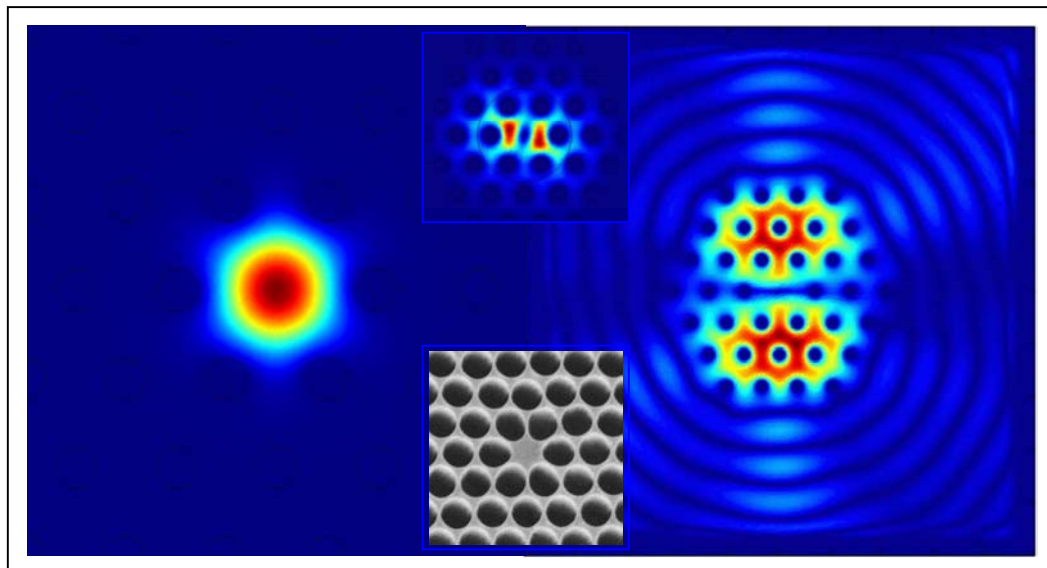


PHOTONIC CRYSTAL (HOLEY) FIBRES FOR SPACE APPLICATIONS

Executive Summary



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1 Abbreviations, Acronyms and Definition of Terms

<i>DIAL</i>	<i>Differential Absorption LIDAR</i>
<i>FOG</i>	<i>Fibre-Optic Gyro</i>
<i>FM</i>	<i>Fundamental Mode</i>
<i>FWHM</i>	<i>Full Width Half Maximum</i>
<i>HF</i>	<i>Holey Fibres</i>
<i>HOM</i>	<i>Higher Order Mode</i>
<i>IR</i>	<i>Infra Red</i>
<i>ISL</i>	<i>Inter Satellite Links</i>
<i>LIDAR</i>	<i>Light Detection and Ranging</i>
<i>LMA</i>	<i>Large Mode Area</i>
<i>NIR</i>	<i>Near Infra Red</i>
<i>OFCG</i>	<i>Optical Frequency Comb Generators</i>
<i>PM</i>	<i>Polarization Maintaining</i>
<i>PBGF</i>	<i>Photonic Band-Gap Fibre</i>
<i>PCF</i>	<i>Photonic Crystal Fibre (index guiding, also known as Holey Fibres)</i>
<i>SC</i>	<i>Super Continuum</i>
<i>SIF</i>	<i>Step Index Fibre</i>
<i>SM</i>	<i>Single Mode</i>
<i>SMF</i>	<i>Single Mode Fibre</i>
<i>UV</i>	<i>UltraViolet</i>

2 Project overview

The material presented within this report demonstrates that the novel light guiding properties of photonic crystal fibres (PCFs) offer significant benefits for a number of space applications ranging from small sensors to large space telescopes and interplanetary data transmission links. These results highlight the need for ESA to initiate further, clearly defined, investigations into the application of PCF technology in order to maximise the benefits for future space missions and to fully utilize the leading position of European science in this field.

In PCFs, which can be made from a single material, light is confined to the core by an array of small longitudinal air holes that define the cladding region. These fibres exhibit a host of novel optical properties that can be tailored over several orders of magnitude simply by changing the size, shape and placement of the air holes. Indeed, many of the optical properties exhibited by PCFs are not possible to achieve using conventional technology.

