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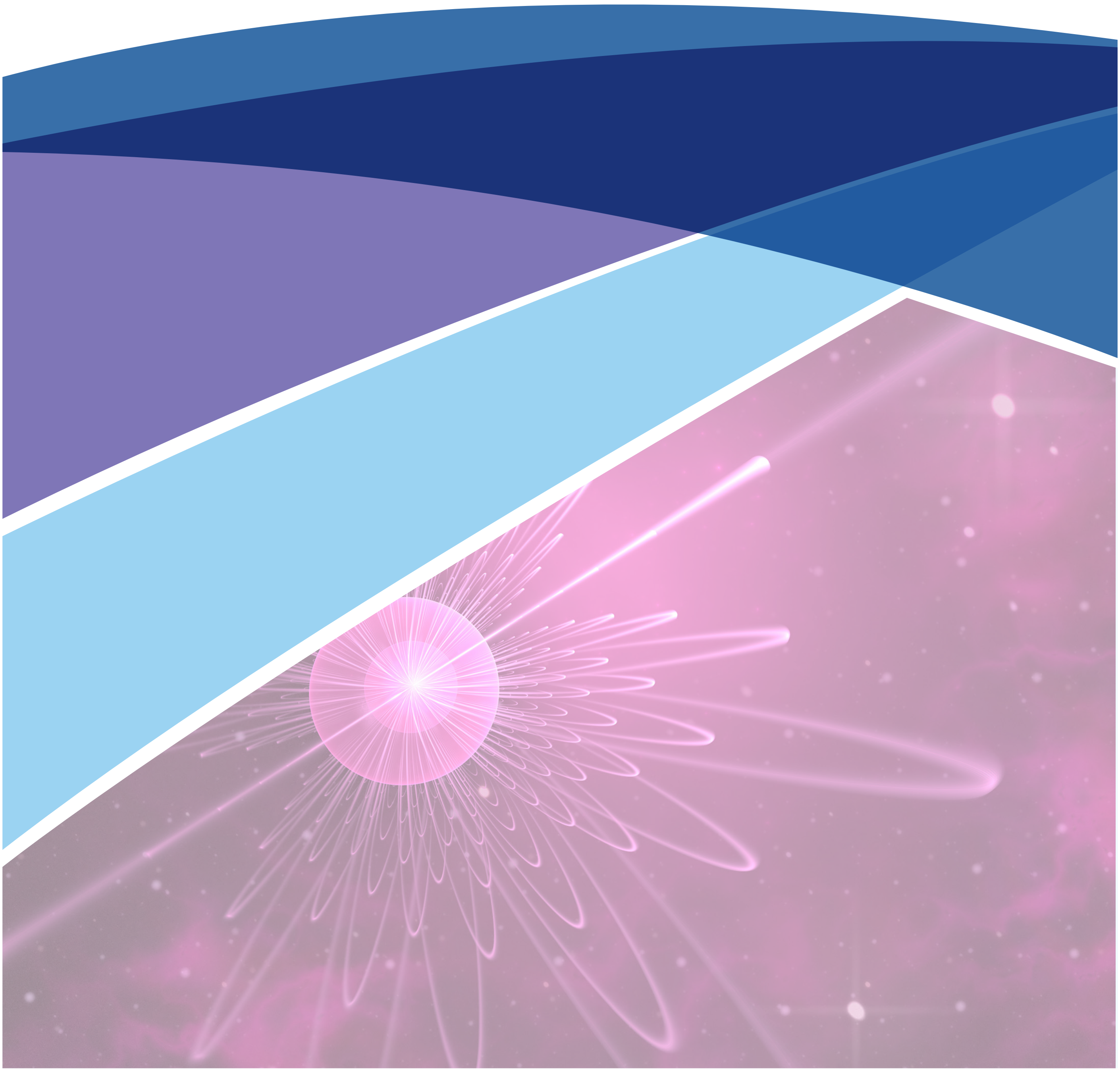
Eight Great Technologies
Quantum Technologies
A patent overview



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#8Great

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Contents

1 Introduction

The UK Government has identified ‘eight great technologies’ plus a further two which will propel the UK to future growth. These are:

- the big data revolution and energy-efficient computing;
- satellites and commercial applications of space;
- robotics and autonomous systems;
- life sciences, genomics and synthetic biology;
- regenerative medicine;
- agri-science;
- advanced materials and nanotechnology;
- energy and its storage;
- quantum technologies;
- the internet of things.

Patent data can give a valuable insight into innovative activity, to the extent that it has been codified in patent applications, and the IPO Informatics team is producing a series of patent landscape reports looking at each of these technology spaces and the current level of UK patenting on the world stage. As an aid to help people understand the eight great technologies and to consider the direction of future funding, the IPO is offering a comprehensive overview of what is already patented in the each of these technologies. This information should not be taken as a direct measure of the level of innovation in the UK; it should be considered in conjunction with other sources of information to form a fuller picture.

This report gives an analysis of the worldwide patent landscape for quantum technologies. In terms of patent landscaping, these technologies fall into the distinct technology areas of quantum telecommunications, quantum computation, quantum sensors and quantum timing and atomic clocks. The datasets used for analysis were extracted from worldwide patent databases following detailed discussion and consultation with patent examiners from the Intellectual Property Office who are experts in these fields and who, on a day-to-day basis, search, examine and grant patent applications relating to these quantum technologies.

This report is based on analysis of published patent application data rather than solely on granted patent data. Data for published patent applications gives more information about technological activity than the figures for granted patents because a number of factors determine whether an application ever proceeds to grant. These include the inherent lag in patent processing at national IP offices worldwide and the patenting strategies of applicants who may file more applications than they ever intend to pursue.

1.1 Quantum technologies: definitions and background

The Informatics team at the IPO published "Quantum Technologies: A patent review for the Engineering and Physical Science Research Council (EPSRC)" in October 2013[1]. This report found that the UK is strong in quantum technologies, particularly quantum telecommunication and computation. The report looked at each technology area from the start of patenting in that area to 2012 but uses different search areas and strategies so the results are not all directly comparable to those in this report. The previous report does however give a useful background into quantum technologies including an analysis of academic publications, which is beyond the scope of this report. The following report uses the same format, methodologies and databases as the other eight great technology reports. Recent patenting activity is analysed in terms of patent families and, where appropriate, raw publication numbers are also used. The following technology areas are analysed:

Quantum telecommunications technologies: these offer the prospect of fundamentally secure communication channels (as one could prove through the laws of quantum physics that no information was intercepted). The patent landscape in this area includes patenting activity relating explicitly to encryption, e.g. quantum key distribution (QKD), as well as transmission systems and components that are specific to quantum communications;

Quantum computation technologies: defined as information processing by using effects that require quantum mechanical description such as superposition and entanglement. These technologies may herald a new computation paradigm in which quantum bits, which can be in a superposition of states, rather than simply existing in either of two distinct states representing a 1 or 0, enable a different form of computer processing that can solve some classes of problem much more effectively than classical computation.

Quantum sensors technologies: where quantum effects such as entanglement or superposition are exploited in the undertaking of high-resolution and highly sensitive measurements of physical parameters. Technologies in this space include superconducting quantum interference devices (SQUIDs) that are very sensitive magnetometers.

Quantum timing and atomic clocks: methods and devices for time keeping which use electron transition frequency or other atomic scale properties as a frequency standard for timekeeping. This technology area has been around for a relatively long time in relation to large cryogenic apparatus kept by national institutions to keep a highly precise and reliable timing standard. Recently, however, there has been resurgence in activity in this area as the application of new technologies enables chip-scale devices of similar precision and accuracy.

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[1] Available here: *http://www.ipo.gov.uk/informatics-quantum.pdf*

2 Worldwide patent analysis

2.1 Quantum telecommunication technologies

2.1.1 Overview

The exploitation of quantum effects in telecommunications technology offers the prospect of fundamentally secure communication channels, as one could prove through the laws of quantum physics that no information was intercepted. Patents in this dataset include those claiming inventions in encryption, e.g. quantum key distribution (QKD), as well as transmission systems and their components, which utilise effects described by quantum physics.

Table 1 gives a summary of the worldwide dataset used for the analysis of quantum telecommunications technologies. The worldwide dataset was limited to patent applications with a publication date range of 2004 to 2013. Publications may be at the application or grant stage, so are not necessarily granted patents. A patent family is one or more published patents originating from a single original (priority) application. Analysis by patent family more accurately reflects the number of inventions present because generally there is one invention per patent family, whereas analysis by raw number of patent publications inevitably involves double counting because one patent family may contain dozens of patent publications if the applicant files for the same invention in more than one country. Hence analysis by patent family gives more accurate results regarding the level of inventive activity taking place.

Table 1: Summary of worldwide patent dataset for quantum telecommunications technologies

Number of patent families	950
Number of patent publications	3,238
Publication year range	2004-2013
Peak publication year	2011, 2012
Top applicant	NEC
Number of patent assignees	690

Figure 1 shows the total number of published patents by publication year (top) and the total number of patent families by priority year (bottom – considered to be the best indication of when the original invention took place). The patent family chart in red does not show any patents filed after 2011 because a patent is normally published eighteen months after the priority date or the filing (application) date, whichever is earlier. Hence the 2012 and 2013 data is incomplete and has been ignored.

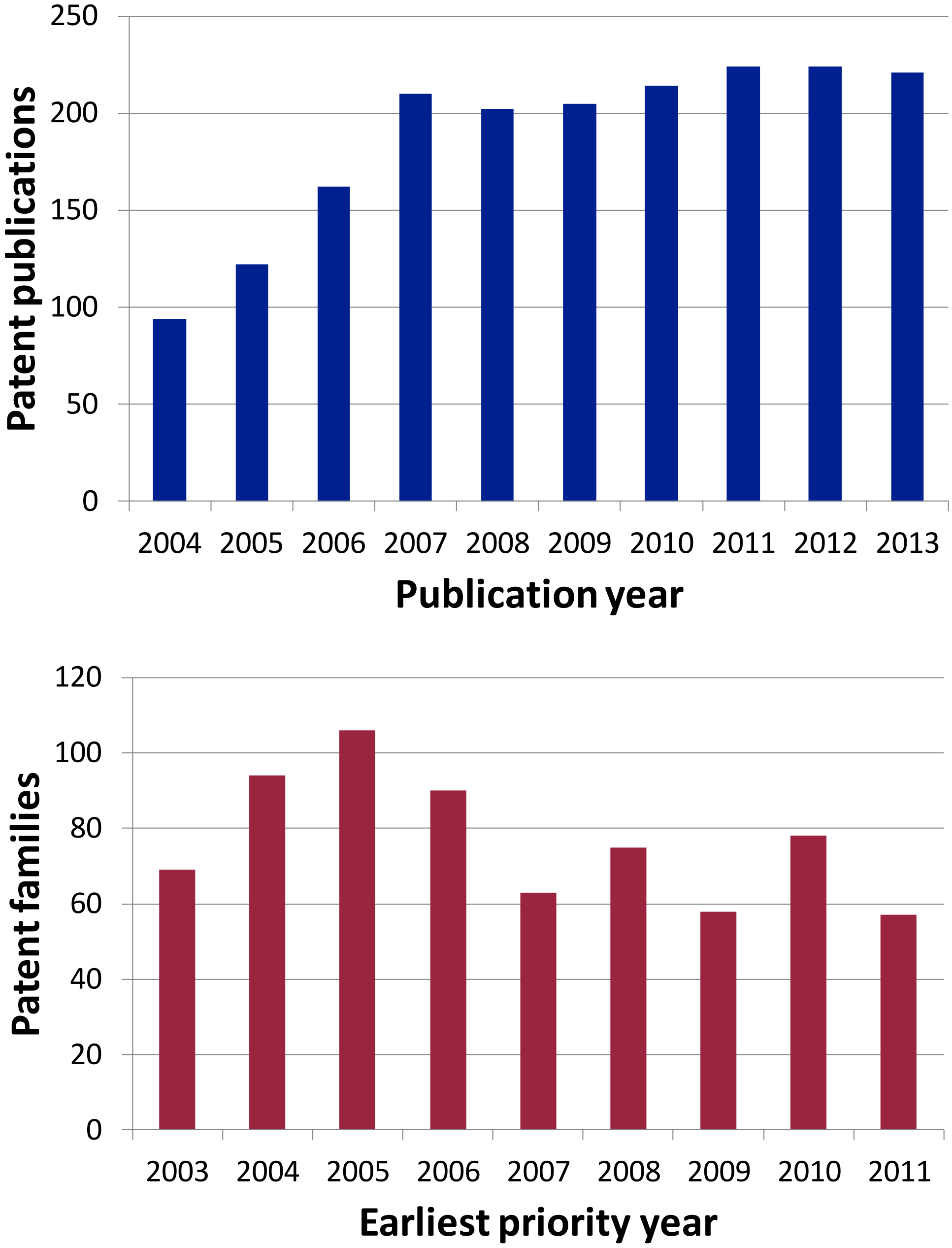

Figure 1: Patent publications by publication year (top) and patent families by priority year (bottom) for quantum telecommunications technologies

The number of families (inventions) increased dramatically between 2003 and 2005. Since a peak of inventions seeking patent protection in 2005, the level of inventions seeking protection has fluctuated around 65 families per year.

Publication numbers (Figure 2 and the top chart (blue) of Figure 1) are useful for looking at the sheer volume of patenting activity and for making comparisons against the trends in overall patenting, i.e. in all technology areas. However they are less useful for direct insight into the number of inventions for which patent protection is sought. They typically include multiple documents relating to the same invention (family) therefore the publication (blue) and family (red) charts in Figure 1 are not directly comparable. For example the apparent plateau in publications between 2007 and 2013 is an artefact of subsequent patent publications relating to earlier inventions whilst there is an underlying decrease in the number of inventions being patented, as evidenced by the patent families chart.

When compared to the overall levels of patenting globally for all subject matter (Figure 2), the rapid increase in annual patent publications in quantum communications technologies of around 30% between 2004 and 2007 is evident. This was well above the annual increase in overall patent publications for these years.

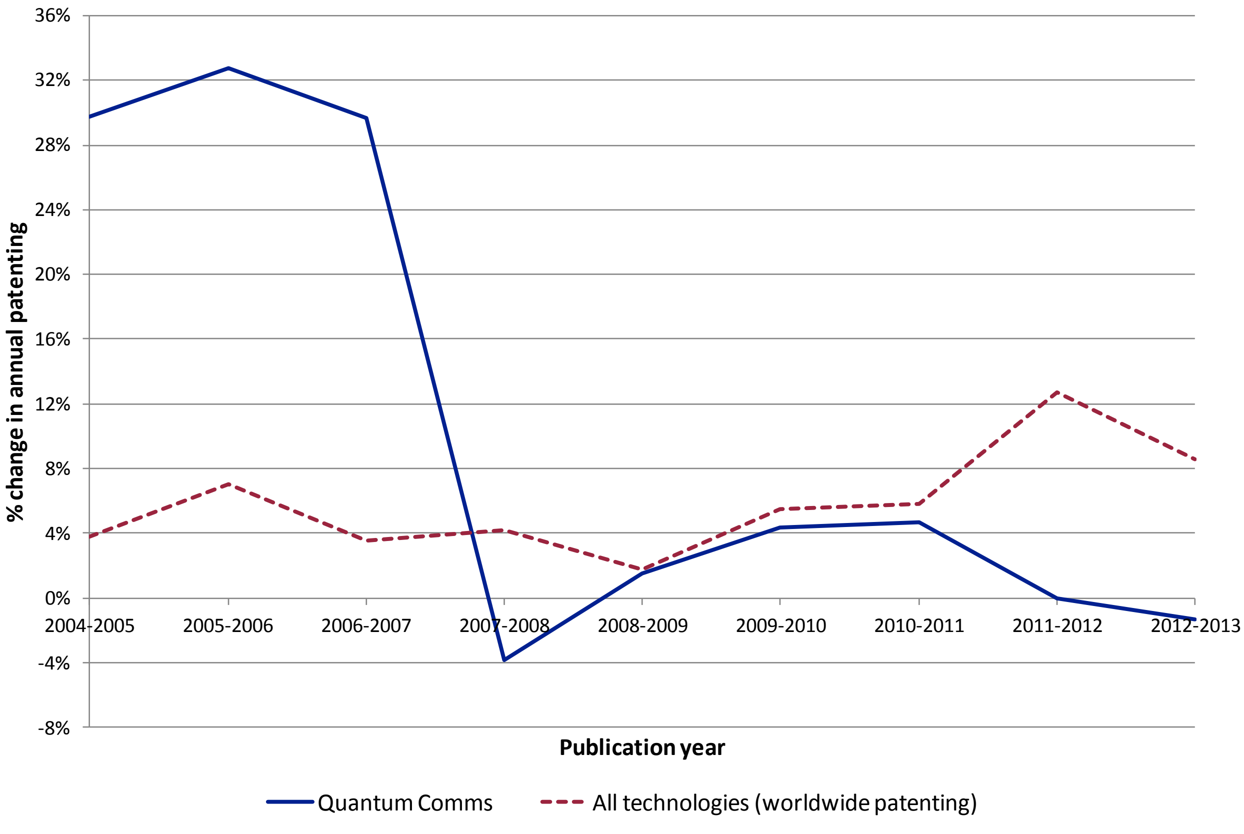

Figure 2: Year-on-year change in quantum telecommunications technology patenting compared to worldwide patenting across all technologies

There is a generally a higher tendency to make patent applications in certain countries. A Relative Specialisation Index (RSI)[2] for each applicant country has been calculated to give an indication of the level of patenting in quantum telecommunications technologies compared to the overall level of patenting in that country, and is shown in Figure 3.

