



ABOUT THE 2009 NOBEL PRIZE IN PHYSICS

THE 2009 NOBEL PRIZE IN PHYSICS (I)

NOBEL COMMITTEE REWARDS RESEARCH IN TECHNOLOGY

The Nobel Prizes in Physics of 2009 have been awarded for two scientific developments that have a profound impact on both consumer technology and scientific research. Charles K. Kao of the Chinese University in Hong Kong was awarded the Nobel Prize "for groundbreaking achievements concerning the transmission of light in fibres for optical communication. The second half of the prize was awarded to two researchers from Bell Labs, Willard S. Boyle and George E. Smith "for the invention of an imaging semiconductor circuit, the CCD sensor." Although the importance of the rewarded work is evident, it came to many as a surprise. It was a surprise to Carlo Séquin, now at the College of Engineering at the

University of California at Berkeley, and who joined Bell Labs after receiving his PhD and started work on the CCD. "My reaction was of absolute delight, I found out that the work we did was actually worth the Nobel Prize," says Séquin.

"I think it is great to give a prize for something that is technology, certainly for the science that it enabled," says Steve Howell, an astronomer at the Planetary Science Institute in Tucson, Arizona.

For astronomers, the invention of the CCD was indeed a revolution. For Dietrich Baade, the leader of the Optical Detector Team of the European Organisation for Astronomical Research in the Southern Atmosphere (ESO), in Garching, Germany, it chan-

ged entirely his work. "This has been the most important development in astronomy the last 30 years or so, if not more, for the simple reason that the predecessor of all the electronic detectors was the photographic plate, and the quantum efficiency of the electronic plate was between 1 and 3 percent. Now, with the solid-state detector, the quantum efficiency reaches almost 100 percent," says Baade. Unlike photographic plates, CCDs allow the repeated exposure of the same area of the sky, making extremely faint objects visible. "The ultra-deep field images obtained with the Hubble Space Telescope are the result of sixty hours of observations—a tremendous number," says Baade. Howell still remembers how the initial design of the Hubble Space Telescope incorporated photographic plates that would be parachuted to Earth or picked up by visiting crews. "The study of distant supernovae, dark energy and dark matter, none of this would have been enabled without CCDs," says Howell.

The commercial impact of optical fibres is even more important than that of CCDs, but the impact on scientific research is definitely as great. The fast transmission of data in fibres not only allows the setting up of super-fast networks like "the grid" developed by CERN for the distribution of data obtained with the LHC, but also of "virtual observatories" in astronomy and other areas of science.

▼ Charles Kao in his laboratory at the Standard Telecommunications Laboratory in the U.K. in the 1960s. (European Pressphoto Agency)



Direct applications of optical fibres also abound, in photonics, laser research, and even in telescopes. Baade explains how the spectrograph used in the search of exoplanets with HARPS (High Accuracy Radial Velocity Planet Searcher) is connected via optical fibres to ESO's 3.6-metre telescope at the La Silla Paranal Observatory in Chile. The individual fibres collect the light of a large number of stars, and carry the light to a spectrograph mounted in a vacuum vessel, making the extremely sensitive instrument independent of telescope motions and temperature changes.

Unfortunately, the nomination of Boyle and Smith for the development of the CCD became the subject of a controversy. During the days following the announcement of the Nobel laureates early October, several researchers questioned on a blog of *IEEE Spectrum* whether the duo really could be viewed as the inventors of the CCD. "The comments were flying back and forth, there is no doubt that there is a controversy," says Séquin. In fact Boyle and Smith

were working on a so-called "bubble memory" for computers, and not on an imaging device. "If you are interested in the basic concept of the charge transport, then I think it is absolutely reasonable to pick Boyle and Smith because they had this crucial discussion in their office that led to this idea," says Séquin. "But if you read the report of the Nobel Committee, it is 90 percent about image sensors and how to make image sensors of high resolution," says Séquin. It was a colleague of Séquin at Bell Labs, Michael Tompsett, who in fact built the first CCD, and who applied for a patent for the device. It was also Tompsett who devised the technology for reading out the information stored on the CCD. "This principle was clearly invented by Tompsett," says Séquin.

