) at 1550nm). The project incorporates a field trial concerned with upgrade of these lines to 40 GBit/s. In order to get around the effects of dispersion we are employing the technique of Mid-Span Spectral Inversion (MSSI) in which the net effects of second order dispersion are cancelled by optical phase conjugation of the signal at a point close to the middle of the link [4].

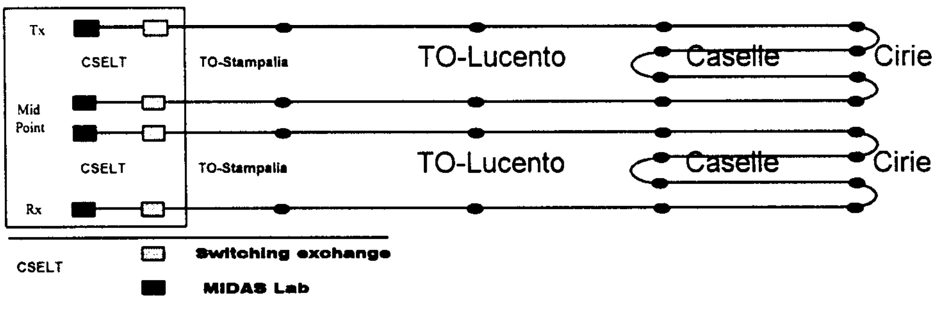

Fig.3 Layout of the CSELT-Cirié-CSELT links (two links, each 70 km long, total transmission length 140km).

The field trial is to take place in Spring 1998 in Italy, using installed lines in the vicinity of Turin. Southampton University and CSELT are the main contributors to this particular trial. Four standard telecommunication fibres have been obtained for the field trial from the ITINERA consortium, which manages this Italhost facility. The four fibres connect CSELT to the small towns of Cirié and Casselle and are now available directly in the MIDAS laboratory. Two 70 km links are available, and the four ports will be connected to the transmitter (Tx), to the midpoint spectral inverter (MPSI), and to the receiver (Rx). The exact line layout is shown in Fig.3. The lines have been fully characterised in terms of loss, dispersion, PMD and polarisation stability. The fibre selection for the field trial has already been made. The average fibre loss, which includes the loss of a considerable number of connectors, is 0.36 dB/km. The average PMD is 0.06 ps/km$^{0.5}$ and the average dispersion is 16.5 ps/(nm.km) at 1550nm. Note that the PMD of the standard fibre lines is considerably less than that measured in the installed dispersion shifted lines to be used in the soliton trial. We will also conduct measurements of the spatial variation of the PMD along the trial lines using Polarimetric Optical Time Domain Reflectometry [5] within the project. Our initial experiments will focus on transmission over a distance of 140 km, although if time permits multiple circulations through the system will be attempted to extend the range.

As with the soliton field trial we follow a fibre based component approach to the system design. The transmitter is once again to be a 10 GHz, regeneratively mode locked fibre laser (in this instance a sigma-laser geometry [6]), modulated at 10 GBit/s and passively multiplexed to 40 GBit/s. A fibre demultiplexing scheme similar to that to be implemented in the soliton trial will be used at the receiver.

We have investigated both fibre and semiconductor options for the phase conjugation function comparing noise performance, signal distortion with signal power, and the application of fibre grating technology for optical noise reduction [7]. Due to the superior power performance, and the advantages in terms of noise reduction we have obtained from the design and fabrication of fibre Bragg grating based narrow-band optical filters, we will be using a fiber based conjugator within the field trial. Using such a conjugator we have now demonstrated dispersion cancellation over 1000 second order dispersion lengths (100km using 2.5ps input pulses), the limit to pulse restoration quality being observed to be third order dispersion [8]

To date most work within this activity has centred on component development and testing, line characterisation and both experimental and numerical simulations in support of the field trial. However, we have already performed a prefield trial over the selected lines at 10 GBit/s using short ~6ps pulses so as to experimentally confirm the viability of the full 40 GBit/s trial. The experimental setup is shown in Fig.4a and is similar to that planned for the full trial other than that the base rate in this instance was only 2.5 GBit/s and that there was no need for demultiplexing at the 10 GBit/s receiver.