Figure 3 indicates that the UK is amongst the three most specialised applicant countries in the world for patenting in this area of technology. Only Japanese and Australian patenting exhibits a similar level of relative specialisation in this technology area. Patenting activity in all other European countries has a negative RSI.

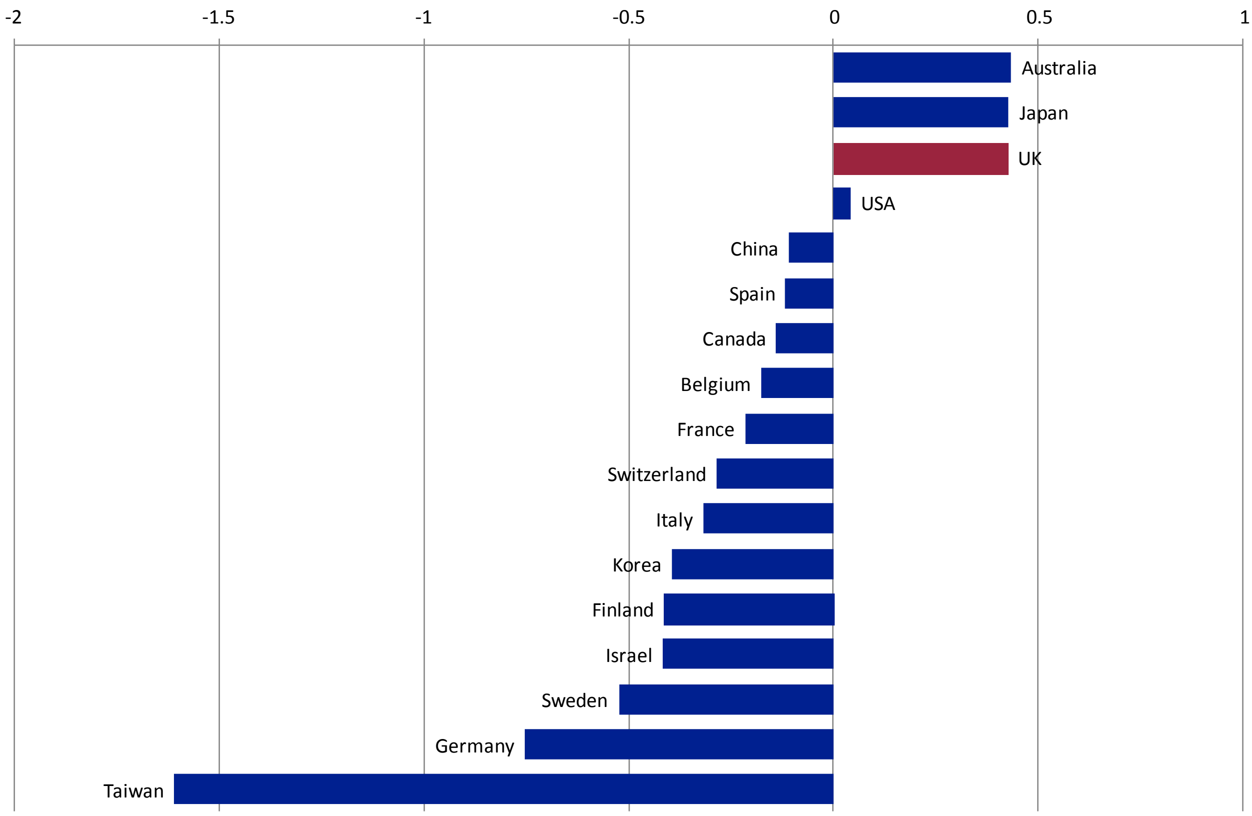

Figure 3: Relative Specialisation Index (RSI) by applicant country for quantum telecommunications technologies

[2] See Appendix B for full details of how the Relative Specialisation Index is calculated.

2.1.2 Top applicants

Patent applicant names within the dataset were cleaned to remove duplicate entries arising from spelling errors, initialisation, international variation and equivalence[3]. Figure 4 shows the top applicants.

Multinationals originating from Japan and the USA make up the top end of the applicants chart. Toshiba do most of their research in this technology area at their Cambridge research laboratory[4] and therefore appear as a UK applicant in this patent landscaping analysis.

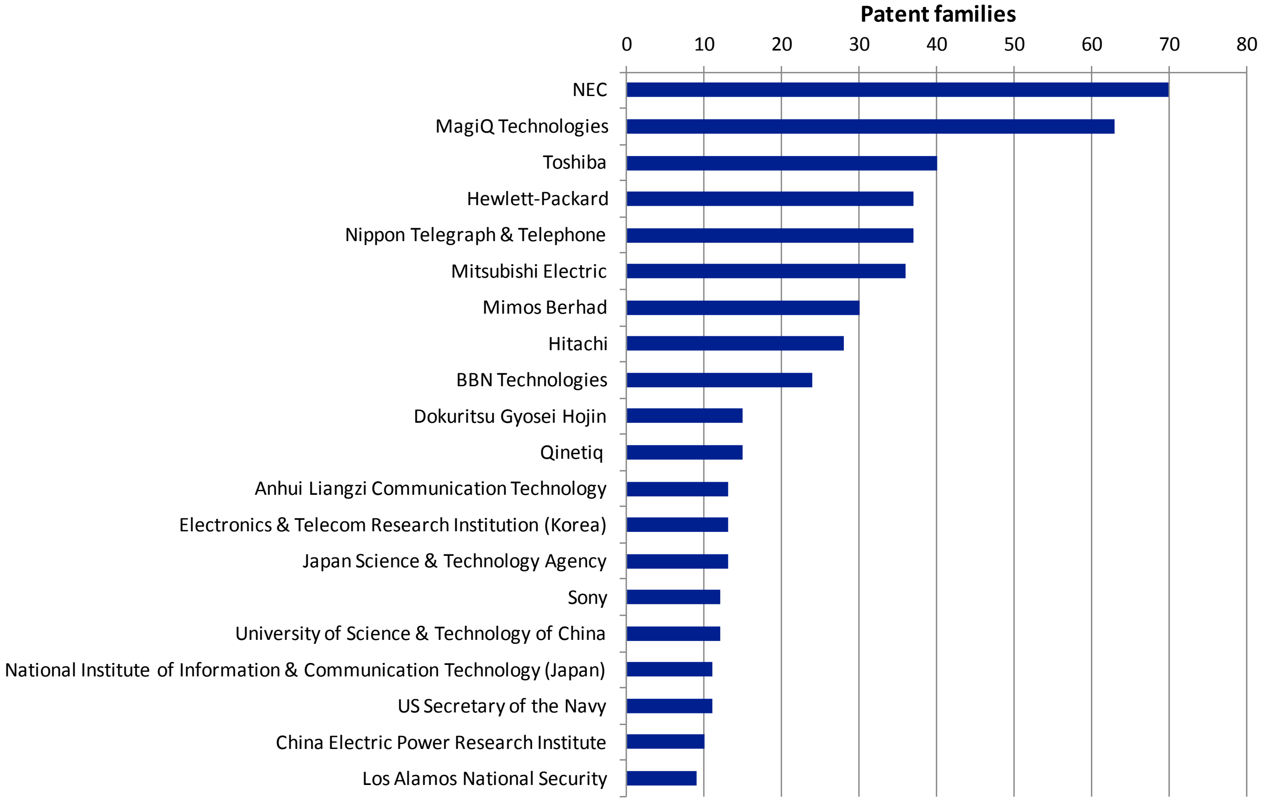

Figure 4: Top applicants for quantum telecommunications technologies

NEC is a Japanese multinational information technology and network solutions company[5]. It has the most patent families of any of the applicants in this patent landscape. The inventions that these families seek to protect relate to all aspects of quantum key distribution and quantum encryption devices. They include use of such telecommunications systems for inter-bank transactions and details of quantum telecommunications technologies at a systems level as well as at a system component level. Including, for example components for control of multi-phase modulation units based on optical wavelength, photo detection, phase-shift detection and key generation,

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[3] See Appendix A.4 for further details.
[4] http://www.toshiba.eu/eu/Cambridge-Research-Laboratory/About-Us/
[5] http://www.nec.com/

With only slightly fewer patent families in this technology area than NEC, MagiQ Technologies, a technology development company from the USA, is far more specialised in quantum computing technologies than the much larger multinational technology giant NEC. In 2003, only four years after being founded, it launched a commercial quantum key distribution product. Andrew Hammond, vice president of marketing and business development at MagiQ (New York)[6] said: "*Navajo Security Gateway is the world's first commercial-grade quantum-key distribution system available now for use over existing fibre-optic cables up to 120 kilometres apart. It offers unbreakable quantum-key distribution as many as 100 times per second, plus layers of VPN [virtual private network] security and classically based data encryption.*"

Similarly to NEC, MagiQ have broad ranging patent families in the technology space ranging from components such as coherent optical pulse generators, diamond-nanocrystal single-photon sources and auto-calibrating single-photon detectors to software and computational methods for controlling quantum telecommunication systems.

Many of Toshiba's patent families focus on systems using quantum dots as the source of entangled photon pairs. Their patent families also seek protection for optics technology for handling photon pairs, quantum repeaters (relay stations) for increasing the distance over which quantum telecommunication is possible, error correction, and a method of selecting a pre-agreed quantum communication protocol.

Hewlett-Packard[7], a multinational originating in the USA, have patent families relating to quantum encryption, quantum repeaters, alignment of hand held devices in order to enable quantum key distribution signal transmission, the use of quantum key distribution in e-commerce transactions and entanglement-creation apparatus.

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[6] Second paragraph of eetimes article available here: http://www.eetimes.com/document.asp?doc_id=1147554

[7] HP do most of their research in this area in Bristol – see section 3.1.

2.1.3 Technology breakdown

Figure 5 shows the top IPC subgroups, and Table 2 lists the description of each of these subgroups. The classifications are not mutually exclusive and each patent family will have many of these classifications applied.

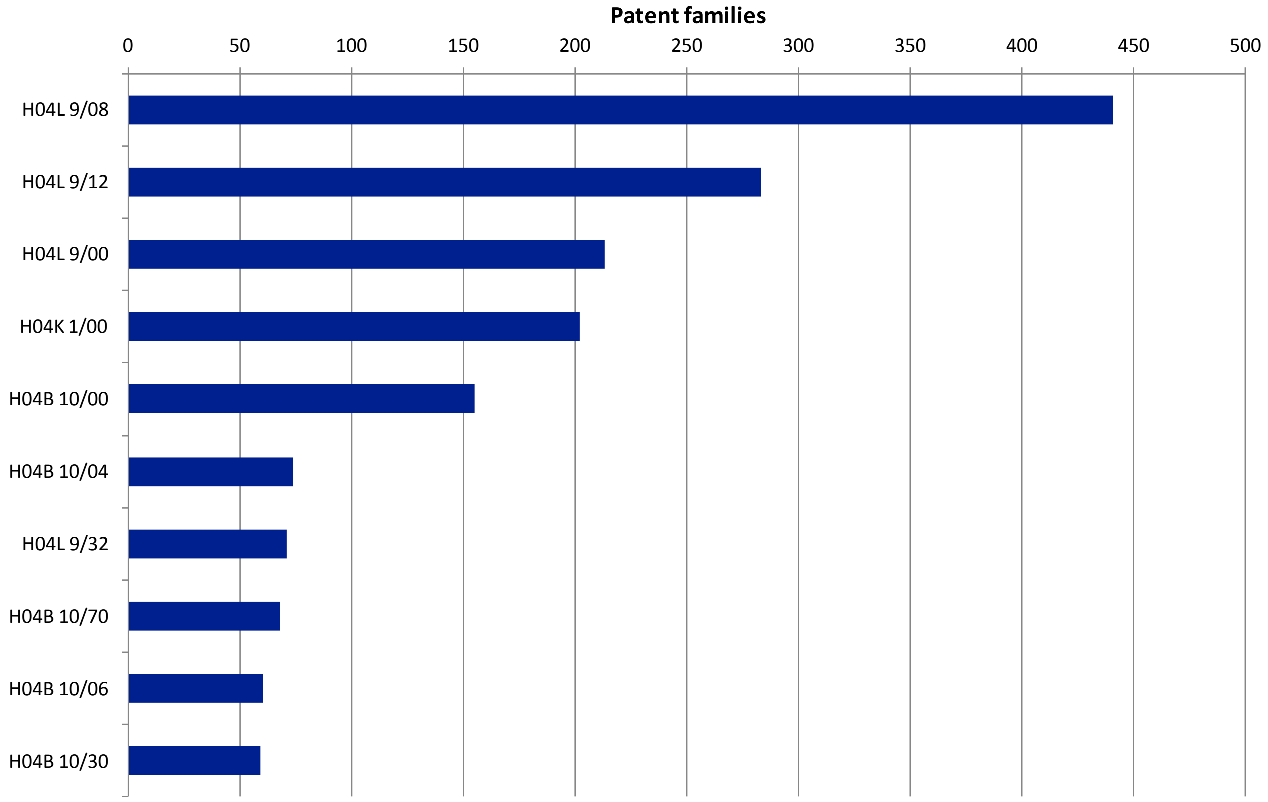

Figure 5: Top IPC sub-groups for quantum telecommunications technologies

Table 2: Key to IPC subgroups referred to in Figure 5

H04L 9/08	Arrangements for secret or secure communication -> the encryption apparatus using shift registers or memories for blockwise coding, e.g. D.E.S. systems -> Key distribution
H04L 9/12	Arrangements for secret or secure communication -> Transmitting and receiving encryption devices synchronised or initially set up in a particular manner
H04L 9/00	Arrangements for secret or secure communication
H04K 1/00	Secret communication
H04B 10/00	Transmission systems employing beams of corpuscular radiation, or electromagnetic waves other than radio waves, e.g. light, infra-red
H04B 10/04	Transmission systems employing beams of corpuscular radiation, or electromagnetic waves other than radio waves, e.g. light, infra-red -> Details -> Transmitters
H04L 9/32	Arrangements for secret or secure communication -> including means for verifying the identity or authority of a user of the system
H04B 10/70	Photonic quantum communications
H04B 10/06	Transmission systems employing beams of corpuscular radiation, or electromagnetic waves other than radio waves, e.g. light, infra-red -> Details -> Receivers
H04B 10/30	Transmission systems employing beams of corpuscular radiation, or electromagnetic waves other than radio waves, e.g. light, infra-red -> Transmission systems employing beams of corpuscular radiation

2.2 Quantum computation technologies

2.2.1 Overview

Quantum computation technologies are defined as devices for information processing, or components for such devices, which utilise effects described by quantum physics such as superposition, coherence, decoherence, entanglement, nonlocality and/or teleportation. These technologies may herald a new computation paradigm in which quantum bits, which can be in a superposition of states, rather than simply existing in either of two distinct states representing a 1 or 0, enable a different form of computer processing that can solve some classes of problem much more effectively than classical computation.

Table 3 gives a summary of the worldwide dataset[8] used for this analysis of quantum computation technologies.

Table 3: Summary of worldwide patent dataset for quantum computation technologies

Number of patent families	777
Number of patent publications	2,675
Publication year range	2004-2013
Peak publication year	2009
Top applicant	D-Wave Systems
Number of patent assignees	685

Figure 6 shows the total number of published patents by publication year (top) and the total number of patent families by priority year (bottom – considered to be the best indication of when the original invention took place). The patent family chart in red does not show any patents filed after 2011 because a patent is normally published eighteen months after the priority date or the filing (application) date, whichever is earlier. Hence, the 2012 and 2013 data is incomplete and has been ignored.

There is a decline in the number of patent families per year over the time period analysed, meaning that there was a decline in the number of inventions for which patent protection was sought in this technology area between 2003 and 2011.

For reasons already discussed[9], patent publications are not directly comparable to patent families. The slight increase in the number of patent publications over the same period is likely to be caused by additional patent publications which relate to of pre-2004 priority filings (inventions (families) which were first filed before 2004).

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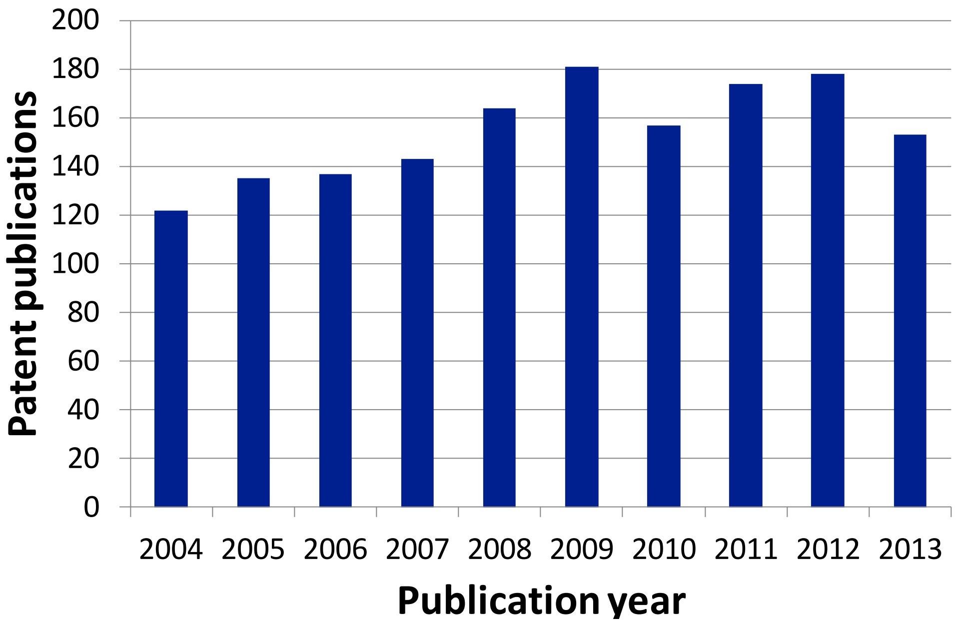
[8] As defined on page 3.
[9] As discussed on page 5.



