Funding Breakthrough Technology

Case summary : Optical Fibres

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This case summary is part of the 'Funding Breakthrough Technology' project. This project is in the commercialisation stream of activities of the EPSRC funded Cambridge Integrated Knowledge Centre (CIKC) in photonics and macro molecular material. Historical case studies of eight breakthrough technologies of the last 60 years are being investigated with the specific focus of how these technologies were supported and finance in their journey from the lab to market. The other case studies are Photovoltaics, Liquid Crystal Displays (LCD), Inkjet printing, Light Emitting Diodes (LED), Giant Magnetoresistance (GMR), Micro electronic mechanical systems (MEMS) and Computed Tomography (CT) and Magnetic Resonance Imaging (MRI).

All of the case study documents are works in progress. If you would like to comment on any of the case study summaries please contact Dr. Samantha Sharpe at the Centre for Business Research on email (s.sharpe@cbr.cam.ac.uk) or telephone (+44 (0) 1223 765 333. As these documents are works in progress we would request that the case studies not be cited without the author's permission.

1. Introduction[1]

Optical fibres are the backbone of today's telecommunications industry. Optical communications refers to any form of telecommunications that uses light as the transmission medium. An optical communications system consists of three elements; a transmitter, which encodes voice and/or data into an optical signal; a channel, which carries the optical signal from origin to destination; and thirdly a receiver, which uncodes the optical signal back into its original format.

Optical fibres are the most common form of optical channel and light emitting diodes are currently the most common form of transmitting the light signal. Infrared light, rather than visible light is mostly used, because optical fibres transmit infrared wavelengths with less attenuation (light loss) and dispersion, than visible light.

In this case study the focus will be on the development of optical fibres, but as the emergence of optical communications as a technology was dependent on the fibres, the light source and the method of transmitting the light source, all three of these areas will be discussed in reference to the development of optical fibres.

2. Early history

The use of transparent fibres (usually glass, but also plastic) to transmit light has a long history. The mechanisms of transmitting light through glass can be traced back to Egyptian times (Hecht 2004). In the Victorians era, these transparent fibres were considered a good 'parlour trick' and they were often used in public science demonstrations. Optical fibres were used to light fountains at World and Science exhibitions throughout the 1880s with impressive results.

However, the early pioneers of optical fibres had thought of widespread applications for these glass fibres including household lighting, glass fabric and medical and

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[1] In completing this case study I relied heavily upon the work of Hecht (2004) '*City of Light: The Story of Fiber Optics'* Oxford University Press: New York, for material, particularly details from the individuals involved in the development of technology that Hecht acquired through many interviews.

dental equipment[2]. Household lighting did not prove to be achievable. The work on glass fabric (used in dresses and lampshades) did not result in any real practical products but it did lead onto work using glass fibres as insulation material.

In the early 1930s two US based glass manufacturers; Corning Glass Works and Owens-Illinois Glass Company formed a joint venture to specifically commercially manufacture fiberglas (trade mark spelling)[3]. By 1935 they were world leaders in fibre-glass production.

Medical and dental equipment was another early need that fibre optics could meet. Inventors had been trying for years to work out a way for physicians to be able to look inside patient's bodies without surgery. Efforts with rigid glass rods had lead to them being described by a contemporary of the day as "one of the most lethal instruments in the surgeon's armamentarium" (Hecht 2004, p41). Optical fibres offered a solution with their flexibility. Using fibres to transmit images or "remote viewing" was a goal shared both by scientists working on early versions of the endoscope as well as those associated with television.

The use of fibre optics to transmit an image was conceived in 1926 by Radio Corporation of America (RCA)[4] researcher William Hansell[5]. He received the patent

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[2] Daniel Colladon, of the University of Geneva was the first to demonstrate light guiding in 1841. Sir Francis Bolton a London city engineer created the fibre optic light fountains for the 1884 International Health Exhibition in South Kensington, London. US inventor William Wheeler filed the first patent for 'light piping' in houses in 1880 (Hecht 2004).

[3] Corning Glass Works would go on to play a critical role in the development of optical fibres for communications. Their corporate strategy of creating alliances and joint ventures would be an essential feature of their success. Other such alliances include Pittsburgh-Corning producing architectural glass and Dow Corning for the production of silicone (Graham 2007).

[4] Radio Corporation of America was founded in 1919 by General Electric (GE) as a publicly held company with GE as the controlling shareholder. The company was formed to create a monopoly on radio technology in the US through government support and navy radio assets, the purchase of the US operations of the UK based Marconi Wireless Company and cooperation from AT&T, United Fruit and Westinghouse in pooling their patents in radio technology Aitken, H. (1985). The continuous wave: Technology and American Radio 1900-1932. Princeton, NJ, Princeton University Press. The end result was government created monopolies in radio for GE and Westinghouse and telephone for AT&T.

[5] Clarence Weston Hansell completed his electrical engineering training as part of an Army training program in the US. He worked for General Electric before joining RCA to found their Rocky Point Radio Transmission Lab. He collected over 300 patents. Hansell first looked to fibre optics as image transmitters in order to see instrument

for 'picture transfer code' using fibre optics in 1930. The use of fibre optics to transmit images bought in the first military interest. Firstly, the security aspect, if images were transmitted with optics was there a way to intercept these images, and then secondly was there a way to scramble the images, so this method could be used for secret communications. Despite these interests, Hansell really went no further with his research. Fibre optics was a side concern for Hansell, his main research was in radio transmission and this was a period of rapid developments in radio.

Fibre optics lay dormant for more than two decades. The main problem with fibre optics, that was not immediately apparent to these early researchers, was the effect of light loss, either through the poor transparency of the glass or leakage of the light in the optical fibre into an adjacent fibre in a fibre bundle.

3. Cladding the fibres

"Optics was a quiet backwater of physics in 1951" (Hecht 2004, p.46)

With increasing technological development in glass manufacturing and the involvement of a number of large glass manufacturers including American Optical and Corning Glass Works, the production of optical fibres increased in ease, and the transparency of the glass increased as well.

However, it was the addition of cladding, an external layer of material with a lower refractive index than the glass, which led to significant increases in the ability of the fibres to transmit light. It was a discussion in 1951 between two professors, Abraham Van Heel, Professor of Physics at the Technical University of Delft, and Brian O'Brien, Professor of Optics at the University of Rochester (US' leading school of optics).

dials that were out of sight but by the time RCA had filed the patent application they had another use in mind, the transfer of newspaper pictures by facsimile transfer.

Their discussion led to Van Heel trialling the use of cladding material (initially plastic) with a lower refractive index on the exterior of the glass fibres[6]. The concept took Van Heel and his lab several years to generate good results of light transmission. By this time O'Brien had moved from the University of Rochester to American Optical and was caught up on a project there designing wide-screen cinema.

Neither of the two researchers filed a patent for their work, O'Brien was too busy and Van Heel an academic was primarily interested in applications for military clients and a publication. On hearing from a colleague that a team of English scientists from Imperial College London were doing similar work, Van Heel rushed an article on his Cladded fibres into a Dutch publication and submitted another article to *Nature*[7]. A mix up in the notification meant that O'Brien did not receive notification of the publication in time for him to submit a patent application[8]. *Nature* held off publication of Van Heel's article for several months and when they published it, they did so adjacent to an article on the Imperial College work.

The work at Imperial College London

Imperial College London scientist Harold Hopkins[9] received a grant of £1500 in 1952 from the Royal Society to investigate the use of glass fibre bundles to develop an endoscope. He had recently met a physician who told of his distress at having to conduct an endoscopy with a rigid glass rod. Hopkins thought that glass fibres may offer some potential and applied for the grant from the Royal Society (Hecht 2004).

[6] Van Hell’s optical department at Delft University was a joint research centre with the Netherlands government. Van Heel’s work was funded by a Netherlands Defence Research Council grant, on behalf of the Royal Netherlands Navy. The navy was interested in using fibre optics to create new periscopes for their submarines Faltas, S. (1988). "The invention of fibre-optic communications." History and Technology **5**(1): 31-49.

[7] Van Heel rushed the publications, but they were still subjected to a lengthy period of vetting by the military before they could be submitted for publication (Faltas 1988).

[8] Despite the previous publications by Van Heel, O’Brien did finally receive a US patent for the cladding of optical fibres in 1958, after which 20 years of litigation over the patent ensued (Faltas 1988).

[9] Harold Hopkins born in 1918, received a university scholarship and graduated with a degree in physics in 1939. As WW11 broke out he was sent to work in an optics company. During the war he earned his doctorate from University of London and received a faculty position at Imperial College of Science and Technology. He avoided military work in the Cold War and went on to design the first zoom lens for fixed-focus lens (Hecht 2004).

He used the money to hire doctoral student Narinder Kapany[10] to work with him on the project. Hopkins and Kapany designed and experimented with cladded fibre bundles and achieved promising results. Hopkins sought advice on submitting a patent, but there was doubt over whether it would be granted (because of a similar prior patent) therefore not wanting to waste money, Hopkins never bothered with the patent. He did try to find an industry partner to development the endoscope with but was not successful, describing to Hecht (2004) in an interview, that all companies "were dead from the neck up" (p.59).

Hopkins and Kapany's work was published in the *Nature* article, together with Van Heel's. "Neither paper was quite sufficient by itself. Yet taken together, the two papers in one of the world's most widely read scientific journals launched modern fibre optics" (Hecht 2004, p.59).