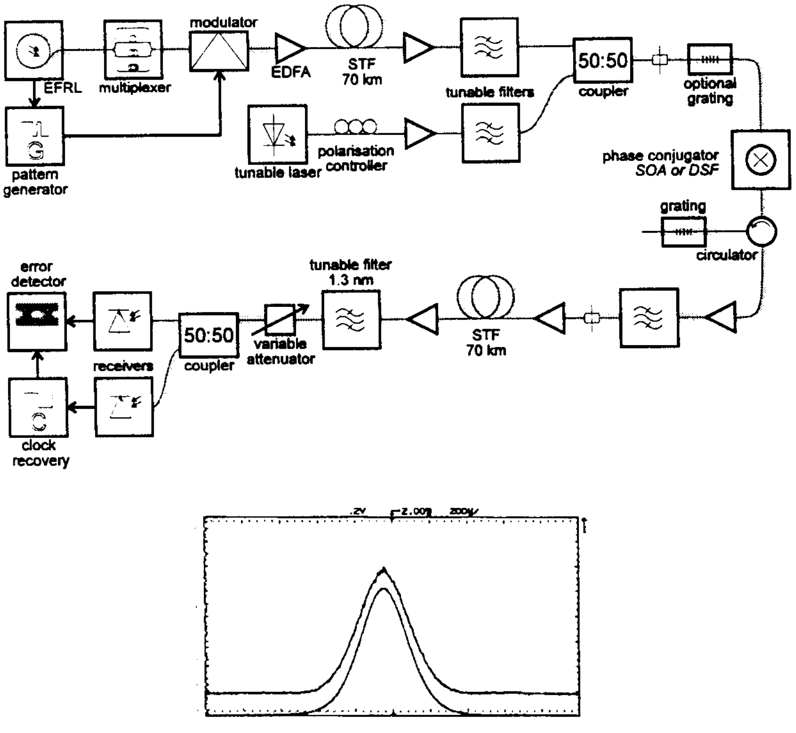

Fig.4 (a) Setup for the 10 GBit/s MSSI field trial over 140km of standard fibre
(b) Input (lower trace) and output (upper trace) autocorrelation function of 6ps pulses before and after MSSI dispersion compensated transmission through 140km of standard fibre.

The experiments showed that excellent dispersion compensation could be achieved for 6ps pulses (as will be used in the actual 40 GBit/s trial) over the full 140km transmission span as illustrated in Fig.4b. This shows the autocorrelation function of the pulses both before and after transmission over the fibre line. Minimal pulse distortion is observed. Moreover error free operation at a BER $<10^{-11}$ over 140km has been obtained with <4dB power penalty using a relatively unoptimised system in terms of ASE noise suppression and conjugator efficiency, giving us every confidence in the feasibility of the full 40 GBit/s trial.

3.3. ADVANCED CONCEPTS FOR FUTURE SOLITON SYSTEMS

In addition to the field trial activities, the project also contains advanced concept activities exploring the key technologies of soliton control, distributed loss compensation and dispersion management for>=40 GBit/s soliton transmission. This element of the project has the potential to enhance the scope of the current 40 GBit/s field trial through the incorporation of soliton control and specification of optimised dispersion maps, but is also critical for extending soliton techniques beyond the scope of the current field trial to far higher single/multi (WDM) channel data rates. The work contains elements of numerical simulation, novel component development and pulse transmission experiments. It is anticipated that further system measurements in this area will be made on the soliton field trial test bed in the near future.

