European Science Foundation
SETTING SCIENCE AGENDAS FOR EUROPE

Exploratory Workshops Scheme

Standing Committee for Physical and Engineering Sciences (PESC)

ESF Exploratory Workshop on

Slow and Fast Light: Fundamental Issues and Applications

Venice, Italy, 7 - 10 October 2007

Convened by: Marco Santagiustina and Carlo Someda

Department of Information Engineering, University of Padova

Co-sponsored by

DEPARTMENT OF INFORMATION ENGINEERING
UNIVERSITY OF PADOVA

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EXECUTIVE SUMMARY

The meeting took place on the Campus of the Venice International University (VIU) (www.univiu.org), located on the island of San Servolo, off St. Mark Square, in Venice, Italy. The old buildings of the University, that were previously used for centuries as a Hospital, were recently restored by the Venice Province Administration, have been a perfect location for an European Science Foundation Exploratory Workshop. Two rooms were reserved for the Workshop; the first, equipped by a projector, for the meeting, and the second, with a magnificent view on the Venice lagoon and its islands, for the coffee breaks and lunches.

Sixteen participants, including the ESF Officer, were lodged on the Campus residential halls; three stayed in a very convenient Guesthouse (Domus Ciliota), in central Venice. Three invited participants could not come: Prof. Giudici (INLS, Nice), Prof. Capmany (Politecnica de Valencia), Dr. Andersson (KTH). The contemporary deadlines for the submission of proposal for ICT Call 2 of the 7th Framework Programme (9th of October 2007) and for the submission of contributions to the Optical Fiber Conference (San Diego, USA, Feb 22-25, 2008) have hampered the full participation of all invited researchers. In fact, besides the three mentioned missing participants, prof. Martinelli (Politecnico di Milano), Dr. Dolfi (Thales Research and Technology) and Dr. Bogoni (Consorzio Nazionale Italiano Telecomunicazioni) were substituted, at the very last minute, by some colleagues of them, from the same institutions, respectively, Prof. Boffi, Dr. Alouini and Dr. Fresi.

The coffee breaks and lunches were provided to all participants through the catering service (CAMST S.c.a.r.l.) that operates on the Island. On the arrival day the participants had dinner freely at the Campus Cafeteria or in central Venice.
Almost all participants moved together by ferry for the Workshop Dinner, organized in a restaurant in downtown Venice on Monday, Oct 8th 2007. The dinner, preceded by a short walk and visit in the nearby St. Mark Square, was very convivial and created a very friendly relation among the participants.
On the second evening (Oct 9th 2007) a party of twelve had a common, more informal, walk and subsequent dinner in a typical Venetian "pub".

Among the participants there are two extra-European speakers, Prof. C. Chang-Hasnain from the University of California at Berkeley (USA) and Prof. G. Eisenstein from Technion (Israel). Their presence added a great value to the Workshop. In fact, they have largely contributed in the last few years to foster the research on the topic of slow and fast light. For such merits Prof. Chang-Hasnain was General Chair and Prof. Eisenstein Program Chair of the Slow and Fast Light 2007 OSA Topical Meeting, held in Salt Lake City, during July 2007.

The Exploratory Workshop was opened by the European Science Foundation Officer, Dr. Antonella Di Trapani, who briefly sketched the mission of the European Science Foundation and the instruments used to implement such mission.
The participants interacted a lot with the Officer during and after her talk, both in questioning her about the instruments that the European Science Foundation has defined to foster the research, and about the agenda of the Foundation for the future.

The following picture was taken on the first day of the Workshop on the Venice International University premises.


From left to right: Vadalà, Di Trapani, Sales, De Rossi, Combriè, Phillips, Boffi, Gonzales-Herraez, Schenato, Thevenaz, Fresi, Eisenstein, Moerk, Van der Poel, Melloni, Reithmeyer, Someda, Chang-Hasnain.