According to Govind Agrawal, who leads the Nonlinear Fiber Optics Group at the University of Rochester in Rochester, New York, the Nobel Committee generally divided the prize between the team who got the idea and the team who implemented

the idea. "In this case they didn't do that," he says. And he also comments on the fact that the 1966 paper by Kao [1], cited by the Nobel Committee, in which he outlines how optical fibres can transport signals over long distances, also has a co-author, George Hockham, who doesn't share the Nobel Prize.

It is clear that the researchers who feel left out are the victims of the rule of limiting the Nobel Prize to maximally three recipients. Increasingly, advances in technology and science are the result of large teams. "Clearly the development of a honest-to-God viable CCD camera involved in the order of 200 individuals," comments Séquin. Perhaps the Nobel Committee should relax its limitation on the number of nominees. ■

■ ■ ■ A. Hellemans

References

- [1] K.C. Kao and G.A. Hockham, Dielectric-Fibre Surface Waveguides for optical frequencies, *Proc. IEEE* 113, 1151 (1966).

THE 2009 NOBELPRIZE IN PHYSICS (II)

CHARLES KAO, PIONEER IN OPTICAL FIBRES

The world is pending on a tiny thread, a thread of glass. Optical fibre is vastly deployed all over the world, to carry our telephone conversations, computer data, TV signals, the internet with its exploding gamma of services, etc. Our economic, social and cultural activities would come to a standstill without the huge communication streams which the tiny silica glass fibre is able to carry. When Samuel Morse introduced the telegraph and Alexander Graham Bell the telephone, the world was dependent on copper wires. And still large parts of the communication networks are using copper, in particular the twisted-pair telephone lines

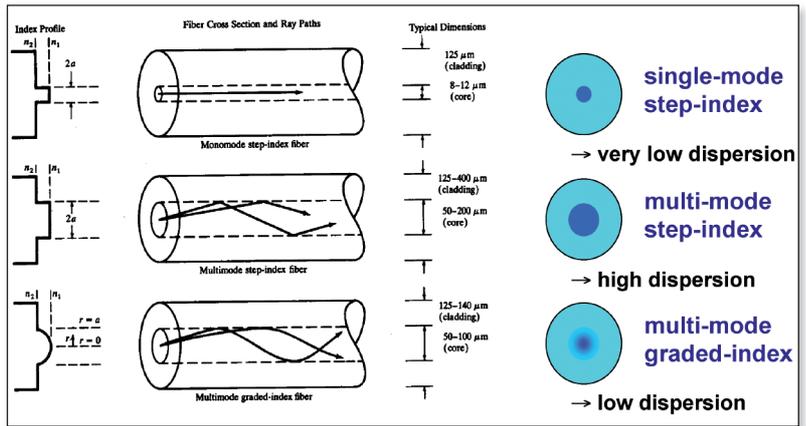
and the coaxial cable CATV lines connecting the users' homes. Electrical signals get attenuated on the lossy copper lines, necessitating lots of amplifiers all over in the networks. The bandwidth of these lines is quite limited, and is running out of steam in view of the fast growing capacity needs of the internet. Moreover, as the world's resources are expiring, copper gets ever more expensive. Charles Kao, who was born in 1933 in Shanghai, and got his PhD degree in Electrical Engineering in the Imperial College London in 1965, recognized these shortcomings already in the mid 60's. He worked as an engineer in Standard Telephones

and Cables (STC) in Harlow, UK, and there he developed his groundbreaking ideas of how to carry light with extremely low losses through glass fibre. He first presented his results in January 1966 in London to the Institute of Electrical Engineers (IEE).

Low-loss light guiding

The guiding of light in curved media was already observed much earlier, e.g. by noticing that in illuminated fountains light was guided by the curved water beams. The light guiding is actually realized by 'total internal reflection': light propagating in a material with a high refractive index is reflected at the interface with ■ ■ ■

