Project no.:	**IST – 511406**
Project acronym:	**URANUS**
Project title:	**Ultrafast Technology for Multicolor Compact High-Power Fibre Systems**
Instrument:	**STREP**
Thematic Priority:	**Priority 2**

Final report
D33

Period covered: from	**1.07.2004-30.06.2007**	Date of preparation: **30.08.2007**
Start date of project:	**1.07.2004**	Duration: **3 years**
Coordinator:	**Prof. Oleg Okhotnikov**	
Project coordinator organisation:	**Tampere University of Technology (TUT), Tampere, Finland**	

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Approved by:	Prof. Oleg Okhotnikov

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1 Publishable Executive Summary

1.1 General overview

Generation of short optical pulses has become an increasingly important technology for many applications including laser-based micromachining, thin-film formation, laser cleaning, medicine and biology. Ultrafast lasers can deliver pulses with enormous peak powers and power densities. These characteristics enable applications such as laser machining and ablation, generation of electromagnetic radiation at unusual wavelengths (such as mm waves and X-rays), and multiphoton imaging. Traditional ultrafast sources have been based primarily on solid-state, bulk-optic technology. Optical fibre technology, which has progressed significantly thanks to efforts related to optical communication, promises a more integrated solution to ultrafast pulse generation than has been possible with bulk optics. In parallel with improvements in short-pulse oscillator technology, fibre technology offers an efficient approach for pulse amplification; this is another essential requirement for industrial applications such as marking, drilling, cutting, welding and almost any imaginable type of material processing.

The overall objectives of the URANUS project were to develop the technology that pursues two primary objectives: *more energetic ultrashort pulses at various wavelengths* and *increased stability*. The project efforts have been focused on the development of ultrashort pulse sources based on fibre lasers technology. The URANUS consortium includes European companies (Fianium Ltd. from the UK, Corelase Oy from Finland, NKT Research from Denmark, Stratophase from the UK) and academic institutions (Tampere University of Technology from Finland, and INESC Porto from Portugal) that worked together to push the limits of ultrafast fibre laser technology, and to exploit innovative fibre-laser systems commercially. The project has demonstrated a positive example of European partnerships involving academia, business and government founded non-profit institutions working together to develop and commercialize new technologies. The synergy of the consortium resulted in a positive impact on the performance of ultrafast optics European industry. By the end of the project Fianium was recognized as the main player in ultrafast fibre laser technology in Europe. Stratophase and NKT strengthened their position as the main suppliers of nonlinear crystals and photonic crystal fibres, respectively. Advances made by Corelase have attracted the attention of a major European laser and application developer (Rofin-Sinar), which acquired Corelase at the beginning of 2007.

1.2 Objectives of the project and main results

The URANUS project aimed at the development of new ultrafast fibre laser technology and its integration into novel application markets. The major objectives of the project were:

1. The development of high-power ultrafast fibre systems operating at wavelengths of 980 nm, 1064 nm, and 1550 nm.

2. The development and field trial of broad-band fibre sources based on frequency conversion via frequency doubling and quadrupling, and supercontinuum generation.

The technical achievements of the project are summarized in Tables 1 and 2.

Table 1: URANUS project goals pertaining to high power sources

Operation wavelength, nm	Average power	Pulse duration	Peak Power	Status of the project in respect to the target
980	1 W	< 10ps	>20 kW	Targets achieved Prototype demonstration (Fianium)
1064	5 W	< 300 fs	>200 kW	Targets achieved Commercial product (Fianium)
1064	20 W	< 15 ps	>15 kW	Targets achieved Commercial products (Fianium, Corelase)
1064	100 W	< 30 ps	> 200 kW	Targets achieved Laboratory demonstration NKT Laboratory demonstration (Fianium)
1550	0.5 W	100 fs	100 kW	Master oscillator developed commercially Amplified lab version demonstrated

Table 2: URANUS project goals pertaining to broad spectrum and multicolour sources

Wavelength, nm	Technology Employed	Average Power	Status of the project in respect to the target
266	Frequency quadrupled 1064 nm fibre lasers	1 W	Target exceeded (2W) Commercial product (Fianium)
355	Sum-frequency using 1064 nm fibre lasers	4 W	Target exceeded (8 W) Commercial product (Fianium)
530	Frequency doubled 1064 nm fibre lasers	8 W	Target exceeded (10 W) Commercial product (Fianium)
775	Frequency doubled 1550 nm fibre lasers	150 mW	Target achieved Laboratory demonstration
400–1800	SC generation using 1064 nm and 1550 nm fibre lasers and photonic crystal fibre	2W Spectral brightness >1 mW/nm	Target exceeded (8 W average power, 5 mW/nm) Commercial product