MAIN OBJECTIVES OF THE WORKSHOP

The search for variable **time-delay/phase-shift lines**, for photonic and microwave applications, has fostered numerous studies in recent years in what is known as **slow and fast light research**. In fact, controlling the speed of light offers a solution to develop this necessary, and often missing, functional device in broadband ICT systems. The group velocities of optical signals can be controlled by linear or nonlinear optical phenomena in different media. Though a lot of research has been already performed the crucial issues of the **ultimate limits and the real perspectives** for the applications are still open problems that need to be explored in detail.
The aim of the Exploratory Workshop was to review the state-of-the-art of the room temperature, photonic technologies for slow and fast light, to underline their advantages and limitations, to identify the possible application fields and the real chances to bring the slow and fast light delay lines into the realm of practical devices.
The workshop gathered many European and two world leading experts in slow and fast light techniques and in the related semiconductor, fiber and microwave fields with the aim of creating, for the first time, a European forum to discuss both the basic issues and the possible applications. Besides this the Exploratory Workshop was intended to enable, for the first time, all European researchers interested in this topic to explore the chances for create a coherent European research effort. In fact, a collaborative research proposal has been, so far, absent on the European stage in this topic, while in the USA a Network of several top universities (a partial list includes: University

of Rochester, Cornell University, Duke University, University of California at Berkeley, University of Southern California) was financed by several millions dollars by DARPA starting in 2004. This funding has played a decisive role in establishing the present US primacy in this key technology.

OVERVIEW OF THE CONTRIBUTIONS AND OF THE DISCUSSION

There were <u>6 invited talks on the first day and 5 during the second day</u>. After each talk plenty of time was allocated to discuss all the issues that were raised in relation to the presentation. The first day was chaired by the Convenor Dr. Santagiustina; the second day by the Co-Convenor, Prof. Someda, because Dr. Santagiustina was, unfortunately, absent because of an Academic meeting to which he had to participate and that were not predictable at the time the Workshop dates were defined.

October 8th 2007

1) The opening lecture, given by **Prof. Johan Peter Reithmaier** (University of Kassel), was dedicated to review the state-of-the-art of semiconductor quantum dots waveguides that can be used for creating slow and fast devices and to identify the challenges to be taken up in order to improve the performance of such devices up to the level that would be necessary for the applications. Several effects occurring in semiconductors have been recognized to be apt for causing slow and fast light. The main ones are: electromagnetic induced transparency, coherent population pulsation, gain saturation and bleaching. Prof. Reithmaier underlined that the main problem is represented by the relatively large gain broadening, due the lack of a sufficient quantum dot density and homogeneity. The improvements in the control of the quantum dots manufacturing will be the key to overcome such problem. Potential techniques to be explored have been identified, such as the strain coupling, the droplet epitaxy and the pre-patterning of the surfaces where quantum dots are to be grown, by means of the high-resolution lithography. The last technique seems the most promising. Additional improvements could also be attained by creating photonic crystal waveguides and wires.
The talk stimulated a long and deep discussion among the main experts of semiconductor based slow and fast light (among which Chang-Hasnain, Eisenstein, Moerk). This leaded to the conclusion that the progresses are slow to be achieved in this field, because they follow the improvements of the semiconductor technology. Higher dot densities are indeed feasible, possibly with photonic crystals. Electromagnetic induced transparency is also a possible interesting technique if nano-structured materials might become available.

2) The second talk was given by **Prof. Chang-Hasnain** (University of California at Berkeley), one of the member of the Slow and Fast Light Project financed by DARPA in the USA. First, she reviewed the main applications of slow and fast light devices, among the others listing: optical processing, microwave signal processing and sensors. Then, she passed to present the coherent population oscillation technique used by her group. The main limitation of the coherent population oscillation technique has been identified in the carrier recovery time which is too long for high speed applications; this limitation, intrinsic of the devices, is very difficult to overcome. Then, she presented the very last results of her group regarding the slowing down of THz bandwidth signal in semiconductors. In particular, the novel technique that was exploited used pulse pre-chirping; with this technique the time delay was extended up to 3 pulse widths, that is a record in the field of slow and fast light.