Developing the endoscope

None of the early researchers involved in cladding optical fibres and creating optical bundles progressed their discoveries any further. When Hopkins could not find any industrial interest he moved onto other things, Van Heel could get no further military funding nor interest corporate giant Philips[11]. However an American researcher from the University of Michigan, Basil Hirschowitz read both articles in *Nature* and arranged to visit both Hopkins and Van Heel. Hirschowitz was a medical researcher; he specialised in gastroenterology and therefore approached the development of an endoscope from a medical rather than optics perspective.

[10] Narinder Kapany was born in 1927. He went to university in India and worked for an optics manufacturer there, before moving to London and Imperial College for his PhD. After completing his PhD Kapany moved the University of Rochester (as O'Brien's replacement) and consulting work with Bausch and Lomb (as major US optical company). Kapany would play a critical role in fibre optics if not through his technological discoveries but through his documenting the progress of the field. Many of the other scientists involved in fibre optics were under military or commercial restrictions and could not publish. From 1955 to 1965 he was lead author on 46 scientific papers and co-author on a further 10, representing 30% of the field (Hecht 2004). He also started his own company Optical Technology in the late 1970s in the US.

[11] The Delft/ Navy project was wound up in 1954, and the technology was offered for sale to Philips. Philips declined believing that optics fibres had poor commercial prospects (Faltas 1988).

Hirschowitz received funding from his university to make this visits to Europe and hire an assistant, a physicist name Lawrence Curtiss[12]. The team attempted to repeat the results detailed by the Imperial College work but found the experiments did not work the same as detailed in the *Nature* article. The Michigan team had to start afresh, with a new glass recipe and technique for making the glass fibres, they also trialled plastic cladding on the glass fibres to reduce the light loss but with limited success. Curtiss then trialled a low-index glass to clad the higher index glass fibres. These fibres achieved the best light transmission to date. This was December 1956 and by the following February they had a prototype endoscope trialled on a patient.

The technology was licensed to American Cystoscope Makers Inc in 1957 on the condition that the Michigan researchers help them start production. Curtiss took a semester off university to work on the production, but never went back. Commercial trials started in 1960 and sales soon after. The device was a success from the start – the company expected to sell 2000 instruments over the 17-year life of the patent, but they were selling 2000 a year.

4. Fibre Optics as a communication medium

"The trickle of innovation reached a critical mass in the 1950s and the young technology slowly emerged into the world. More advances followed, including a series of breakthroughs that in twenty years transformed a crazy idea into the backbone of the global telecommunications network" (Hecht 2004,p.117)

Despite some early imaginings of the potential of fibre optics as a communications medium in the 1920s it would not be until the 1960s and 1970s that these applications would be considered as serious options, and for much of this time fibre optics would be seen as the backup to the much more favoured technology of microwave millimetre waveguides.

[12] The research program cost $5500 over the two years it ran; $4000 of this cost went on the salary of Curtiss (Hecht 2004).

Increasing intensity of communication needs

Throughout the 1950s the telecommunications industry was well aware of its need to increase capacity (Bell 1988; Kwon 1999). The industry-wide recognised next step was to use microwave frequencies in the form of waves. Wave guides provide the boundaries for these waves, directing them to their destination. Waveguides are long tubes either made of electrically conductive material or non-conductive insulation. Millimetre waveguides[13] were considered the next big thing.

In the US, AT&T had enjoyed a monopoly position in telecommunications for some seventy five years. The size of their business meant their R&D programs were well resourced. Government regulation also ensured that public telecommunication costs covered all of their R&D expenses (Graham 2007). AT&T Research labs, Bell Labs had significant investments in millimetre waveguide research. According to Bell Labs, this was going to be the next generation of communications technology and they would not easily be dissuaded from this view (Alfermess, Olsson et al 2000).

In Britain the Post Office (BPO) had responsibility for telephone services in the UK. The BPO had a team of some 100 researchers on their millimetre waveguide research projects (Hecht 2004). Standard Telecommunications Laboratories (STL)[14], the first commercial telecommunications company in the UK also had research groups investigating millimetre waveuides.

Despite their popularity millimetre waveguides had serious limitations. Signals would degrade if the waves had to go around corners, therefore all the waveguides had to be installed in completely straight lines, a difficult task and expensive to an urban

[13] Millimetre waveguides were named as such because the wavelengths were a number of millimetres (2-5mm)

[14] STL was a division of International Telephone and Telegraph (ITT). ITT was considered the biggest telecommunications company in Europe in the 1960s and 1970s and had a clear presence in the UK domestic electronics market after it acquired the British electronics manufacturer Kolster-Brandes (KB) and their colour television manufacturing line. ITT sold its communications assets in 1986 to Alcaltel, which in turn merged with Lucent Technologies (AT&T spin off including Bell Labs) in 2006.

area[15]. The reluctance of the telecommunications industry (particularly AT&T and Bell Labs[16]) to move away from millimetre waveguides despite their growing list of inadequacies may have slowed the initial process of fibre optics as a communications medium, but also meant that the profits of this telecommunications revolution followed a less than expected path.

Alec Reeves and STL

STL had abandoned its millimetre waveguide program relatively early. STL did not have the same level of resources as AT&T and had to make sure their research spend was directed to where they could obtain an advantage (Hecht 2004). By the early 1960s STL had wound up their millimetre waveguide research.

The director of exploratory research at STL, North London was Alec Reeves[17], some what of a legend in electronics in this time period, he had a talent for technology foresight that well known and supported (Hecht 2004). Reeves proposed skipping over microwave frequencies altogether and moving to optical frequencies (the gap between the two being a factor of 100,000 (Hecht 2004)). Reeves obtained a military contract to explore optics and hired physicist Murray Ramsay[18] from University College London.

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[15] "Millimetre waveguides were as ill-matched to winding along the tangled streets of London as rigid metal pipes were to looking down a patient's throat into his stomach. Post Office engineers wanted a cable they could snake through utility ducts already buried underground" (Hecht 2004, p.118).

[16] Bell Labs did have research programs on fibre optics, but these were minor and dwarfed by their expenditure on millimetre waveguides, this together with their 'not invented here' attitude meant they were not going to give up easily, as the following quote demonstrates…"No one (at Bell) pretended it (millimetre waveguides) were going to be cheap or easy, but with government regulations assuring a return on their investment, AT&T was ready to spend untold billions" (Hecht 2004, p.161)

[17] Alec Reeves was born in 1902 and began career in electronics after WW1. In 1937, whilst working at ITT's Paris Laboratory he devised 'Pulse code modulation' to reduce noise from building up in a telephone line. Pulse code modulation is currently the standard method of transmitting digitized voice and video signal, but it was decades before its time. As a result, Reeves earned nothing from his patent (neither did ITT) as it had lapsed long before the technology was needed.

[18] Murray Ramsay would be the first person to demonstrate optical transmission of an image or 'remote viewing' to the Queen at the Institute for Electrical Engineers Centenary exhibition in 1971. The Queen was interested, but Lord Mountbatten who accompanied her proved to be more influential, an electrical engineer himself, and well placed in government, he ensured information on the progress of fibre optics was spread (Hecht 2004 – based on interview with Ramsay).

Reeves also obtained internal funding from STL to investigate whether optical fibres could be used as waveguides and under what conditions. He gave the task to two engineers at STL; Charles Kao and George Hockman.

Optical waveguides - setting the theoretical limits

In order to think about whether optical fibres could be used as waveguides Kao and Hockman had to consider the properties of glass. Their research showed that theoretically optical fibre communications would achieve faster and larger capacity transmission at commercially feasible rates – if the right material could be found (Graham 2007). Kao calculated that if they could produce glass which had attenuation rate of 20dB per kilometre fibre optics could work commercially. The attenuation rate of glass fibre in 1965 was 1000dB per kilometre, so this was considered very much a theoretical proposition, a long way from reality.

Kao and Hockman presented their findings at a conference of the Institute of Electrical Engineers in London in 1966 and in a publication a few months later. The findings were viewed as radical and essentially theoretical but they caught the interest of the BPO[19]. STL researcher Murray Ramsay reflected on the 1966 publication, "…If one looks back now at that paper, it is interesting to note how many of what were then optimistic assumptions have been realized or handsomely exceeded…"(Ramsay 1973).

The properties of glass needed to be investigated to find out how clear glass could be produced. Kao and Hockman found that no-one really knew the answer to this question (Hecht 2004). The BPO did not manufacturer any of their own equipment, so when investigating glass transparency with Kao, they contacted their speciality glass supplier in New York, Corning Glass Works, for some samples of their purest glass (Graham 2007).

[19] Specifically the attention of Robert Williamson White, head of the Waveguide Development Section at BPO Research Station, Dollis Hill, London. White's research team had 100 scientists working on millimetre waveguides, yet White was sceptical about their prospects (given that they had to be buried 6-feet underground and in a straight line) (Hecht 2004).

The BPO's interest was such that they set up an internal fibre optic research group at Dollis Hill. In addition they gave Kao and Hockman a small research grant to continue their work on optical fibres at STL (amount unknown). Equally as important as the grant, the collaboration with BPO, Dollis Hill allowed the STL researchers access to sophisticated measurement instruments at BPO to measure the impurities in glass samples (Hecht 2004). Finally the BPO also supported another research group, a joint programme between the Royal Signals Research and Development Establishment (RSRE) and the Electronics Department at the University of Southampton, under the leadership of Professor Alex Gambling[20](Gambling 1988).

The RSRE/ Southampton research was focused on establishing the feasibility of cheap, low bandwidth optical fibre communication over short distances (multimode fibres[21]), whilst the STL and BPO research was focused on long distance and maximum bandwidth optical communications (single mode fibres) (Gambling 1988; Hecht 2004).