■ a medium with lower refractive index, provided that the incidence angle on this interface is larger than the critical angle. As this reflection is very efficient and causes negligible losses, light can be confined and guided through the water beam. Obviously more stable solutions than water beams are needed, so similar experiments were done with homogeneous threads of glass. Endoscopy could be done with many of these glass threads united in a single cable. However, small scratches and other irregularities at the surface of the glass destruct the total internal reflection process, and light leaks out. Hence the losses of such homogeneous threads were too high for guiding light over larger distances. Moreover, impurities in the glass itself contributed to the losses. Charles Kao came up with fused silica (silicon dioxide) as the perfect material for very low loss light guiding. And the fibre structure itself should not be a homogeneous thread, but should have an inner core having a high refractive index, surrounded by a glass cladding with a lower index. Thus the boundary was nicely protected and could serve as a reliable close-to-perfect mirroring surface for guiding the light beam. Kao's claim which he presented in 1966 was that, with fused silica glass and the core-cladding structure, losses of less than 20 decibels per kilometer should be feasible, *i.e.* more than 1% of the light power should still remain after propagation through 1 kilometer of fibre. In 1970, Keck and co-workers at Corning



▲ FIG. 1: Silica optical fibres (diameter 125μm each)

Glass in the US indeed demonstrated light guiding in such optical fibre with less than 20 dB/km loss. Modern optical fibre has a standardized outer diameter of only 125 micrometer, within 1 μm. This is about the thickness of a human hair (see Fig. 1). Regarding attenuation, it has made a huge progress since its invention, while still following Kao's principles. It now conveys more than 95% of the light through 1 kilometer of fibre, *i.e.* it has a loss of less than 0.2 dB/km. This has only been possible by bringing the purity of the silica glass to the extreme, using precisely controlled environmental conditions, very sophisticated chemical vapour deposition techniques for building a structured perform, excluding every tiny amount of water, and drawing the preform into a very tightly controlled fibre. The diameter of the fibre's core has a major impact on the light guiding properties: when it is on the order of the wavelength, it can be shown that the fibre is able to guide light only in a single mode: hence it is called a single-mode optical fibre (see Fig. 2). When it is much thicker, many more modes can be guided: a multi-mode fibre. Each mode has a different propagation time; thus an optical pulse, which is guided by these modes, will get dispersed and is broadened when it arrives at the fibre's end. When pulses broaden, they cannot be put closely together anymore without serious overlap.

Hence this modal dispersion phenomenon limits the rate at which pulses can be transmitted, so the bandwidth of the fibre. The modal dispersion can be reduced by accelerating the light rays which are making the larger excursions when travelling through the core, so by reducing the refractive index of the core towards the cladding, see Fig. 2. Such 'graded-index multimode fibre' shows a clearly larger bandwidth than its step-index counterpart. Obviously, a single-mode fibre shows hardly any pulse broadening, and thus has the ultimate bandwidth. Single-mode fibre is by far the most wide-spread fibre type. Multimode fibre is only applied for shorter links, such as in in-building networks. Thanks to its larger core, it is easier to connect than single-mode fibre.

Dispersion and losses

The bandwidth of single-mode fibre is mainly limited by material dispersion (since the refractive index of the silica glass is slightly dependent on the wavelength) and by waveguide dispersion (since the electrical field spreads out from the core into the cladding, and this spreading becomes larger at increasing wavelength). Material dispersion and waveguide dispersion have opposite signs, and can cancel each other. For silica glass, this happens at a wavelength of about 1.31 μm, the so-called 'zero-dispersion wavelength'. At this wavelength, the fibre reaches its ultimate bandwidth,

▼ Professor Charles Kao (third from right) poses shoulder-to-shoulder with students from the Chinese University in Hong Kong on the first day of the 1994-95 academic year. Copyright © The Chinese University of Hong Kong



and the bandwidth of the whole fibre link is then only limited by the spectral purity of the laser transmitter.

The fibre's losses depend on the wavelength of the light, and reach their lowest value around 1.55 μm , which is in the near infra-red. As Fig. 3 shows, the low-loss wavelength region of the fibre represents a huge optical frequency range, and thus an extremely large capacity for guiding telecommunication signals. A laser diode, which is another crucial element in an optical fibre communication link, can send light pulses at a very high repetition rate, at tens of giga-Hertz, but only occupies a tiny part of this optical frequency range. But many of these laser diodes, each operating at a slightly different optical frequency, can be put in parallel and thus together convey massive amounts of data. Using this so-called 'wavelength division multiplexing', in the laboratory transmission has been achieved with speeds exceeding 21 terabits per second. Such a capacity would allow that one half of the world's population can have a phone conversation with the other half, just through one tiny silica optical fibre as thick as a human hair!