For example, consider the case of polarization maintaining (PM) fibres, which are used in fibre-optic gyros (FOGs). In a PCF, the high index contrast between glass and air enables birefringence to be created simply by introducing asymmetry into the fibre structure with values far in excess of those possible using conventional stress applying techniques. In addition, the optical properties of PM PCFs made in this way are found to be practically independent of temperature. This is a particular advantage for FOGs, where temperature induced effects can significantly degrade performance.

PCF technology also offers significant benefits over conventional fibre designs for the DARWIN modal filter, which has a required operational range of 4-20 μm . The ability to create a light guiding structure from a single material is not only beneficial in terms of mechanical and chemical stability, but is also particularly enabling for mid-IR wavelengths, where the task of selecting compatible materials for conventional core/clad structures is extremely challenging. Moreover, since PCFs can have significantly improved broadband coupling efficiencies it may be possible to replace the current three filter solution by two PCF filters. Results strongly indicate that it may be possible to cover even the entire 4-20 μm range with a single PCF filter via more complex PCF design.

Although the fibre laser work summarised here shows that the available pulse energies are far less than those required in the laser based missions of the Earth Observation Programme WALES, ATLID, etc. PCFs show real potential for compact frequency selection, tuning and stabilization units. In addition, smaller, more efficient fibre lasers could be used in mini-lidars to monitor CO_2 and aerosols, whilst their narrow line width at high continuous average power would be welcomed in satellite communications such as those required in the ARTES Element 4 Programme. Given the high wall-plug efficiency (35% at 1035 nm) and the obvious benefits for reduced power consumption, we believe ESA should develop a clear roadmap and qualify fibre laser technology for space applications.

Many other PCF properties are also advantageous for a wide range of space applications. For example, white light generation via super continuum/frequency comb generation may be beneficial in space based spectroscopy and navigation applications. Further possibilities could also be realised by combining PCF gas cells and fibre Bragg grating technology to create reliable wavelength locking and tuning. Data transmission applications in radiation environment would benefit from the PCF single material design. In addition, the ability to create PCFs with extremely low bend losses provides real potential for smaller, lighter space structures.

Most importantly, the enabling properties of PCFs outlined above are backed-up by the proven excellent mechanical and radiation resistance properties of pure silica, which would be the PCF material of choice in most of the applications discussed. Furthermore, hollow core PBGFs have been shown to exhibit the lowest radiation induced losses ever reported, with attenuation levels almost unchanged relative to the unexposed fibre

In summary, this report outlines many attractive possibilities for PCF technology in space applications, and we believe that that ESA would certainly benefit from further investigation into this dynamic and rapidly emerging research field. The results presented here outline specific applications in which PCF technology holds significant advantages that could be realised in the immediate future.

3 Introduction to PCFs

The optical fibre was arguably one of the most influential technological developments in the latter half of the 20th century. With losses as low as 0.15 dB/km, optical fibres have revolutionised telecommunications across the planet. Their ability to transfer large quantities of data at high speed over incredibly large distances is unmatched.

The basic design of optical fibres however, first proposed over a century ago, has remained largely unchanged. In recent years great interest has been generated by a novel type of micro structured optical fibre in which light is confined to the core by an array of small air holes that define the cladding.

The first work on micro structured optical fibres actually dates from the early 1970's when pure silica fibres with cores supported by a few thin structural membranes were investigated for low-loss transmission [Kaiser et al (1973),]. Although impressive results were obtained, the research was soon stopped due to the successful development of vapour deposition based techniques for low loss preform fabrication. Interest was re-ignited in 1996 with the development of micro structured fibres with more complex cladding geometries, now known by many names, including (but not limited to) photonic crystal, holey, micro structured and band-gap fibres [Knight et al (1996),]. The current burst of interest in these fibres is fuelled by the many unusual and useful optical properties that have been demonstrated, including photonic band-gaps at optical wavelengths, broad-band single-mode guidance, unique dispersion properties and extreme nonlinearities (amongst others).