Early work at the Southampton Research Group[22]

In the joint research program with RSRE,[23] RSRE concentrated on the development of the transmitters, receivers and components, whilst the Southampton group worked on establishing glass fibre properties and fibre fabrication techniques (Gambling 1988). The Southampton group had experience in laser development and the

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[20] Alec Gambling joined the Electronics Department at Southampton University in 1957 and initially carried out research on microwaves, but soon after developed an interest in lasers as an optical source for communications. He led the optical fibre research group through much of the 1960s and 1970s. He became Dean of the Electronics Department in 1970 and was the first Director of the Opto-Electronics Research Centre, established at Southampton University in 1989.

[21] Multimode fibre were wide enough to transmit a number of wavelengths at a time, as opposed to single mode fibres, which can only transmit one, which was the focus of work at STL.

[22] In preparing this summary of the role of the Optical Fibre Group at Southampton University I have drawn heavily on a publication by Alec Gambling, Gambling, A. (1988). The Optical Fibre Group: The Early Years. Opto-Electronics Research Centre, Southampton University..

[23] Military interest in fibre optics was their role in emerging electronic warfare. Electric systems were vulnerable to jamming and electromagnetic energy from nuclear explosions. It was thought that optical transmissions may represent a way around this (DeCusatis, C., Ed. (2007). Handbook of Fiber Optic Data Communication.).

millimetre waveguides but not in glass. Research fellow and glass specialist Peter Laybourne was appointed to fill this gap in 1968[24].

The group also approached a number of UK glass manufacturers in an attempt to learn more about furnaces and fibre 'pulling' fabrication and engage 'industry' in the research but were not able to find any assistance. The lack of assistance, although making things slow to start with may have turned out for the best, as not knowing anything about glass fabrication, nothing was taken as given, every detail was controlled for, and there was extreme precision in measurement. The 'wire wound fibre drawing tower' built by the team during this period is still in use today at the Opto-electrics Research Centre at Southampton University (Gambling 1988). By 1969 they had got fibre attenuation down to 400dB per km and then 150dB per km shortly afterwards.

Continued work at STL

In 1967 the BPO formed a consortium to further address the problem of glass purity called the 'Low Loss Optical Fibre Consortium'. The consortium included the BPO, STL, Barr and Stroud (a Scottish optics company) and British Titan products (experts in ultra pure materials) (Dyott 1986). The initial grant and these later contracts from the BPO were critical to STL's continued work. In the same year (1967), ITT contributed only US$34k into the fibre optics program.

The BPO Research Centre was in a fortunate position to fund a lot of research. The previous year US management consultants had reported to the BPO management that they were not spending enough on research and development. As a consequence the BPO put an additional £12m into BPO R&D programs, an enormous amount at the time (Dyott 1986). This meant there was research budget for even the wildest ideas; this was how fibre optics was still considered by the majority of the industry. R.B. Dyott was one of the first new hires into the BPO research centre at

[24] Although the details of the research grant were agreed to in early 1966, the University did not receive the money until January 1968, hence the delay in appointing the research fellow (Gambling 1988).

Dollis Hill, and he described the optical fibre project as being “born with a silver spoon it its mouth” as a result of the massive funding increase (Dyott 1986, p.199).

In 1969 Kao produced the clearest optical fibre yet, created from fused silica. These fibres had a loss calculated at between 5dB and 0dB per km[25]. Although creating the fibres was a complicated process and the fibres themselves were extremely delicate, it showed what could be done.

Shortly after Kao announced his results, Bell Labs started a small fibre optic program of their own, just in case. Research in Japan also started (particularly on graded index fibres), and STL was informed, that after one of the US Director’s of ITT had read about the results in a trade journal, they could ask for a bigger budget (Hecht 2004).

The role of the British Post Office

The BPO played a critical role in accelerating the development of fibre optics. The seed funding for the research programs at STL and Southampton/ RSRE meant that UK industry was at the forefront of fibre optics development. This allowed a technology that many saw as ‘blue skies’ to gain traction in industry where technological leadership came from the US, particularly AT&T and Bell Labs. As evidenced in the following quote from Graham (2007) “The BPO’s initiative had catalysed a transition that skipped most of the intermediate steps envisioned by AT&T, establishing fibre optics as the material base for a new international communications infrastructure” (p253).

The BPO also played a role in bringing the science and advanced techniques of glass manufacturing into the development of optical telecommunications, “…the BPO played a crucial role to bring two industries (glass and telecommunications) together and make them work in association” (Kwon 1999).

[25] However to measure the fibres, they had to be destroyed, with small pieces of glass broken off the fibre to calculate the light loss.

By the time fibre optics communication systems were being installed in cities around the world the BPO had undergone massive transformation, with the telecommunications function spun off into a new organisation, British Telecom. These changes could be one reason in the explanation for why the UK did not make more from its early start on fibre optics. One firm who definitely benefitted from their research into optical fibres was BPO's specialist glass supplier, Corning Glass Works.

The role of Corning Glass Works

Corning Glass Works was founded in 1851 and located in the upstate New York town of Corning. For much of its history the company had been associated with speciality glass production. They made glass bulbs for Thomas Edison's electric lamps, glass tubes for the first electronic televisions (Hecht 2004) and were most famous for their development 'Pyrex', 'Corelle' and 'Corningware' (Graham 2007).

Corning had provided the BPO with the test samples of its clearest class for their fibre optic research with STL. As a glass manufacturer their strengths were in glass fabrication techniques. Corning was responsible for the development of 'fused silica' in the 1930s the material that Kao used to produce his clearest fibre. Other research teams were reluctant to use fused silica (because of its low refractive index and the high temperature furnaces it required) but Corning had clear expertise.

No glass manufacturers were investigating optical fibres for telecommunications. Corning had some experience with optical fibres, but their interest was simply for light transmission purposes including later work on endoscopes (Bell 1988). American Optical[26] (another US glass manufacturer) was completing research on optical waveguides but other than that nothing that related to telecommunications.

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[26] American Optical was one of the three largest optics companies in the US in the 1950's. Founded in 1869 to make wire rimmed spectacles. They established a research lab in 1909 and many eminent optical and glass researchers worked for AO throughout the 20th century. AO did not really get into fibre optics in any major way; the majority of their scientific effort was placed into developing optical and scientific equipment. In 2000 AO was acquired by Australian optical firm SOLA Histories, I. D. o. C. (2007).

The STL/ Kao research paper of 1966[27] started Corning's manager of the electro-optics research group, Robert Maurer[28] thinking that there may be something more to optical fibres (Bell 1988, Kwon 1999), but compared to the research teams and budgets the major communications labs had he was reluctant to commit where they could not usefully achieve something (Hecht 2004). After BPO's request for materials and some preliminary research Corning scientists' found that the field was not too far ahead of them (in terms of the quality of glass fibres being created). Corning contacted a number of potential customers[29] in 1968, and promptly negotiated agreements (and funding) from Siemens in Germany, Pirelli in Italy and BICC in England to support their research into optical fibres for telecommunications[30] (Hecht 2004).

Corning's research was based on glass made from silica, as to Maurer's knowledge no other group was focusing on silica[31]. The Corning group developed a new method of fabricating pure silica fibres, and doping these fibres (to overcome the low refractive index problem) with a vapour deposition method for applying titanium dioxide. In 1970 they created single mode optical fibres with a loss level of less than 20dB. In later tests they could achieve loss of only 2dB. These fibres proved that optical communications were viable but they were a long way from having manufactured fibres they could sell.

Corning was also in a tricky intellectual property position. Corning did not publish their findings until two years later in December 1972. By this time Corning had been

[27] Corning did not access this paper until 1968 as they did not subscribe to an electrical engineering journal, all being materials scientists. Article was pointed out by a BPO contact (Bell 1988).

[28] Robert Maurer was research director of the optical fibre program at Corning Sullivan Park Research Centre. He earned his doctorate from MIT in temperature physics before joining Corning in 1952.

[29] Target customers were current telecommunications cable providers, if optical fibres were to emerge as the next generation fibres, they would still need to be produced as cables.

[30] The biggest customer, and local one as well, was AT&T, but they were not interested in fibre optics.

[31] Silica was more difficult to work with than traditional glass. Traditional glass melts and can be pulled into fibres at between 1200-1500 degrees, silica needs temperature well over 2000 degrees to even soften. Silica also has the lowest refractive index of any glass (Bell 1988).

granted the patents to the fundamental techniques behind the fibre fabrication. However, at the time the low loss fibres were being developed, Corning and AT&T signed a cross-licensing patent deal on semiconductors and optoelectronics. The deal meant either company could use the other's patents without paying royalties (Hecht 2004). Corning thought that they had a good deal, that Bell Labs being too focused on millimetre waveguides would not be interested in their optoelectronics work, whereas they could take advantage of Bell's work on semiconductor work for one of their subsidiaries Signetics[32] (Graham 2007).

Instead, when Corning announced their low loss fibres, Bell was months away from cancelling their millimetre waveguide project in 1973 and going seriously into fibre optics. The Corning scientists believed they could lose all their early advantage in this cross-licensing deal. Bell on the other hand, thought that they could easily replicate Corning's results[33] and they were more worried about Corning accessing their laser work, so they never pushed for access to Corning's work anyway.

Corning then went back and negotiated alliances with the cable manufacturers that had previous supported their work, Siemens, Pirelli, BICC and added two new ones, the national Telecommunications Research Labs of France and Germany. These partnership agreements provided the associates with access to Corning's research findings, test samples and access to licence the technology when it became available (Graham 2007). Each of the five associates paid $100,000 per year for five years (beginning 1972/73)[34]. This enabled the Corning fibre optic program to continue unscathed during the worst downturn in Corning's sales (1973) (Graham 2007).