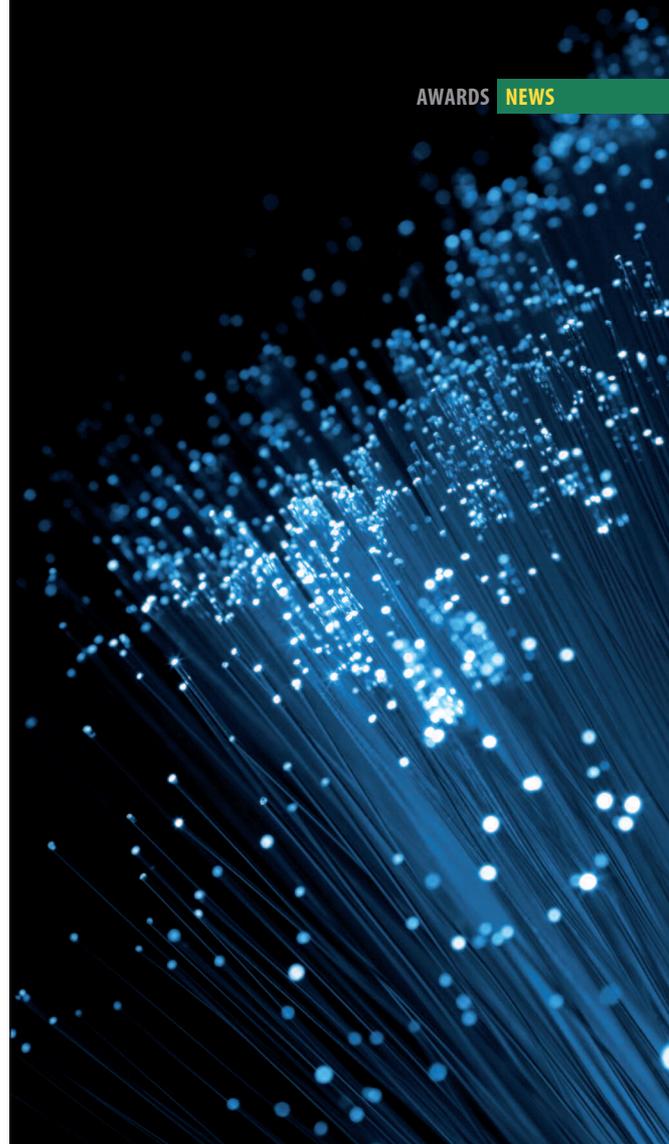
Nowadays optical fibre is installed all over the world. The total length amounts to some 1 billion kilometers, 25000 times the circumference of the earth! Many fibre links are connecting the continents together; e.g., the transatlantic links bridge the ocean between Europe and North America, ca. 6000 km, and the transpacific links between the west coast of the US and Japan, ca. 9000 km, with an intermediate landing point in Hawaii. Although the fibre has very low losses, such distances cannot be bridged without amplification. The advent of the optical fibre amplifier, in particular the erbium-doped fibre amplifier (EDFA) was another landmark in the evolution history of optical communication systems. When doped with the rare earth material erbium which is brought into an excited state by optical pumping with another laser, the

doped optical fibre can amplify optical signals directly without converting them first into electrical signals. Many wavelength channels can be amplified all-optically and simultaneously, which makes such an optical amplifier an essential component in long-haul wavelength-multiplexed systems.

Fibre-to-the-home and fibre-in-the-home

Whereas silica fibre has conquered telecommunication networks in the long-haul parts, spanning oceans, continents, but also countries and cities, the final drop to the user's home is in most places still on twisted-pair copper lines and/or coaxial copper cables. This final access drop is more and more becoming the bottleneck in offering high capacity to the user. Hence fibre is now increasingly being installed all the way to the homes in access networks, replacing the copper lines, and by virtue of its tremendous capacity hosting all the services offered by the copper media (triple play: video, voice, and data) and any service yet to come! In Japan, fibre-to-the-home has already outnumbered the copper twisted pair connections (the digital subscriber line, DSL). And the US and many European countries are progressing in the same direction. Connection speeds to the home are typically 100 Mbit/s both to and from the home; in Japan, even 1 Gbit/s is introduced.