3.3.1. *Soliton loss compensation*

Soliton communication systems based on lumped Erbium Doped Fibre Amplifiers (EDFAs) and uniform, dispersion shifted fibre offer great potential for high capacity soliton transmission. However, there are inherent limitations within such system implementations for both OTDM and WDM transmission. OTDM transmission is limited by the constraints of average soliton dynamics which require that the soliton period of the pulses (z_0) should be much greater than the amplifier spacing (L_a) [9]. At high data rates (~40 GBit/s) the perturbation to the pulses due to the fibre loss becomes too severe resulting in a violation of 'average', or 'guiding centre', soliton dynamics and eventual decay of the pulses [10]. In WDM systems soliton pulses of different wavelengths suffer frequency shifts as they collide, which ultimately result in timing jitter and resultant loss of information unless the length scale over which they collide is kept greater than twice the amplifier spacing [11]. Moreover, and more significant from a practical perspective, is the fact that the collision process results in the uncontrollable growth of four wave mixing products which once again leads to the generation of timing jitter[12]. The only way to eliminate these deleterious effects is to eliminate the loss/gain cycle induced perturbations to the local balance between dispersion and nonlinearity by ensuring fundamental soliton propagation throughout the system. This can be achieved either by using a distributed amplifier to cancel the local fibre loss [13], or by the use of a Loss Compensating Dispersion Decreasing Fibre (LCDDF) [14]. In the later case the dispersion of the transmission fibre decays exponentially along its length so as to exactly follow the decrease in optical intensity and hence the strength of the nonlinear interaction. An exact balance between the two effects at all points along the fibre is thus ensured and as far as the soliton is concerned the fibre becomes lossless. Within MIDAS we have examined both the options of LCDDFs and distributed amplification through Raman scattering.

3.3.1.1. *LCDDF fabrication, characterisation and transmission.* We have developed fabrication technology for long (40km) LCDDF using control of the waveguide dispersion (and thereby total dispersion at a fixed wavelength) along the fibre length by control of the fibre's external diameter (core diameter), a technique first demonstrated over much shorter fibre lengths by workers at General Physics Institute, (Moscow)[15]. Critical to the fabrication of such long fibres is preform type and quality. We have examined the fabrication of such fibres from both step index and dispersion shifted preform types for both high and low average dispersions values and dispersion ranges[16-20]. Moreover, we have performed systematic distributed dispersion measurements, made using a backscattered four wave mixing technique [21], of the dispersion variation in such fibres to obtain estimates of the quality of the match to the fibre loss profiles and of the achieved dispersion accuracy [22]. In Fig.5 we show a plot of the measured dispersion variation in a 38 km LCDDF with dispersion designed to vary from 6ps/nm.km at the input to 0.55 ps/(nm.km) and with an average loss of 0.265 dB/km. It can be seen that an excellent match to the fibre loss is obtained over the full fibre length.

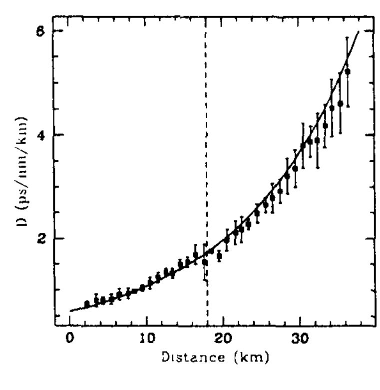

Fig.5 Experimentally determined (data points) and design dispersion profile (solid line) of a 38km LCDDF fabricated by the diameter control technique.

The average deviation between the measured and the desired profile is less than 8% for the whole length. This indicates that an excellent degree of control over dispersion is possible over significant fibre lengths. Of particular note is the control achieved at the low dispersion end of the fibre. In this regime an average error of <0.05 ps/nm/km is obtained over the 18 km of fibre comparable with the measurement uncertainty and is of the same magnitude as deviations from nominal uniform dispersion observed over 10 km length scales in commercial dispersion shifted fibre. Although this degree of dispersion error is small, it can still be significant for fibres with dispersion tapering close to the zero-dispersion wavelength as are likely to be required for most real world applications. Note that dispersion control of this form can be applied to generate more exotic dispersion profiles, as required for more complex dispersion managed systems e.g. quasi-soliton systems with a similar degree of absolute dispersion control.