This period really marked the beginning of Corning's entry into the telecommunications market. As Graham (2007) states, "…this chance encounter

[32] Corning acquired Signetics, a spinoff from Fairchild Semiconductors in mid-1960s as part of an effort to get into the electronic components market (Graham 2007).

[33] Bell was confident, as the largest and most well resourced telecommunications research lab in the US, that they could quickly match Corning's low loss fibres.

[34] Siemens would be the only one of the five to renew their five year agreement. Siemens was determined to become the European leader in the provision of optical cables (Graham 2007).

(between BPO and Corning) triggered one of the most definitive technological incursions of modern times. In less than twenty years, this same Corning Glass Works, operating on the outer periphery of the communications industry, would establish itself as the leading supplier of optical fibre for long- and short-distance communications in the world" (Graham 2007, p.253).

6. Complementary technology development

Semiconductor diode lasers

The early 1960s saw the development of complementary technology that was necessary for fibre optics to reach their full potential. The properties of a laser operation had been proposed by Townes and Schwlow in 1957. In September and October 1962, four groups of scientists would simultaneously develop semiconductor laser diodes for the first time. The group at General Electric led by Robert Hall would be the first.

As was the case for early optical fibres, this first technological breakthrough, represented a significant milestone, but was really just the beginning of the hard work (Ramsay 1973). It would take a decade to perfect long lifetime, room temperature semiconductor diode lasers that could operate with a continuous wave (continuous sources of light, rather than early 'pulse' lasers).

The announcement of such a breakthrough came one month before Corning made their breakthrough with low loss fibres. Izuo Hayashi and Morton Panish at Bell Labs demonstrated the first continuous wave, double hetero-structure, room temperature laser in May 1970. This was closely followed by a group of Russian Scientists[35] and RCA.

[35] Technically the Russians were the first, but as they published in a Russian journal, not available in the US until several years later, and the Russian government was not fond of announcing their technological developments, the 'first' is credited to Bell Labs – the Russian scientist involved, Zhores Alferov was later awarded the Nobel prize for 'developing semiconductor heterostructures used in high speed and optoelectronics' along with the another US researcher Herbert Kroemer (who created the hetero-structure the laser was based on)and Bell Labs Jack Kilby (inventor of the integrated circuit) (Hecht 2004).

This enabled fibre optic researchers to start to put together the transmission channel (fibres) and a light signal (semiconductor lasers), but neither was a finished product, the lasers would only last a few hours at most and the fibres were brittle and prone to break with temperature changes. Bell Labs kept developing lasers, and by 1977 had lasers with a lifetime of a million hours, which were viable for telecommunications. In this same time period optical fibres would progress through three generations of fibres; single mode low loss fibres, multimode graded index fibres, before finally back to single mode ultimate low loss fibres.

7. Fibre optic communications becomes a reality

"To the American communications industry, fibre optics was at best a vague hope from some distant future. It had not obvious connection with the near term trends…the British were the wild-eyed optimists" (Hecht 2004, p.161).

The first real-life test of optical fibre communications system came in 1975. A lightning strike in southern England had taken out the two-way radio antenna used by the Dorset Police to communicate with their eastern division at Bournemouth. The Chief Constable contacted the Home Office about organising a new system, and one that would not fail in similar conditions. The head of the Home Office Police Scientific Development Branch in London, Geoffrey Phillips, thought of fibre optics. He had previously been at the MoD where he had learned of the progress and potential of fibre optics for communications. Dorset Police were put in contact with STL who jumped at the opportunity to test their communication system in the field. By September 1975 a fibre optic telecommunication system was operating in Dorset, the first in the world (Hecht 2004). In this same year more than US$50 million was spent on the development of fibre optic components and systems (Montgomery 1977).

Other tests were not far off, AT&T commenced testing their fibre optic system in Atlanta, and other systems in France, Germany, Japan and Britain followed in 1977. AT&T was slow off the mark again. Their trials used the multimode graded index fibres (second generation fibres). Yet research in the UK, specifically at STL and University of Southampton, showed that difficulties with these fibres[36]. When the feasibility problems with multimode graded index fibres appeared insurmountable development work quickly refocused on single-mode fibres (third generation fibres).

The continuing issue for single-mode fibres was matching up the light source with the fibre. The match needed to be precise otherwise light loss would occur from the light source into the fibre, regardless of the light attenuation of the fibre. Two further developments would see the single-mode fibres made feasible – the invention of long-wavelength lasers (at MIT Lincoln Labs) and the creation of new fibres (3^{rd} generation fibres) that had even lower loss levels of 0.46dB per km by Nippon Telegraph and Telephone (NTT) in Japan.

Long wavelength lasers were invented by Chinese-born MIT scientist J. Jim Hsieh in the mid to late 1970s. Hseih had been researching gallium arsenide semiconductors and was working on a US Air Force contract attempting to develop 1.06 micrometer diode lasers for space communication he thought that such lasers would also have applications in fibre optics. He abandoned traditional two element semiconductor compounds when they proved unsuitable and trialled four element compounds (gallium, indium, arsenic on an indium phosphide substrate) which emitted light at between 1.21 and 1.25 mm (Hecht 2004).

Hsieh was invited to Japan to present his research to NTT and within a year the Japanese had also developed long wavelength lasers. Hsieh left MIT in 1979 to found a start-up company Lasertron[37] to commercialise the research with Ken Nill[38]. The

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[36] The multimode fibres transmitted on a number of modes, but in further testing the multiple waves of light would affect each other, and the affect amplified over distance, also electronic amplifiers necessary in long distance communication, could only amplify one wavelength at a time.

[37] For much of the 1980's Lasertron was the largest independent supplier of long-wavelength lasers into the American market (Hecht 2004). Lasertron was acquired in 1995 for $108 million by Waltham-based Oak Industries. At this time the company employed 180 people, about 60 in engineering, and had $30m revenues, mostly from sales in Europe and Asia. In addition to devices designed in-house, Lasertron transferred 980nm laser chip technology from IBM Zurich, and licensed the technology for uncooled loop lasers from Bellcore. The company has a small amount (<5%) of (US) government funding (Purvis, G. (2005). "Manufacturing Focus InGaAsP meets InGaAS: Axcel gets Lasertron pedigree." III-Vs Review **18**(4): 40-41.). In 1999 Oak Industries was

new company immediately caught the interest of the Ministry of Post and Telecommunications of the People's Republic of China, who were seeking to modernise their telecommunications networks. Political tensions at the time led Hsieh and Nill to focus on accessing venture capital fund raising rather than the Chinese offer, but when it came to negotiations, the Chinese offer compared more favourably than the VCs (more money, no equity, and manufacturing expertise[39]).

Long wavelength lasers complemented the research work at NTT into lower loss fibres in 1977. Researchers at NTT found that by removing Boron from the core glass fibres this led to more pure fibres and the additional effect that the glass dried further and removed additional water particles from the silica as well. Doping the fibres with germanium led to glass fibres with an attenuation of 0.46dB per km. From these fibres researchers estimated that two billion bits per second of data could be carried (Hecht 2004, p.186).

The UK Post Office split off their telecommunications activities in the early 1980s. The new telecommunications organisation, British Telecom (BT) trialled single mode fibres for long distance telecommunications between Martlesham and Ipswich (1982) and achieved such positive results that they started installing single-mode systems in 1983. NTT quickly followed suit in Japan (with 3rd generation fibres). Bell Labs in the US however thought single-mode fibres were only suitable in long distance as submarine cables (Alferness, Kogelnik et al. 2000), so when AT&T installed a digital high-capacity communications network for the Washington to Boston (Northeast Corridor) route, completed in 1984 and using multi-mode graded index fibres it was "almost instantly obsolete" (Hecht 2004, p.196).

acquired by Corning Inc, who shut Lasertron down in 2003. In 2005 Jim Hseih acquired Axcel Photonics Inc., another high power laser developer and manufacturer.

[38] Ken Nill was a former MIT Lincoln Lab employee and colleague of Hsieh who had left previously to found a laser instruments company, which he had since sold on.

[39] However, again due to political tensions, Chinese manufacturing engineers were not allowed to assist Lasertron in the creation of production techniques and systems for manufacturing the lasers (Hecht 2004).

Deregulation of the long distance telecommunications sector in the US in the mid 1980s and a more favourable attitude to new technology by AT&Ts competitors saw fibre optics communications using single-mode fibres take off. Other telecommunications companies such as MCI and Sprint quickly installed single-mode fibre networks and, now needing to compete, AT&T adapted.

8. Erbuim doped fibre amplifier

"It is safe to say that starting in 1989, erbium-doped fibre amplifiers were the catalyst for an entirely new generation of high capacity, under-sea and terrestrial fibre optic links and networks" (Becker, Olsson et al 1997, p.8).

The next leap forward in fibre optics would come with experimentation in amplifying the light signal in fibres. Amplifiers were essential in long distance communications. UK tests from the Martlesham to Ipswich trial in 1982 showed that light in the new pure, single-mode fibres could travel for up to 90km before amplifications was necessary, other tests showed averages of about 50km. In terrestrial communication networks this was not such an issue, in the UK case telephone infrastructure existed, at least every 30km to provide to provide an access point for amplification. Undersea networks were more complicated. Prior to the development of erbium-doped optical amplifiers, electronic amplifiers or 'electronic regenerators' were used to amplify fading light signals in the fibres. These regenerators were periodically spaced along the optical fibre and consisted of a photo-detector to detect the weak light signal, electronic amplifiers and timing circuitry to maintain the timing of the signals and a laser to send the signal along the next span of the fibre (Becker, Olsson et al. 1997).