The coordinating organization is *Tampere University of Technology (TTY). TTY* is also the main player in the development of semiconductor components for ultrafast fibre lasers. The other partners develop photonic crystals fibres (*NKT Research and Innovation,* Denmark), fibre Bragg gratings (*INESC Porto*, Portugal), nonlinear optical crystals (*Stratophase Ltd*., UK), ultrafast high-power fibre systems (*Fianium Ltd*.), and applications (*Corelase Ltd.,* Finland).

1.3 Main technologies developed in URANUS

Semiconductor saturable absorber mirrors

An essential component for generating ultrashort-pulses with fibre lasers is the semiconductor saturable absorber mirror (SESAM). SESAM-based fibre lasers have a compact size, are environmentally stable and can produce ultrashort pulses with picosencond and femtosecond durations. Within the project, we have identified the principal mechanisms that cause ultrashort pulse shaping in a fibre laser and we have optimized the SESAMs for operation at 1550 nm, 1060 nm, and 980 nm. The technology has been commercialized through a spin-off company, RefleKron Oy, of the Tampere University of Technology that was established at the beginning of the project.

Photonic bandgap fibre for intracavity dispersion compensation, amplification, and supercontinuum generation

In URANUS, we demonstrated for the first time the use of a solid-core photonic bandgap fiber to compensate the dispersion of an ytterbium mode-locked laser. We showed that using semiconductor saturable absorber mirror together with solid-core photonic bandgap fiber enables the self-starting all-fibre mode-locked laser operating around 1-µm wavelength range. This approach may constitute an important *step towards novel generation* of ultrafast fiber osillators. Another even more advanced configuration of an environmentally stable soliton laser uses *ytterbium-doped all-solid photonic bandgap* fibre providing both gain and dispersion compensation at 1 µm. Special PCFs were designed to enhance supercontinuum generation using 1060 nm ultrafast lasers as seed source. The results obtained have exceeded the expectations in terms of average power, spectral density and emission bandwidth.

Nonlinear crystals for frequency conversion

Periodically-poled crystals have been investigated as high-efficiency nonlinear media for frequency conversion. During the URANUS project the focus of this work has been towards applications in frequency doubling of the short-pulse infrared fibre lasers developed within concurrent work-packages. When designing a frequency converted laser system, it is important that the periodically-poled grating matches properly the pump source characteristics to achieve maximum conversion efficiency from infrared to visible wavelengths. For example, longer gratings are typically required to achieve higher conversion efficiencies, but grating length is also inversely proportional to the spectral bandwidth of the crystal. As short-pulse fibre lasers typically feature broad spectral outputs (> 1nm) this leads to a requirement for short crystals with lengths of around a hundred microns (or less), requiring often unachievable fabrication tolerances.

Amplifiers and system demonstrations

Various types of high power amplifiers have been developed to scale up the power delivered by the mode-locked fibre oscillators. Much of the effort has been focused on 1064 nm systems because of the expected high commercial impact. The key technologies investigated within this work part are Yb-doped fibers with low nonlinearity, pump combining techniques and pulse and spectral management techniques. These developments are at the basis of the commercial fiber systems presented in tables 1 and 2.

1.4 Use and dissemination

Main educational and dissemination activities

- More than 30 articles published in peer-reviewed scientific journal and conference proceedings
- Four PhD theses based on results obtained in URANUS were completed in the course of the project

- URANUS contributed to the organization of an International Summer School (2005) and one Workshop (2006)
- Several invited talks to international conferences
- Project web pages: www.orc.tut.fi/uranus.html

URANUS results exploitable commercially

Product	**Owner**	**Exploitation status**
SESAM	TTY	TTY has established a spin-off company, RefleKron, which started to commercialize SESAMs
PCFs for supercontinuum generation	NKT	Highly non-linear PCF is used in commercial super-continuum sources
PPLN crystals for frequency conversion	STR	Stratophase upgraded its PPLN products for 1550 nm and 1060 nm and has introduced new PPLNs at 980 nm
Master oscillators generating ultra-fast laser pulses	FNL	Commercialized as the Femto-Master fibre laser oscillator
High power ultra-fast fibre laser systems	FNL	Commercialized products: - *Picosecond fibre laser systems FP1060* - *UVPower: visible to UV ultrafast fibre laser systems*
	COL	Commercialized as a turn-key picosecond ultrafast fiber laser system, X-lase, with an integrated optical processing head
Supercontinuum fibre source	FNL	Commercialized as a range of SC450 white light sources
	NKT	Commercialized white light source by NKT's sister-company Koheras