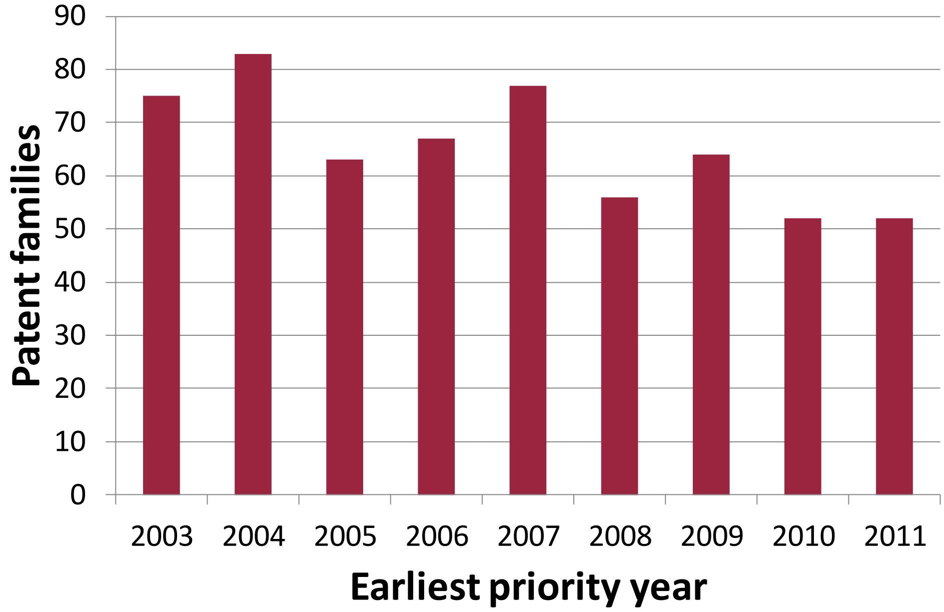


Figure 6: Patent publications by publication year (top) and patent families by priority year (bottom) for quantum computation technologies

Figure 7 contrasts the annual change in patents published in quantum computation technologies with the annual change for patents published in all technologies. Since the dataset is small, relatively large fluctuations in publications relating to quantum computation when compared to publications across all technologies are not surprising as a few more or less publications will make a relatively large difference for a small dataset.

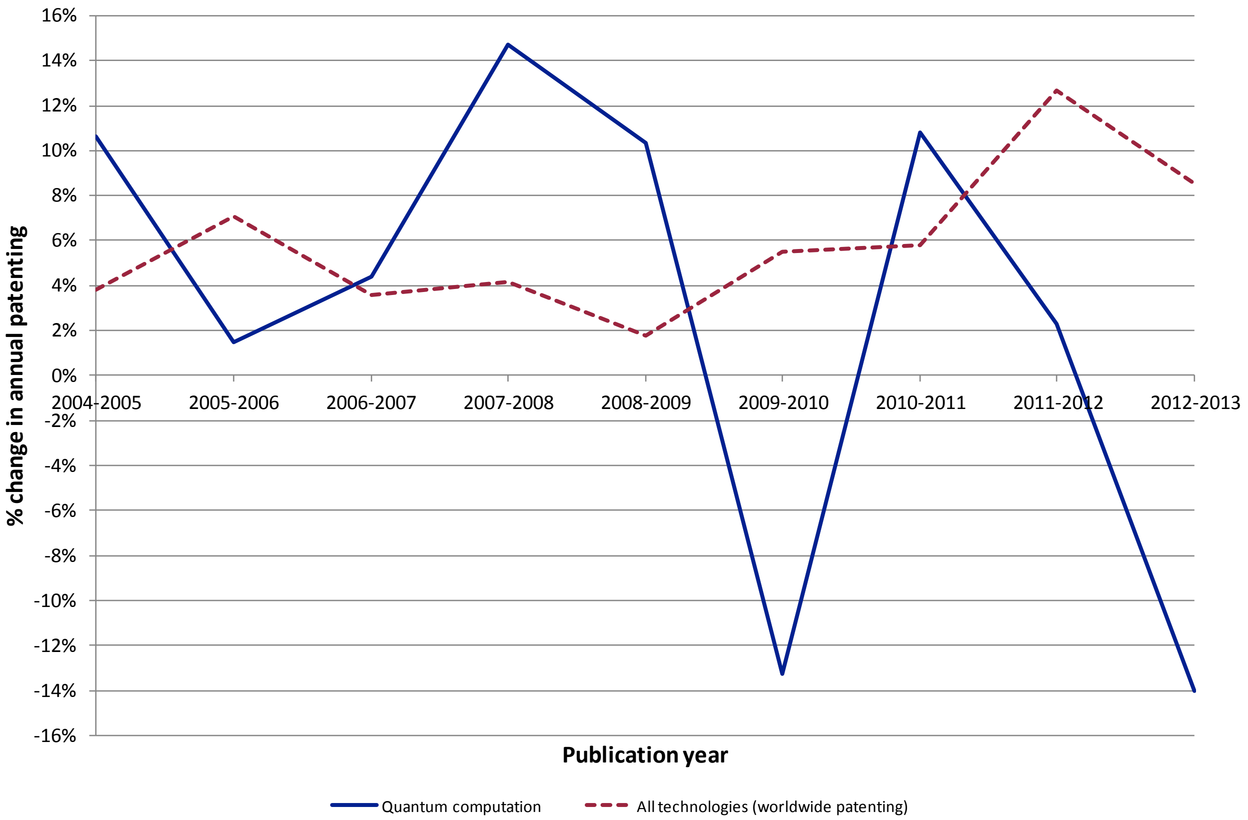


Figure 7: Year-on-year change in quantum computation technology patenting compared to worldwide patenting across all technologies

There is a generally a higher tendency to make patent applications in certain countries. A Relative Specialisation Index (RSI)[10] for each applicant country has been calculated to give an indication of the level of patenting in quantum computation technologies compared to the overall level of patenting in that country, and is shown in Figure 8.

Figure 8 indicates that, similarly to RSI position in quantum telecommunications technologies, the UK is among the three countries most relatively specialised in quantum computation technologies patenting. No other European countries are relatively more specialised patenting in quantum computing technologies. Furthermore, the UK is relatively more specialised in this technology area than the USA and Japan.

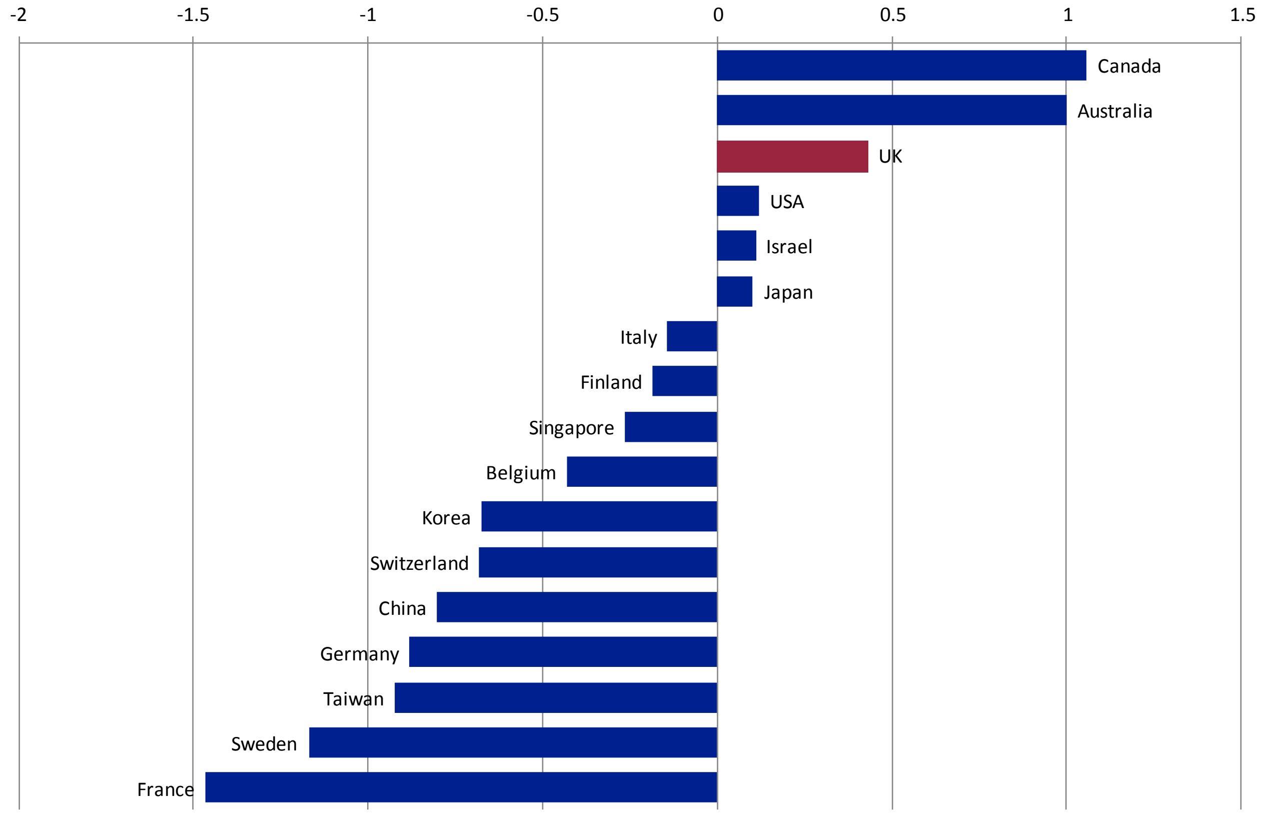


Figure 8: Relative Specialisation Index (RSI) by applicant country for quantum computation technologies

[10] See Appendix B for full details of how the Relative Specialisation Index is calculated.

2.2.2 Top applicants

Patent applicant names within the dataset were cleaned to remove duplicate entries arising from spelling errors, initialisation, international variation and equivalence[11]. Figure 4 shows the top applicants.

Multinationals originating from North America and Japan make up the top end of the applicants chart. D-Wave systems are based in Canada. Toshiba do most of their research in this technology area at their Cambridge research laboratory and therefore appear as a UK applicant in this patent landscaping analysis.

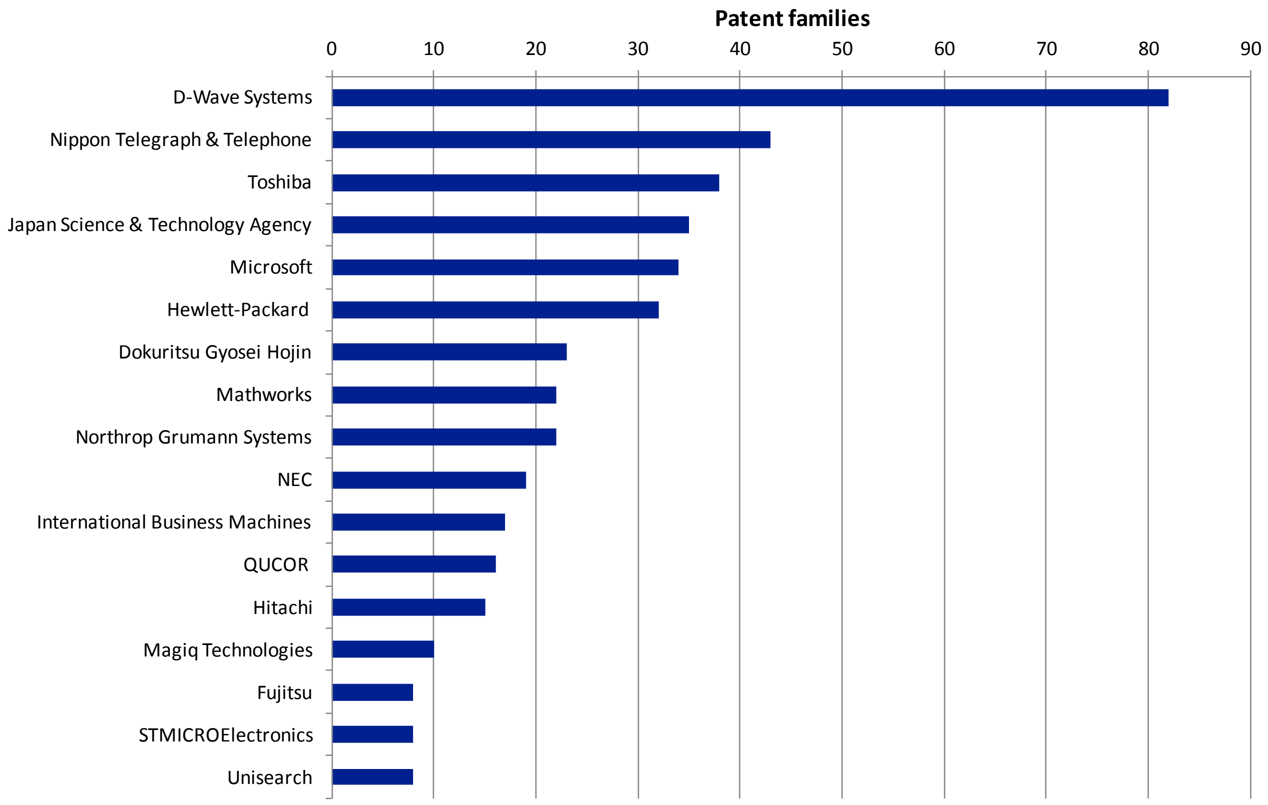


Figure 9: Top applicants for quantum computation technologies

D-wave's patent families cover inventions such as multi-terminal junction qubits that have a superconducting loop connecting them, various initialisation, control, measurement and coupling techniques for qubits. As well as an integrated development environment for a digital computer system which has a quantum computing system executing quantum machine language instructions by compiling quantum logic with N qubits.

Nippon Telegraph & Telephone have patent families relating to a qubit based on a Cooper-pair box, a betting system involving using a data carrier in which bit information is encoded in four quantum states, a quantum algorithm conversion method, a quantum computer comprising qubits connected via a superconductive Josephson junction field effect transistor (JOSFET), a quantum cash issue apparatus and a quantum voting system,

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[11] See Appendix A.4 for further details.

amongst other things.

Toshiba, who were mentioned above in relation to quantum telecommunications technologies, have a similar portfolio of patents in this dataset: their patent families relate to optical devices for generating and handling entangled photons. This technology is useful for both quantum computation and telecommunications.

The Japan Science and Technology Agency patent families include some relating to devices and methods for the creation, initialisation and control of qubits predominantly they relate to the use of nuclear magnetic resonance based on a nuclear spin elements in solid material, whilst other families focus on polarization-entangled photon generation.

Microsoft's patent families seek protection for, amongst other things, quantum computation based on a lattices structure and as systems for simulating quantum computation.

In a similar manner to Toshiba, Hewlett-Packard's patent family portfolio within the quantum computation technologies relates mainly to methods, components and devices for quantum computation based on similar optical technology to their patent family portfolio in the quantum telecommunications dataset.

Dokuritsu Gyosei Hojin are Japanese government funded, arms-length, non-profit making organisations, similar to the Technology Strategy Board (TSB) in the UK. They are typically involved in education, research and development. The patent families under this applicant name relate to various methods of forming quantum logic gates, qubits and other components such as superconductive wiring and tunnel magneto-resistive elements that are useful in quantum computers.

2.2.3 Technology breakdown

Figure 10 shows the top IPC subgroups, and Table 4 lists the description of each of these subgroups. The classifications are not mutually exclusive and each patent family will have many of these classifications applied.

