SIR CHARLES KUEN KAO
4 November 1933 — 23 September 2018
SIR CHARLES KUEN KAO

4 November 1933 — 23 September 2018

Elected FRS 1997

BY JOHN MIDWINTER FRS*

Charles Kao was the pioneer who suggested using glass fibre waveguide as a means of carrying laser-light over long distances for telecommunications traffic. In his seminal paper published in 1966, he spelled out the appropriate design parameters and performance characteristics that would be needed for a successful system to emerge. At the time, the idea was widely ridiculed. Within a few years, however, in a brilliant set of spectrophotometric experiments, Kao demonstrated that pure silicon dioxide materials exist that have the required very low attenuation. In due course, the problems of creating optical fibres of the required dimensions and strength were solved and optical fibres now dominate telecommunications worldwide. Without them, contemporary communications would be unthinkable. Kao was awarded the 2009 Nobel Prize in Physics for his ‘groundbreaking achievements concerning the transmission of light in fibres for optical communication’.

EARLY LIFE

Charles Kao was born in Shanghai on 4 November 1933. His parents were both professional people, his father having studied law and his mother classics. Two siblings, a brother and sister, had died tragically during an earlier measles epidemic; later he had a younger brother who subsequently studied civil engineering in Hong Kong and became a well-known specialist in hydrodynamics.

From an early age, Charles was immersed in both Chinese and Western UK culture, covering both the arts and sciences. In his early years he studied Chinese classics at home with a personal tutor, as well as English and French at the Shanghai World-School. His grandfather was a scholar, poet and artist and his father’s cousin was an astronomer. It thus is reasonable to assume that from a very early age his mind was stretched and tuned in a way that few

* john.midwinter@btopenworld.com
others could match, and it seems to have given him an unusually vivid yet also down-to-earth imagination.

**MOVES TO HONG KONG AND UK**

In 1949 Charles moved with his family to Hong Kong, the same year that Mao Zedong became chairman of the Chinese Communist Party, events that were likely linked. He qualified at school for a place at the University of Hong Kong, but apparently they had closed their electrical engineering department a few years earlier; sadly, this was the very subject that Charles wanted to study. As a result, he came to England and studied for his first degree at Woolwich Polytechnic, now the University of Greenwich. There he successfully passed four A-level subjects and was allowed to enter the engineering degree programme, from which he graduated in 1957 with a BSc in electrical engineering. He then joined Standard Telephone & Cables Ltd (STC) Microwave Systems Division, part of the American International Telephone & Telegraph (ITT) company, where he completed a one-year apprenticeship. After a further two years working there, he felt a desire to move into research and was allowed to transfer to the company’s research arm, Standard Telecommunications Laboratories (STL), based in Harlow, Essex.

Before his move to STL, Charles had met Gwen, a lady from a British Chinese family whose Chinese name was May Wan Wong and who was also working at STC. They married in 1959 and in the following years had two children, a son and a daughter, who now both live in Silicon Valley, California. Gwen remained his constant companion until he died in 2018.

At STL, Charles found himself working with Tony Karbowiak as his supervisor on microwave waveguide systems, soon after the first maser had been built by Charles Townes and colleagues working at Columbia University (Gordon et al. 1955). There was a large international research programme seeking ways to use guided microwave radiation to carry large quantities of telecommunications traffic, since free-space communication using microwaves was already being deployed but needed large aerial towers and regeneration at fairly frequent intervals. Then, the first laser was developed and described by Theodore Maiman working at Hughes Laboratories (Maiman 1960). Each invention generated a huge buzz of interest in the potential these new high-frequency electromagnetic-wave sources offered for high data-rate communication systems and, as a result, laboratories all over the world were starting to experiment on potential ways to exploit them, both for free-space and guided-wave communication systems. Moreover, it was obvious that with optical frequencies being much higher than millimetre microwaves, they offered great potential for carrying huge amounts of information. However, the downside was that light would not travel through clouds, mists or heavy rain without suffering very heavy attenuation. It was against this background that Charles Kao’s work was undertaken. Later, however, great interest developed in the possibility of using free-space lasers to communicate in space, where there are working systems to this day.

**KAO AND HOCKHAM (1966) AND KAO’S PIONEERING RESEARCH**

Soon after joining STL, Charles enrolled as an external PhD student with the electrical engineering department at University College London, with Professor Harold Barlow, a
well-established microwave engineer, as his supervisor. This led to the award of a London University PhD degree in 1965. As a result, he became well qualified for a life in research, almost entirely by his own efforts.