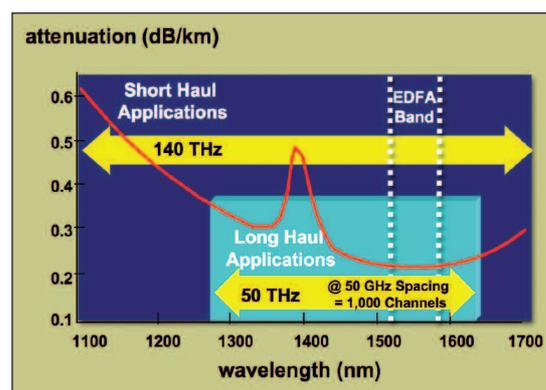
But Fibre to the Home is not the end game yet in the quest of bringing the ultimate communication highway to the user. After having reached the doorstep, the highway needs to be extended into the home, up to the devices of the user himself. Thus research is now being directed to optical fibre systems for in-home, where it becomes crucially important to make the system robust, and easy to install, preferably in a do-it-yourself fashion. Silica fibre is brittle and has to be installed with precision tools and by skilled personnel. As an alternative, plastic optical fibre (POF) is coming up, which can be



▲ FIG. 2: Light guiding by optical fibres ©istockphoto

made much thicker, and is ductile. This makes it much easier to handle and to install, even by unskilled persons. Its losses are by far not as low as those of silica fibre, but as in-home link lengths are short, that is not a show-stopper. Like the silica fibre proposed by Kao, also the POF has a core-cladding structure. Its large diameter causes a high modal dispersion, and thus severely limits its bandwidth for longer lengths. But again, lengths are short, and thus this is not lethal. Special techniques are being developed to convey Gbit/s

▼ FIG. 3: Attenuation of silica single-mode fibre .



■ data streams over POF networks. Also techniques are being investigated to carry microwave radio signals over the fibre in order to meet the user's needs for broadband wireless communication without having to put comprehensive microwave radio equipment everywhere.

So by pioneering optical fibre, Charles Kao has opened the road towards real broadband communication, where the sky is the limit, and light is shining into a bright future where we can communicate with each other without any borders! ■

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About the author

Ton (A.M.J.) Koonen is a Full Professor at Eindhoven University of Technology, in the Electro-optical Communication Systems Group, being Chairman of this group since 2004. He worked for over 20 years in applied research in broadband telecommunication systems: as a member of technical staff at Philips

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THE 2009 NOBELPRIZE IN PHYSICS (III)

W. BOYLE AND G. SMITH FOR THE CCD

October 6th, 2009 was a great day for the solid-state imaging community. The Nobel Prize in Physics went to Willard Boyle and George Smith, two Bell Labs co-workers who invented the Charge-Coupled Device (CCD). The CCD has created a revolution in Science and technology as well as in society at large.

I am wondering whether W. Boyle and G. Smith ever realized that their invention would have such a great impact:

- on society : these days everyone has a digital still camera, many have a camcorder all provided with a CCD, some even with three CCDs. All TV images we see today are being cap-

tured by means of CCD cameras; many medical diagnoses are relying on CCD images as well. Other application fields are security, astronomy and scientific cameras. In many applications these days CCDs are being challenged by CMOS (Complementary Metal Oxide Semiconductors) image sensors, but it can easily be understood that CCDs paved the way in solid-state imaging, for CMOS as well;

- on the semiconductor business: many companies made quite a profitable consumer business out of CCDs. Examples are Sony, Panasonic, Sharp, Toshiba, NEC, FujiFilm,

Kodak, Philips, E2V, Fairchild, DALSA, LG, Thomson, Sarnoff, SITe, Ford Aerospace.

- on the imaging technology: after the introduction of the CCDs, the classical imaging tube quickly disappeared from the scene. CCDs are more compact, lighter in weight, less power hungry, lower supply voltage, no burn-in effects, no image lag, no maintenance and immune to electromagnetic fields. CCDs only had advantages over the imaging tubes, even a lower price. The CCDs opened a great new field of imaging applications that were never possible without solid-state image sensors,

- on the scientific and technical community: the basic CCD invention of Boyle and Smith was a great inspiration for many other great engineers: Walden invented the buried channel CCD, Esser invented the peristaltic CCD, Kosonocky the floating diffusion and White added the correlated-double sampling. But the CCD performance improved quite a lot after the introduction of the pinned photodiode by Teranishi. From that moment, the CCD business really started to boom. Many other important inventions were inspired by the work of W. Boyle and G. Smith.

