Information Society Technologies

NANO UB SOURCES • EU

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Specific Targeted Research Project – STREP

NANO UB-SOURCES

Ultrabroad bandwidth light sources based on nano-structuring devices

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Final report

Final, publishable activity report

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NANO UB-SOURCES – Final report

Project summary and objectives

The scope of NANO UB-SOURCES is to develop a new generation of broad bandwidth, compact, cost-effective, user-friendly lasers based on photonic device technology that enable significant improvement in early cancer diagnosis and monitoring of retinal diseases that are worldwide leading causes of blindness in the aging population. Modern medicine emphasizes development of diagnostic techniques that detect disease in its early stages, when treatment is most effective and irreversible damage can be prevented or delayed. Using the new light source technology developed by the consortium in optical coherence tomography (OCT) and time-resolved spectroscopy make it possible to obtain relevant clinical data both for diagnosing disease early, when treatment is most effective, and to accurately track disease progression.

In today's OCT systems the performance-limiting bottlenecks are the relatively narrow bandwidth of the light sources currently available and the output power level. By extending this bandwidth two- or threefold axial resolution is increased from tens of microns to the subcellular scale, which essentially represents a breakthrough in non-invasive imaging. NANO UB-SOURCES addresses this bottleneck issue by developing light sources based on structuring quantum dots (QD) distributions using epitaxial methods. Hence, the consortium will generate the first QD based superluminescent diode with a tapered waveguide. Within this project, specially tailored PCFs are also realised for the purpose of providing broad spectra via pumping by picosecond sources. For both choices of technology, the main challenge will be achieving broad bandwidth operation at relatively high output power levels, i.e., tens of mW, in order to obtain signal-to-noise-ratios of interest for clinical applications. Furthermore, the epitaxial methods to be used for nanostructuring, characterisation tasks and modelling techniques advance materials science in the field. NANO UB-SOURCES thus contributes to new understanding on the influence of parameters, such as dot density, composition and size in QD structures on their optical properties. Finally, the sources are compact and cost-effective.

The resulting system development within NANO UB-SOURCES enable unprecedented non-invasive, in-vivo early diagnosis of diseases that are worldwide leading causes for blindness as well as cancer diagnosis of neoplastic changes and real time therapy monitoring in dermatology. The direct impact will be early detection in a variety of ocular pathologies such as age-related macular degeneration and the possibility for early cancer diagnosis in the area of dermatology.

In the short term, the technology developed in NANO UB-SOURCES is imperative in order to overcome the performance-limiting bottleneck for clinical applications of OCT and tissue diagnostic spectroscopy. Overcoming this bottleneck leads to new, significant commercial markets. In particular, the axial resolution of OCT, which is related to the source bandwidth, must be improved, which is exactly the purpose of NANO UB-SOURCES.

In the long term, applications within important market segments, such as optical fibre sensors, automotive applications (gyroscopes, accelerometers, etc.) or telecom, would benefit directly from the developed devices. Moreover, the gained knowledge on the fundamental laser design and manufacturing processes will lead to new or improved devices in the before-mentioned areas.