Astonishingly, it was just one year after he completed his PhD studies that Charles published with co-author George Hockham the paper for which he is now world famous (1)*. It was entitled ‘Dielectric-fibre surface waveguides for optical frequencies’, and not only described the electromagnetic theory for the design of such a circular dielectric waveguide but also set out the performance parameters it should achieve if it were to have any hope of competing with the then well-established coaxial-cable designs used for long-haul data transmission in the telecommunications network as well as the microwave systems under development (figure 1).

Most critically, he spelled out a maximum allowable attenuation of 20 dB/km, meaning 1% transmission through 1 km of fibre, or better, as being essential for success since that would require signal regeneration at worst about every two kilometres, similar to the coaxial-cable technology of the time. Higher attenuation levels would require more frequent regeneration, making the system hopelessly uneconomic.

At the time, typical glass fibres only carried light for distances of a few metres before it was lost by absorption, and the idea that telephone engineers would sit in open manholes in the rain or snow jointing fibres that were a shade over 1/10th of a millimetre in diameter with a light-carrying core of about 1/100th of a millimetre diameter was clearly ridiculous.

The fibre design that he proposed was what we now know as the ‘single-mode fibre’. This design has a very small light-carrying core of about 1/100th of a millimetre diameter and, while history has shown his vision here to have been correct, at the time it made selling his

* Numbers in this form refer to the bibliography at the end of the text.
idea to the engineering community much more difficult. On the other hand, the advantage of
the design is that it only allows a single light path (mode) and thus minimizes pulse spreading,
making very high data-rate transmission possible.

Two other fibre designs were known at the time. A fibre of the type used for fibre-optic
illuminations on Christmas trees had a light-carrying core much larger than the single-mode
design, but this allowed light to travel by many different pathways, each at a different speed,
so that pulses of light became spread out and data bandwidth was severely limited. It is
known as a ‘step-index multi-mode fibre’. The other design was the ‘graded-index’ design,
in which a large light-carrying core was fabricated with a refractive index distribution that
varied parabolically from a maximum at the fibre centre curving down to the cladding index
at its periphery. This design also supported many different light paths, like the step-index
design, but presented a larger core diameter, making jointing easier than for the single-mode
design while ensuring that all the different ray paths suffered roughly the same transit delay.

Samples of bulk glass from most sources at that time had much higher attenuations than
20 dB/km because the oxide powders that were mixed and melted to form them contained
levels of transition metal contaminants, such as iron and copper, that produced coloration by
absorption, and hence attenuation. Undeterred by this, Charles set out to find if there were any
sources of glass with low enough attenuation to meet his fibre specification. He did this by
taking bulk samples of 10 cm length and measuring their attenuation in the laboratory (2, 3).
To do this he designed and built a sophisticated spectrophotometer with exceptional sensitivity.
Using it, he was able to show that pure silica (SiO₂) materials existed with attenuations in the
bulk form as low as ca 4 dB/km, corresponding to an attenuation in his bulk sample of order
10⁻⁴, a very small fraction of the reflection loss from the surface. This in itself was a truly
remarkable piece of experimental science and it ensured that others started to take his optical
fibre proposal more seriously.

Some problems with Kao’s vision

We know now that all Charles’ work correctly pointed the way forward towards both a material
that would be suitable for low-loss fibres using fused silica and an optimum fibre design, the
single-mode fibre; but it also demonstrated an exceptional experimental ability on his part,
along with his co-workers. The result was that by about 1970, he had described not only the
concept of a single-mode optical fibre waveguide suitable for high data-rate transmission but
had also established that a suitable material almost certainly existed from which to fabricate
it. However, this left unsolved a very major technological problem, namely, how to take a
bulk silica sample and convert it into a cored fibre waveguide without destroying its low
attenuation properties, a problem compounded by its very high melting temperature of around
1700 °C.