2 Summary of achievements for each work package

WP	Objectives	Achievements	Deliverables
WP2: Master sources	Development of SESAMs optimized for fibre lasers	SESAMs operating at 1550 nm, 1060 nm and 980 nm	D1- D7, D13: Summary report on optimized SESAM prototypes
	Developments of components and methods for intracavity dispersion compensation of mode-locked fibre lasers	Tapered fibres, Gires-Tournois dispersion compensators, solid core PCFs, and chirped Fibre Bragg gratings suitable for intracavity dispersion compensation at around 1 μm	D8, D9: Modelling and fabrication of FBGs and chirped FBGs D10. Modelling and fabrication of Gires-Tournois compensators D12: Fabrication and delivery of PCFs for dispersion compensation
	Development of compact fibre oscillators	Commercial fibre oscillator with compact foot-print at 1550 nm and 1060 nm wavelength ranges	D14-D16: Summary report concerning performance of 1550 nm, 1060nm, and 980 nm mode-locked fibre laser prototypes
WP3: Optical amplifiers	Development of novel doped LMA PCFs for amplification of ultrashort pulses	Yb-doped LMA PCFs used for amplification of ps pulses with 100 W average power	D17: Delivery of Yb-doped LMA-PCFs. D18: Delivery of Er/Yb-doped LMA PCF
	Development of MOPA systems at 1550 nm	PP=100 kW, PW=100 fs, Pavg = 0.5 W (see table 1)	D19, D22: Delivery of amplified 1550 nm ultrafast fibre system
	Development of MOPA systems at 1060nm	Commercial systems: Pavg =5 W, PW =300 fs Pavg =20 W, PW < 15 ps Pavg =100 W, PW < 30 ps	D20, D23: Delivery of amplified 1060 nm ultrafast fibre system
	Development of MOPA systems at 980nm	Pavg = 1 W, PW=10 ps	D21, D24: Delivery of 980 nm amplified ultrafast fibre system
WP4: Nonlinear crystals	Fabrication of PPLN crystals operating at 1550 nm, 1060nm and 980 nm	Commercial crystals optimized for operation with short optical pulses.	D25: Report summarizing the fabrication and performance 1550 nm, 1060 nm , and 980 nm PPLNs
	Frequency converted ultrafast fibre systems	Commercial ultrafast fibre systems for visible and UV: Pavg= 1W @ 260 nm Pavg= 4W @ 355 nm Pavg= 8W @ 530 nm	D26: Report summarizing the development and performances of frequency converted fibre systems
WP5: SC sources	Development of highly nonlinear fibre	New PCFs (including PM) optimized for SC generation using 1060 nm seed.	D27: Report on PCF developments
	Development of SC sources	Commercial products: Pavg = 8W, 5mW/nm, 400 nm–1800 nm	D28: Report on the development and performances of SC sources

WP6: Field trial	Monitoring of the market requirements. Identifying new applications	Applications feedback and evaluation of the suitability of the system for micromachining applications	D29: Manufacturability of components and systems and review of market demands
	Developing a turn-key system suitable for industrial applications	Commercial system delivered to customers for testing	
WP7: Use and dissemination	Raising the public awareness regarding the results achieved in URANUS.	More than 30 journal papers and conference presentations	D11: Webpage implementation D30: Dissemination and use plan D31: URANUS workshop D32: Technology implementation plan
	Improving the education with a focus on ultrafast fibre optics	4 PhD theses 3 Diploma theses	
	Commercialising the results	New commercial products: - SESAMs optimized for fibre lasers, improved PPLNs (crystals operating at 980 nm have been developed within URANUS), new PCFs, high-power ultrafast fibre systems (UV, visible and infrared), SC sources	

WP1 was concerned with management. It consisted of specific actions related to project monitoring and reporting.