The LCDDF fibres fabricated within the project have been used in single pass and recirculating loop experiments to provide demonstrations of high quality soliton loss compensation. In single pass experiments we have shown loss compensation over transmission distances in excess of 40 soliton periods (38km) [16]. In loop experiments (in collaboration with A.D. Ellis BT Laboratories) we have shown stable pulse transmission over total propagation distances in excess of 80 soliton periods and normalised amplifier spacings in excess of 5 soliton periods using 10 GBit/s data on pulses of ~5 ps [18]. Furthermore we have experimentally demonstrated error free transmission of 10 GBit/s, 4.8ps pulses over 4500km at 10 GBit/s in a 20 km, low dispersion LCDDF fibre with average dispersion 0.17 ps/(nm.km) [19]. The pulses could be transmitted error free over 1000km at 40 GBit/s. The limiting effects of Raman scattering, acousto-optic interactions and higher order dispersion to single channel, high bit-rate propagation in such fibres are currently under investigation.

3.3.1.2. *Raman amplified soliton systems.* Raman amplifiers for soliton systems offer the attraction that the transmission fibre is its own amplifier, providing distributed amplification and elimination of the resonance affects associated with conventional lumped amplification. The first experiments with soliton transmission used Raman amplifiers and produced encouraging results [9], but the lack of inexpensive and reliable pump sources and the appearance of the more efficient erbium-doped fibre amplifiers put the Raman amplifier into the shade. However the development of highly efficient fibre lasers with output powers of up to 1 W could have a significant impact on the viability of Raman amplified systems and we have experimentally investigated this option.

We have experimentally demonstrated low distortion, subpicosecond pulse propagation over 33 km of dispersion shifted fibre using Raman gain for fibre loss compensation where the availability of efficient Er/Yb codoped fibres and fibre gratings makes it possible to design a simple and robust pump source operating at 1535 nm [24]. The fibre dispersion of 1.2 ps/nm km at the signal wavelength of 1560 nm made the soliton propagation distance as long as 150 dispersion lengths - the longest distance for single span soliton transmission reported so far. A bidirectional scheme allowed us to obtain a more uniform distribution of the pump and to reduce the amount of shed non-soliton component, giving rise to the possibility of transmitting a 100 GBit/s stream of solitons over 1000's of km [25]. The Raman amplifier can therefore provide a real challenge to the EDFA in soliton transmission systems.

3.3.2. *Soliton Transmission and control using nonlinear gain*

Although dispersion management and the like can be used to ensure the stability of ultrashort soliton pulses propagating in an amplified transmission line, other interactions of the soliton can restrict the usefulness of such systems. During propagation along an optical fibre a soliton interacts with optical and acoustic fields generated by other solitons and optical amplifiers. The result of such interactions is a change of the soliton central frequency which translates into a change in group velocity and causes an uncertainty in the soliton arrival time that in turn results in error if the pulse fails to arrive in its assigned time slot.

Several techniques have been suggested to suppress or at least reduce the instability of a soliton data stream [26-28] by making the soliton transmission line more sophisticated i.e. consisting of not only transmission fibres and EDFAs but also spectral filters, modulators and (or) saturable absorbers.

Within MIDAS we are examining the development of nonlinear saturable absorbers (NSA) for use as soliton control elements in 40 GBit/s systems. By using a NSA and appropriate spectral filtering one can provide additional loss for linear radiation e.g. ASE noise relative to the soliton. If the excess linear gain at the fibre amplifier is high enough to compensate the soliton loss but not sufficient for the compensation of linear radiation excess loss, then in such a system one can expect stable soliton propagation with suppressed low-level non-soliton components and thereby reduced timing jitter [29]. To date we have made experimental proof of principle measurements using a fibre based (Nonlinear Amplifying Loop Mirror) nonlinear saturable absorber [30] and are currently investigating the use of more practical options. In particular we are investigating both polymer and semiconductor MQW materials. Recovery time and saturation fluence are the key parameters for system performance. The current known limit for the operation speed of the polymer saturable absorbers for soliton control under development within the consortium is above 50 GBit/s, and by suitable chemical modification of the molecular structure this may be extended to beyond 100 GBit/s with a molecular charge transfer concept.

4. Conclusion

The MIDAS project is progressing well to its final objectives of field demonstrations of 40 GBit/s data transmission techniques, both soliton and linear, and is making significant contributions to basic research studies in the area of advanced soliton systems. The undertaking of such trials illustrates the EU's strong commitment to the deployment of advanced communications infrastructures within Europe, it remains however to be seen if either of the approaches investigated within the project will be commercially developed.

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