NANO UB-SOURCES: Main technical advances

SLDs: Modelling and devices

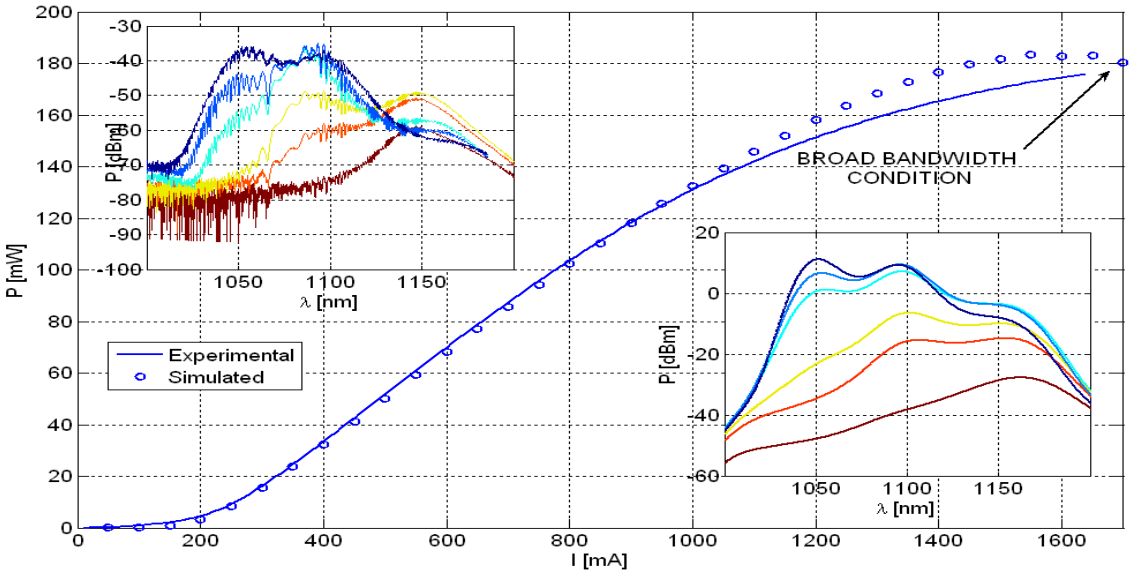
The modelling applied the code nextnano^3 in order to handle the simulation of the DWELL material to define new structures with chirped emission to obtain SLD having flat amplified spontaneous emission (ASE) emission. In addition, one may also apply the model to define parameters to be used in non excitonic simulation models. An example of the fine agreement between simulation and experimental results is shown in the figure.

Three major simulation codes have been developed for SLD analysis:

- a very simple one based only on a rate equation for carriers in the GS, ES1 and ES2, WL, SCH and propagation equations for the ASE generated from GS and ES. This code allowed to evaluate the

first SLD equal power point emission from GS and ES, to give directions for the design of realized structures and to propose new multi-sections devices with larger power.

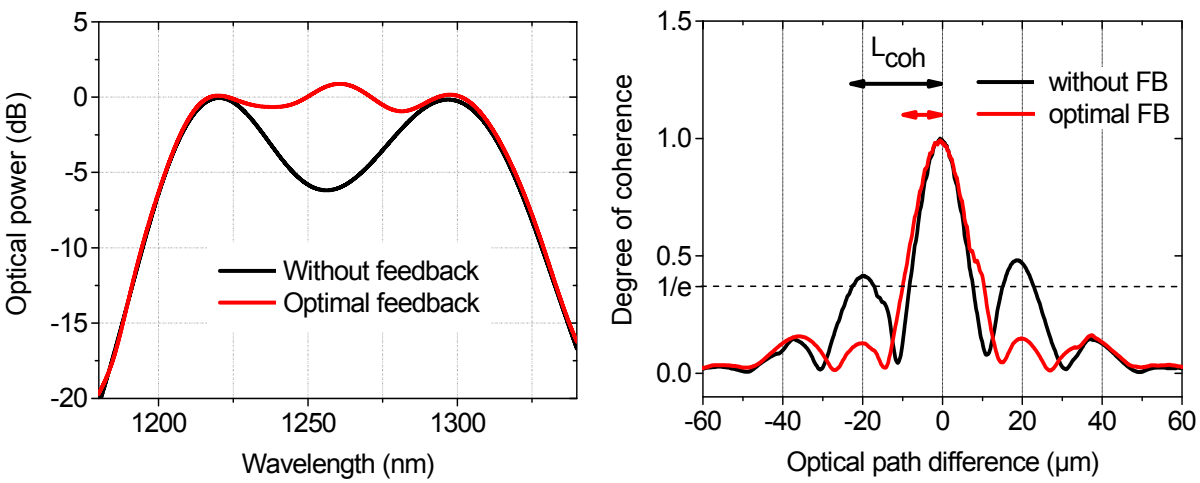
- at the same time a simulator based on the MPRE model was developed. Its predictability features were very good but its simulation time was very demanding for PT group computer capability.
- In the last year a novel simulation approach for SLD was proposed and realized. It has respect to MPRE model a similar accuracy with a simulation time reduced at least of one order of magnitude. Very good agreement with experimental data was obtained, as evident from the figure.