Fibre light guides were fairly common at that time, used for Christmas tree decorations and
as fibre-optic probes that allowed one to see round corners, the latter using a large bundle of
fibres fused in fixed positions relative to one another at each end but left flexible in between.
But these were all made from low melting point glasses using the ‘rod-in-tube’ method,
whereby a rod of the higher refractive index material for the light guiding core was slid into a
tube of lower refractive that provided the cladding. The composite structure was then fed into
a furnace that melted one end, from which a fibre filament could be pulled.
The problems with this approach were several. The very process of forming and assembling the rod and tube was very difficult to achieve without attracting any contamination, and the core–cladding interface of the drawn fibre usually carried imperfections left over from the fabrication and assembly process so that the attenuation of the fibre was always significantly greater than that of its bulk constituents.

**His attempts to ‘sell’ his ideas**

After Charles published his now famous paper in 1966 (1) describing the design requirements for the optical fibre, he travelled extensively, visiting telecommunications companies and laboratories around the world explaining his ideas and hoping to persuade them to take seriously the challenge of making them a reality. It seems that most laboratories showed little interest, one suspects for the very reasons outlined earlier: namely, that any good engineer would confidently view them as pure ‘cloud-cuckoo-land’. Fortunately, there were a few notable exceptions, including NTT in Japan and the British Post Office Telecommunications Lab (now BT), then in Dollis Hill, North London, and now in Martlesham, Suffolk.

At that time, I was working in the USA on other optical technologies and it was only in 1971 that I was invited to return to the UK to lead a group that was already heavily involved in the low-loss fibre quest at the Post Office Research Centre (Telecommunications Division). The Optical Communications Division was headed by Frank F. Roberts, known to everyone as FFR. He had been completely sold on Charles’ ideas and had persuaded the Post Office to commit considerable resources in an attempt to realize them. Much later, in 1981, the Post Office telecommunications business was split off from the postal business to become British Telecom, which in turn was privatized in 1984.

**Indications the dream was becoming reality**

Well before these events, Charles’ ideas had been given a huge boost from a very unexpected source. In 1970, the Institution of Electrical Engineers (IEE) in London (now the Institute of Engineering and Technology) ran a conference entitled ‘Trunk Telecommunications by Guided-Waves’, which called for papers on microwave and optical guided-wave communication systems. In a paper entitled ‘Radiation losses in glass optical waveguides’, Robert Maurer reported that his team at the Corning Glass Company Sullivan Research Center in Corning, New York, which included Donald Keck and Felix Kapron, had succeeded in making an optical fibre with Charles’ target attenuation of 20 dB/km at a wavelength of 633 nm, the HeNe gas laser wavelength (Kapron et al. 1970). However, how they had made the fibre and from what material was a very closely guarded secret. The date was 1 October 1970, and the news started a worldwide race to finally achieve a truly practical realization of Charles’ ideas. More information can be found in a report by Jeff Hecht in the Optics & Photonics News magazine (Hecht 2020).

After the conference, Robert Maurer and his colleagues visited the Post Office Research Centre in Dollis Hill, North London, and took along a sample of their low-loss fibre, where it was re-measured and their low attenuation claims confirmed; but apparently there was a serious problem as well. The fibre was extremely fragile and easily broken and was thus obviously useless for pulling into underground ducts. An unexpected benefit of this was that
when the sample was being tested in Dollis Hill, a small amount broke off, was later retrieved by Post Office staff and was chemically analysed, proving that the primary constituent was pure silica. Later it appears that the strength problem was fixed relatively easily by applying a protective plastic coating to the freshly drawn glass fibre surface before it had had any possibility of touching a solid surface and getting scratched.

**RETURN TO HONG KONG AND THE CHINESE UNIVERSITY**

In the same year as the above conference (1970), Charles left STL and moved back to his boyhood home, Hong Kong, where the Chinese University (CUHK) in the Shatin District had asked him to set up a new electrical engineering department. It was a new university, having only recently been founded in 1963 by the amalgamation of three further-education colleges, and it was growing rapidly. There had been very limited progress in making suitably low-loss fibre in the UK and the experience of seeing that Corning had apparently cracked the problem was probably very dispiriting for Charles, so a new challenge was probably very welcome.

During his first return to CUHK, Charles was appointed reader and then to the chair of Professor of Electronics. He built up both undergraduate and graduate study programmes of electronics and oversaw the graduation of his first students. Under his leadership, the School of Education and other new research institutes were established.