The discussion that followed the presentation was mostly dedicated to consider the real perspectives of slow and fast light techniques for optical buffering. The opinions on this issue were rather divergent. From one side the results are very encouraging but on the other hand the performance of devices seems very far from reaching the figures of merit that are necessary for an optical device to compete with the electronic counterparts.

3) The morning session was concluded by the presentation of **Prof. Phillips** (Imperial College London) and it was devoted to the electromagnetic induced transparency in semiconductor nanostructures. Such a technology is able to provide a surrogate of the atomic vapor, the most common used materials for electromagnetic induced transparency, to obtain transparency through a gain without inversion. Very interesting results have been shown in which a 40-fold reduction of the light speed was associated to a large bandwidth. The main limitation of the technique has been remarked to be the fact that the effect is very slow so the change of speed is still not suitable for many applications.
Regarding the latter remark, that was made, by some of the participant the speaker pointed out his view that regardless of the future the applications, the topic of slow and fast light is mainly a paradigmatic test bed of many interesting phenomena. All the participants agreed, though many underlined that applications are possible and the technique presented is indeed very promising for bringing the electromagnetic induced transparency into the number of techniques at room temperature, that could finally found applications.

The final part of the morning session was dedicated to the discussion of the main issues raised by the presentations. In particular, the participants returned back to the problem of the possible applications of semiconductors techniques. The prevalent opinion was that the **semiconductor based technology could be the winning one** in slow and fast light applications, mainly if the perspective of high integration of devices is pursued. **Fiber optics**, which is probably the only one really providing at this moment the right figures of merit, might instead found interesting, but specific, applications. **Microwave photonics** was mostly indicated as the **main field of application**; many participants expressed the opinion that a breakthrough, winning, applications might be found only in that field. The issue of requirements for optical buffers was more controversial. Though the analysis so far conducted are sometimes simplified ones, there are indeed physical constraints on the size of the devices that limit, even with large progresses of the techniques, to some tens of bits the real performance of slow and fast light devices for optical buffers. In spite this number is not enough for the most important applications in telecommunications, such as Internet routers, in which IP frames are by far larger, there could be some niche application when other protocols are considered. In those cases, slow and fast light could show many of the very attractive, breakthrough, properties of all optical techniques, such as a large bandwidth, the transparency to the optical signal and the reduced size. Besides the applications, it was also remarked that the attention paid by the scientific community to the field of slow and fast light is very high because of the **basic science features** that characterize all the techniques. In particular, the discussion remarked that **slow and fast light science intersects** many features of photonics like, **semiconductor** waveguides, **quantum dots**, **nanostructures**, **photonic crystals, optical fibers**. The interdisciplinary nature of this research topic makes it a fascinating, multifaceted test bed for research and a real challenge for creating new synergies among different but very close sectors of the photonic research.

In the afternoon, the invited speakers continued to present other point of view, about the semiconductor technologies for slow and fast light.

4) The first contribution was lectured by **Prof. Moerk** (Technical University of Denmark). He reviewed the work of his group about gain/absorption cascaded modulation in semiconductor waveguides, a particular type of coherent population oscillation technique for slow and fast devices. The main limitation of the coherent population oscillation technique, as already reported in a previous talk, is the carrier lifetime that does not enable to overcome the value of one in the delay-bandwidth product figure of merit. In spite of this shortcoming, the technique presented by prof. Moerk is mature for direct application and he showed that with a few sections, consisting of commercial waveguides, the time-bandwidth figure of merit can reach the value of one. This fact opens the way to applications in microwave photonics, where a tunable delay of one pulsewidth in the optical signal corresponds to a 2π phase shift of the microwave modulation. The main obstacles in such technique arise from amplified spontaneous emission noise, that is quite high because the amplifier section works at saturation and from the low quality of the quantum dot distribution. Pattern dependent effects are also possible when a sequence of pulses is considered.
During the discussion that followed the talk a few specific questions were raised to the speaker, in particular with regard to the lack of the study of the distortions on the scale of the microwave signal. This topic also leaded the participants to discuss another important issue that is the definition of the delay. In fact, without distortion this can be easily defined as the time delay induced by a slow and fast light technique to the pulse peak. When distortion is a feature of the propagation this definition fails. All the participants agreed that further thoughts and investigations are needed in order to define the slow and fast light delay.