Comparison between simulated (circles) and experimental (continuous line) PI characteristics for the 6 mm-long 4 μm-wide chirped 3QDL×3 SLD (VN1127). Emissions from the 3 different groups of QD layers have central emission wavelengths separated by 30 nm (1114 nm, 1144nm, 1174 nm). Insets show the simulated and experimental spectra at injected current I = 50, 125, 185, 600, 1000, 1700 mA. A first broad-band condition is achieved at 185 mA, a second one is achieved at an injection current close to 1700 mA corresponding to a 180 mW output power.

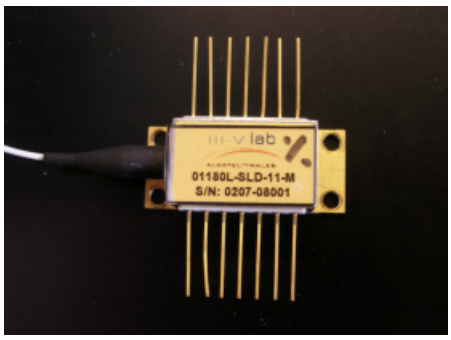
SLDs: Intensity noise and tunable coherence properties

High precision noise measurements were carried out by TUD to investigate the QD-SLD intensity noise behaviour. A major result is the observation that an increase in the SLD spectral bandwidth is accompanied by a decrease in intensity noise. An excess-noise model perfectly described the experimental results. All investigated SLDs exhibit excess noise character with a relative intensity noise (RIN) in the range of -130dB/1Hz. Furthermore, the model identified amplified spontaneous emission (ASE) as the main cause of intensity noise in QD-SLDs.



Optical spectra (left) and coherence function (right) of SLD VN1035, 6mm without (black) and with optimal feedback (red).

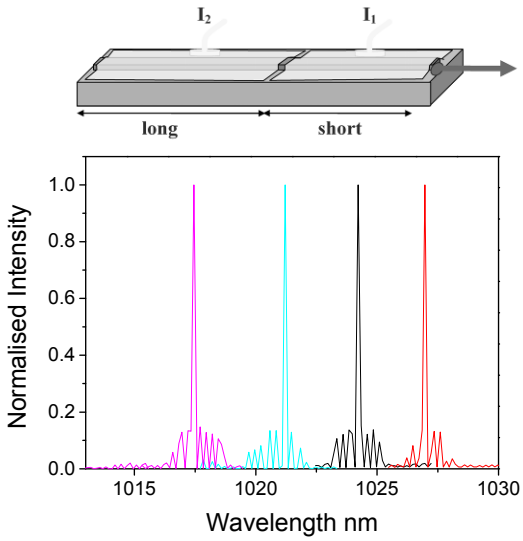
Investigating the feedback sensitivity of QD-SLDs, TUD succeeded in optimizing the coherence properties by the experimental technique of frequency selective feedback. For well-selected feedback parameters, the dip that occurs in the optical spectrum in between GS and ES emission was reduced thus realizing ultrabroad spectral emission. Consequently, the coherence length was improved by a factor of more than 2, accompanied by an increase of 40% in output power.



SLD devices were selected for packaging at both targeted wavelengths (1050 nm and 1300 nm, although the centre wavelength of the latter was shifted towards 1200 nm). The modules at 1200 nm were tested in optical coherence tomography (OCT) systems.