In 1971, I returned from America to the Post Office Research Centre to lead the group still working on the problems of making low-loss fibre. The Post Office had no expectation that it would manufacture fibre for its own network, but the group was charged with ensuring that so far as possible the company would be a ‘very well informed customer’. I remember meeting some of Charles’ colleagues at STL, but by then he was on the other side of the world. However, I do recall that he returned to STL every summer for a brief visit and we met during one of these.

**FURTHER MOVES: USA, GERMANY AND HONG KONG**

In 1974 Charles left CUHK and moved to Roanoke, Virginia, USA, to re-join ITT at a laboratory there that was studying optical fibre systems. Initially he held the position of chief scientist and then later of director of engineering. Then, in 1982, he was appointed director of corporate research for ITT and moved his base to the ITT Advanced Technology Center in Shelton, Connecticut, with a brief to initiate new and innovative research for the company. Finally, in 1985, he spent a year with the ITT-SEL Research Centre in Stuttgart, West Germany. He returned to ITT in the USA in 1986, but a year later was invited to return to CUHK to become its vice-chancellor, a position that he then held until 1996, when he retired from full time activity, although he continued to be involved in numerous other activities.

**THE TECHNOLOGY ADVANCES**

During the 1980s, it became widely realized that very low attenuation glass could be made by the flame oxidation of silicon tetrachloride (SiCl₄) in an oxy-hydrogen flame to form silica, SiO₂. Silicon tetrachloride is available in a liquid form that can be distilled to remove
impurities using a process developed for the semiconductor industry. It was thus readily available, and the same was true of germanium tetrachloride (GeCl$_4$), which similarly can be oxidized to GeO$_2$ by burning it in an oxy-hydrogen flame. It was also realized that there were two truly fundamental loss mechanisms in silica; namely, Rayleigh scattering, which varies as $(\text{wavelength})^{-4}$, thus strongly favouring system operation at longer wavelengths, and also absorption from the Si–O bond oscillation, which peaks at about 9 microns in the near infra-red.

The result of these two mechanisms combined is a fundamental minimum loss of about 0.5 dB/km in silica at around 1.5 micrometre wavelength, and this is where many fibre systems now operate. These very low losses have made possible very large distances between regenerators, and hence require extremely low pulse dispersion in each kilometre of fibre. This all made the case for using Charles’ original fibre design of a single-mode waveguide virtually obligatory, and most long-haul fibre cable systems now do exactly that.

**His dream realized in practice**

With the benefit of hindsight, we can now look back on Charles’ career and see what a massive impact it has had on the human race. At an early stage in the development of optical fibres, Charles was already strongly favouring his single-mode design for long-distance optical communication rather than the graded-index multi-mode systems that were used for the earliest installations. However, the single-mode design was considered too difficult to handle in the ‘real world’ of the telecommunications cable business because its light carrying core was of the order of 100$^{th}$ of a millimetre in diameter whereas the multi-mode graded-index designs were typically 50–60 times larger. They did not offer such large bandwidth, but provided enough for the early deployments. However, as the attenuation of mass-market fibres continued to fall and traffic demand grew, practical experience in installing fibres also accumulated, and a time was reached in the mid 1980s when his original single-mode vision started to look very attractive and soon became well established.

Charles was also a visionary of modern submarine communication cables and largely promoted the idea of using light for this purpose. It was a business in which STL/STC had long been heavily involved, so he would have been well aware of the needs. In 1980, a 5 km length of an experimental submarine cable containing both graded-index and single-mode fibres was laid in Loch Fyne in Scotland, with both fibre designs looped at the underwater end to produce 10 km-long fibre links for testing purposes. He predicted in 1983 that the world’s seas would soon be littered with fibre-optic cables, five years ahead of the time that such a trans-oceanic fibre cable first became operational. Today, single-mode fibre-optic systems carry almost all the long-haul telecommunications traffic, both overland and undersea, so his vision has been proven to be absolutely 100% correct. A vivid demonstration of the capability of single-mode fibre was given by STC in 1988, when they laid an undersea fibre cable from Dartmouth across the English Channel to Guernsey, a distance of 133 km, and operated it without any signal regeneration *en route* at the then standard UK date rate of 140 Mbit/s.

**Optical fibre’s impact**

It is difficult grasp the impact that optical fibres have had on humanity (see, for example, Hecht 2020). I recall when we were living in the USA around 1970, if we wanted to make a
phone call to our parents in the UK, we had to book a call with the phone company long before making it, and only when the connections were all made did our phone ring and we were told we could talk. Moreover, this was very expensive.