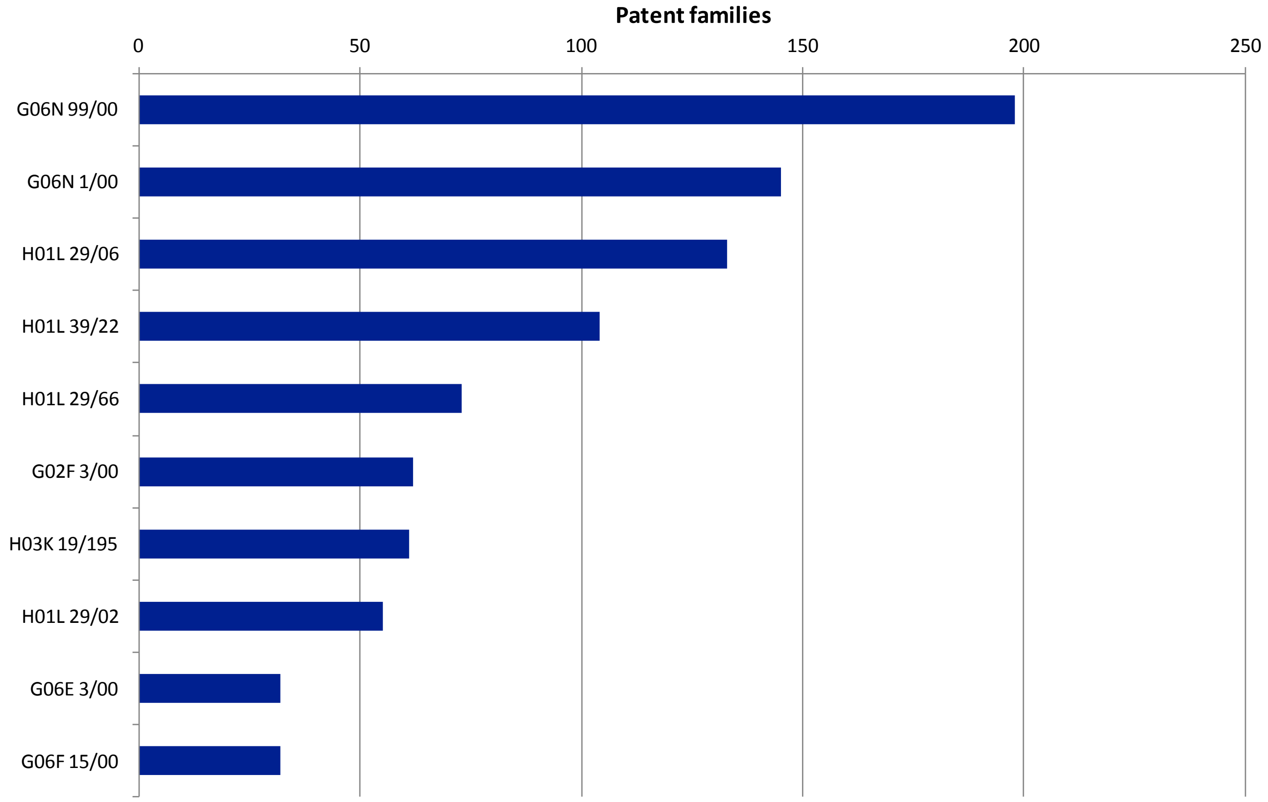


Figure 10: Top IPC sub-groups for quantum computation technologies

Table 4: Key to IPC subgroups referred to in Figure 10

G06N 99/00	Computation based on specific computational models; subject matter not provided for in other areas of this subclass
G06N 1/00	Computer systems not provided for in groups G06N03/00-G06N07/00
H01L 29/06	Semiconductor devices specially adapted for rectifying, amplifying, oscillating or switching and having at least one potential-jump barrier or surface barrier; Capacitors or resistors with at least one potential-jump barrier or surface barrier, e.g. PN-junction depletion layer or carrier concentration layer; Details of semiconductor bodies or of electrodes thereof -> Semiconductor bodies -> characterised by their shape; characterised by the shapes, relative sizes, or dispositions of the semiconductor regions
H01L 39/22	Devices using superconductivity or hyperconductivity; Processes or apparatus specially adapted for the manufacture or treatment thereof or of parts thereof -> Devices comprising a junction of dissimilar materials, e.g. Josephson-effect devices
H01L 29/66	Semiconductor devices specially adapted for rectifying, amplifying, oscillating or switching and having at least one potential-jump barrier or surface barrier; Capacitors or resistors with at least one potential-jump barrier or surface barrier, e.g. PN-junction depletion layer or carrier concentration layer; Details of semiconductor bodies or of electrodes thereof -> Types of semiconductor device
G02F 3/00	Optical logic elements; Optical bistable devices
H03K 19/195	Logic circuits, i.e. having at least two inputs acting on one output; Inverting circuits -> using specified components -> using superconductive devices
H01L 29/02	Semiconductor devices specially adapted for rectifying, amplifying, oscillating or switching and having at least one potential-jump barrier or surface barrier; Capacitors or resistors with at least one potential-jump barrier or surface barrier, e.g. PN-junction depletion layer or carrier concentration layer; Details of semiconductor bodies or of electrodes thereof -> Semiconductor bodies
G06E 3/00	Devices not provided for in group G06E01/00, e.g. for processing analogue or hybrid data
G06F 15/00	Digital computers in general; Data processing equipment in general

2.3 Quantum sensor technologies

2.3.1 Overview

Quantum sensor technologies are defined as sensors in which quantum effects such as entanglement or superposition are exploited in the undertaking of high-resolution and highly sensitive measurements of physical parameters. Technologies in this space include superconducting quantum interference devices (SQUIDs) that are very sensitive magnetometers.

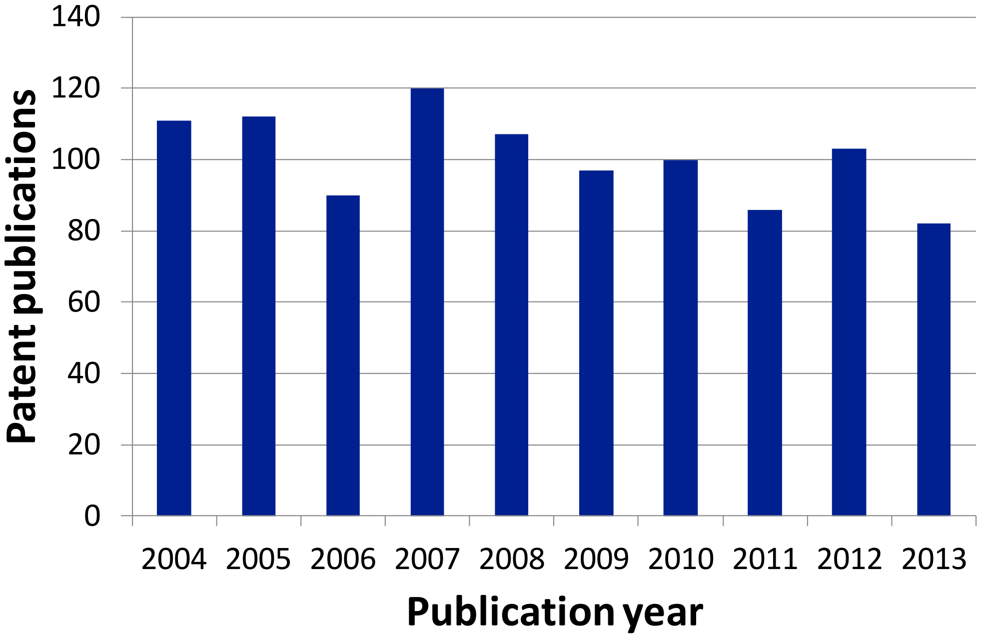
Table 5 gives a summary of the worldwide dataset[12] used for this analysis of quantum sensor technologies.

Table 5: Summary of worldwide patent dataset for quantum sensor technologies

Number of patent families	547
Number of patent publications	1,953
Publication year range	2004-2013
Peak publication year	2007
Top applicant	Hitachi Ltd
Number of patent assignees	572

Figure 11 shows the total number of published patents by publication year (top) and the total number of patent families by priority year (bottom – considered to be the best indication of when the original invention took place). The patent family chart in red does not show any patents filed after 2011 because a patent is normally published eighteen months after the priority date or the filing (application) date, whichever is earlier. Hence, the 2012 and 2013 data is incomplete and has been ignored

[12] As defined in section 2.1.1.



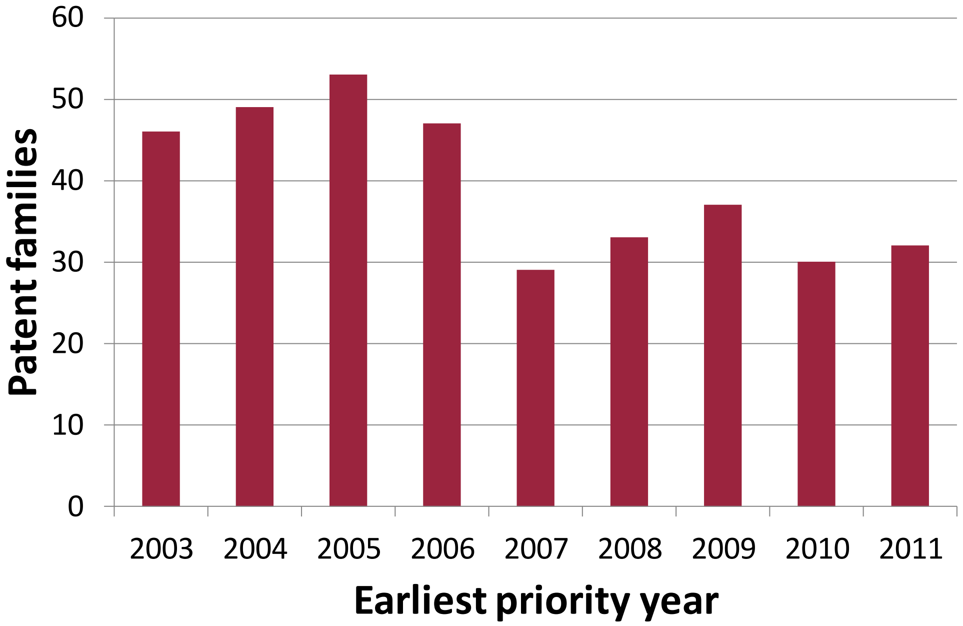


Figure 11: Patent publications by publication year (top) and patent families by priority year (bottom) for quantum sensor technologies

The number of patent families (inventions) claiming a priority date per year between 2003 and 2006 was roughly steady at around 50 inventions per year. There was a drop in the number of inventions claiming priority in 2007 and between then and 2011 there has been around 30 inventions per year in this technology area.

A chart illustrating year on year change of patenting in quantum sensor technologies compared to worldwide patenting across all technologies has not been included as it is clear from the patent publication chart in Figure 11 that the annual publication rate fluctuates around 100 patent publications a year between 2004 and 2013. This level of patenting, which is broadly static over the time period, is at odds with sustained annual increases exhibited by patenting across all technology areas that is illustrated by the red dotted line in Figure 2 and Figure 7.

There is generally a higher tendency to make patent applications in certain countries. A Relative Specialisation Index (RSI)[13] for each applicant country has been calculated to give an indication of the level of patenting in quantum telecommunications technologies compared to the overall level of patenting in that country, and is shown in Figure 12.

Australian patenting exhibits the highest specialisation in quantum sensor technologies, followed closely by patenting activity in Japan. The UK exhibits a negative RSI, but is still relatively more specialised than any other European country in quantum sensor technologies.

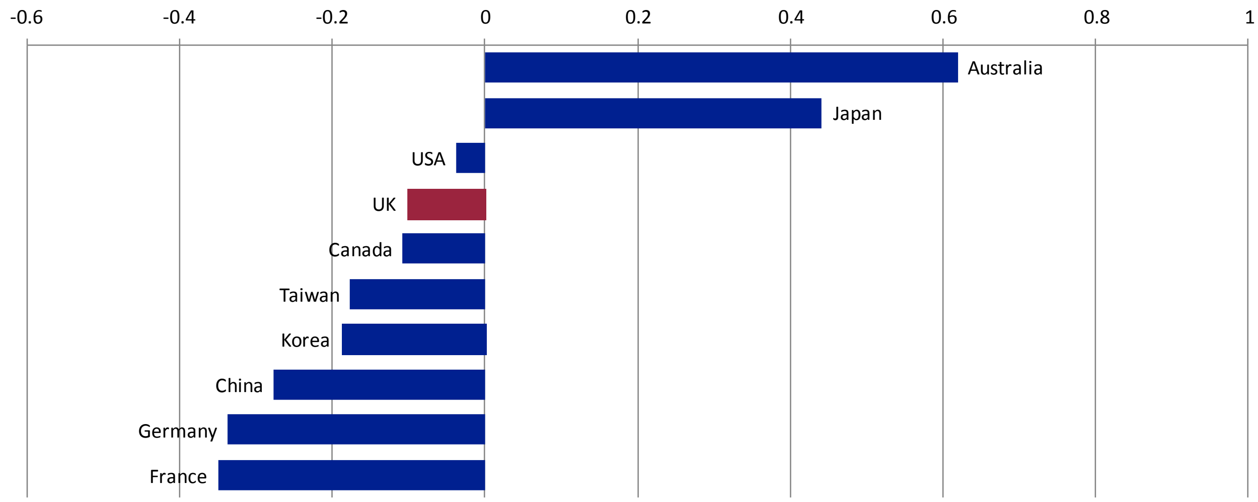


Figure 12: Relative Specialisation Index (RSI) by applicant country for quantum sensor technologies

2.3.2 Top applicants

Patent applicant names within the dataset were cleaned to remove duplicate entries arising from spelling errors, initialisation, international variation and equivalence[14]. Figure 13 shows the top applicants.

The top two applicants are Japanese based multinationals (Hitachi and Sumitomo). Japanese applicants dominate the dataset with many Japanese government institutions, agencies and universities inventing in this area (Japan Science & Technology Agency, Dokuritsu Gyosei Hojin, Kanazawa Institute of Technology, Toyohashi University of Technology, and the International Superconductivity Technology Centre) as well as Japanese based multinationals Seiko Epson, Toshiba[15], Yokogawa and Matsushita.

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[13] See Appendix B for full details of how the Relative Specialisation Index is calculated.
[14] See Appendix A.4 for further details.
[15] Although Toshiba (Japanese multinational) is classified as a UK applicant in applicant in the country analysis in this dataset because their research in this technology area is done at their Cambridge Research Laboratory, resulting in patent application which have a UK

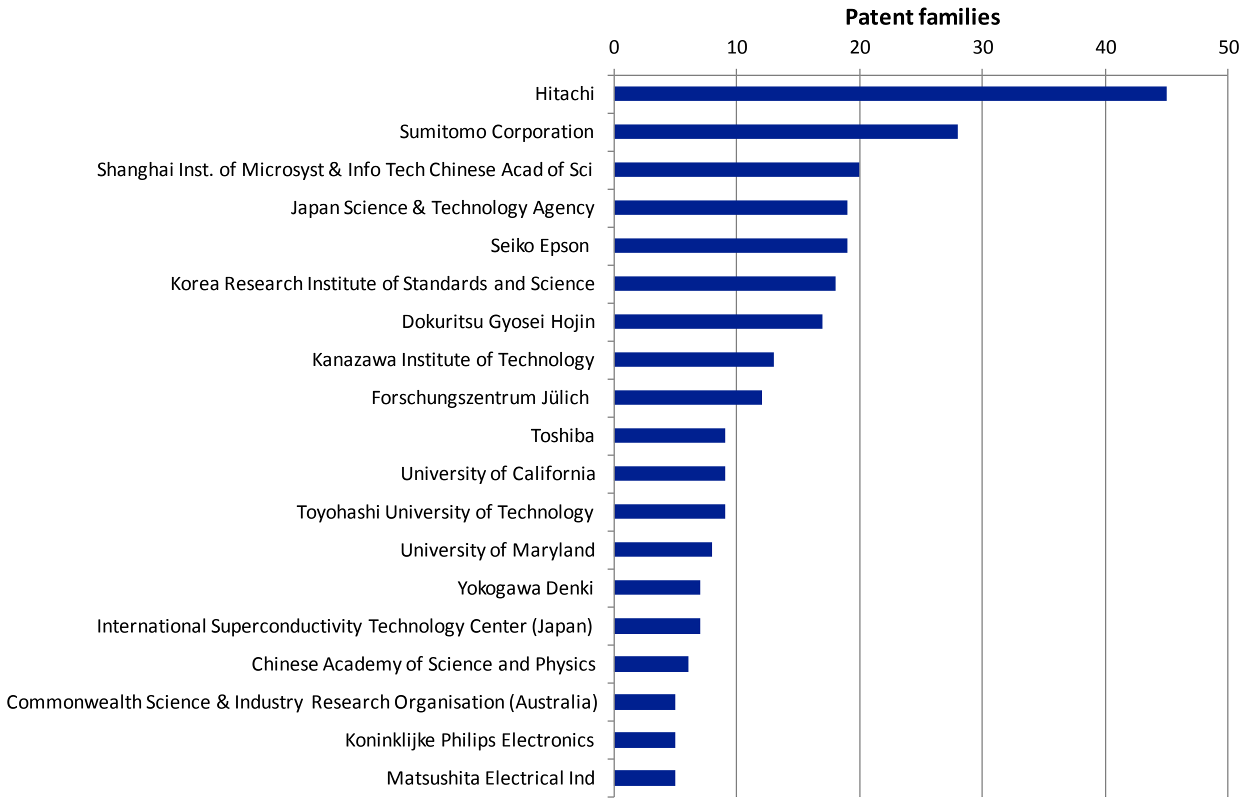

Figure 13: Top applicants for quantum sensor technologies

Inventions relating to superconductive quantum interference devices (SQUIDs), make up most of the quantum sensor technology dataset. Hitachi's patent families comprise inventions related to improvements in such devices as well as to improvements in their components, fabrication and methods of use. This includes use of such devices to measure biomagnetism, to compare cryogenic electric currents for improved sensitivity and reduced size, the fabrication of a single flux quantum circuit and techniques and designs to improve temperature management.

Sumitomo Corporation and NEC are both members of the Sumitomo Group[16]. Sumitomo patent families in this technology area include a magnetic foreign-material detector for superconductive fluids, a high temperature superconductive quantum interference element for a magnetic sensor, an immunity testing method involving using a SQUID to detect magnetized labels stuck to antibodies, as well as many other inventions involving use of SQUIDs and improvements to their components and fabrication.

The Shanghai Institute of Microsystems and Information Technology (Chinese Academy of Science) patent families relate to simulation, design and calibration of SQUIDs.

Japanese Science and Technology Agency patent families include a quantum entanglement generating and detecting device which adjusts relative phases of squeezed light beams travelling in opposite directions in a ring interferometer, a charge density wave quantum interferometer and many inventions relating to use and design of SQUIDs.

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assignee address.

[16] http://en.wikipedia.org/wiki/NEC

Seiko Epson is a Japanese multinational specialising in electronics such as computer printers as well as information and imaging related equipment and timepieces. Their 19 patent families in this dataset describe quantum interference devices, a cooling apparatus for such interference devices, methods of using such devices to inspect insulated wire for defects, a superconductive radiation detector that uses a transition edge sensor and a quantum interference device based on gaseous caesium atoms.

2.3.3 Technology breakdown

Figure 14 shows the top IPC subgroups, and Table 6 lists the description of each of these subgroups. The classifications are not mutually exclusive and each patent family will have many of these classifications applied.