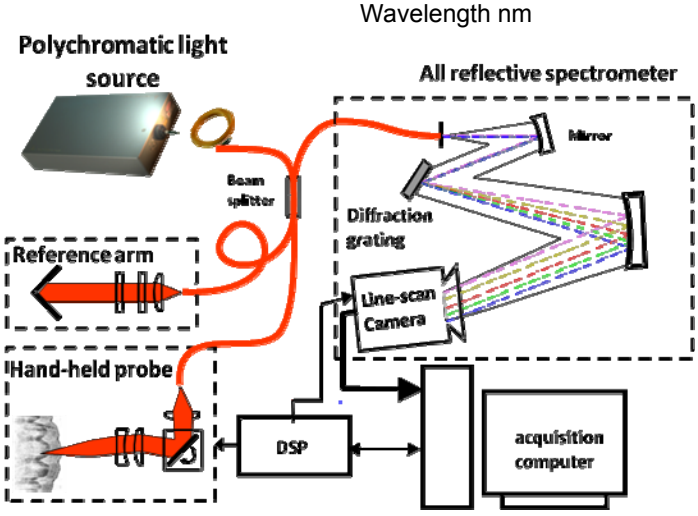
Light sources

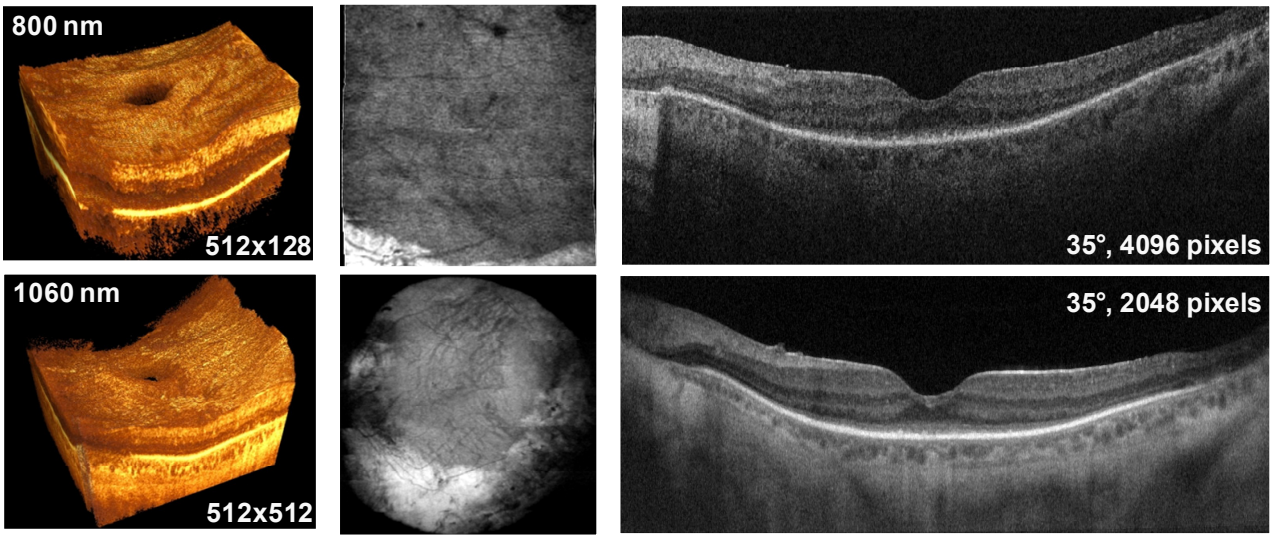
USS has developed a multisection device consisting of ridge waveguide with electrically isolated contactable sections achieved by etching through the ridge contact and the heavily doped p-region of the device. From this USS has been able to demonstrate a novel all electronic monolithically integrated swept laser source at 1050 nm. Although the device was not part of the original work plan it should be emphasised at this point, because it has great potential for future exploitation. In particular, USS has applied for a patent based on these results (R. Hogg et al. UK Patent Application 2007 GB0715063) and has now published the initial studies in Applied Physics Letters (2007).