PCFs are typified by the small, longitudinal air holes that define the cladding region. PCFs exploit the unique optical properties arising in dielectric materials with wavelength-scale regions of high index contrast. The wealth of different fibre designs stems from the fact that the optical properties of these fibres are sensitive functions of the cladding configuration, which can, via careful design and fabrication, be tailored to suit a wide variety of application needs. PCFs are typically separated into two classes, defined by the mechanism of light guidance: (1) index guiding PCFs, also known as holey fibres, in which light is guided in a solid core by a modified form of total internal reflection and, (2) band-gap guiding PCFs, also known as photonic band-gap fibres (PBGFs), in which guidance is achieved via photonic band-gap effects generated by the periodic nature of the cladding and low-loss guidance within a low-index (i.e. hollow) core is possible. The development of PCFs is now one of the most vibrant research areas.

Thus far, little work has been conducted to explore the potential of PCFs for space applications. It was with this in mind that ESA requested a study to be conducted to investigate the potential of PCFs with respect to space applications. The report presented here is the output of this study. It summarises the properties of PCFs, exploring their technological potential and their applicability to space.

This report is split into three main sections in line with the initial requirements from the SoW. The first section (WP1) describes the general properties of PCFs and relates them to a number of space applications. These include fibre optic gyroscopes, frequency combs generation, fibre lasers, fibre gas cells, data transmission and the methods for minimising the bend loss in PCFs. The second section (WP2) describes the results of series of environmental and mechanical tests conducted on several PCF samples to determine their likely performance in

the space environment. It also includes a detailed review of published radiation and mechanical tests of similar fibres. Section 3 (WP3) looks at the potential use of the PCF in specific missions – DARWIN and WALES.

Finally, conclusions and recommendations are drawn as to the future development of PCFs in relation to space applications.

4 Evaluation of Photonic Crystal Fibres for Space Applications

The material presented in this section (WP1) explores the technological potential of PCFs for a number of space applications, including fibre optic gyroscopes (FOGs), frequency comb generation, fibre lasers, fibre gas cells and data transmission. The methods developed for minimising bend loss in PCFs are also summarised. PCF technology is found to offer many benefits relative to conventional technology in the areas described above, as summarised in the following.

Fibre optic gyroscopes (FOGs): PCF technology possess many attractive qualities for FOGs; offering higher values of birefringence than possible using conventional stress applying technology and also enabling almost zero temperature birefringence dependence. This potentially eliminates one of the major limitations to the accuracy of FOG in most space applications, in which the required operating temperature range is -55°C to 85°C . The largest birefringence values in PCFs are achieved for small core (few μm), high NA PCFs with very low bend loss sensitivity, which are compatible with small outer cladding dimensions ($<50\ \mu\text{m}$) and hence for ultra-compact FOG. These PCFs are made from pure silica and thus offer good radiation resistance properties, while the use of PBGFs, made in a PM format, offers yet better radiation resistance. It thus appears that PCF technology is extremely attractive from the perspective of space borne FOG and we recommend further ESA activity in this direction.

Frequency comb generation: White light generation via super continuum/frequency comb generation in PCFs may be beneficial in space based spectroscopy and navigation applications. Recent developments suggest that it would be possible to build an efficient SC source with fibre pumping. Such a source would include a pump diode, a fibre laser and a highly nonlinear PCF. The fibre laser would require length of just a few meters, the SC PCF would be several cm in length and the whole system should be integrated/spliced together in a compact, light weight package, suitable for space applications. The dispersive characteristics of the SC PCF would need to be optimised to suit specific combinations of pump wavelength and target output wavelength range. However, further work in this direction is required to develop space certifiable systems.

Fibre lasers: PCF technology is attractive for high power lasers and amplifiers from a number of perspectives: it enables both large-mode-area single-mode designs and high NAs designs (>0.6) for pump confinement and delivery. This reduces the length of dual-clad fibre devices and extends the wavelength tuning ranges for fibre laser technology. PCFs can be made entirely from silica, which offers power-handling advantages relative to polymer-clad designs. Kilowatt class operation of PCF lasers has now been achieved. In addition, hollow-core PBGFs can deliver much higher power levels than conventional fibre. Guidance of f_s pulses of more than 2 MW peak power has been demonstrated in 2003.