3 Effort and budget consumption

3.1 Person-Month Status Table

CONTRACT N°: IST – 511406									
ACRONYM: URANUS									
PERIOD: 01.07.2005 - 30.06.2006									
Workpackage		**Total effort**	**Coordinator (TTY)**	**FNL**	**STP**	**NKT**	**INESC**	**Corelase**	**Statutory TTY**
WP1 Management	**Period 3:**	7.17	1	0	0.22	0	0.5	0.45	5
	Period 2:	9.02	4.5	1.2	0.27	0.5	0.5	1.05	1
	Period 1:	8.76	0.6	0.8	0.33	1	0.33	1.7	4
	Planned total:	25.5	8.50	2	1	2	1	2	9
WP2 Sources	**Period 3:**	23	13	0	0	0	0	0	10
	Period 2:	37.7	18	3.4	0	5.3	6	0	5
	Period 1:	55.6	12	6.6	0	12	5	0	20
	Planned total:	99	36	10	0	12	11	0	30
WP3 Amplifiers	**Period 3:**	26.3	10	1	0	3.6	0	1.7	10
	Period 2:	33.4	11	8.5	0	8.9	0	3	2
	Period 1:	14.45	3.65	4.5	0	0	0	4.3	2
	Planned total:	81	28	12	0	18	0	9	14
WP4 Nonlininear conversion	**Period 3:**	15.58	7	0.41	2.37	2.8	0	0	3
	Period 2:	25.03	6	5	10.03	0	0	0	4
	Period 1:	9	1	0	5	0	0	0	3
	Planned total:	50	14	6	18	0	0	0	12
WP5 SC	**Period 3:**	4.5	2.5	1	0	0	0	0	1
	Period 2:	29.68	10.5	4.68	0	9.5	0	0	5
	Period 1:	3	0	0	0	3	0	0	0
	Planned total:	45	15	6	0	14	0	0	10
WP6 Field trials	**Period 3:**	12.68	0	3.23	0	0	0	9.45	0
	Period 2:	3.4	0	1.25	0	0	0	2.15	0
	Period 1:	0.6	0	0	0	0	0	0.6	0
	Planned total:	18	0	5	0	0	0	13	0
WP7 Use and dissemination	**Period 3:**	21.07	10	1	2.07	0	3	3	2
	Period 2:	7	0	1	1	1	0	0	4
	Period 1:	4.5	0	0.5	0	0	0	0	4
	Planned total:	34	8	3	2	4	3	4	10
Total MM	**Y3 total:**	110.3	43.48	6.64	4.66	6.4	3.5	14.6	31
	Y2 total:	145.2	50	25	11.3	25.2	6.5	6.2	21
	Y1 total:	95.91	17.25	12.4	5.33	16	5.33	6.6	33
	Y1+Y2+Y3	351.44	110.75	44.04	21.29	47.6	15.33	27.4	85
	Planned total:	352.5	109.5	44	21	50	15	30.25	85