5) Then, **Dr. De Rossi** of Thales Research and Technology gave his presentation entitled "Dispersion engineering in III-V based membrane photonic crystals for slow-wave applications". In particular he stressed the maturity of the membrane photonic crystal technology, that provides low loss devices (2dB/cm), broad tenability of the dispersion properties, very high Q factor cavities. Since three-dimensional photonic crystal technology has not reached a precision level sufficient for the device manufacturing, two-dimensional techniques, integrated by waveguiding structures in the third dimension will be exploited. A very large group index can be attained and the main problem, hampering the development of real devices, is the disorder that causes power leakage and uncertainty in the dispersion characteristics. He also indicated that very promising results could be reached in III-V semiconductor materials that can provide additional functions such as the integration of laser sources on the same chip.
The discussion at the end of the talk underlined that photonic crystals is a major technique for the progress of slow and fast light devices, as well as of other photonic devices in which the tuning of the dispersion is a must.

6) The final talk was given by **Prof. Melloni** from the Politecnico di Milano (Italy) who presented a technique for slow and fast light based on coupled ring resonators. The device is able to provide quantized delays, by putting out of resonance one coupled resonator in a chain of many. The technique is very simple, provide large delays and broad bandwidths and therefore is highly promising. The main limitations are the losses, the dispersion that causes distortions and by the disorder and the fact that resonance among coupled rings are controlled by temperature and so the tuning is slow in comparison with the signal bandwidth. Some calculation presented by prof. Melloni underlined that for optical buffering of Gibabit Ethernet and Asynchronous Transfer Mode packets very high, though not unphysical, gain compensation would be needed; for Internet Protocol this technique would not work.
The results presented in the talk stimulated, once more, the discussion about the optical buffer applications, confirming that for some applications slow and fast light techniques could be useful, though a breakthrough application in the world widespread Internet Protocol based network is not feasible.

The day wrap up session was very short, since the discussions at the end of each talk were very deep and had already underlined the many aspects of slow and fast light. The Convenor pointed out that semiconductor technique for slow and fast seems to have reached the level of maturity for taking such devices in the realm of practical applications. Microwave photonics is possibly the field where slow and fast light may be a breakthrough, winning technique. Optical buffers are more limited. Semiconductor techniques like quantum dot waveguides and membrane photonic crystals are very promising to further improve the performances of such devices.

October 9th 2007

7) During the first talk **Prof. Eisenstein** of the Technion, reviewed the main achievements of slow and fast light experiments in Raman assisted, parametric optical fiber amplifiers and also in Brillouin amplifiers. First he introduced the general problem of the definition of the delay in slow and fast light, in particular in relation with the signal distortion. Then, he presented the parametric based technique, that yielded the record results for slow and fast light figures of merit in optical fibers. Time delays of the order of 1.5 pulsewidths, for very broadband signals have been obtained. Experiments were conducted also for digital signals, demonstrating the fidelity of such technique. The main limitations of the technique are due to the pump-signal relative polarization, that is hard to be controlled in real fibers and by the dispersion characteristics of the fibers, in particular the variation of the zero dispersion wavelength along the longitudinal axis. Numerical solutions showed the change in the mean gain statistics due to the polarization and dispersion fluctuation effects. Brillouin slow and fast light were also briefly reviewed.
The discussion was mainly focused onto the relative weight of the different impairments due to the linear and nonlinear fiber effects. In particular, besides the birefringence and dispersion issues the role of the real and imaginary part of the Raman coefficient has been remarked, showing that the former may affect the delay spectra.