▼ The two inventors of the CCD with one of the very first CCD cameras, developed by Bell Labs, illustrating their great invention.





▲ FIG. 1: Shown here is a 48 Mpixel CCD imager with a size of 48 mm x 36 mm, used in highest-end digital photography (courtesy DALSA, Eindhoven).

Principle of CCD

A Charge-Coupled Device essentially consists of a 2-D array of tiny pixels which convert light into electrical charge (see Fig. 1). Each pixel may be considered as a small group of capacitors carrying a charge. The working principle of a CCD is based on the transfer of charge packets from one capacitor to the next one. The charge is thus transported across the array, and read out at one corner. Pixels located close to the output amplifier have to undergo just a few transport cycles, while the charge of pixels located at the far side of the output stage has to move over quite a long distance towards the output. The image captured by the CCD can be easily reconstructed based on the fact that the pixels become available at the CCD output in a serial way, and in a similar sequence they are displayed on a monitor.

The transport takes place in the silicon material, and is driven by digital pulses. In its simplest form, every CCD pixel is composed out of 4 of such capacitors. With 4 capacitors per pixel, the charge packets can be shifted from one pixel to the next one without being mixed up. Every capacitor can be extremely small, for a classical consumer imager, the pixels go down to 2.0 μm or even less. That means that the individual CCD capacitor is less than 0.5 μm . Note that this is just about the wavelength of visible light.

Fabrication and performance

The design, lay-out and fabrication of these capacitors needs to be done in such a way that it allows a smooth transfer of the charge packets. This transport is not perfect. If its efficiency is not 100 %, some electrons from the charge packets will get lost. In the very early days of the CCDs, the transfer efficiency was about 99 %, but in modern CCDs the transfer efficiency can be as high as 99.99999 %.

On one hand, the industry tries to make the pixels as small as possible, but on the other hand, the number of pixels put on a single CCD chip is increasing. Consumer devices have pixel counts up to 14 Mpixels, but imagers for professional use (e.g. astronomy, video-grammetry) have pixel counts ranging to over 150 Mpixels. Taking into account the 4 capacitors per pixel, this gives rise to over 600,000,000 individual capacitors on a single chip!

With respect to the performance of the CCDs, in many aspects they perform as well as the human eye (e.g. sensitivity, low-light level imaging, speed). In some aspects the CCDs do even better than the human eye (noise performance, radiation hardness), but in others, the CCDs still can learn from the human eye (power dissipation, parallel processing of the information).

Future perspectives

CCDs do need a dedicated production process to fabricate the image sensors, and unfortunately, these processes are not available on every corner of the street. This observation makes the CCD rather expensive compared to its competing technology, being the CMOS image sensor. Especially for consumer devices (e.g. mobile phones), the outstanding imaging performance of the CCD cannot compensate for the cost difference between CCDs and CMOS image sensors. But on the other hand, for very specific market segments as well as for professional applications, the CCDs are superior over CMOS image sensors (e.g., broadcast applications, astronomy, medical instrumentation;

see examples in Figs. 2 and 3). Their image quality is better and the cost advantage of CMOS technology is much less or even non-existing.

Although the CCD is celebrating its 40th anniversary, it still deserves its place in the digital imaging business. ■

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Prof. Albert J.P. Theuwissen (1954) received his PhD in electrical engineering from the Catholic University of Leuven (Belgium). As of 2001 he is part-time professor at Delft University of Technology (Delft, Netherlands) where he teaches courses in solid-state imaging and coaches PhD students in their research on CMOS image sensors. He is presently running his own company "Harvest Imaging", focusing on training, teaching and coaching of people active in the field of digital imaging.



▲ FIG. 2: HDTV camera containing 3 CCD imagers. The pixels of the imagers are designed in such a way that the camera can be used according to different HDTV standards (courtesy Grass Valley, Breda).

▼ FIG. 3: CCD cameras intended for industrial vision applications. The imagers have pixel counts in the range of 1 Mpixels - 8 Mpixels and can produce monochrome and colour images at higher frame rates (courtesy of Adimec, Eindhoven).