3.2 Cost Budget Follow-up Table - in respect to the total planned budget

Contract N°:	IST – 511406	Acronym: URANUS				Date:	20.7.2006	
PARTI-CIPANTS	TYPE of EXPENDITURE	TOTAL PLANNED	ACTUAL COSTS (EUR)				Pct. spent	Remaining Effort/Budget (MM/EUR)
			Period 1	Period 2	Period 3	Total	Total	
P1:TTY	Total Person-month	109,00	17,25	50,00	43,48	110,73	102 %	-1,73
	Personnel costs	334857,00	52577,15	124964,98	159385,00	336927,13	101 %	-2070,13
	Consumables	140351,00	33480,88	49741,19	46876,73	130098,80	93 %	10252,2
	Other costs incl. overhead	124792,00	27252,71	47235,62	60120,55	134608,88	108 %	-9816,88
	Total Costs	600000,00	113310,74	221941,79	266382,28	601634,81	100 %	-1634,81
P2:FNL	Total Person-month	44,00	12,40	25,00	6,63	44,03	100 %	-0,03
	Personnel costs	202101,37	60248,84	107280,50	43396,17	210925,51	104 %	-8824,14
	Consumables	110520,95	66268,18	39645,83	28592,88	134506,89	122 %	-23985,94
	Other costs incl. overhead	71942,26	25431,78	30455,25	17276,95	73163,98	102 %	-1221,72
	Total Costs	384564,58	151948,80	177381,58	89266,00	418596,38	109 %	-34031,8
P3:STP	Total Person-month	21,00	5,33	11,30	5,00	21,63	103 %	-0,63
	Personnel costs	144215,40	34199,13	82386,86	46529,97	163115,96	113 %	-18900,56
	Consumables	102376,73	28533,49	45137,28	14830,13	88500,90	86 %	13875,83
	Other costs incl. overhead	58058,53	14266,25	26839,72	13783,63	54889,60	95 %	3168,93
	Total Costs	304650,66	76998,87	154363,86	75143,73	306506,46	101 %	-1855,8
P4:NKT	Total Person-month	50,00	16,00	25,20	6,39	47,59	95 %	2,41
	Personnel costs	195915,27	90170,00	79330,50	0,00	169500,50	87 %	26414,77
	Consumables	79706,84	51281,00	19425,84	32573,00	103279,84	130 %	-23573
	Subcontracting	108371,86	0,00	83640,63	35421,00	119061,63	110 %	-10689,77
	Other costs (no. overhead)	9086,42	4000,00	1086,42	1000,00	6086,42	67 %	3000
	Total Costs	393080,39	145451,00	183483,39	67994,00	396928,39	101 %	-3848
P5:INC	Total Person-month	15,00	5,00	6,50	3,50	15,00	100 %	0
	Personnel costs	42364,65	19080,85	11658,80	11275,39	42015,04	99 %	349,61
	Consumables	67292,70	55367,68	11925,02	6808,50	74101,20	110 %	-6808,5
	Equipment	11785,70	3928,56	3928,57	3928,56	11785,69	100 %	0,01
	Third party	30784,44	0,00	15286,44	9792,36	25078,80	81 %	5705,64
	Other costs incl. overhead	61523,05	33926,32	14320,73	10828,43	59075,48	96 %	2447,57
	Total Costs	213750,54	112303,41	57119,56	42633,24	212056,21	99 %	1694,33
P6:COL	Total Person-month	28,75	6,50	6,20	14,60	27,30	95 %	1,45
	Personnel costs	169245,05	38721,25	41023,80	84893,70	164638,75	97 %	4606,3
	Consumables	67772,88	5189,16	30793,05	45515,22	81497,43	120 %	-13724,55
	Other costs incl. overhead	75778,44	22302,33	18166,78	30168,84	70637,95	93 %	5140,49
	Total Costs	312796,37	66212,74	89983,63	160577,76	316774,13	101 %	-3977,76
TOTAL	Total Person-month	267,75	62,48	124,20	79,60	266,28	99 %	1,47
	Personnel costs	1088698,74	294997,22	446645,44	345480,23	1087122,89	100 %	1575,85
	Consumables	568021,10	240120,39	196668,21	175196,46	611985,06	108 %	-43963,96
	Equipment	11785,70	3928,56	3928,57	3928,56	11785,69	100 %	0,01
	Subcontracting	108371,86	0,00	83640,63	35421,00	119061,63	110 %	-10689,77
	Third party	30784,44	0,00	15286,44	9792,36	25078,80	81 %	5705,64
	Other costs incl. overhead	401180,70	127179,39	138104,52	133178,40	398462,31	99 %	2718,39
	Total Costs	2208842,54	666225,56	884273,81	702997,01	2253496,38	102 %	-44653,84

	TYPE of EXPENDITURE	BUDGET	ACTUAL COSTS (EUR)				Pct. spent	Remaining Budget (EUR)
			Period 1	Period 2	Period 3	Total	Total	
Statutory effort TTY (AC)	Total Person-month	85	33,00	21,00	31,00	85,00	100 %	0
	Personnel costs	240000	84227,69	69561,72	89916,69	243706,10	102 %	-3706,1
	Consumables	60000	21447,00	24188,59	20318,45	65954,04	110 %	-5954,04
	Travel	7500	1860,31	1651,50	1002,05	4513,86	60 %	2986,14
	Total Costs	307500	107535,00	95401,81	111237,19	314174,00	102 %	-6674

4 Final remarks

Despite the remarkable achievements made in URANUS, there are many R&D issues that need to be addressed to further advance the ultrafast fibre laser technology. The next phase of developments spun-out from URANUS will be focused on issues dealing with improvements in the following areas:

- *Advanced photonic crystal fibres with lower loss, improved high-order dispersion, and amplification efficiency;*
- *Further optimization of the nonlinear crystals for frequency doubling and quadrupling to support more energetic pulses and broader bandwidths;*
- *Scaling the output power of ultrafast fibre based MOPA systems to 100s W.*
- *Extending the operation wavelength range of ultrafast fibre systems to the mid-infrared regions.*