While large core PCF designs allow for high average powers, small core PCF designs can offer interesting opportunities for low power lasers. Small core high NA PCFs allow for doped fibres with extremely tight mode-confinement / high gain efficiencies, which can be used to make fibre lasers with ultra low thresholds and optical amplifier offering large gains for very modest pump powers. Such small core amplifiers could be of extreme interest for space borne instruments where efficient power usage is a primary consideration. In addition, small core PCF technology favours high birefringence fibre designs typically used to promote single-polarisation operation, providing a straightforward and convenient means to ensure PM laser operation (with the benefit of greatly reduced temperature sensitivity birefringence relative to conventional solid core fibre technology). These features promise benefits in terms of laser size, efficiency and performance in fibre lasers for space applications.

Data transmission: Although the transmission losses of PCFs are currently larger than those of conventional telecommunications fibres (the minimum reported values of propagation loss in SIFs, PCF and PBGFs are 0.15, 0.28 and 1.2 dB/km respectively, significant advances have been made in recent years and it is reasonable to suppose that the losses of PCFs will be soon comparable to conventional technology. Indeed, the theoretical minimum losses of PBGFs are lower than those of solid core fibres at ~ 0.1 dB/km. At present PCFs are routinely fabricated in 10's of km, and PBGFs have been fabricated in lengths up to 345 m Recent studies have demonstrated the potential of endlessly single-mode low-loss PCF as a high bit-rate and large capacity transmission medium, with ultra wide transmission windows of more than 160 THz It has also been shown that PCF technology can be used to create large-mode-area fibres which are an attractive alternative to graded index fibres in optical data-communication environments suitable for efficient coupling into VCSEL sources. In one study into this type of PCF (multi-mode with a 50 μm core diameter), quasi error-free 10 Gbit/s data transmission was demonstrated. Although this particular PCF was multi-mode and suffered large bending losses, recent work has shown that it is possible, via careful design, to fabricate PCF with even larger cores (core dimension 63 x 56 μm) that are single-mode with practical levels of bend loss at 1 μm . This has the potential to considerably enhance the bandwidth-length product for low-cost, VCSEL-based data communication systems.

There may be certain niche applications for high speed transmission lines with increased radiation hardness. PCF technology is potentially of great benefit here. For example, it should be possible to develop single mode PBGF transmission fibres with reasonable loss e.g. dB/km scale with >20 dB reduced radiation sensitivity due to the reduced modal overlap with the solid material regions of the fibre which are prone to radiation damage.

We consider this to represent a very interesting and technical opportunity that could stand to benefit enormously from the unique properties of PCF technology.

Multi-aperture fibre linked imaging interferometers: PCFs show advantages over the conventional single-mode fibres in almost every aspect of their application in imaging interferometers. The large mode area, broadband operation, superior polarization properties and the possibility to produce a fibre from a single infrared transparent material are really enabling.

However, further development is needed in the area of PCF couplers/dividers. The broadband operation may be wasted if the couplers/dividers are not capable of covering the respective wavelength range. Although PCFs couplers have shown potential in covering much larger

wavelength range compared to traditional ones, more work would need to be done to assess if covering the 2 – 20 μm (“extended” DARWIN) wavelength range was possible.

Similarly, in the visible and near infrared ranges, covering more than 500 nm with a PCF coupler with a 50:50 coupling response has been demonstrated. In addition, PCF technology can also be used to create PM couplers. However, it does not seem possible that these two properties (broadband and PM operation) could be achieved in the same fibre.

In both cases bulk optic components offer the best solution at the moment. Even there PM silica PCFs pigtailed may offer advantages for use either side of the bulk optic components.

Minimising bend loss: While the large index contrast between air and silica means that small-core geometries possess intrinsically small bending losses, the bend loss of larger mode areas fibres can also be improved, relative to conventional designs, with PCF technology. For example, by utilising the confinement loss properties of PCF, effectively single-mode fibres with mode areas up to 1500 μm^2 (core dimension 63 x 56 μm) at 1 μm have been created [Error! Reference source not found.]. In a similar technique, PCF technology has been used to create a hybrid fibre design that can be tightly coiled (~ 0.011 dB/turn at 1.55 μm for a bend radius of 5 mm) and is compatible with conventional telecom fibre [Error! Reference source not found.-Error! Reference source not found.]. These advances have potential applications in areas such as high power beam delivery, data transmission and fibre-to-the-home (FTTH) networks.