Optical coherence tomography

The high speed frequency domain OCT system for 1060 nm (see figure) developed within the consortium was interfaced to a preliminary patient module, modified for operation at 1060 nm to enable clinical retinal imaging at this wavelength and compared to an OCT system operating at 800 nm. It has been used for demonstration of improved visualization of three-dimensional 1060nm for visualizing choroidal structures in patients, cf. figure: Three-dimensional OCT at 800nm (top) vs.1060nm (bottom) of a patient with retinitis pigmentosa. Three-dimensional rendering (left) and high definition B-scans (right) demonstrated improved penetration into and hence visualization of the choroid. En face fundus images of the choroid can be extracted from volumetric OCT data sets. High speed 3D 1060nm OCT therefore now enables unprecedented visualization of all three choroidal layer giving access to the entire choroidal vasculature. In addition two-dimensional choroidal thickness maps might have significant impact in the early diagnosis of retinal pathologies like glaucoma, age-related macular degeneration and might contribute to a better understanding of myopigenesis.

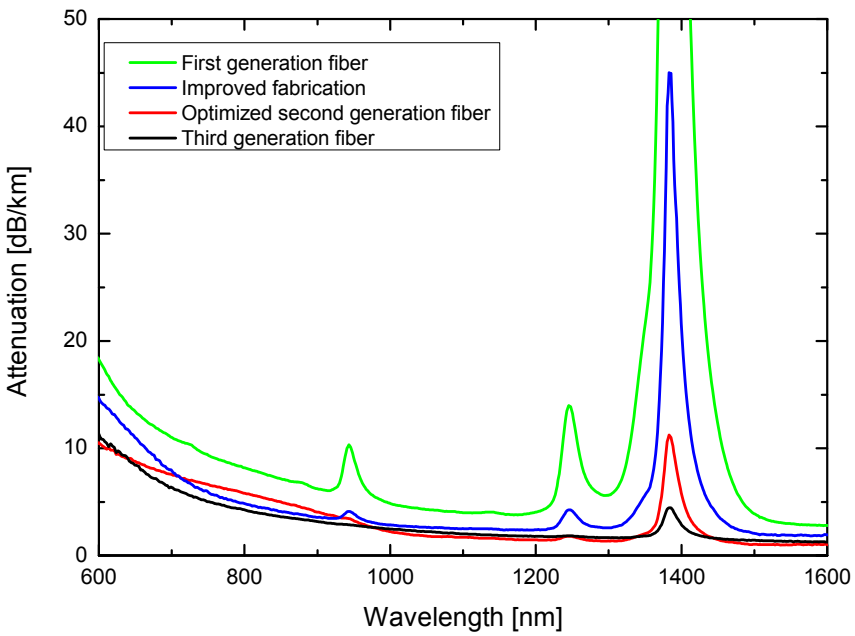




Three-dimensional OCT at 800nm (top) vs.1060nm (bottom) of a patient with retinitis pigmentosa. Three-dimensional rendering (left) and high definition B-scans (right) demonstrated improved penetration into and hence visualization of the choroid. En face fundus images of the choroid extracted from volumetric OCT data sets.

Photonics crystal fibres

Optimized third generation nonlinear photonic crystal fibers for supercontinuum generation have been fabricated and characterized. The aim has been to improve the supercontinuum generation performance of the fibers by optimizing the dispersion profile and reducing the attenuation of the fibers. The attenuation improvements have been obtained through the use of several methods and process optimizations. Compared to the first generation fibers, the OH attenuation at 1.4 µm has been improved more than an order of magnitude, and the third generation fiber exhibits a record low loss at the OH peak of only 4.47 dB/km as shown in the figure below. This third generation low attenuation fiber has been used in a picosecond pumped supercontinuum setup thereby benchmarking the performance compared to the original fibers. The setup was an all-fiber picosecond pumped setup in which the nonlinear fiber was pumped by a mode-locked fiber laser (KOHERAS ps-laser). Compared to the first supercontinuum source delivered to Lund on the early fibers, the optimized third generation fibers result in increased efficiency and much broader and flatter spectra, making the output more suitable for OCT as well as different types of spectroscopy. The optimized fibers are now commercially available and are used in commercially available supercontinuum sources.



Comparison of spectral attenuation of the first generation fiber, an improved test fiber, the optimized second generation fiber, and the third generation fiber.