The concept of optical amplifiers had been thought of in the late 1960s in both the UK by Alec Reeves (STL) (Ramsay 1973) and Eli Snitzer in the USA (American Optical). Alec Reeves thought semiconductor devices would provide optical amplification, but Snitzer thought it would be lasers[40] (Hecht 2004). Snitzer completed some tests to

[40] Lasers can amplify light if light is shined into the laser at the right wavelength; the light stimulates excited atoms to emit more light at that same wavelength, instep with the input light (Hecht 2004, p213).

show that fibre with their cores doped with neodymium could amplify light. However laser work was only in its infancy at this time, the light signal created lasted only milliseconds. The work was at a dead end and discontinued (Millennium Prize 2008).

Twenty years later however, much more powerful lasers were available and the need for optical amplifiers was great[41]. Three researchers at two institutions are credited with inventing erbium-doped optical amplifiers; Emmanuel Desurvire and Randy Giles from Bell Labs and David Payne[42] from the University of Southampton. Payne was first to publish a paper about erbium-doped fibre amplifiers, but Desurvire and Giles were first to make it a working tool (Millennium prize 2008)

Payne's optoelectronics research group at the University of Southampton, experimented with different compounds that would afford glass fibres different abilities. The aim of the research was to create fibres with different sensing abilities of their surrounding environments, the UK Navy was interested in acoustic sensors that could detect Soviet submarines (Hecht 2004). The group repeated the work of Snitzer using neodymium to dope the core of single-mode fibres. They then tried all the heavy earth elements (14 elements) and discovered that erbium doped fibres had interesting optical properties. Progress was not fast however; "…It took us 26 publications on fibre lasers before we realized that, if we took the mirrors off and looked at what the gain was, we'd have a huge gain of 30dB…" (Hecht 2004, p241).

Erbium doped fibres had the advantage of being able to amplify signals at an adequate level (30dB) and feasibly over a number of wavelengths (as was the advantage of the multi-mode graded index fibres). The problem to overcome was

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[41] Electrical amplifiers consumed a lot of power and restricted the use of fibres since one fibre can carry many laser signals of different wavelengths, but an electronic amplifier can only handle one laser signal at a time. A long distance connection needed electrical amplifiers every 500–600 km.

[42] David Payne received his PhD from the University of Southampton, the first one awarded in opto-electronics and has remained at the University of Southampton ever since. He started as Research Fellow, then the Pirelli Research Fellow in fibre optics, Senior Research Fellow, to currently be Professor and Head of the Optoelectronics Research Centre. He co-founded Southampton Photonics (SPI), to commercially manufacture erbium doped fibre and it is a leading company (amongst a small number) that manufacture industrial and surgical lasers.

finding the right light at the right wavelength to stimulate the erbium ions to create the maximum amplification.

Desurvire and Giles at Bell labs were also investigating erbium doped fibres and fibre lasers. Bell had a long history of development around the laser, dating back to 1974 but Desurvire could not get anyone in laser research at Bell to develop a laser that would emit light at the wavelength required. Desurvire had built an optical fibre amplifier at Bell Labs (although second to the one at Southampton) and collected detailed measurements from the amplifier that allowed him to make a theoretical model of how to achieve maximum light amplification (right wavelength) (Hecht 2004).

The research department of the Japanese NTT created laser diode in 1989 that could emit light at the required frequency. Bell Labs moved quickly to license the technology and later that year made the first practical erbium-doped fibre amplifiers (Millennium prize 2008). The erbium-doped fibre amplifiers received a further boost when the other earlier identified difficulty of multiple wavelengths in the one fibre; dispersion (wavelengths of different lengths getting out of sync with each other) was overcome when Corning produced new single mode fibre that allowed shorter wavelengths to catch up with longer wavelengths in 1992. By 1995 NTT could send 10 billion bits per second at 16 different wavelengths through 1000 km of fibre with erbium amplifiers (Hecht 2004).

Of course this increase in available bandwidth came at the time when the internet was beginning to develop. The internet which began in 1991 as a network of computers at the Centre for European Nuclear Research (CERN), had by 1993 grown to include 500 networked servers, and by 1994, 10,000 servers. By 1995 and 1996 the cable division of Pirelli, Lucent Technologies (spin off from AT&T) and a multitude of start-ups including Ciena[43] all introduced commercial erbium-doped fibre

[43] Ciena was founded in 1992 to commercialise optical networking components (wave-division multiplexing) that allow fibres to increased bandwidth for cable TV transmissions. The technology was developed by General Instruments Corporation (GI) (after Bell Labs developed the initial process and erbium-doped fibre amplifiers

amplification systems. The fibre optics industry was soon caught up in the tech bubble of the late 1990s and early 2000s, with path of Lucent Technologies providing one of the best examples of the boom then bust that followed[44].

9. Summary and conclusions

The development of fibre optics from science to commercial reality took place in three periods of development. The first wave of development used optical fibres in specialist medical equipment, endoscopes and dental equipment. The second wave saw the beginning of fibre optics being considered for communications transmission purposes - this required advances in the techniques for producing glass, understanding the properties of glass and light as a communications medium, and also the invention of other complementary technology namely the semiconductor laser diode. The third wave of activity related to increasing the bandwidth of optical transmission through the development of even clearer glass, optical amplifiers and correct wavelength lasers.

British scientists played a role in each of these stages of development. British industry also played an important role in promoting, testing and introducing the technology into the communications industry. Funding for UK research as was the case for most of the international programs was mainly from corporate funding but also importantly grants and government contracts, particularly military but also telecommunications departments (as in the early stages of the technologies

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became available). GI could not afford to develop the technology due to debt problems. GI's head of optical technology research David Huber convinced management to license the technology to him, and started Ciena. After a slow start, Huber managed to raise US$3.3m in 1994 from VC Sevin Rosen Funds, and by 1996 had raised $40m. Ciena manufactured its own optical filtering devices and its first product went on sale in 1996. Sales in the first year of this product allowed Ciena to post first profit of $14m in 1996. IPO followed in 1997, where the company achieved an opening market capitalization of $2.1b and first day valuation of $3.4b – the largest of any start-up ever. Huber resigned in 1997 (Ciena Record in International Directory of Company Histories,(2007)). Ciena was hard hit in the tech crash, losing 80% of revenues in 2001, but has since returned to stable growth.

[44] Lucent Technologies was spun off from AT&T in 1996. It quickly became a popular stock, arguably the most widely held stock in the USA. In 1998 it was the sixth largest company in the USA Endlich, L. (2004). Optical Illusions: Lucent and the crash of telecom. New York, Simon and Schuster.. However by 2000 the firm was in trouble, it started a two-year program to shed some 62,000 jobs and its stock market capitalisation had declined by more than US$80bn. Lucent hastily spun off its business systems activities in Avaya Communications in 2000 and its microelectronics component activities into Agere Systems in 2002 (Sterling, C. H., P. W. Bernt, et al. (2006). Shaping American Telecommunications: A history of technology, policy, and economics. London, Routledge.. Lucent itself merged with French telecommunications company Alcatel in 2006.

development many government ownership of telecommunication activities was dominant) in the early, pre-commercial stages of the technologies development.

Military requirements from fibre optics in these initial phases were not as arduous as commercial requirements. Applications required smaller capacities (hence no need for amplifiers) and their main advantages to military customers were in their small size, and freedom from electrical interference and cross talk (Ramsay 1973).

The effect of telecommunications deregulation in the UK, USA and to a lesser extent Europe also impacted on the development and customer base for optical fibres. Up until 1982 (when the divesture of AT&T took place) the role played by other US communications providers was small. AT&T could dominate the market and its direction (Kwon 1999). By 1986 fibre optics covered 60,486 miles in the US, US Sprint (merger between GT&E and US Telecom) had 23,000miles, AT&T 10,200 and MCI 7,000 miles (Kwon 1999).

On the following pages some patent analysis is presented of the optical fibre industry. As optical fibres is a broad field, three different patent classifications (US patents) cover the areas of activity mentioned in this case report (Optical communications, Optical waveguides and Optical systems and elements). The global activity of optical fibres is reinforced by this patent analysis as is the role of the dominant organisations and companies across the supply chain, i.e. glass manufacturer Corning, cable manufacturers Pirelli and Siemens. The company patent data also highlights the merger activity of the dominant companies involved, i.e. AT&T, Lucent Technologies, Alcatel, ISEC, STC and ITT's activities now all effectively under the current Alcatel-Lucent Inc.