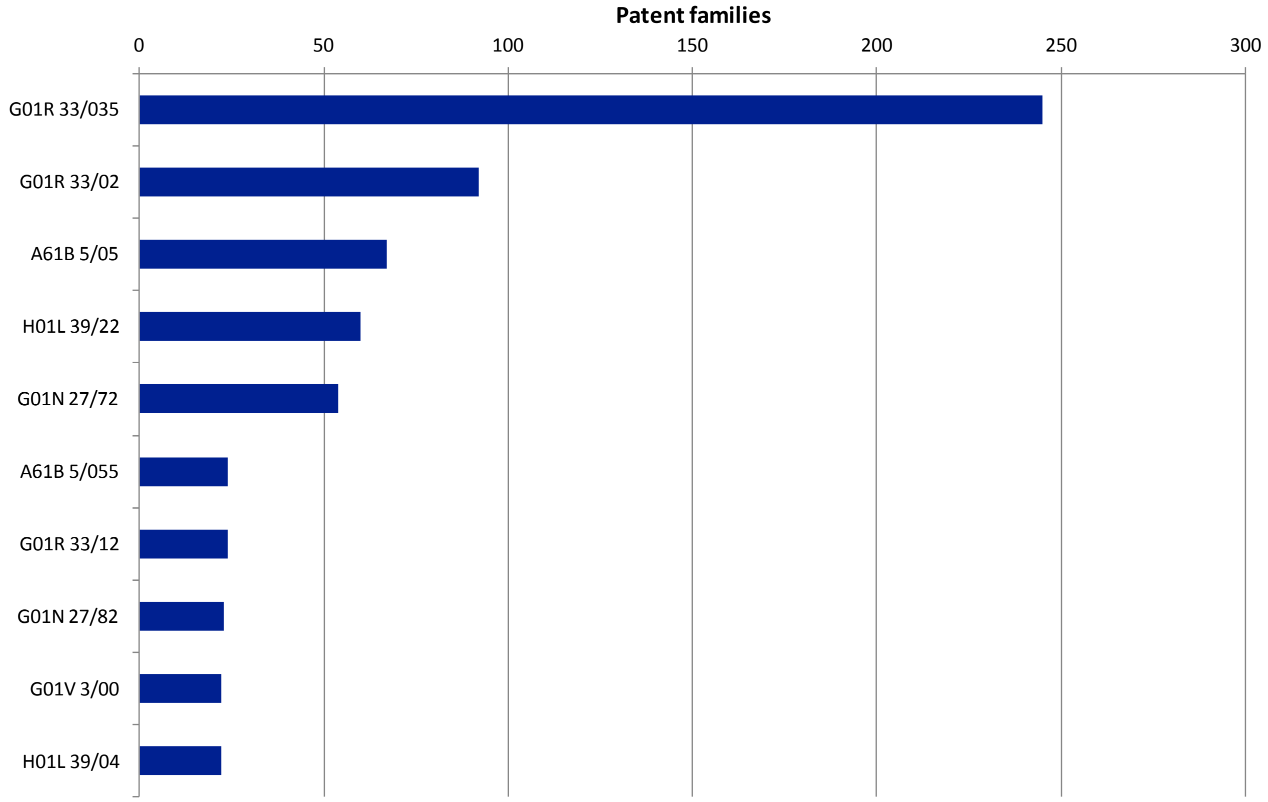

Figure 14: Top IPC sub-groups for quantum sensor technologies

Table 6: Key to IPC subgroups referred to in Figure 14

G01R 33/035	Arrangements or instruments for measuring magnetic variables -> Measuring direction or magnitude of magnetic fields or magnetic flux -> using superconductive devices
G01R 33/02	Arrangements or instruments for measuring magnetic variables -> Measuring direction or magnitude of magnetic fields or magnetic flux
A61B 5/05	Measuring for diagnostic purposes; Identification of persons -> Measuring for diagnosis by means of electric currents or magnetic fields
H01L 39/22	Devices using superconductivity or hyperconductivity; Processes or apparatus specially adapted for the manufacture or treatment thereof or of parts thereof -> Devices comprising a junction of dissimilar materials, e.g. Josephson-effect devices
G01N 27/72	Investigating or analysing materials by the use of electric, electro-chemical, or magnetic means -> by investigating magnetic variables
A61B 5/055	Measuring for diagnostic purposes; Identification of persons -> Measuring for diagnosis by means of electric currents or magnetic fields -> involving electronic [EMR] or nuclear [NMR] magnetic resonance, e.g. magnetic resonance imaging
G01R 33/12	Arrangements or instruments for measuring magnetic variables -> Measuring magnetic properties of articles or specimens of solids or fluids
G01N 27/82	Investigating or analysing materials by the use of electric, electro-chemical, or magnetic means -> by investigating magnetic variables -> for investigating the presence of flaws
G01V 3/00	Electric or magnetic prospecting or detecting; Measuring magnetic field characteristics of the earth, e.g. declination or deviation
H01L 39/04	Devices using superconductivity or hyperconductivity; Processes or apparatus specially adapted for the manufacture or treatment thereof or of parts thereof -> Details -> Containers; Mountings

2.4 Quantum timing and atomic clock technologies

2.4.1 Overview

Quantum timing and atomic clock technologies are defined as methods and devices for time keeping which use electron transition frequency or other atomic scale properties as a frequency standard for timekeeping. The atomic clock was theorised by Lord Kelvin in 1879. The first practical atomic clock, based on caesium-133 atoms, was built by Louis Essen in 1955 at the National Physical Laboratory[17]. This technology area has been around for a relatively long time in relation to large cryogenic apparatus kept by national institutions to keep a highly precise and reliable timing standard. Recently however, there has been resurgence in activity in this area as the application of new technologies enables chip-scale devices of similar precision and accuracy.

Table 1 summarises the worldwide dataset[18] used for this analysis of quantum timing and atomic clock technologies.

Table 7: Summary of worldwide patent dataset for quantum timing and atomic clock technologies

Number of patent families	160
Number of patent publications	515
Publication year range	2004-2013
Peak publication year	2012
Top applicant	Honeywell
Number of patent assignees	160

Figure 15 shows the total number of published patents by publication year (top) and the total number of patent families by priority year (bottom – considered to be the best indication of when the original invention took place). The patent family chart in red does not show any patents filed after 2011 because a patent is normally published eighteen months after the priority date or the filing (application) date, whichever is earlier. Hence, the 2012 and 2013 data is incomplete and has been ignored.

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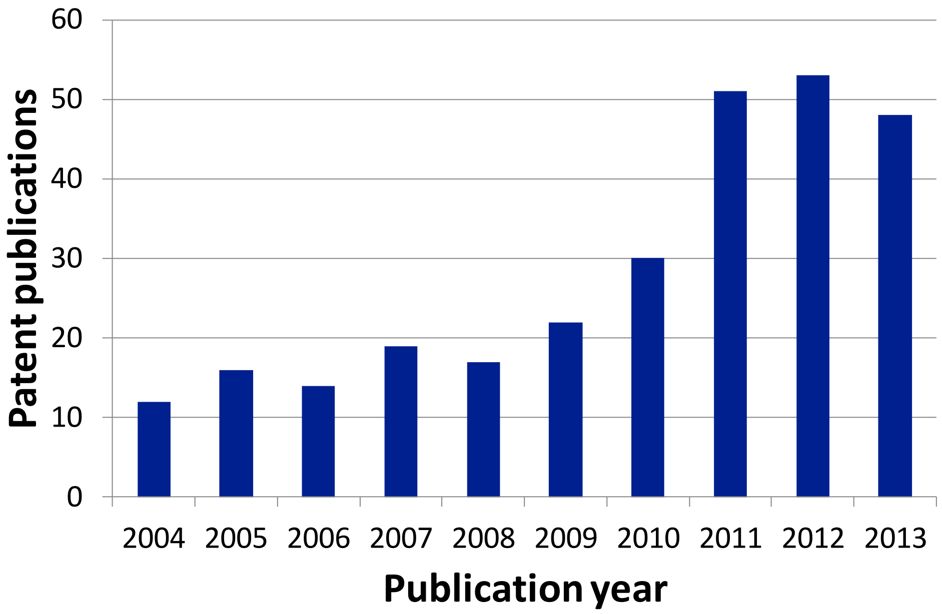
[17] http://en.wikipedia.org/wiki/Louis_Essen

[18] As defined on page 3.



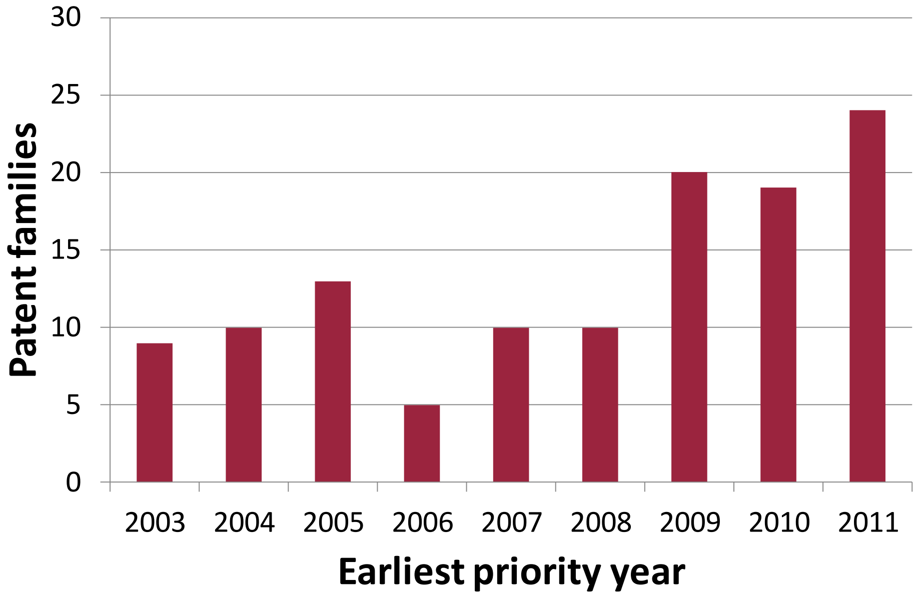


Figure 15: Patent publications by publication year (top) and patent families by priority year (bottom) for quantum timing and atomic clock technologies

Both the number of inventions seeking patent protection (families) per year and the number of patent publications per year have increased over the time scale covered by the quantum timing and atomic clock technologies dataset.

The number of patent publications in this dataset is too small to create a meaningful RSI chart therefore no RSI chart is included for this technology area.

2.4.2 Top applicants

Patent applicant names within the dataset were cleaned to remove duplicate entries arising from spelling errors, initialisation, international variation and equivalence[19]. Figure 16 shows the top applicants.

Only 4 of the 15 top applicants are corporations, illustrating a high proportion of academic and government funded research in this area. This may not be surprising given that quantum timing and atomic clock technologies have historically been the backbone of timing standards which are of interest to governments for universal time standards and academics for the challenge of defining ever more accurate and stable clocks.

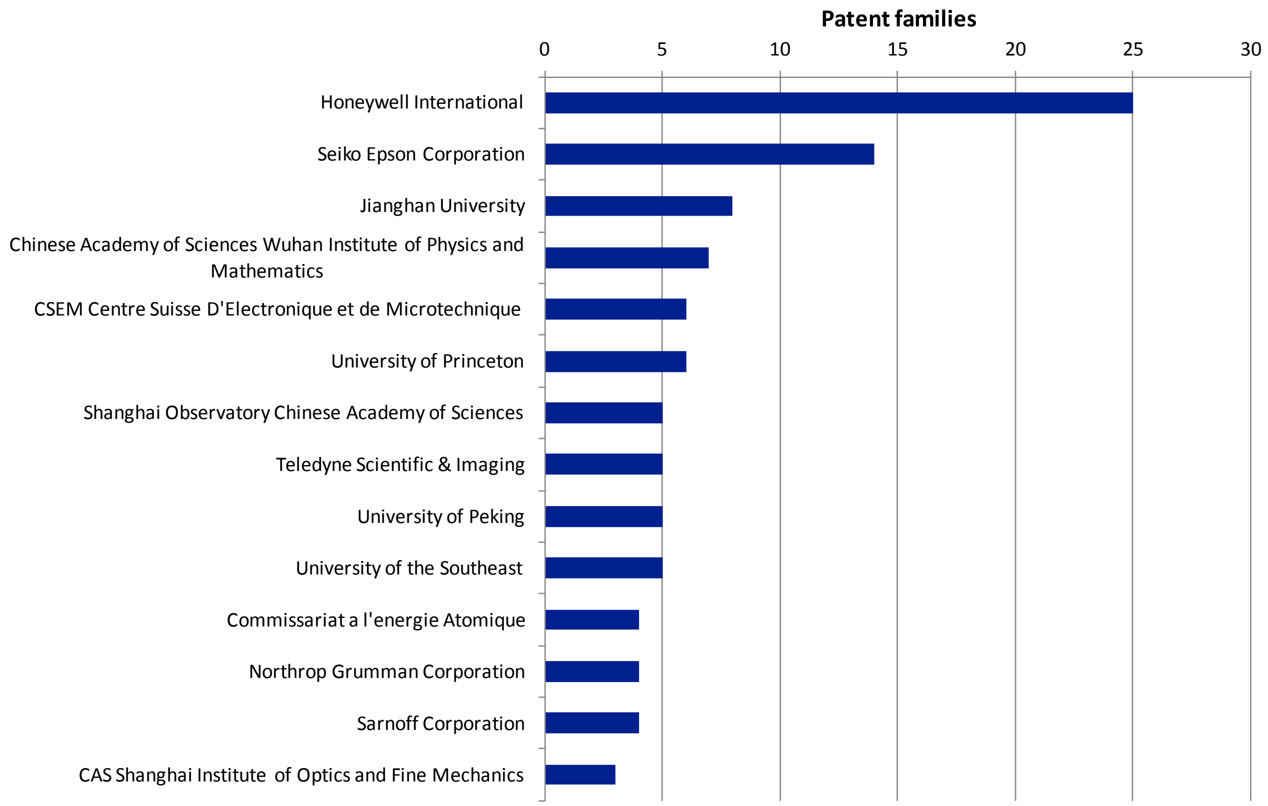


Figure 16: Top applicants for quantum timing and atomic clock technologies

Having noted the predominance of academic and government applicants, it is perhaps also worth noting that the largest two applicants are corporations.

Honeywell is a USA based multinational conglomerate company with a long history[20] of research and development of both consumer and defence sector products ranging from thermostats to napalm to automated computer systems and turbochargers. Headquartered in New Jersey, Honeywell have the most patent families of any applicant in the dataset (25). These inventions relate to chip-scale atomic clocks that utilise cold atomic clouds as the sensing element.

Seiko Epson has the second largest presence in the dataset with 14 families. These

19 See Appendix A.4 for further details.
20 http://honeywell.com

include inventions relating to coherent population trapping systems for atomic frequency acquisition in an atomic clock for use in a mobile phone.

2.4.3 Technology breakdown

Figure 14 shows the top IPC subgroups, and Table 6 lists the description of each of these subgroups. The classifications are not mutually exclusive and each patent family will have many of these classifications applied.

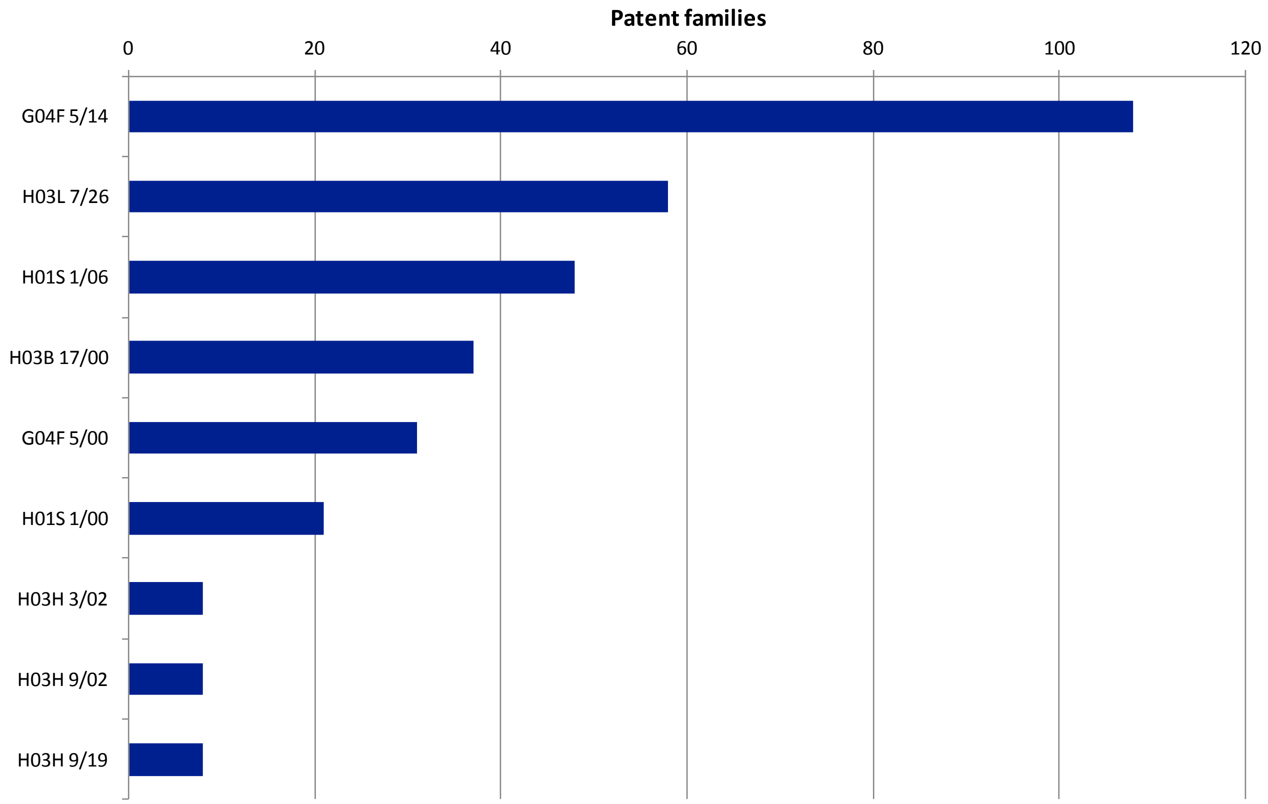


Figure 17: Top IPC sub-groups for quantum timing and atomic clock technologies

Table 8: Key to IPC subgroups referred to in Figure 17

G04F 5/14	Apparatus for producing preselected time intervals for use as timing standards -> using atomic clocks
H03L 7/26	Automatic control of frequency or phase; Synchronisation -> using energy levels of molecules, atoms, or subatomic particles as a frequency reference
H01S 1/06	Masers, i.e. devices for generation, amplification, modulation, demodulation, or frequency-changing, using stimulated emission, of electromagnetic waves of wavelength longer than that of infra-red waves -> gaseous
H03B 17/00	Generation of oscillations using radiation source and detector, e.g. with interposed variable obturator
G04F 5/00	Apparatus for producing preselected time intervals for use as timing standards
H01S 1/00	Masers, i.e. devices for generation, amplification, modulation, demodulation, or frequency-changing, using stimulated emission, of electromagnetic waves of wavelength longer than that of infra-red waves
H03H 3/02	Apparatus or processes specially adapted for the manufacture of impedance networks, resonating circuits, resonators -> for the manufacture of electromechanical resonators or networks -> for the manufacture of piezo-electric or electrostrictive resonators or networks
H03H 9/02	Networks comprising electromechanical or electro-acoustic elements; Electromechanical resonators -> Details
H03H 9/19	Networks comprising electromechanical or electro-acoustic elements; Electromechanical resonators -> Constructional features of resonators consisting of piezo-electric or electrostrictive material -> having a single resonator -> consisting of quartz

3 The UK landscape

3.1 Quantum telecommunications technologies

3.1.1 UK applicants

Figure 18 shows Toshiba and QinetiQ as the top UK applicants. As previously mentioned, Toshiba do most of their research in this technology area at their Cambridge research laboratory[21] and therefore appear as a UK applicant in this patent landscaping analysis. Many of Toshiba's patent families focus on systems using quantum dots as the source of entangled photon pairs. Their patent families also seek protection for optics technology for handling photon pairs, quantum repeaters (relay stations) for increasing the distance over which quantum telecommunication is possible, error correction, and a method of selecting a pre-agreed quantum communication protocol.