These achievements are in good agreement with the project objectives of WP5 as it has been possible through design and production optimizations to obtain fibers with much lower attenuation resulting in supercontinuum generation with increased efficiency and much broader and flatter spectra. These spectral characteristics makes the output much more suitable for ultrahigh resolution OCT as well as different types of spectroscopy, in accordance with the main project objective of WP5.

Time-resolved spectroscopy

NANO UB-SOURCES has developed novel state-of-the-art ultra-wideband time-of-flight absorption/scattering spectrometer system. The resolution and spectral tuneability range of the novel instrument by far exceed the parameters of similar instrument reported to date. We have clearly demonstrated the outstanding performance of the device by performing simultaneous scattering and absorption measurements on biological tissue samples. Notably, these advances have only become possible due to recent availability of the novel PCF developed within the framework of NANO UB-SOURCES. It is also important to stress the prospective impact the instrument may have on the biomedical applications:

- Small differences in the cumulative absorption spectra of four major breast tissue absorbers, i.e. oxy/deoxy -hemoglobin, water, and bulk lipid between the tumour and normal tissue can be used to identify specific cancer biomarkers. Accuracy, selectivity and, spatial resolution of this method is heavily dependent on the precision and resolution of the instrument applied to determine absorption spectra in the turbid tissue of the breast.
- The efficiency and predictability of photodynamic cancer therapy of tumours in internal organs have been suggested to be improved using intra-operative measurements with feed-back. Such measurements can provide maps over the optical properties within the organ as well as the biodistribution of the photo-sensitizer drug during the treatment. Enhancing the resolution of interstitial non-invasive fluorescence tomography may is also become crucial in such measurements.
- A third application where this instrument may become instrumental would be in longitudinal studies of treatment response, particularly in the development of new treatments, including pharmaceutical research. In such studies researchers aim at measuring the development caused by the treatment, preferable non-invasively as the same animal then can be followed. Molecular imaging techniques are developed for this. One of the most interesting techniques is here fluorescence tomography/imaging. Absolute measurements using this technique require precise knowledge of the tissue optical properties. Here this technique becomes critically important.
- Finally TOF spectroscopy in turbid media is highly relevant for the pharmaceutical industry. It can be used for many diverse industrial applications such as qualitative and quantitative analysis of powders, pellets, tablets, freeze-dried products, etc. As a powerful analytical technique TOF absorption/scattering spectroscopy in NIR spectral range is capable to provide major cost savings both in the pharmaceutical developments, product control and in the fabrication process monitoring.

Exploitation

The NANO UB-SOURCES consortium expects that the technology developed within the consortium will be exploited on commercial basis.

<u>Crystal Fibre A/S – Exploitation</u>

The facilities at CF are geared for producing photonic crystal fibres at high volumes. The market potential in bio-photonic applications represents an important and rapidly growing opportunity. It is within the strategy of CF to exploit this opportunity and two areas are immediately attractive: a) nonlinear fibres for supercontinuum generation for OCT, and b) spectroscopy. CF would mass produce the fibres and supply them to system manufacturers or produce the sources in a joint venture. CF has commercialised the fibres developed within NANO UB-SOURCES, and they are now part of their product range.

Dissemination

In NANO UB-SOUCES, dissemination of results is clearly defined in terms of presenting results in scientific journals and through the presence of consortium members at international conferences. During the entire, a high number of publications have been published in peer-reviewed scientific journals and at scientific conferences.

The consortium web site (www.nano-ub-sources.org) is updated regularly in order to disseminate results of public and general interest, and also to provide internal communications channels between partners, e.g. document sharing. The latter is accomplished through a password-protected, back-office part of the site.

An important part of the web site is the tutorial section. As part of each consortium meeting, tutorials are prepared by the hosting institution with purpose of providing basic knowledge to other partners within the consortium. It has been decided to make these tutorials part of our dissemination strategy. Therefore, the tutorials are being published at the public web site with the purpose of providing general education within the areas covered by NANO UB-SOURCES.

Consortium

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