Figure 1 - US Patents granted in Optical systems and elements (Class 359) by year 1963-2009

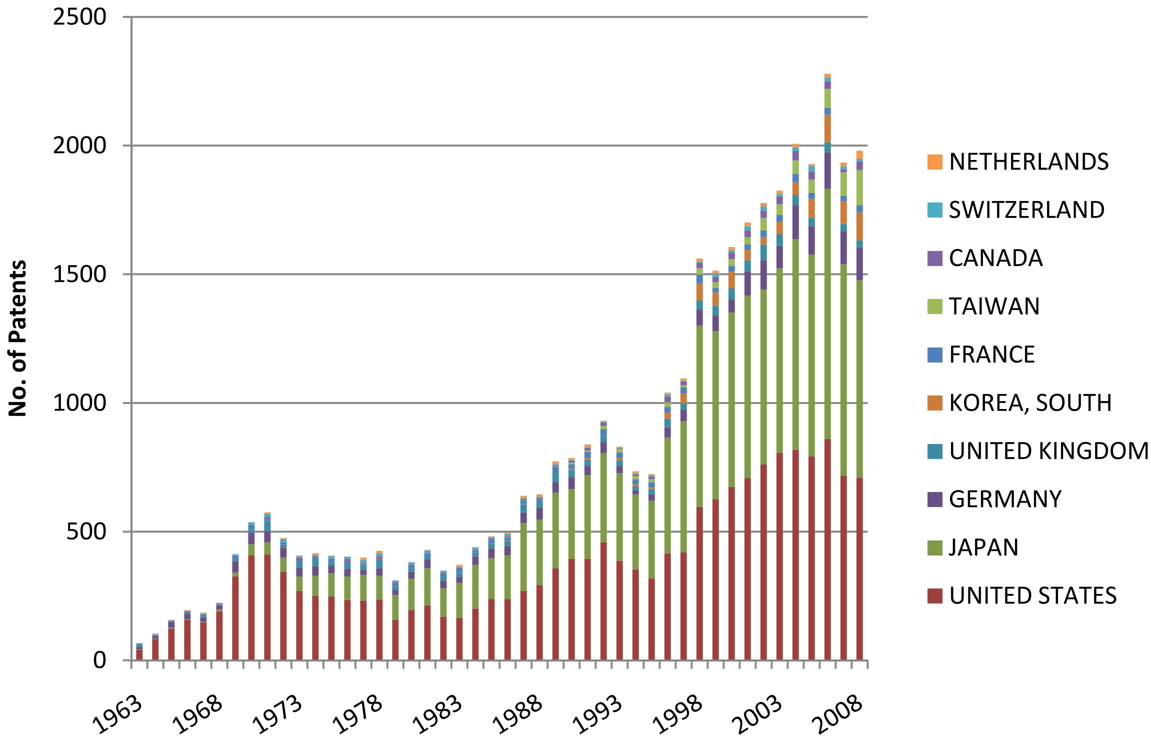

Figure 2 - % contribution of top Optical systems and elements (Class 359) patenting countries (1^{st} inventor) by year 1963-2009

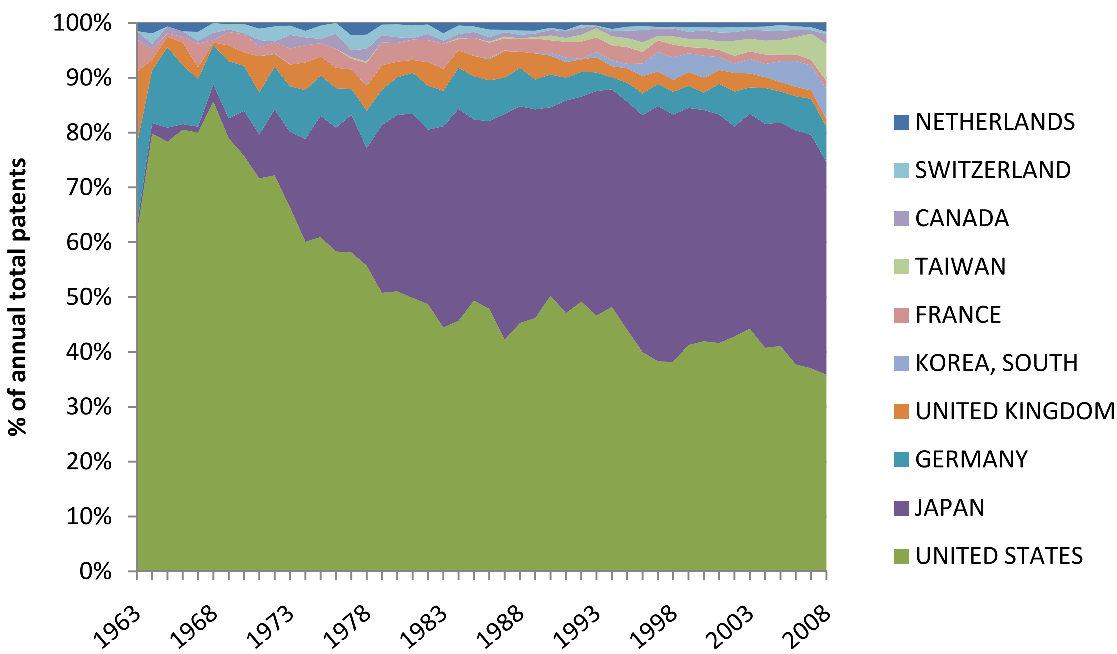

Figure 3 - US Patents granted in Optical waveguides (Class 385) by year 1963-2009

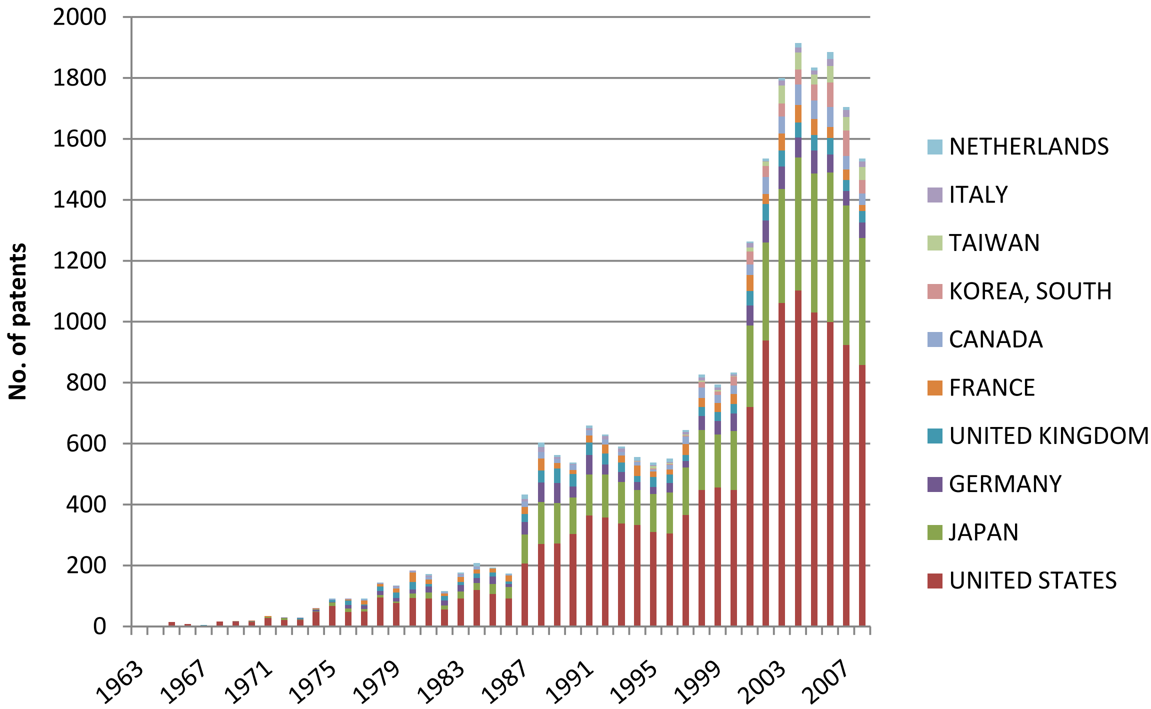

Figure 4 - % contribution of top Optical waveguides (Class 385) patenting countries (1st inventor) by year 1963-2009

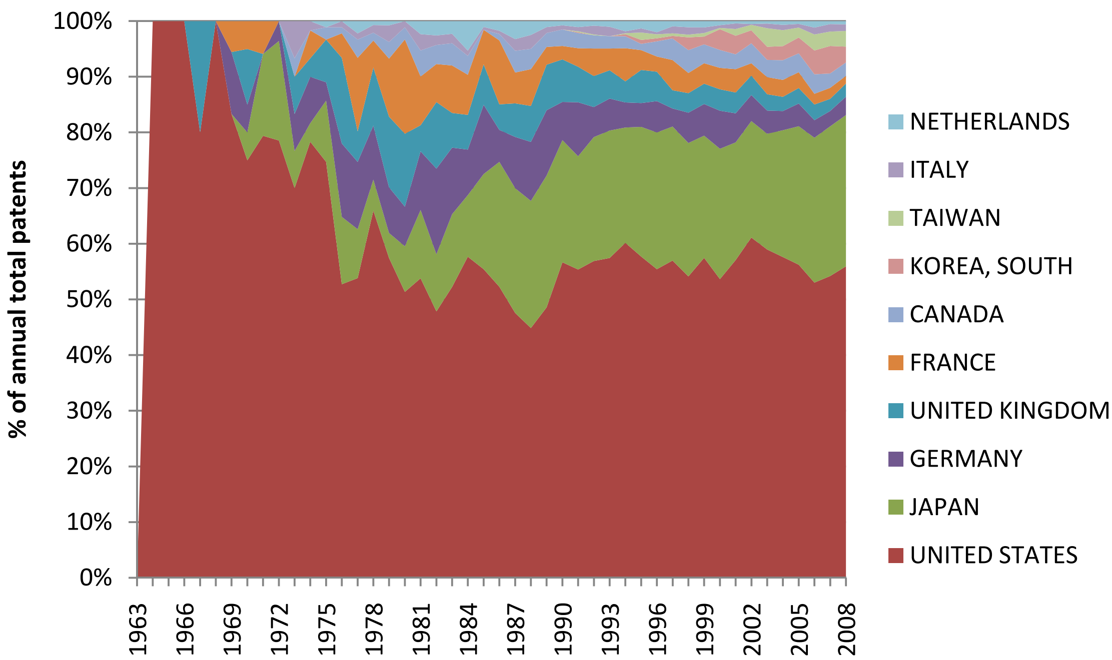

Figure 5 - US Patents granted in Optical communications (Class 398) by year 1963-2009