Fibre gas cells: Gas cell devices based on PCF technology have been shown to exhibit high efficiency and performance, excellent long-term pressure stability and ease of use and have been exploited for a wide range of applications, including sensing and nonlinear gas devices. Such devices possess important advantages over conventional gas cell technologies, including long optical lengths in small devices, requiring extremely small volumes of gas. They could be very beneficial as compact references in spectroscopy and lasers.

5 Study of the Effects of the Space Environment on PCF

There has actually been little work published on the effects of ionising radiation on micro structured fibres. Most research shows that the radiation response of index guiding PCF is probably identical to pure silica core fibres. Although some reports indicate high radiation induced losses in PCF, it is found that these losses can be entirely accounted for by the radiation induced losses of Suprasil-F300 fused silica glass by Heraeus, from which PCF are typically made [RD24]. However, PCF have also been fabricated from high purity VAD silica glass, from which the cores of radiation hard conventional fibres are made.

In addition, preliminary results presented this year at OFC demonstrated the potential of hollow core PBGFs, which were shown to exhibit the lowest radiation induced losses ever reported with attenuation levels almost unchanged relative to the unexposed fibre. Note that this work was not included in the printed paper and has yet to appear in any published work.

A number of studies have shown that the mechanical properties (tensile strength and dynamic fatigue) of PCFs are typically found to be comparable to conventional solid fibres. Studies have also shown that the tensile strength of PCFs is dependent on the fibre cross section and that the strength increases with the width of the solid outer cladding and as the air holes decrease in size. Although humidity inside the air holes in a PCF can cause large levels of

loss at temperatures below 0°C, this can be mitigated to 0.001 dB/m by heating the fibre in a vacuum and purging with dry gas. In addition, studies have also shown that the tensile strength of open ended PCFs can decrease with time after a few days exposure with condensed water. However, we note that PCFs can be very easily sealed from environmental contaminations by collapsing the fibre ends. We also note that for solid core PCF with small holes the minimum long term bend radius is probably very similar to that recommended for conventional solid fibre (~ 2 cm radius).

The novel geometries of PCFs also introduce new challenges to the process of interconnection as the issues of end face treatment such as cleaving, polishing and splicing are more complex. Several studies have demonstrated successful techniques for reliably achieving high quality end faces and robust, low-loss splices in PCFs.

A series of tests were also made as part of this study as a first step towards gauging the ability of micro structured fibres to survive the space environment and conditions of launch. These tests looked at the response of PCF to: (1) vibration, (2) rapid depressurisation, (3) cold shock in liquid nitrogen and (4) elongation. After each of the mechanical and thermal shock tests, each of the PCF samples considered showed no degradation in optical performance. This is an indication that PCFs can withstand serious mechanical and thermal loading. The elongation tests also demonstrated that an elongation of the PCFs up to 1% was not problematic and could be repeated several times without failure. Life testing of the PCFs (elongation up to 1%) was not possible in the test set-up used, but should be considered if PCF are to be used in applications where they are stretched many times.

In conclusion, the material presented here demonstrates that index-guiding PCFs can exhibit comparable performance in terms of mechanical strength and radiation induced loss, in addition to other practical end-face issues such as cleaving, polishing and splicing. As such, these novel fibres have been proven as real, practical alternatives to conventional technologies. In contrast, and as a result of the fact that PBGFs were realised a number of years after the first index-guiding PCF, there has been little assessment of the practical performance of these fibres to date. However, recent work has shown that PBGFs offer significant advantages in terms of radiation induced attenuation and preliminary studies indicate that the mechanical properties of PBGFs are comparable to solid optical fibres. Furthermore, as the air holes are of comparable size in PBGFs and PCF, it is probable that other practical issues such as end face preparation will not differ significantly from those of the index guiding PCF.

6 Elaboration of PCF for Darwin and WALES Missions

In this section, the potential use of PCF in the DARWIN and WALES missions have been considered. For the DARWIN mission, we investigated the broadband coupling efficiency for single-mode PCFs and evaluated their modal filtering capabilities. For the WALES mission we looked at the possibility to implement PCFs in the transmitter section and also in the filtering part of the received section.

PCFs for DARWIN

The results presented here show that PCFs can exhibit improved broadband coupling efficiencies relative to conventional single-mode step-index fibres for a simple plane wave

input focussed with a single fixed lens. Whilst this level of improvement is probably not sufficient to enable a single fibre modal filter to be feasible, it may be sufficient to enable the current design to be reduced from a 3-fibre to a 2-fibre solution. Furthermore, it may be possible to significantly optimise the broadband coupling efficiency by considering a hybrid SIF/PCF design or a more complex PCF cladding geometry and tailoring the wavelength dependence of the mode area to match the input beam.