8) The second invited speaker, **Prof. Thevenaz** (from Ecole Polytechnique Federal de Lousanne), dedicated his presentation to the state-of-the-art Brillouin based slow and fast light. This effect is widely known to be probably the most mature phenomenon to control the group velocity in fibers. The relative low powers needed to induce the phenomenon, the very simple gain control in Brillouin amplifiers makes it very attractive for immediate applications, though the experiments require a fine optimization. Its limitations are only imposed by the Brillouin shift, that sets the highest bandwidth to about 10GHz, which could be, however, broadened by multiple pumping configurations. The applications of Brillouin based slow and fast light setups in the field of sensing has been reviewed, showing the great potential of this technique to enhance the sensitivity of devices.
The discussion started from the very last topic of the presentation, by analyzing the real chances of the enhancement of sensitivity. The opinions were rather divergent; prof. Herraez pointed out that is any enhancement exists very careful experimental and theoretical investigations must be carried out to reveal it.

9) The morning session was closed by the **Dr. Schenato** and **Prof. Someda** talk. In the presentation an analytical formula setting the ultimate limitation for the time delay in parametric fiber amplifiers was given. This limit has been shown to depend on the dispersion parameters (second and fourth order dispersion coefficients) and on the fiber nonlinearity. A systematic numerical study of the effects of the polarization mode dispersion of the fiber was also presented. While the mean gain decreases following the maximum gain curve, the delay is much more affected by the fiber birefringence. The variance of the delay is also very high for large polarization mode dispersion coefficients.

During the discussion, prof. Eisenstein remarked the influence of Raman gain, and that the application of the fiber based schemes are going to be very difficult due to the uncertainty of the fiber parameters in standard fibers and the high cost of special fibers that could eliminate such problems. Prof. Someda suggested to consider the use of spun fibers that may provide a low-cost, reliable solution, at least for the birefringence issue.

10) The second part of the afternoon was devoted to two presentations regarding the applications of the slow and fast light devices. **Prof. Sales** (Universidad Politecnica de Valencia) gave a general overview of the topic of microwave photonics; this research field is dedicated to realize microwave high frequency devices. To this purpose the superb broadband, low attenuation and low distortion characteristics of photonics are exploited. Several microwave filter design methods were reviewed as well as the applications of phase shifters to phased array antennas. The exploitation of slow and fast light devices, in particular Brillouin amplifiers, shows a great potential for introducing a completely new functionality in those filters, that is chance to tune their passband without changing the filter bandwidth. With respect to phase shifters, the applications of cascaded semiconductor amplifier and absorbers stage could provide, in principle, a shift of 180 degrees, that would mean a complete control on the phased array beam steering. The results of the device modeling were shown.
During the discussion it was remarked that microwave photonics is probably the real clear-cut application of slow and fast light. Infact, in micro- and millimeter waves the limitations imposed by electronics seem not simple to be overcome. Phase-shift lines, has been observed, are rather difficult to be implemented, are expensive and their performance rather poor in comparison with the requirements. Therefore slow and fast light devices can be a breakthrough in that field in which photonics performance are overwhelming the electronics.

11) The final talk, given by **Dr. Alouini**, from Thales Research and Technology, who gave a very interesting perspective as a representative of a great enterprise of the private sector. He presented several applications of slow and fast light to radar systems. Phased array are typically radar antennas and require a careful phase shift tuning to enhance the beam steering control and avoid problems like the beam squint. Photonics is already present in such applications, as shown by Dr. Alouini, since the remote feedings of the antennas are realized through optical fiber links. Thales applications are based on a massive parallelization of optical signals, differently delayed by tunable spatial paths. Such scheme requires very expensive solutions and the perspective given by slow light devices is considered extremely interesting. The target for radar applications is to get hundreds micro-second delays with tens of Ghz bandwidth signals. Very promising results wave been shown for semiconductor optical amplifiers but also other structures like photonics crystals and fiber optics dispersive lines have the potentials of providing such figures of merit. The extension of semiconductor techniques to ultrawide band wireless communication systems can be also envisaged.
As a conclusion of the talk, the participants found the contribution of Thales to this workshop as a real key of interpretation to the issue of the possible applications. Indeed, the development of photonics based technology for radar systems is a rather important topic and in this case slow and fast light is viewed, by the majority of the participants as the only technology apt to provide a viable solutions.