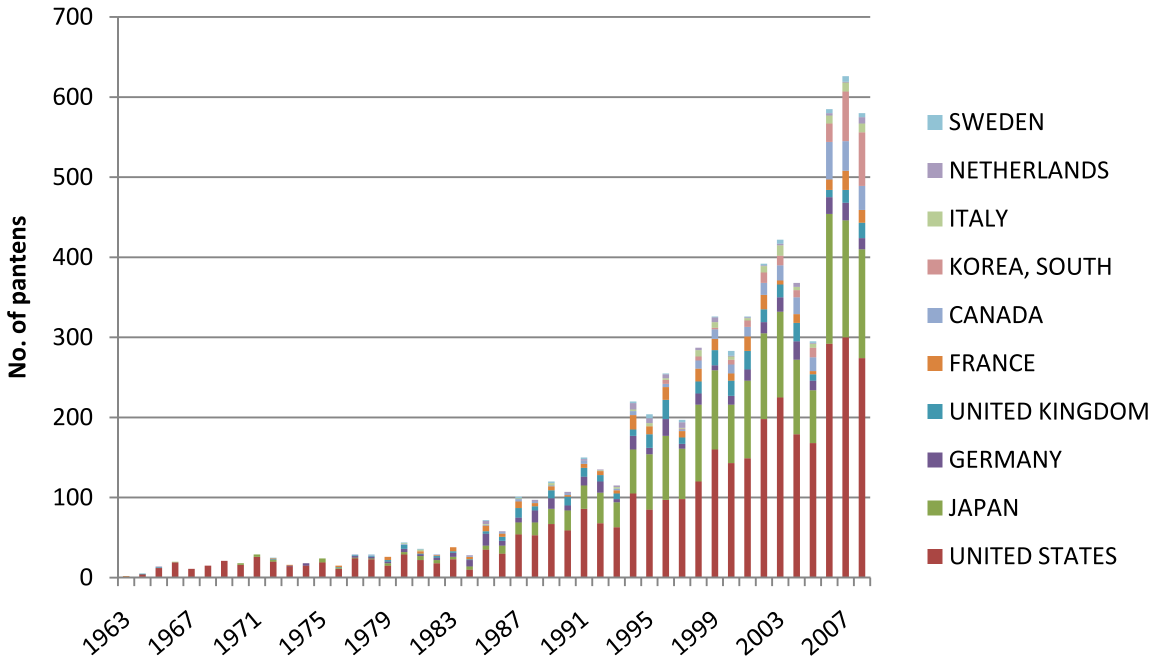

Figure 6 - % contribution of top Optical communications (Class 398) patenting countries (1st inventor) by year 1963-2009

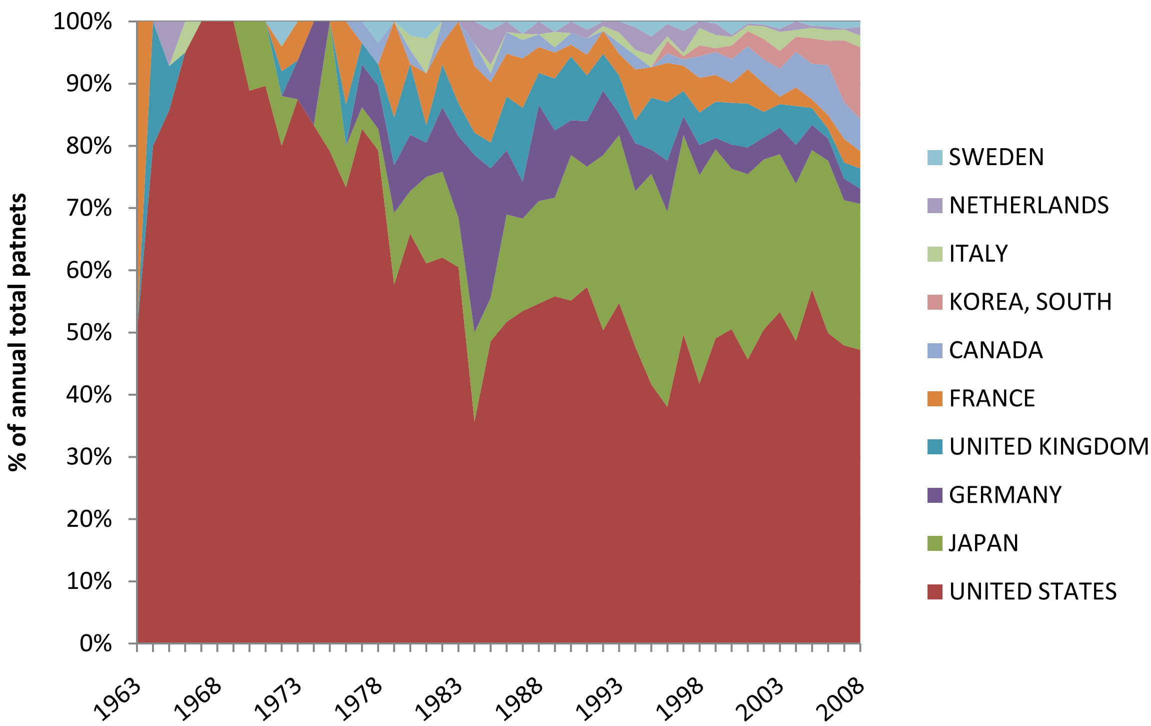

Figure 7 Leading firms for Optical systems and elements 1970-2009 (Technology class 359)

	Top 20 Patent Holders 1970s	**Top 20 Patent Holders 1980s**	**Top 20 Patent Holders 1990s**	**Top 20 Patent Holders 2000s**	**Top 20 Total Patent Holders**
1	AT&T CORP.	CANON KABUSHIKI KAISHA	NIKON CORPORATION	CANON KABUSHIKI KAISHA	CANON KABUSHIKI KAISHA
2	OLYMPUS OPTICAL CO., LTD.	OLYMPUS OPTICAL CO., LTD.	OLYMPUS OPTICAL CO., LTD.	FUJINON CORPORATION (FORMERLY FUJI PHOTO OPTICAL)	OLYMPUS OPTICAL CO., LTD.
3	IBM CORPORATION	NIKON CORPORATION	CANON KABUSHIKI KAISHA	OLYMPUS OPTICAL CO., LTD.	NIKON CORPORATION
4	CANON KABUSHIKI KAISHA	MINOLTA CAMERA CO., LTD.	ASAHI KOGAKU KOGYO KABUSHIKI KAISHA	FUJITSU LIMITED	ASAHI KOGAKU KOGYO KABUSHIKI KAISHA
5	RCA CORPORATION	ASAHI KOGAKU KOGYO KABUSHIKI KAISHA	EASTMAN KODAK COMPANY	OLYMPUS CORPORATION	MINOLTA CAMERA CO., LTD.
6	NIKON CORPORATION	U.S. PHILIPS CORPORATION	MINOLTA CAMERA CO., LTD.	NIKON CORPORATION	FUJINON CORPORATION (FORMERLY FUJI PHOTO OPTICAL)
7	AMERICAN OPTICAL CORPORATION	HUGHES AIRCRAFT COMPANY	HUGHES AIRCRAFT COMPANY	SONY CORPORATION	FUJITSU LIMITED
8	UNITED STATES OF AMERICA, NAVY	RICOH COMPANY, LTD.	MATSUSHITA ELECTRIC INDUSTRIAL	SAMSUNG ELECTRONICS CO., LTD.	EASTMAN KODAK COMPANY
9	U.S. PHILIPS CORPORATION	CARL ZEISS STIFTUNG	FUJITSU LIMITED	PENTAX CORPORATION	RICOH COMPANY, LTD.
10	BAUSCH & LOMB, INC.	XEROX CORPORATION	FUJINON CORPORATION (FORMERLY FUJI PHOTO OPTICAL)	RICOH COMPANY, LTD.	SONY CORPORATION
11	EASTMAN KODAK COMPANY	UNITED STATES, AIR FORCE	RICOH COMPANY, LTD.	SEIKO EPSON CORPORATION	MATSUSHITA ELECTRIC INDUSTRIAL
12	XEROX CORPORATION	UNITED STATES, ARMY	TEXAS INSTRUMENTS, INCORPORATED	3M INNOVATIVE PROPERTIES Co	AT&T CORP.
13	POLAROID CORPORATION	UNITED STATES OF AMERICA, NAVY	SONY CORPORATION	ASAHI KOGAKU KOGYO KABUSHIKI KAISHA	OLYMPUS CORPORATION
14	ASAHI KOGAKU KOGYO KABUSHIKI KAISHA	AT&T CORP.	XEROX CORPORATION	LUCENT TECHNOLOGIES INC.	SAMSUNG ELECTRONICS CO., LTD.
15	MINOLTA CAMERA CO., LTD.	IBM CORPORATION	LUCENT TECHNOLOGIES INC.	MINOLTA CAMERA CO., LTD.	XEROX CORPORATION
16	3M COMPANY	ROCKWELL INTERNATIONAL CORPORATION	3M COMPANY	EASTMAN KODAK COMPANY	HUGHES AIRCRAFT COMPANY
17	UNITED STATES OF AMERICA, ARMY	MATSUSHITA ELECTRIC INDUSTRIAL	NEC CORPORATION	MATSUSHITA ELECTRIC INDUSTRIAL	TEXAS INSTRUMENTS, INCORPORATED
18	HITACHI, LTD	EASTMAN KODAK COMPANY	AT&T CORP.	TEXAS INSTRUMENTS, INCORPORATED	LUCENT TECHNOLOGIES INC.
19	ERNST LEITZ WETZLAR GMBH	UNITED STATES OF AMERICA, DoE	FUJI PHOTO FILM CO., LTD	GENTEX CORPORATION	IBM CORPORATION
20	UNITED TECHNOLOGIES CORPORATION	HITACHI, LTD	DAEWOO ELECTRONICS COMPANY, LTD.	CORNING INCORPORATED	PENTAX CORPORATION