The patent families from QinetiQ predominantly comprise EP, US, JP and WO patent publications only and appear to relate to quantum key distribution (QKD) systems and methods at a high level of abstraction, or at least without much technical level detail in the titles and abstracts. The exceptions to this include a family also having UK and Canadian patent publications which relates to fabrication of an electro-optic waveguide polarisation modulator for use in integrated optical waveguides in a quantum cryptography system, an "add drop multiplexer" and an optical receiver for use in QKD networks.

BT's patent families include system level QKD methods for quantum cryptography.

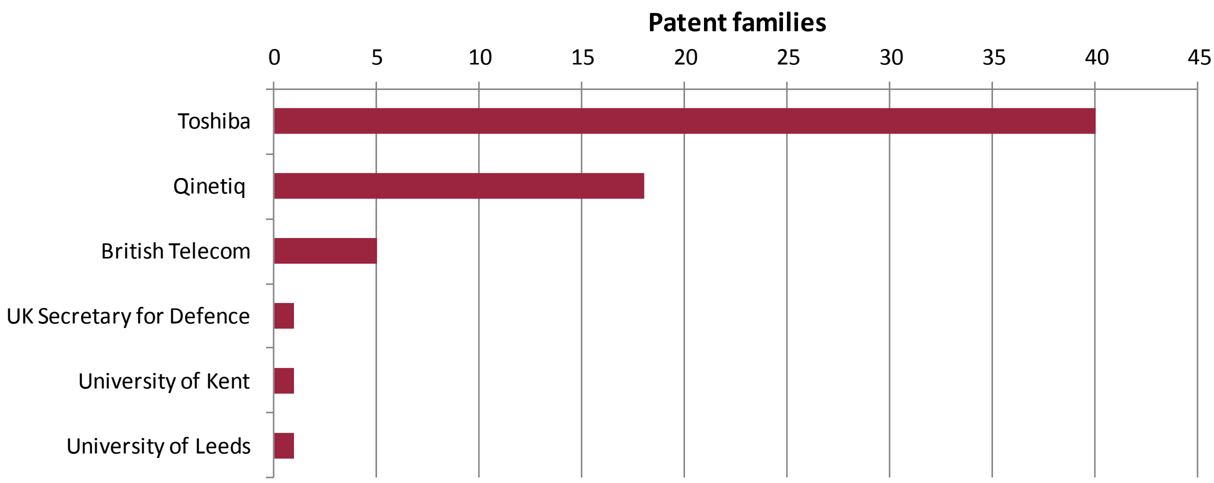


Figure 18: UK applicants for quantum telecommunication technologies

[21] http://www.toshiba.eu/eu/Cambridge-Research-Laboratory/About-Us/

3.1.2 Collaboration between UK applicants

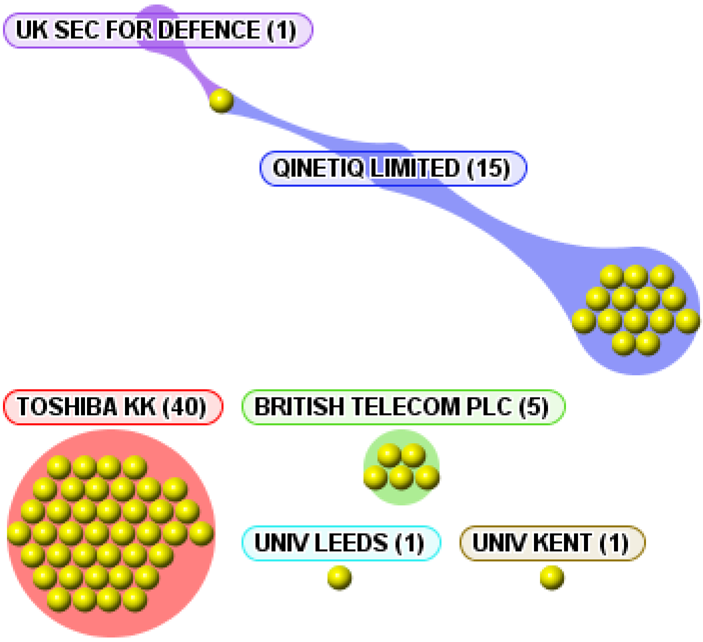


Figure 19: Map of collaborations between UK applicants for quantum telecommunication technologies

3.1.3 UK inventor mobility

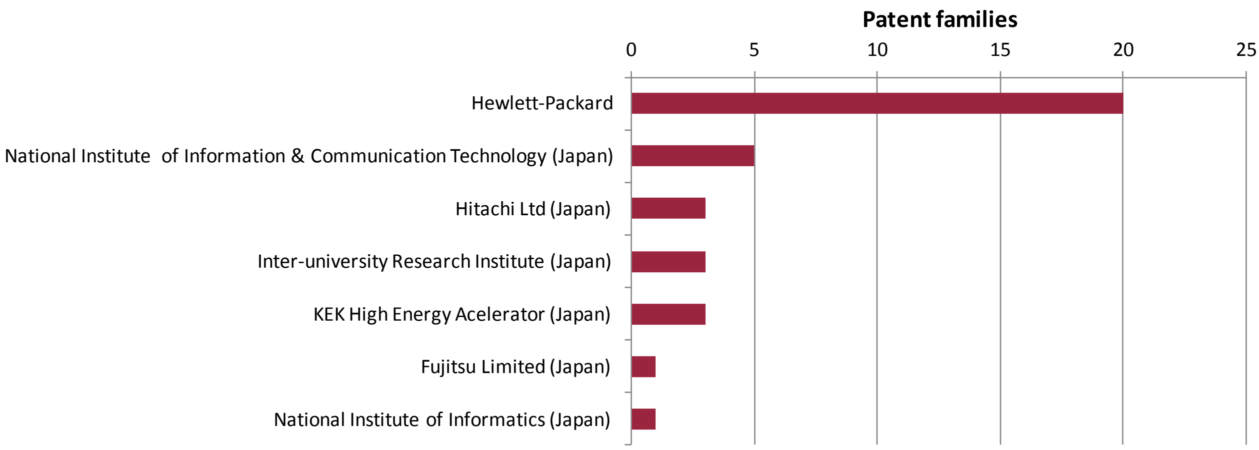


Figure 20: Worldwide applicants with named UK-based inventors for quantum telecommunication technologies

Hewlett-Packard (HP) has research labs in Bristol which are their second largest research location[22]. Of their 37 patent families, 20 originate from this research centre. The inventions these families represent relate to low level technical detail of quantum cryptography systems including components such as quantum repeaters, and entanglement creation apparatus.

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[22] http://www.hpl.hp.com/bristol/

3.1.4 How active is the UK?

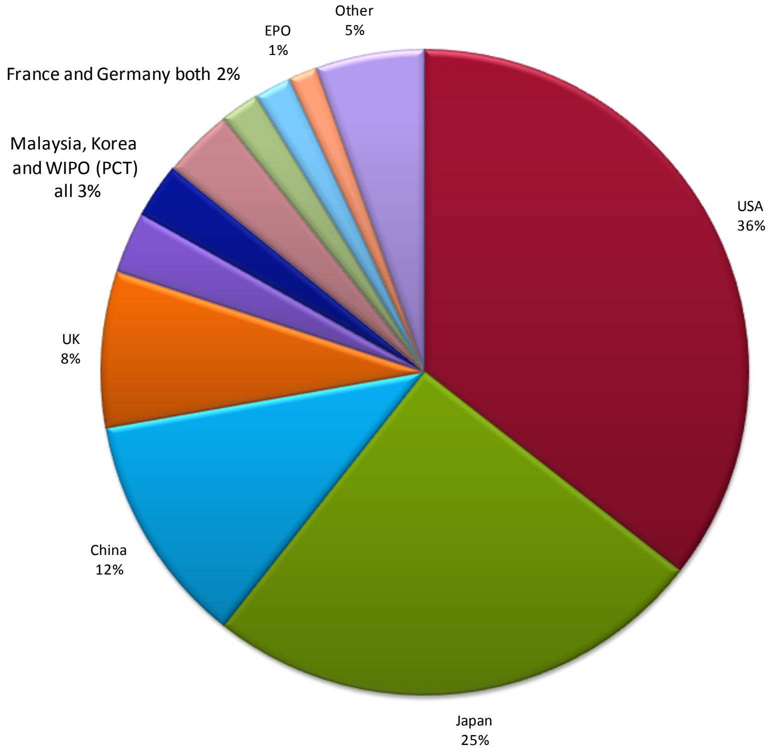

Figure 21: Priority country distribution for quantum telecommunication technologies

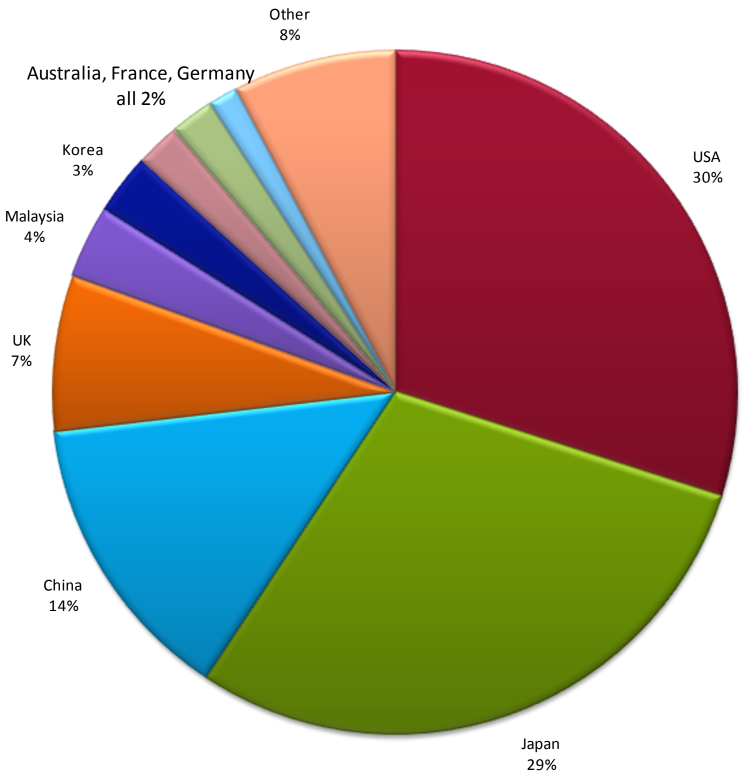

Figure 22: Applicant country distribution for quantum telecommunication technologies

3.2 Quantum computation technologies

3.2.1 Top UK applicants

As discussed above Toshiba do most of their research in this technology area at their Cambridge research laboratory. Their technology focus is also discussed in 2.2.2.

Element Six have patent families relating to preparing high purity diamond materials for use as a host material for a quantum spin defect that has a long coherence time at room temperature.

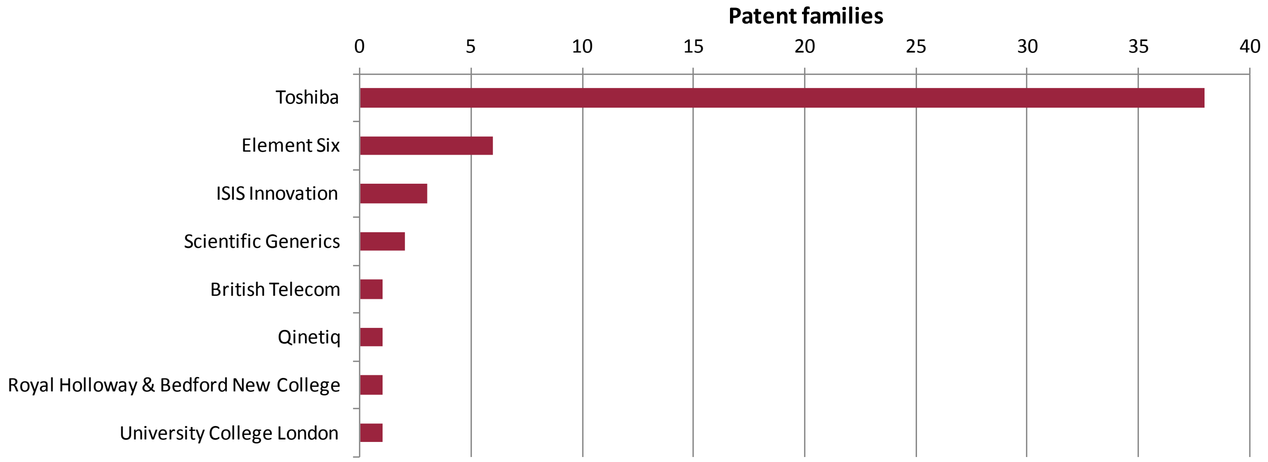

Figure 23: UK applicants for quantum computation technologies

3.2.2 Collaboration between UK applicants

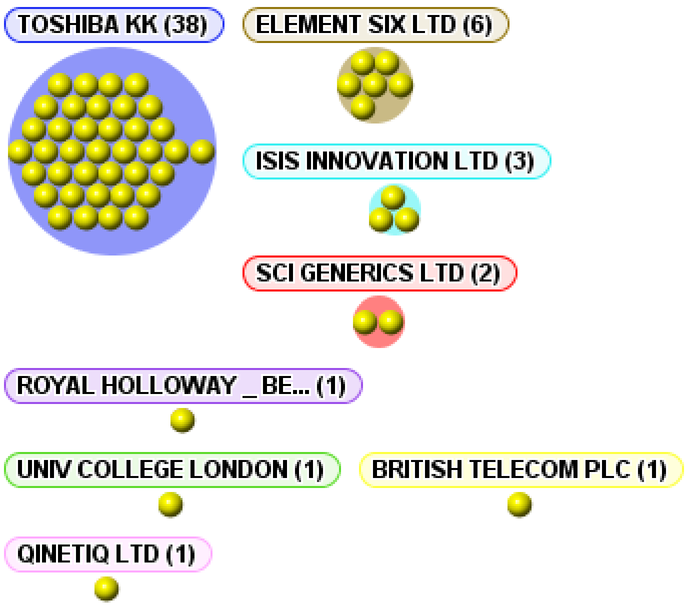

Figure 24: Map of collaboration between UK applicants for quantum computation technologies

3.2.3 UK inventor mobility

As mentioned above, Hewlett-Packard (HP) has research labs in Bristol. Of their 32 patent families, 21 originate from this research centre. The inventions these families represent relate to low level technical detail of quantum cryptography systems including components such as quantum repeaters, and entanglement creation apparatus.

Hitachi has a research laboratory embedded in the University of Cambridge[23]. UK researchers based at this laboratory had involvement in most of their inventions (11 of their 15 patent families) in this technology. These inventions include a method of using quantum dots to create qubits, photon sources that have a single electron turnstile and an optical control unit and quantum information processing devices utilising quantum dot components.