CONCLUSIONS

The Workshop final results, as also summarized, during the final discussion are the following.
The control of propagation velocity of optical signals has been demonstrated over the past few years using various optical phenomena and different media. This field, which is known as slow and fast light has already left a large scientific impact. The critical observation, based on a detailed understanding of current approaches, conducted during the Workshop, leads however to the unequivocal conclusion that the **current state of the art devices are incapable of supporting the envisioned practical applications**.
The **potential of slow and fast light** is nevertheless **immense** and slow and fast devices represent a completely new approach to realize a necessary, and often missing, function in broadband Information and Communication Technology systems: a continuous variable delay/phase shift. The **impact** of such device will be enormous **in applications** such as **microwave and millimeter wave photonics**, where a controlled optical phase could add a degree of freedom not possible by any electronic means. However, the realization of practical devices awaits a new revolutionary class of technologies to be implemented.
As for the technologies, during the Workshop **three technologies** were discussed that, at different levels of maturity, provide tunable delay/phase-shift lines. Namely they are: **semiconductors, fibers and coupled resonators**. A deep understanding of the fundamental limitations of each technology were presented and several proposals to optimize them have been discussed and identified.
In the field of semiconductor several effects can be exploited to tune the group index at selected frequencies. Coherent population pulsation is the most used, though cascaded amplification-absorption stages are also reaching valuable results. Electromagnetic induced transparency is also progressing through solid-state, room temperature, engineered materials that simulate the behavior of the well known low temperature vapors.
The **breakthrough** progresses that can be foreseen in the field of **semiconductors slow and fast light** are going to be originated by the research in **quantum dots** waveguides and **photonic crystals**. Controlled growth and positioning of quantum dots, by means of pre-patterning, in specific locations within a photonic crystal structures has been identified as a possible key to fully exploit the interaction of the optical field with the semiconductor nanostructures. The extraordinary flexibility offered by photonic crystals might be utilized to engineer specific propagation properties, leading to miniaturization and massive parallelization of slow and fast light functions.
A second type of semiconductor based approach can use **semiconductor optical amplifiers** in conjunction with **electro-absorption modulators**, both incorporating nanostructure based active regions. In fact, in quantum dots waveguides fast response times can be achieved by combining saturable gain and loss; in this way it becomes possible to engineer the complex (amplitude and phase) frequency dependent transfer function thus realizing controllable delays over large bandwidths.
All of these considerations, and the obvious superiority of semiconductor technologies in terms of large scale integration, imply that the semiconductor technology is therefore the most promising for a future, widespread application of slow and fast light technology.

Indeed, for several applications, the **preferred** optical medium could be an **optical fiber** due to its low loss, wide bandwidth, at the conventional telecom wavelengths and its property to serve as an element for long storage times. The **Brillouin amplification** has been certainly identified as the most mature slow and fast light technique. Its main limitation is the bandwidth (about 10GHz) that can be further extended at the expense of the simplicity of the device. Optimization of Brillouin amplifiers for specific slow and fast light applications is also necessary.
The technique that can provide the best performance has been identified as **narrow band parametric amplification**, which has already achieved the widest bandwidth and largest tuning

range of all techniques. Further progresses can be predicted with the use of new types of specialized fibers, such as photonic crystal with pre-designed dispersion functions. **Mitigating** the adverse effects of **random birefringence** and of the **random variation of the zero dispersion wavelength** has been also identified as two fundamental issues to be resolved. Spun or any other fiber type enabling polarization control have been identified as a possible solution to the former problem.