Figure 8 Leading firms for Optical waveguides 1970-2009 (Technology class 385)

	Top 20 Patent Holders 1970s	**Top 20 Patent Holders 1980s**	**Top 20 Patent Holders 1990s**	**Top 20 Patent Holders 2000s**	**Top 20 Total Patent Holders**
1	AT&T CORP.	AT&T CORP.	AT&T CORP.	LUCENT TECHNOLOGIES INC.	LUCENT TECHNOLOGIES INC.
2	UNITED STATES OF AMERICA, NAVY	SIEMENS AKTIENGESELLSCHAFT	LUCENT TECHNOLOGIES INC.	SUMITOMO ELECTRIC INDUSTRIES	SUMITOMO ELECTRIC INDUSTRIES
3	CORNING INCORPORATED	U.S. PHILIPS CORPORATION	SUMITOMO ELECTRIC INDUSTRIES	CORNING INCORPORATED	CORNING INCORPORATED
4	SIEMENS AKTIENGESELLSCHAFT	SUMITOMO ELECTRIC INDUSTRIES	CORNING INCORPORATED	FUJITSU LIMITED	FUJITSU LIMITED
5	ITT CORPORATION	AMP INCORPORATED	NEC CORPORATION	INTEL CORPORATION	INTEL CORPORATION
6	ISEC (ITT CORP. UNIT)	ITT CORPORATION	SIEMENS AKTIENGESELLSCHAFT	CORNING CABLE SYSTEMS LLC	CORNING CABLE SYSTEMS LLC
7	AMERICAN OPTICAL CORPORATION	HITACHI, LTD	FUJITSU LIMITED	ALCATEL	ALCATEL
8	THOMSON-CSF	STANFORD UNIVERSITY	3M	FURUKAWA ELECTRIC CO., LTD.	FURUKAWA ELECTRIC CO., LTD.
9	GTE LABORATORIES, INC.	UNITED STATES OF AMERICA, NAVY	NORTHERN TELECOM LIMITED	SAMSUNG ELECTRONICS CO., LTD.	SAMSUNG ELECTRONICS CO., LTD.
10	POST OFFICE	NORTHERN TELECOM LIMITED	SIECOR CORPORATION	NEC CORPORATION	NEC CORPORATION
11	RCA CORPORATION	HUGHES AIRCRAFT COMPANY	WHITAKER CORPORATION	ADC TELECOMMUNICATIONS, INC.	ADC TELECOMMUNICATIONS, INC.
12	UNISYS CORPORATION	THOMSON-CSF	BRITISH TELECOMMUNICATION	AGILENT TECHNOLOGIES, INC.	AGILENT TECHNOLOGIES, INC.
13	NIPPON SELFOC CO., LTD	CORNING INCORPORATED	FURUKAWA ELECTRIC CO., LTD.	3M INNOVATIVE PROPERTIES COMPANY	3M INNOVATIVE PROPERTIES COMPANY
14	IBM CORPORATION	BRITISH TELECOMMUNICATION, PLC	MOTOROLA, INC.	FINISAR CORPORATION	FINISAR CORPORATION
15	NORTHERN TELECOM LIMITED	ISEC (ITT CORP. UNIT)	UNITED STATES OF AMERICA, NAVY	FITEL U.S.A. CORP.	FITEL U.S.A. CORP.
16	AMP INCORPORATED	RAYCHEM CORPORATION	IBM CORPORATION	IBM CORPORATION	IBM CORPORATION
17	NEC CORPORATION	KOKUSAI DENSHIN DENWA KABUSHIKI KAISHA	HUGHES AIRCRAFT COMPANY	FUJIKURA LTD.	FUJIKURA LTD.
18	SUMITOMO ELECTRIC INDUSTRIES	TRW INC.	AMP INCORPORATED	JDS UNIPHASE CORPORATION	JDS UNIPHASE CORPORATION
19	U.S. PHILIPS CORPORATION	GTE LABORATORIES, INC.	HITACHI, LTD	HON HAI PRECISION IND. CO., LTD.	HON HAI PRECISION IND. CO., LTD.
20	UNITED STATES OF AMERICA, ARMY	IBM CORPORATION	NIPPON TELEGRAPH & TELEPHONE CORP.	NORTEL NETWORKS LIMITED	NORTEL NETWORKS LIMITED

Figure 8 Leading firms for Optical communications 1970-2009 (Technology class 398)

	Top 20 Patent Holders 1970s	**Top 20 Patent Holders 1980s**	**Top 20 Patent Holders 1990s**	**Top 20 Patent Holders 2000s**	**Top 20 Total Patent Holders**
1	AT&T CORP.	AT&T CORP.	FUJITSU LIMITED	FUJITSU LIMITED	FUJITSU LIMITED
2	UNITED STATES OF AMERICA, NAVY	SIEMENS AKTIENGESELLSCHAFT	AT&T CORP.	LUCENT TECHNOLOGIES INC.	LUCENT TECHNOLOGIES INC.
3	HUGHES AIRCRAFT COMPANY	NEC CORPORATION	NEC CORPORATION	NORTEL NETWORKS LIMITED	AT&T CORP.
4	UNITED STATES OF AMERICA, ARMY	UNITED STATES OF AMERICA, NAVY	LUCENT TECHNOLOGIES INC.	ALCATEL	NEC CORPORATION
5	IBM CORPORATION	IBM CORPORATION	BRITISH TELECOMMUNICATION, PLC	NEC CORPORATION	NORTEL NETWORKS LIMITED
6	GTE LABORATORIES, INC.	ISE CORPORATION (ITT CORP. UNIT)	ALCATEL N. V.	SAMSUNG ELECTRONICS CO., LTD.	ALCATEL
7	THOMSON-CSF	KOKUSAI DENSHIN DENWA KABUSHIKI KAISHA	CANON KABUSHIKI KAISHA	CIENA CORPORATION	SIEMENS AKTIENGESELLSCHAFT
8	UNITED STATES OF AMERICA, NASA	U.S. PHILIPS CORPORATION	IBM CORPORATION	AT&T CORP.	SAMSUNG ELECTRONICS CO., LTD.
9	ITT CORPORATION	THOMSON-CSF	HITACHI, LTD	HITACHI, LTD	HITACHI, LTD
10	UNITED STATES OF AMERICA, DoE	UNITED STATES OF AMERICA, ARMY	SIEMENS AKTIENGESELLSCHAFT	FINISAR CORPORATION	IBM CORPORATION
11	NEC CORPORATION	WESTINGHOUSE ELECTRIC CORP.	KOKUSAI DENSHIN DENWA KABUSHIKI KAISHA	NIPPON TELEGRAPH & TELEPHONE CORP.	CIENA CORPORATION
12	MATSUSHITA ELECTRIC INDUSTRIAL	RCA CORPORATION	NORTHERN TELECOM LIMITED	MATSUSHITA ELECTRIC INDUSTRIAL	BRITISH TELECOMMUNICATION, PLC
13	UNITED STATES, AIR FORCE	ITT CORPORATION	U.S. PHILIPS CORPORATION	IBM CORPORATION	CANON KABUSHIKI KAISHA
14	ISE CORPORATION (ITT CORP. UNIT)	LICENTIA PATENT-VERWALTUNGS-GMBH	MOTOROLA, INC.	SIEMENS AKTIENGESELLSCHAFT	NIPPON TELEGRAPH & TELEPHONE CORP.
15	WESTINGHOUSE ELECTRIC CORP.	BRITISH TELECOMMUNICATION, PLC	GTE LABORATORIES, INC.	ELECTRONICS & TELECOMMUNICATIONS RESEARCH INSTITUTE	MATSUSHITA ELECTRIC INDUSTRIAL
16	FORD AEROSPACE CORPORATION	CANON KABUSHIKI KAISHA	NIPPON TELEGRAPH & TELEPHONE CORP.	SONY CORPORATION	ALCATEL N. V.
17	ZENITH ELECTRONICS CORPORATION	BELL COMMUNICATIONS RESEARCH, INC.	SCIENTIFIC-ATLANTA, INC.	OKI ELECTRIC INDUSTRY CO., LTD.	UNITED STATES OF AMERICA, NAVY
18	MASSACHUSETTS INSTITUTE OF TECHNOLOGY	GENERAL ELECTRIC COMPANY	CIENA CORPORATION	AGILENT TECHNOLOGIES, INC.	KOKUSAI DENSHIN DENWA KABUSHIKI KAISHA
19	TEXAS INSTRUMENTS, INCORPORATED	HITACHI, LTD	BELL COMMUNICATIONS RESEARCH, INC.	UNIVERSITY OF CALIFORNIA, THE REGENTS OF	FINISAR CORPORATION
20	GENERAL ELECTRIC COMPANY	UNISYS CORPORATION	FRANCE TELECOM	CORVIS CORPORATION	SONY CORPORATION

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