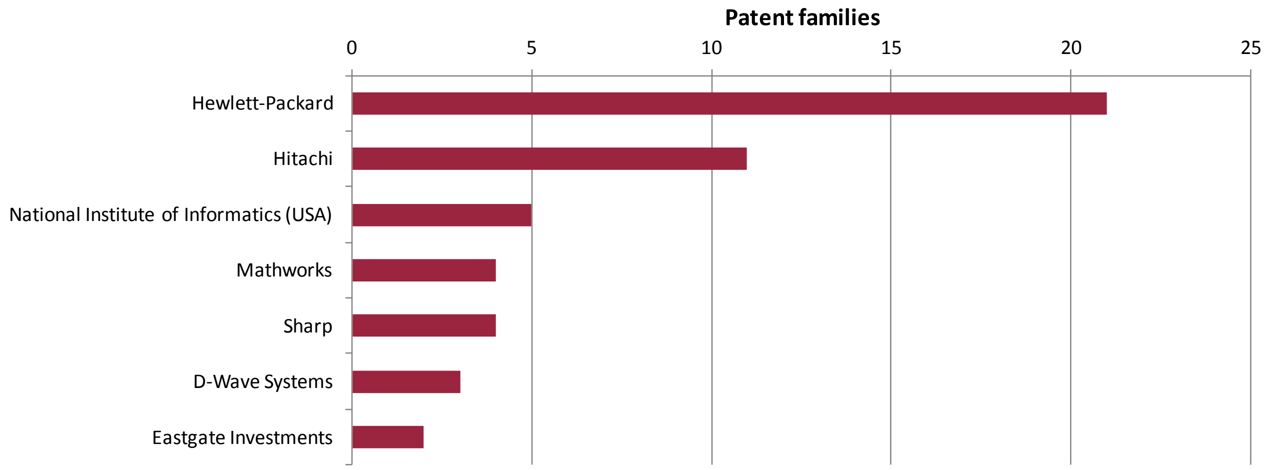

Figure 25: Top worldwide applicants with named UK-based inventors for quantum computation technologies

[23] http://www.hit.phy.cam.ac.uk/ and http://www.hitachi.co.uk/about/hitachi/research/

3.2.4 How active is the UK?

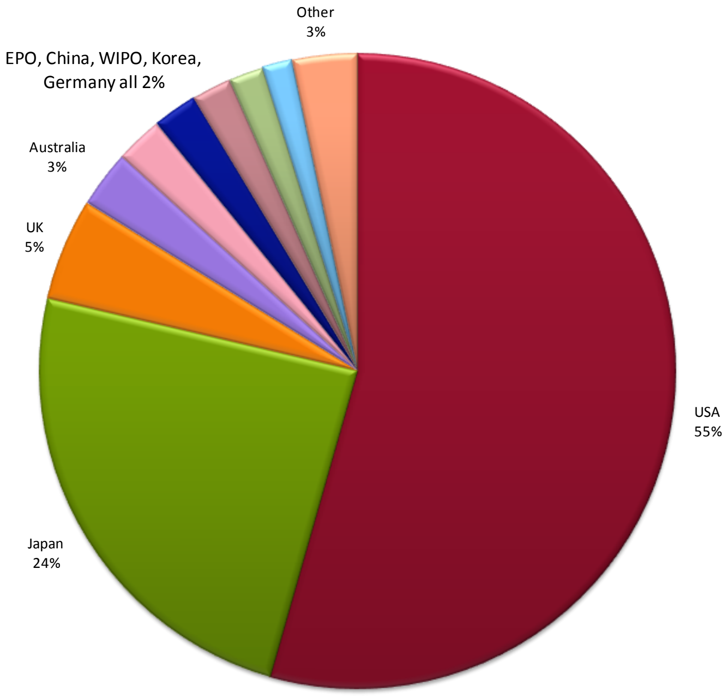

Figure 26: Priority country distribution for quantum computation technologies

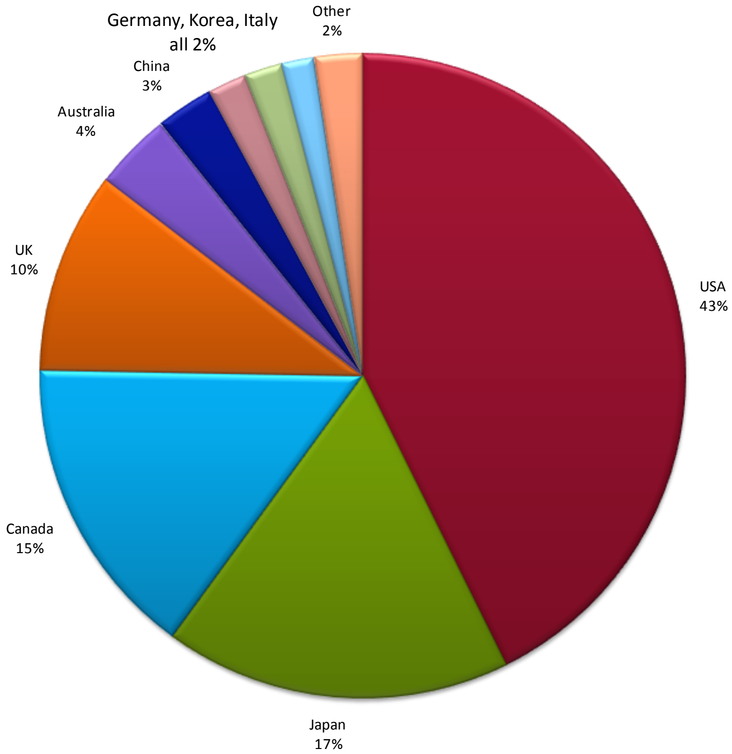

Figure 27: Applicant country distribution for quantum computation technologies

3.3 Quantum sensor technologies

3.3.1 Top UK applicants

As discussed above Toshiba do most of their research in this technology area at their Cambridge research laboratory. Their patent families relate to improvements and uses of superconducting quantum interference devices (SQUIDs).

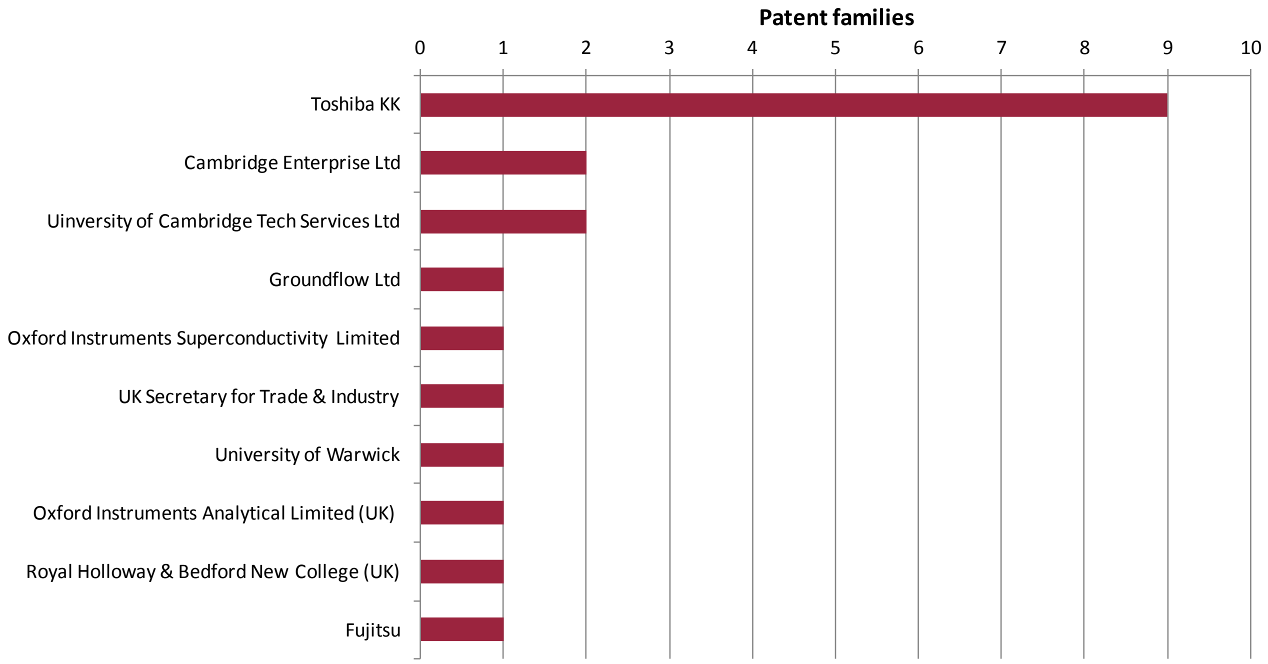

Figure 28: UK applicants for quantum sensor technologies

The patent family resulting from the collaboration between Fujitsu, and Cambridge University technology transfer service (which is named as Cambridge Enterprise Ltd and University of Cambridge Tech Services in the dataset – these are the same entity identified differently on different publications relating to the same patent family), evident in Figure 29, relates to sensing magnetic or electric field using quantum interference with a device that uses charged quantum entangled entities, a source of acoustic waves to provide input current and a splitter to divide the input current into two paths.

3.3.2 Collaboration between UK applicants

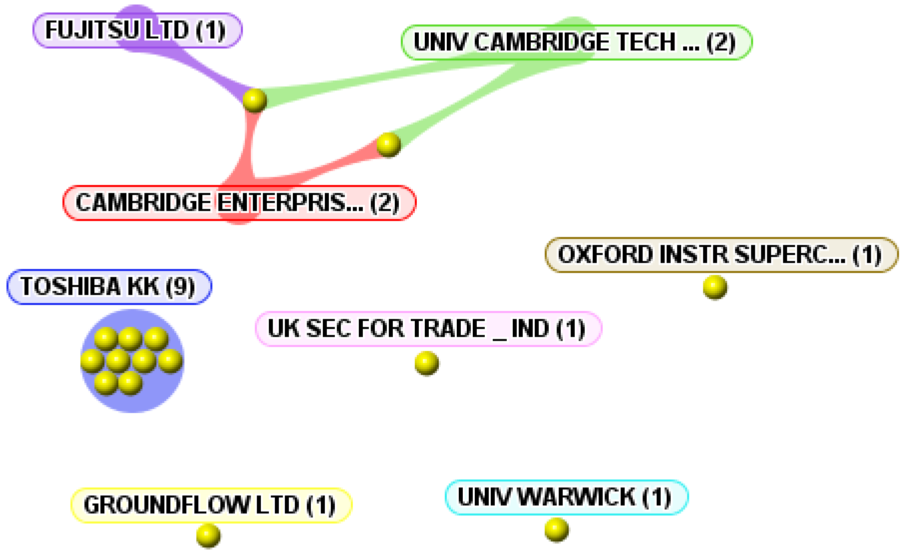

Figure 29: Map of collaboration between UK applicants for quantum sensor technologies

3.3.3 UK inventor mobility

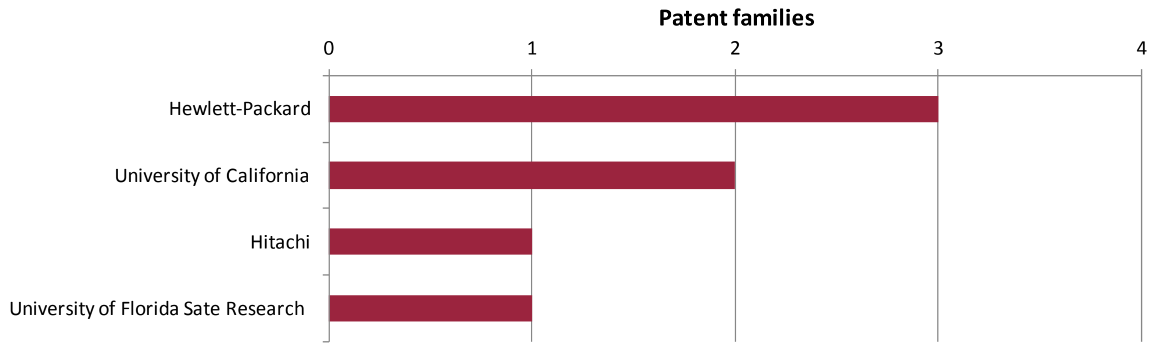

Figure 30: Top worldwide applicants with named UK-based inventors for quantum sensor technologies

3.3.4 How active is the UK?

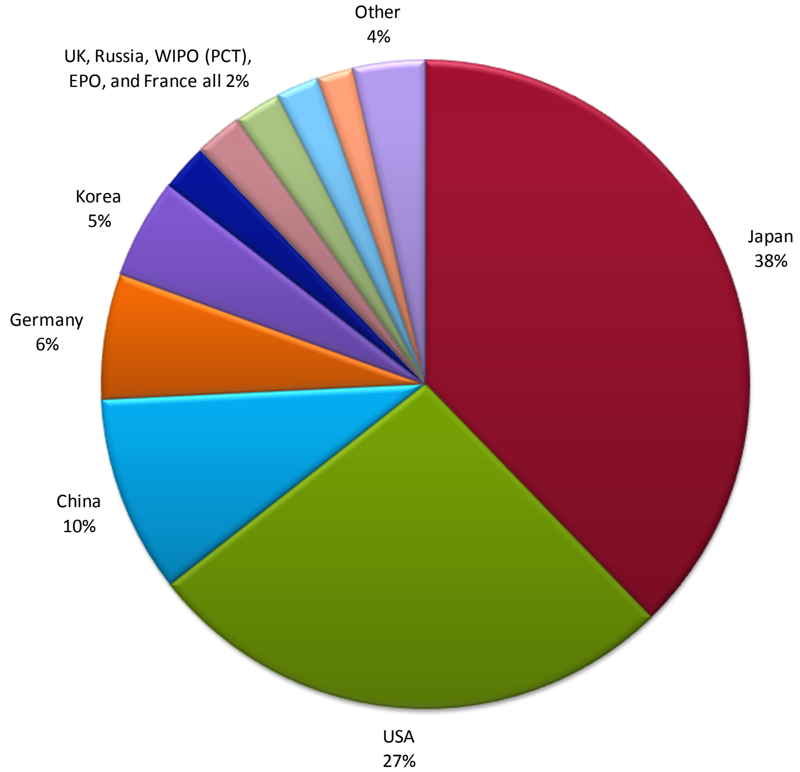

Figure 31: Priority country distribution for quantum sensor technologies

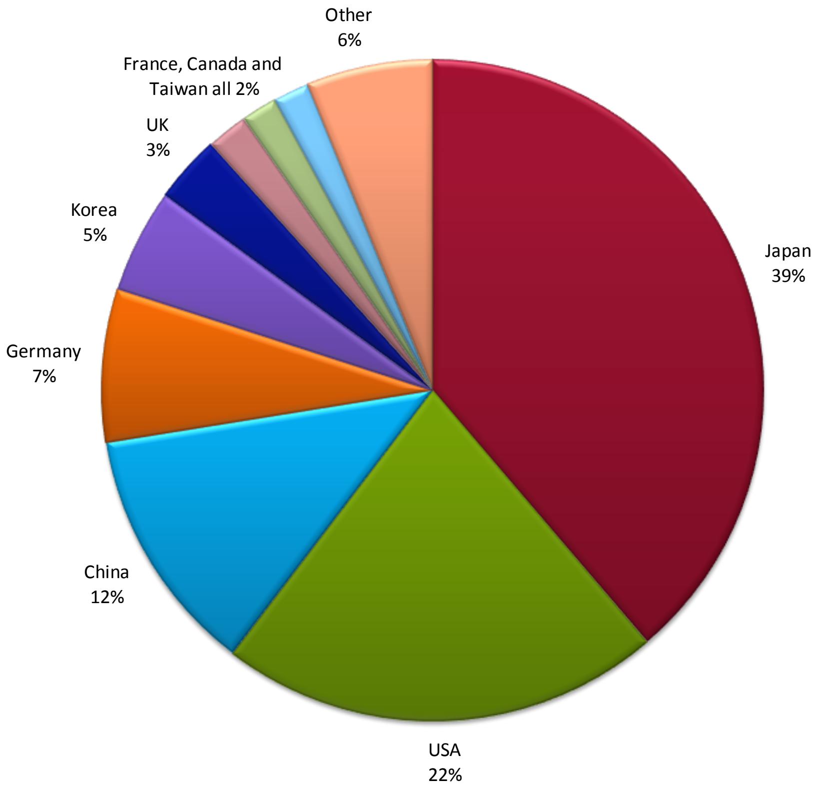

Figure 32: Applicant country distribution for quantum sensor technologies

3.4 Quantum timing and atomic clock technologies

This technology area comprises only three patent families from UK applicants. This is too small a dataset to report on in a similar manner to sections 3.1 to 3.3 above.

3.4.1 Top UK applicants

ISIS Innovation have a family of patents related to an *“atomic clock that has a controller that receives output of detection device and controls magnet device to derive oscillations at frequency determined by energy difference between states of system which is caused to undergo transitions.”*

Non corporate assignee Fallon Martin has a patent family comprising a patent related to *“Semiconductor micro-fabricated atomic clock structure, has metal interconnect structure touching substrate and making electrical connections to circuit elements to realize photodiode circuit.”*

The University of Glasgow has a single patent family in the dataset related to a *“Frequency reference device for use in e.g. magnetic field sensor, has driving unit including negative differential resistance oscillator, where detected characteristic of frequency reference signal is utilized to control driving signal.”*

3.4.2 Collaboration between UK applicants

There is no collaboration between the three UK applicants.

3.4.3 UK inventor mobility

There are three families which have UK inventors named on them in the dataset, corresponding to the three applicants discussed in the section above.

3.4.4 How active is the UK?

The UK is not very active in patenting in this area. There are only three UK applicants in the dataset, putting the UK behind the USA (55), China (46), Switzerland (6), Japan (6), France (5) and Germany (4).