With regard to the **applications**, some **microwave photonics** slow and fast light devices have been defined can be superior to their electronic counterparts. Some specific examples of breakthroughs have been envisioned during the Workshop and include, **true time delay antenna feed systems** for radars and **ultra wide band wireless communication**, complex **microwave and millimeter wave filters** for different bandwidth ranges, **high spectral purity tunable opto-electronic oscillators** for high frequencies as well as **low jitter pulse sources** and injected locked oscillator systems.
State of art phased array antenna feed systems use electronic phase shifters and hence can not handle very broad band signals. Present photonics solutions are based on dispersive, spatially distributed fiber-optics that is hard to control. **Slow and fast light devices** can give compact, reconfigurable optical delay lines that might **revolutionize** radar and wide band data communications as they will enable wide bandwidths and processing in parallel channels.
Microwave photonics filters can take great advantage from the research in Brillouin slow and fast light; the sophisticated tunable phase shifters that can be developed could lead to a new generation of filters featuring complex valued coefficients. These filters will allow the ultimate performance for the tuning and reconfiguration of the complex filter transfer function. A major envisioned breakthrough is the complete freedom to locate poles and zeros of the complex filter transfer function, which is impossible with any current electronic technology. Semiconductor technology (in particular amplification-absorption stages) can offer vastly improved flexibility.
Finally, high spectral purity microwave oscillators can be envisioned, which employ slow and fast light devices such as Brillouin or parametric fiber amplifiers or controllable photonic crystal waveguides and cavities. Broad band elements might enable operation at very high frequencies, 60 GHz and above, with large tenability and stability that surpass present day oscillators.

To conclude **slow and fast light techniques are at the forefront of the photonics research**. Several important, not else attainable, **immediate applications** can be found in **microwave photonics**. To this aim, it is believed by the participants of the Workshop that new device concepts, which merge fundamental issues with a set of focused engineering goals, are necessary and might have a large impact across a wide range of other broad band applications.
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FUTURE DEVELOPMENTS

The research in **slow and fast light** is in essence **multidisciplinary** and requires a **multifaceted approach** that **intersects** several research topics, from **fundamental physics** of **semiconductors**, to **nonlinear optics** and **fibers**. The application viewpoint also requires strong competences in optical communications and microwave engineering. Then, a **great synergy** among the researchers should be fostered. Besides the specific applications slow and fast light is a **privileged test bed** for several **pure science** disciplines and the achievements in such research might **foster** the progress of very fundamental topics such as **quantum dots semiconductor physics, photonic crystal devices, optical fiber amplifiers**.

In the final discussion the participants agreed that the slow and fast light scientific community has a real need to find <u>a frame within which cooperate</u>. To this purpose, seconding the request of the participants, the ESF Officer, Dr. Di Trapani, presented in a great detail the possible instruments through which the European Science Foundation can finance research efforts.

At the end of Dr. Di Trapani presentation is was clear to all that the most suitable instrument provided by ESF could be Research Networks. However, the next deadline for such instrument was too close to the Workshop event for the participant to have a real chance to write a proposal.
COST Actions, that are also run by ESF, were also discussed, though this instrument provides funds for meetings not for research and development activities.
Besides the ESF schemes, the chance of submitting a proposal to the European Commission, through the 7th Framework Programme, was also obviously considered. The subject of slow and fast light might fit within the Information and Communication Technology objective, though the Calls of 2007 (the second of which was closing exactly during this discussion) were not including any reference to this specific topics.
Since the slow and fast light research is yet at the forefront of science a possible chance has been identified in the Future and Emerging Technologies scheme, that is an open submission scheme. In fact, a small subset of the participants, had submitted, just before the Workshop, a proposal for the first stage evaluation of the this Call[1].
In any case, it was clear, from the discussion, that a broader action, involving European research teams not participating in the previously mentioned submission, could be also started. The only other instrument that could possibly be pursued was identified as the Research Training Networks of the People Program of the 7th Framework Programme. The participants committed themselves to collect the information about this instruments and for a possible future proposal.
In any case they all agreed that it would be a good idea to maintain this community alive by organizing another workshop, a year from now, even without any sponsor like the ESF in the present case.
In conclusion, the **Exploratory Workshop**, besides being a successful event in providing a **forum for a scientific discussion** on the topic of **slow and fast light**, has also fostered a clear chance for gathering the European community of researchers in this field. There are very good chances for a FET research Consortium to be created in the near future and/or a broader Research Network to be designed on a longer time.

Padua (Italy)**,** Dec 3rd 2007.