Many long-haul calls at that time were routed via satellites orbiting far above the Earth’s surface, massively increasing the distance travelled by the signal and hence the time taken, meaning that conversation was very stilted by the transit delay of seconds. The notion that one might have had a 1 Mbit/s connection to one’s own home almost for free would have been regarded as impossible, and suggesting that one would have 100 Mbit/s into one’s own home would have seemed like lunatic-raving.
Figure 3. Charles and Gwen waiting to be interviewed at the time of his Nobel Award. (Online version in colour.)

WORLDWIDE FAME AND DECLINING HEALTH

Once it became clear to the whole world that Charles’ ‘crazy 1966 vision’ of a single-mode optical fibre had truly transformed the way that the human race communicated, both locally and globally, honours and awards started to shower upon him. He was awarded nearly 20 honorary doctorates and even more fellowships and honorary professorships by universities and learned societies from around the world as well as numerous prizes and medals. From 1993 to 1994, he was president of the Association of Southeast Asian Institutions of Higher Learning. In 1996, he donated to Yale University, and the Charles Kao Fund Research Grant was established to support Yale’s studies, research and creative projects in Asia. The list was
finally capped by the award of the Nobel Prize for Physics in 2009 (figure 2). On hearing that he had won it, he is reputed to have said: ‘I am absolutely speechless and never expected such an honour.’ This was a reaction very much in the character of this modest but brilliant man! In 2010 he was knighted by Queen Elizabeth II for ‘services to fibre optic communications’.

Charles was chairman and a member of the Energy Advisory Committee of Hong Kong for two years, and retired from the position in 2000. Also in 2000, he was appointed a member of the Council of Advisors on Innovation and Technology of Hong Kong, and co-founded the Independent Schools Foundation Academy, which is located in Cyberport, Hong Kong. He was its founding chairman in 2000 and stepped down from the board in 2008.

From around 2004, Charles had started to show the early symptoms of Alzheimer’s disease. Sadly, he slowly became increasingly incapacitated by it until he finally died in the Bradbury Hospice in Hong Kong on 23 September 2018 at the age of 84. I very well remember meeting him and Gwen in London around 2009 after the Nobel Prize Ceremony (figure 3) and, whilst it was very good to see an old friend again, it was already apparent that he was becoming somewhat detached from the world. However, I shall always count myself extremely lucky to have known him throughout much of his world-changing life, both as a friend and as a working colleague.

LIST OF HONOURS

Election to the following academies and institutions:

1988 Royal Swedish Academy of Engineering Sciences (IVA)
1989 Royal Academy of Engineering, UK
1990 National Academy of Engineering, USA
1992 Academia Sinica, Taiwan
1994 Hong Kong Academy of Engineering Sciences
1996 Chinese Academy of Sciences
1997 Royal Society, UK
   Institution of Electronic and Electrical Engineers (IEEE), USA
   Institution of Electrical Engineers (IEE), UK
   Hong Kong Institution of Engineers (HKIE)

Honours and awards:

1976 Morey Award of the American Ceramic Society
1977 Stewart Ballantine Medal of the Franklin Institute, USA
1978 Rank Prize of Rank Trust Fund, UK
   Morris H. Liebmann Memorial Award of the IEEE
1979 L. M. Ericsson International Prize of Ericsson Foundation, Sweden
1980 Gold Medal of the Armed Forces Communications and Electronics Association, USA
1985 Alexander Graham Bell Medal of the IEEE
   Marconi International Fellowship of the Marconi Foundation, USA
   Columbus Medal of the city of Genoa, Italy
1987 C & C Prize of the Foundation for Communication and Computer Promotion, Japan
Sir Charles Kuen Kao

1989 International Prize for New Materials of the American Physical Society, USA
1992 Gold Medal of the International Society for Optical Engineering (SPIE), USA
1993 Commander of the Most Excellent Order of the British Empire (CBE)
1995 Gold Medal of Engineering Excellence of the World Federation of Engineering Organizations (WFEO)
1996 Japan Prize in the field of Information, Computer and Communication Systems of the Science and Technology Foundation of Japan
Prince Philip Medal of the Royal Society of Engineering, UK
1999 Charles Stark Draper Prize of the National Academy of Engineering
2001 Millennium Outstanding Engineer Award, Hong Kong
2006 Gold Medal Award, Hong Kong Institute of Engineers
2009 Nobel Prize for Physics
2010 Knight Commander of the Most Excellent Order of the British Empire (KBE)
Grand Bauhinia Medal (GBM), Hong Kong