4 Patent landscape map analysis

In order to give a visualisation of the patent landscape for the entire technology space covered by this report, and to check the validity of the assumption that the four technology areas analysed above are largely distinct, a patent map of all of the datasets combined is created. Published patents (not patent families) are represented on the patent map by dots and the more intense the concentration of patents (*i.e.* the more closely related they are) the higher the topography as shown by contour lines. The patents are grouped according to the occurrence of keywords in the abstract and major topics appear on the patent map[24].

4.1 Patent landscape map analysis: quantum telecommunications technologies

The landscape map for quantum technologies is shown in Figure 33. This map was produced using only the “Uses” and “Advantages” parts of the WPI abstract, in order to provide a clearer picture of the dataset.

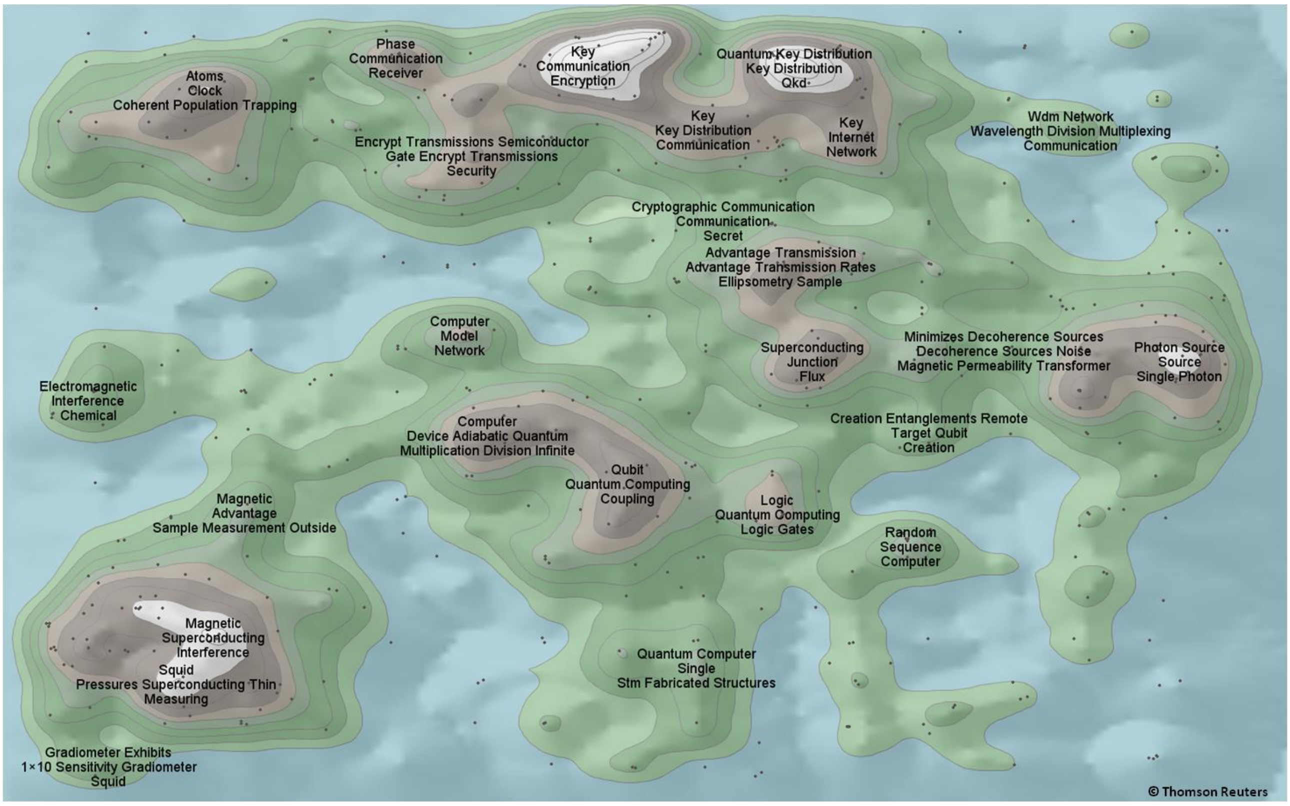

Figure 33: Patent landscape map of all patents relating to quantum technologies combined

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[24] Further details regarding how these patent landscape maps are produced is given in Appendix C.

When analysing the patent landscape map, illustrated in Figure 33, it is evident that the patent publications from the 4 groups of quantum technologies are clustered into 4 different sectors. These sectors are illustrated graphically in Figure 34.

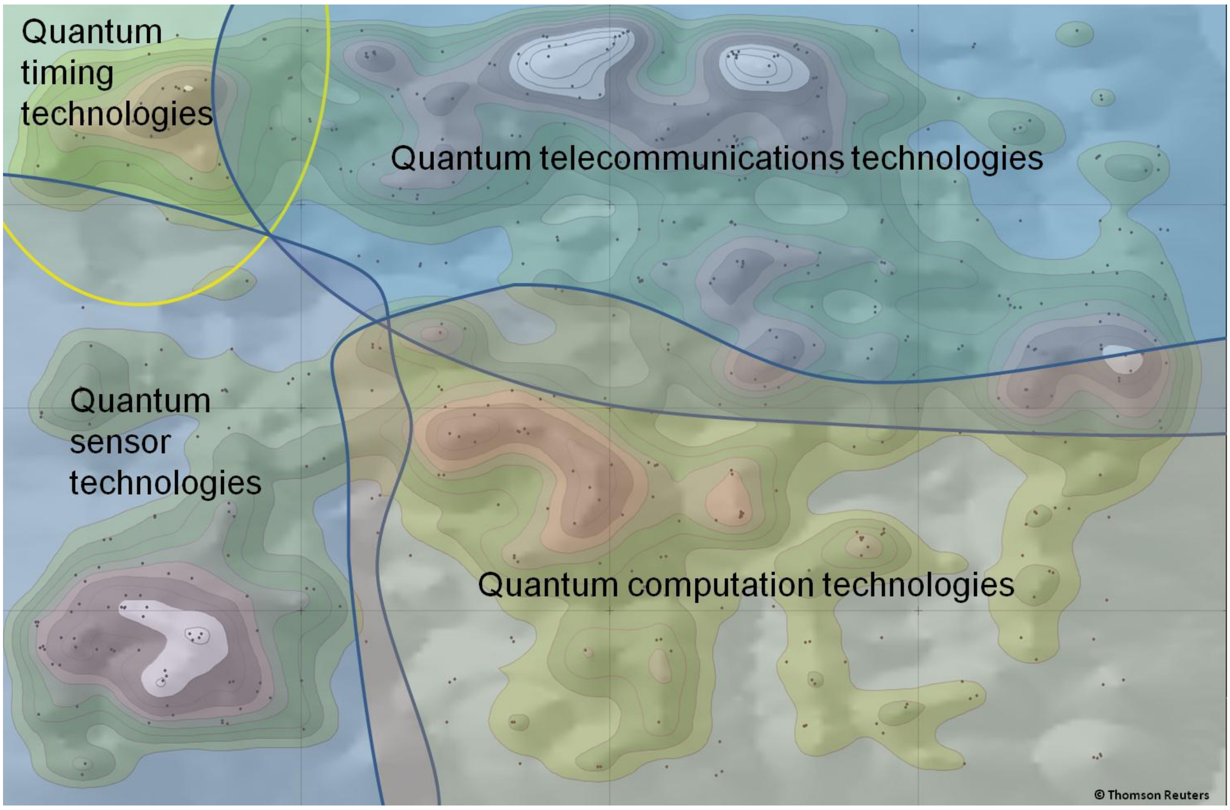

Figure 34: Patent landscape map of all patents relating to quantum technologies combined with the distinct technology areas overlaid

5 Conclusions

Between 2004 and 2013 there has been worldwide patenting activity in quantum telecommunications technologies (950 families), quantum computation technologies (777 families), quantum sensor technologies (547 families) and quantum timing and atomic clock technologies (160 families). In comparison to patent filing in other areas of technology, these are small but significant levels of patenting.

There is some overlap between these areas, particularly since many components which utilise quantum effects can be applied to both telecommunications and computation, whilst timing and clock technologies find application in sensing and telecommunications. On the whole however, these are largely distinct areas of technology which are subject to different trends and therefore warrant separate patent landscaping analysis.

5.1 Quantum telecommunication technologies

There was a peak in patenting activity in 2005 with 100 patent families filed. Following this there has been a lower, but sustained, level of patenting activity of around 65 patent families per year.

Patenting from UK applicants is relatively specialised in quantum telecommunications technologies with UK amongst the most specialised applicant countries in the world in this field, alongside Japan and Australia. The UK is significantly ahead of any other European country in terms of its patenting specialisation in this area, all other European countries being less specialised in quantum telecommunication technologies than their average technological specialisation.

Large companies and multinationals from Japan and the USA are the most prolific patent applicants in this area. Toshiba, the third largest applicant in this area, with 40 patent families, carries out quantum technologies research in the UK at its Cambridge research laboratories. Hewlett-Packard, the fourth largest applicant, has research labs in Bristol and of their 37 patent families, 20 originate from here.

The UK presence is evident from the UK appearing fourth in terms of priority country (8% of families have a GB priority) and applicant country (7% of families have a UK-based applicant). In comparison to what might be expected from patent landscaping analysis of other areas of technology[25], these are significant percentages for the UK when compared to the USA (1st), Japan (2nd) and China (3rd) since the data for these figures is not adjusted for propensity to patent or relative size in terms of GDP, population, etc.

5.2 Quantum computation technologies

There has been a slight decline in patenting activity over the time period of the analysis from more than 70 patent families filed in 2003 and 2004 to just over 50 in 2010 and 2011.

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[25] For example the other areas of technology included in the Eight Great Technologies, reports available here: *http://www.ipo.gov.uk/informatics.htm*

UK applicants are the third most specialised of any countries patent applicants in the patenting of quantum computation technologies; more specialised than applicants from the USA and Japan: second only to Australia (2nd) and Canada (1st).

D-Wave systems of Canada have almost twice as many (82) patent families as the next most prolific applicant, Nippon Telegraph (43). The most prolific applicants consist predominantly of Japanese and North American companies. Toshiba, with its UK research base, is the third most prolific patent applicant with 38 patent families. Hewlett-Packard (6th) and Hitachi (13th) also use the UK as a base for their research into quantum computation technologies.

The UK presence in quantum computation is evident from the UK appearing third in terms of priority country (5% of families have a GB priority) fourth in terms of applicant country (10% of families have a UK based applicant). As discussed in the quantum telecommunications conclusion above, these are significant percentages for the UK when compared to the USA (1st), Japan (2nd) and China (3rd) since the data for these figures is not adjusted for propensity to patent or relative size in terms of GDP, population, etc.

5.3 Quantum sensor technologies

There were around 50 patent families filed per year between 2003 and 2006 followed by around 30 families a year from 2007 to 2011.

UK patent applicants are relatively less specialised in patenting in this technology area when compared to an average level of patenting for UK patent applicants across all technologies. Despite this lack of relative specialisation, UK applicants are still more relatively specialised in patenting in this field than any other European country.

Japanese applicants, including a larger number of agencies and institutions than were seen in quantum computation or quantum telecommunications, dominate the top patent applicants chart in quantum sensing technologies. However, the most prolific patent applicants are Japanese multinationals Hitachi and Sumitomo (NEC). Toshiba are by far the most prolific of UK based applicants in this technology area with 9 patent families relating to improvements and uses of superconducting quantum interference devices (SQUIDs).

The UK has a much smaller share of priority country (2%) and applicant country (3%) than it does in quantum telecommunications or computation technology. These proportions are more like what might be expected based on typical UK statistics from previous patent landscaping analysis in other technology areas.

5.4 Quantum timing and atomic clock technologies

This is a very small dataset which contains only 160 patent families. It exhibits a recent increase in patenting activity from around 10 patent families filed per year from 2003 to 2005 to around 20 patent families per year being filed from 2009 to 2011.

Honeywell and Seiko Epson are most active in patenting, both of whom are developing portable chip-scale atomic clocks based on quantum mechanical effects.

Appendix A Interpretation notes

A.1 Patent databases used

The *Thomson Reuters* World Patent Index (WPI) was interrogated using *Thomson Innovation*[26], a web-based patent analytics tool produced by *Thomson Reuters*. This database holds bibliographic and abstract data of published patents and patent applications derived from the majority of leading industrialised countries and patent organisations, *e.g.* the World Intellectual Property Organisation (WIPO), European Patent Office (EPO) and the African Regional Industry Property Organisation (ARIPO). It should be noted that patents are generally classified and published 18 months after the priority date. This should be borne in mind when considering recent patent trends (within the last 18 months).

The WPI database contains one record for each patent family. A patent family is defined as all documents directly or indirectly linked via a priority document. This provides an indication of the number of inventions an applicant may hold, as opposed to how many individual patent applications they might have filed in different countries for the same invention.

A.2 Priority date, application date and publication date

Priority date: The earliest date of an associated patent application containing information about the invention.

Publication date: The date when the patent application is published (normally 18 months after the priority date or the application date, whichever is earlier).

Analysis by priority year gives the earliest indication of invention.

A.3 WO and EP patent applications

International patent applications (WO) and European patent applications (EP) may be made through the World Intellectual Property Organization (WIPO) and the European Patent Office (EPO) respectively.

International patent applications may designate any signatory states or regions to the Patent Cooperation Treaty (PCT) and will have the same effect as national or regional patent applications in each designated state or region, leading to a granted patent in each state or region.

European patent applications are regional patent applications which may designate any signatory state to the European Patent Convention (EPC), and lead to granted patents having the same effect as a bundle of national patents for the designated states.

[26] http://info.thomsoninnovation.com

Figures for patent families with WO and EP as priority country have been included for completeness although no single attributable country is immediately apparent.

A.4 Patent documents analysed

The dataset for analysis was identified in conjunction with patent examiner technology-specific expertise. A search strategy was developed and the resulting dataset was extracted in July 2014 using International Patent Classification (IPC) codes, Co-operative Patent Classification (CPC) codes and keyword searching of titles and abstracts in the *Thomson Reuters* World Patent Index (WPI) and limited to patent families with publications from 2004 to 2013.

The applicant and inventor data was cleaned to remove duplicate entries arising from spelling errors, initialisation, international variation (Ltd, Pty, GmbH *etc*.), or equivalence (Ltd., Limited, *etc*.).

A.5 Analytics software used

The main computer software used for this report is a text mining and analytics package called *VantagePoint*[27] produced by *Search Technology* in the USA. The patent records exported from *Thomson Innovation* were imported into *VantagePoint* where the data is cleaned and analysed. The patent landscape maps used in this report were produced using *Thomson Innovation*.

[27] *http://www.thevantagepoint.com*

Appendix B Relative Specialisation Index

Relative Specialisation Index (RSI) was calculated as a correction to absolute numbers of patent families in order to account for the fact that some countries file more patent applications than others in all fields of technology. In particular, US and Japanese inventors are prolific patentees. RSI compares the fraction of technology area specific patents found in each country to the fraction of patents found in that country overall. A logarithm is applied to scale the fractions more suitably. The formula is given below:

$$\log_{10}\left(\frac{n_i/n_{total}}{N_i/N_{total}}\right)$$

where

n_i = number of technology area specific patents in country i
n_{total} = total number of technology area specific patents in dataset
N_i = total number of patents in country i
N_{total} = total number of patents in dataset

The effect of this is to highlight countries which have a greater level of patenting in the specific technology area than expected from their overall level of patenting, and which would otherwise languish much further down in the lists, unnoticed.

Appendix C Patent landscape maps

A patent landscape map is a visual representation of a dataset and is generated by applying a complex algorithm with four stages:

i) **Harvesting documents** – When the software harvests the documents it reads the text from each document (ranging from titles through to the full text). Non-relevant words, known as stopwords, (e.g. “a”, “an”, “able”, “about” etc) are then discounted and words with common stems are then associated together (e.g. “measure”, “measures”, “measuring”, “measurement” etc).

ii) **Analysing documents** – Words are then analysed to see how many times they appear in each document in comparison with the words’ frequency in the overall dataset. During analysis, very frequently and very infrequently used words (i.e. words above and below a threshold) are eliminated from consideration. A topic list of statistically significant words is then created.

iii) **Clustering documents** – A Naive Bayes classifier is used to assign document vectors and Vector Space Modelling is applied to plot documents in n-dimensional space (i.e. documents with similar topics are clustered around a central coordinate). The application of different vectors (i.e. topics) enables the relative positions of documents in n-dimensional space to be varied.

iv) **Creating the patent map** – The final n-dimensional model is then rendered into a two-dimensional map using a self-organising mapping algorithm. Contours are created to simulate a depth dimension. The final map can sometimes be misleading because it is important to interpret the map as if it were formed on a three-dimensional sphere.

Thus, in summary, patents are represented on the patent map by dots and the more intense the concentration of patents (*i.e.* the more closely related they are) the higher the topography as shown by contour lines. The patents are grouped according to the occurrence of keywords in the title and abstract and examples of the reoccurring keywords appear on the patent map. Please remember there is no relationship between the patent landscape maps and any geographical map.

Please note that the patent maps shown in this report are snapshots of the patent landscape, and that patent maps are best used an interactive tool where analysis of specific areas, patents, applicants, inventors *etc* can be undertaken ‘on-the-fly’.

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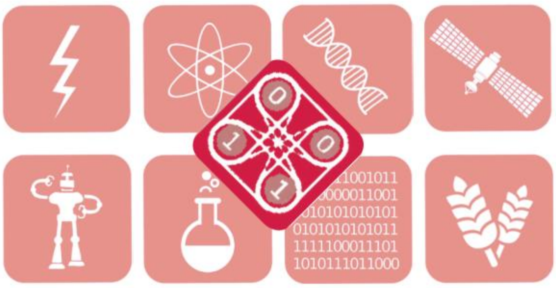

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