The Convenor: Marco Santagiustina   the Co-Convenor: Carlo G. Someda

[1] The project has passed the first evaluation stage on Nov 16th 2007 and the Consortium has been invited to

FINAL WORKSHOP PROGRAM

Sunday 7 October 2007
Evening *Arrival*

Monday 8 October 2007

09.00 **Welcome**
Presentation of the European Science Foundation (ESF)
Antonella di Trapani (Standing Committee for Physical and Engineering Sciences)

09.20 **Opening remarks**
M. Santagiustina, University of Padova, Italy

09.30 **Invited Talk**
J. P. Reithmaier, University of Kassel, Germany
Semiconductor quantum dots waveguides for slow and fast light

10.15 **Invited Talk**
C. Chang-Hasnain, University of California at Berkeley, USA
The bandwidth Slow and Fast Light in Semiconductor Optical Amplifiers

11.15 *Coffee Break*

11.45 **Invited Talk**
C.C. Phillips, Imperial College London, United Kingdom
Quantum Optics and Slow Light Experiments with Semiconductor Nanostructures Artificial-atom

12.30 **Open discussion**
During this session the features and problems of semiconductor devices for slow and fast light devices will be discussed, based on the results presented during the first two talks.

13.15 *Lunch at VIU*

15.00 **Invited Talk**
J. Moerk, Technical University of Denmark, Denmark
Light slow-down in semiconductor waveguides due pulsations to population

16.00 **Invited Talk**
A. De Rossi, Thales Research and Technology, France
Dispersion engineering in III-V based membrane photonic crystals for slow-wave applications

17.00 *Coffee Break*

17.00 **Invited Talk**
A. Melloni, Politecnico di Milano, Italy
Topic: Coupled resonators slow wave structures: potentiality and limits

18.10 Day wrap-up: Discussion on Semiconductor effects and waveguides: the fundamental limitations for slow and fast light devices and the perspective for real applications

20.00 *Workshop dinner in Venice*

Tuesday 9 October 2007

09.00 **Invited Talk**
G. Eisenstein, Technion, Israel
On the balance of delay bandwidth and signal fidelity in fiber based slow light systems; Implementation in parametric amplification and bandwidth broadened Brillouin scattering.

10.00 **Invited Talk**
L. Thévenaz, École Polytechnique Fédérale de Lausanne, Switzerland.
Efficient and optimized slow and fast light in optical fibres using stimulated Brillouin scattering

11.00 *Coffee Break*

11.30 **Invited Talk**
L. Schenato, **M. Santagiustina**, **C.G. Someda**, Universita' di Padova, Italy
Polarization effects in slow and fast light fiber amplification

12.30 **Open discussion**
During this session the features and problems of fiber devices for slow and fast light devices will be discussed, also stimulated by the previous presentations.

13.00 *Lunch at VIU*

14.30 **Invited Talk**
J. Capmany, **S. Sales**, Universidad Politecnica de Valencia, Spain
Microwave Photonics applications of the slow light effects

15.30 **Invited Talk**
M. Alounini, **S. Tonda-Goldstein**, **P. Berger**, **D. Dolfi**, **J.-P. Huignard**, Thales Research and Technology, France
Slow light in semi-conductor amplifiers: application to programmable time delays for optically carried microwave signals

16.30 *Coffee Break*

17.00 **Presentation of the funding schemes of the European Science Foundation (ESF)**
Antonella di Trapani (Standing Committee for Physical and Engineering Sciences)

17.30 **Workshop Final Discussion**
Realisation of slow and fast light devices. Overview of the realistic perspective for applications in optical and microwave signal processing. Possible actions for Research Programs.

20.00 *Informal Dinner in Venice*

Wednesday 10 October 2007
Morning *Departure*

FINAL LIST OF PARTICIPANTS

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STATISTICAL DATA

Male: 18
Female: 2 (including ESF Officer)

Young researchers (<35 years old): 3
Senior researchers (>35, <60): 15
Emeritus researchers (>60): 2

Repartition by country of work:

CH	1
DE	2
DK	2
ES	2
FR	4
IL	1
IT	6
UK	1
US	1