Honorary degrees:

1985 Chinese University of Hong Kong
1990 University of Sussex
1991 Soka University
1992 University of Glasgow
1994 University of Durham
1995 Griffith University
1996 University of Padova
1998 University of Hull
1999 Yale University
2002 University of Greenwich
2004 Princeton University
2005 University of Toronto
2007 Beijing University of Posts and Telecommunications
2010 University College London
University of Strathclyde
2011 University of Hong Kong

Honorary professorships:

1995 Peking University
Tsinghua University
University of International Business and Economics, Beijing
Beijing University of Posts and Telecommunications
1996 Chinese University of Hong Kong
Imperial College London (Visiting Professor)
1997 Zhejiang University
1998 City University of Hong Kong
1999 Hong Kong University of Science and Technology (Adjunct Professor)
2003 Taiwan University
Appointment to government committees:

1996–2000 Chairman, Energy Advisory Committee
1998–2000 Member, Information Infrastructure Advisory Committee, Information, Technology and Broadcasting Bureau
2001–2003 Director, Hong Kong Science & Technology Park Ltd
1999–2003 Member, University Grants Committee
2000–2002 Member, Council of Advisors on Innovation and Technology

ACKNOWLEDGEMENTS

The portrait photograph was provided to the Royal Society by Charles Kao. All other photographs were provided by the Kao family.

AUTHOR PROFILE

John Edwin Midwinter FRS FREng FIET FIEEE Flnst.P is Emeritus Pender Professor at University College London (UCL). He graduated in physics from Kings College London in 1961 and started research at the Royal Radar Establishment in Malvern, Worcestershire, working on a variety of projects before focusing on the newly emerging subject of non-linear optics. While at Malvern, he wrote his PhD thesis as an external London student and submitted it in 1967, just before emigrating to America where he worked for Perkin Elmer Corporate Research Center in Norwalk, Connecticut, for about two and a half years. Then, after about one year with Allied Chemical in Morristown, New Jersey, he returned to the UK and in 1971 joined what was then the Post Office Research Centre, later to become BT Laboratories. While there, he headed the team developing optical fibre communication systems. It was during this time that he got to know Charles Kao, who was then working in Harlow at STL. In 1984, he moved to the electrical engineering department at UCL, initially to a personal chair but later becoming head of department and a vice-provost of the college. In 2004, he retired to his home in Suffolk, where he now lives.

REFERENCES TO OTHER AUTHORS

Gordon, J., Zeiger, H. & Townes, C. 1955 The maser: new type of microwave amplifier, frequency standard, and spectrometer. Phys. Rev. 99(4), 1264–1274. (doi:10.1103/PhysRev.99.1264)

Hecht, J. 2020 The breakthrough birth of low-loss fiber optics. Optics and Photonics News, March 2020. (https://www.osa-opn.org/home/articles/volume_31/march_2020/features/the_breakthrough_birth_of_low-loss_fiber_optics/)

Kapron, F. P., Keck, D. B. & Maurer, R. D. 1970 Radiation losses in glass optical waveguides. Appl. Phys. Lett. 17, 423. (doi:10.1063/1.1653255)

Maiman, T. H. 1960 Stimulated optical radiation in ruby. Nature 187, 493–494. (doi:10.1038/187493a0)

BIBLIOGRAPHY

The following publications are those referred to directly in the text. A full bibliography is available as electronic supplementary material at https://doi.org/10.6084/m9.figshare.c.5200048.

1. 1966 (With G. A. Hockham) Dielectric-fibre surface waveguides for optical frequencies. Proc. IEE 113(7), 1151–1158. (doi:10.1049/pee.1966.0189)
2. 1968 (With T. W. Davies) Spectrophotometric studies of ultra low loss optical glasses. I: single beam method. J. Phys. E Scient. Instrum. 1(11), 1063–1068. (doi:10.1088/0022-3735/1/11/303)
3. 1969 (With M. W. Jones) Spectrophotometric studies of ultra low loss optical glasses. II: double beam method. J. Phys. E Scient. Instrum. 2(4), 331–335. (doi:10.1088/0022-3735/2/4/307)