Investigations of the modal filtering capabilities of PCF reveal that lengths of approximately 25 cm are required in order to achieve a 10^6 suppression factor for the HOM. Although this is an order of magnitude larger than the lengths predicted for single-mode step index fibres, it still represents a practical length scale. In addition, it is noted that bending the fibre could almost certainly be used to significantly reduce this required length and that preliminary investigations indicate that, via careful design of the structure, the bending losses of the fundamental mode can be acceptably low across the wavelength range of interest.

One further point to note is that the reflected light from the input/output air/glass interfaces in fibres made from high index glasses can be quite large. For example, for the refractive index considered here ($n=2.16$) a total of $\sim 24\%$ of the incident light will be reflected by the input and output fibre faces. This is something that clearly requires consideration.

A preliminary investigation of materials suitable for PCFs the mid-IR wavelengths as required by the DARWIN mission was also undertaken. This study found that although there are quite a number of chalcogenide glasses that are suitable for the mid-infrared region, the wavelengths at which these glasses can be used to access fall far short of that required by the DARWIN project 4 -20 μm transparency window.

The material that is currently the most promising for this wavelength range is silver halide (typically a combination of AgBr and AgCl). In general the optical and mechanical properties of these polycrystalline materials are worse than those of glasses and present significant design and fabrication challenges. For example, silver halide materials are photosensitive to visible light, and transmission is observed to decrease with time. Fibres made from these materials are weak with ultimate tensile strengths of about 80 MPa for a 50/50 mixture of AgBr/AgCl. Despite these challenges, recent work has seen the development of solid PCF constructed from this material, although the spatial modal quality and transmission losses of these fibres are extremely poor due to the large size of the crystal domains and stress induced defects. In addition, a suitable coating material has yet to be found that will enable the leaky higher-order and cladding modes to be efficiently absorbed.

In conclusion, the results presented here demonstrate that:

- PCF technology offers promise as a broadband modal filter, with improved broadband coupling relative to conventional designs and sufficient levels of modal filtering over practical length scales;
 - PCF technology also offers advantages in terms of material choice, with greater control over the refractive index profile and improved thermal stability resulting from the possibility of single material fibres;
 - the broadband launch could be significantly improved by exploring more complex lens designs/coupling systems.
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PCFs for WALES

We looked carefully at the WALES instrument configuration and parameters in search of potential benefits that PCFs could bring to it. These included the pump laser, the dial laser, the frequency stabilisation unit and the receiver stage.

The high energies, at which the pump and the DIAL laser operate are above the levels achieved using fibre lasers. Although PCFs extend their capabilities in terms of peak power, it is not visible at the moment how fibre lasers could meet the high energy requirement.

The wavelength separation assembly in the WALES receiver section looks in general attractive for implementation of fibre Bragg gratings because of their extremely high peak reflection in narrow wavelength bands. A more detailed analysis however leads to the conclusion that because of the large size of the receiver telescope, the signal gain in the filtering stage will be eliminated by the loss of coupling efficiency due to the speckle structure, even if LMA PCFs are applied.

It might be beneficial to implement PCF technology in the WALES frequency stabilization unit. It is attractive from the perspective of providing reduced temperature tuning responses and stronger selection of the 930 nm laser transition in Nd doped silica based glasses. It would be interesting to investigate the viability of using integrated sealed sections of PBG fibre containing water vapour to provide for long interaction length fibre based vapour cells for referencing and line locking.

In addition, options exist for implementing PCFs and fibre Bragg gratings in new multi-wavelength laser sources. Novel device concepts could be investigated, e.g. the use of a four-core, dual-clad holey Nd-doped PCF incorporating individual tuning elements for each core (sharing the pump radiation between what are essentially 4-separate laser cavities) or the use of a single-core PCF amplifier in a cavity providing four discrete wavelength selective paths, defined by narrowband fibre Bragg gratings. Such designs could eventually reduce the mass and improve the parameters of the frequency stabilisation unit.

Document data

The final report has 136 pages, contains 75 figures and 198 references.
