Spectroscopy & the invention of the Photophone

Alexander Graham Bell is best known for the invention of the telephone, but he was a man of many parts. This year marks the hundredth anniversary of his first successful transmission of voice messages via a beam of light. In the course of his experiments he also stumbled upon another very useful discovery — the photo-acoustic effect.

by DR CLIVE COOGAN*

"Mr Bell, if you hear what I say, come to the window and wave your hat." These words, heard by Alexander Graham Bell through a telephone earpiece connected to "an illuminated receiver" seem scarcely likely to be the introduction to a new branch of optical spectroscopy, but they were! Serendipity in science had struck again!

The words were spoken by Sumner Tainter, Bell's friend and assistant, from the top of the Franklin St. Schoolhouse in Washington DC, 213 metres away from Bell's laboratory in 1325, L Street. Tainter was operating the transmitter of a "photophone" which Bell had conceived and which was probably the first successful transmission of voice via a light beam.

The year was 1880 and August this year marks the centenary of that first voice transmission by light beam. Remarkably, this concept had been implemented only a few years after the first successful telephones; due of course to the same ingenious Scot, Alexander Graham Bell. What would Bell have made of current efforts, particularly in his own Bell Telephone Company, to convert all telephone communications to messages carried on light beams using optical fibres and lasers and the whole new gamut of electro-optic devices?

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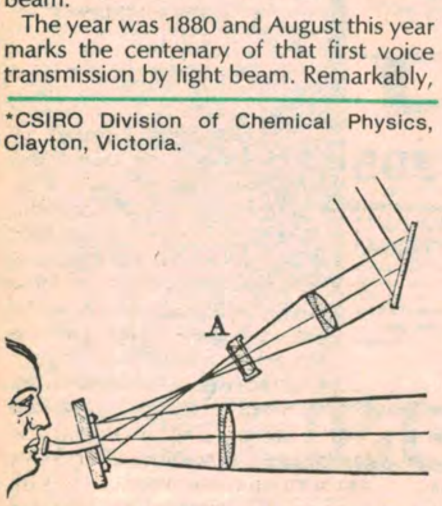


Fig. 1: in Bell's "Photophone", sunlight was reflected onto a mirror that vibrated in response to speech, causing the light beam to vary in intensity.

In the laboratory, Bell and Tainter had succeeded in transmitting spoken messages using oxy-hydrogen light and even the light from a kerosene lamp or a candle, but as they were in earshot of one another they regarded this as suspect, and so arranged the 213 metre test-track.

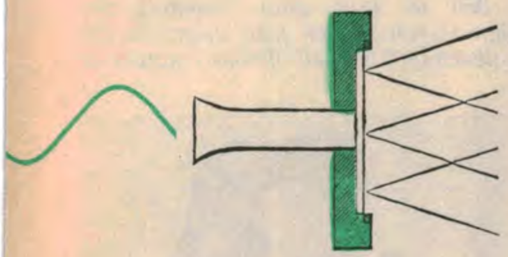
Selenium had only fairly recently been discovered to be a photoconductor (in fact selenium itself was not known until 1817 when Bezelius separated it from sulphur and tellurium). It was found that crystalline selenium had a very high resistance, and a certain Mr Willoughby Smith began using it as an insulator in shore-end tests of submarine cables. He cast bars with a resistance of 1400 megohms, which Bell points out was equivalent to the resistance of a cable from Earth to the Sun! However Willoughby Smith's assistant, Mr May, found that its resistance was lowered when it was exposed to light, which finding Willoughby Smith published in 1873. Rapid development then took place so that by 1875 the selenium photoconductor cell was fairly well established.

Bell realised that this might constitute a means of optical communication, so he made himself a selenium cell "about the size of a dime", which emigre Bell explained for the benefit of his English readers was "a small silver coin about the size of a *fourpenny* (sic!) bit. Its value is 10 cents". Bell proposed in 1878 the possibility of "hearing a shadow", or the transient change in current through the cell when the light falling on it was suddenly cut off. He passed the current through the selenium cell through one of his telephone earphones.

A few days later Willoughby Smith told the Society of Telegraph Engineers that he had indeed "heard a shadow", or rather the reverse — the removal of a shadow falling on a selenium bar in circuit with a telephone and a battery. Also, although unknown to Bell at the time, a letter to "Nature" a few weeks later asked whether anyone had experimented with the selenium cell in circuit with a telephone, as it seemed to the writer "not unlikely that sounds would be produced in the telephone by the action of light of variable intensity upon the selenium element in circuit with it."

Others were actively at work on the idea within weeks also. By September or October of 1878 (Bell had forgotten which), a Mr A. C. Brown of London disclosed confidentially to Bell the details of "a most ingenious invention of his, of which we may yet hear more" which converted various light intensities to sound. Also hard at work was a Mr W. D. Sargent of Philadelphia, who had a device in which the action of the voice caused a light to fall intermittently on a selenium cell causing, as we can see in hindsight, a hideously distorted voice signal.

However, Bell had a better idea. He had toyed with the notion of a rapidly rotating disc in which there were uniformly spaced holes near the circumference, so that light passing through the disc and falling on the selenium cell would be intermittently interrupted. He reasoned that this would produce a musical note. But on further consideration he decided that all the audible effects that were present in a telephone could be reproduced by cor-



responding variations in the intensity of light falling on a selenium cell. To put this into practice he set to work to devise an apparatus which would produce variations in the intensity of a parallel beam of light.

After a few false starts, he finally settled for a very simple device, a silvered disc of mica or thin glass, vibrated by sound waves, which was used as a mirror. This is shown in Fig. 1, taken from Bell's paper in the Journal of the Society of Telegraphic Engineers of 1880.

Vibrations changed the diaphragm from a plane mirror into one of slight concavity or convexity, changing the intensity of light reflected from it as received at a selenium cell. For a light source he settled for the Sun, which meant that he had to use a heliostat mirror. He also produced an improved selenium cell. The complete apparatus is shown in Fig. 2.

Using this type of apparatus the photophone was born, and Bell waved his hat to Sumner Tainter. However, it has taken a long time for the photophone to gain much altitude, and we are only just beginning to see its potential realised.

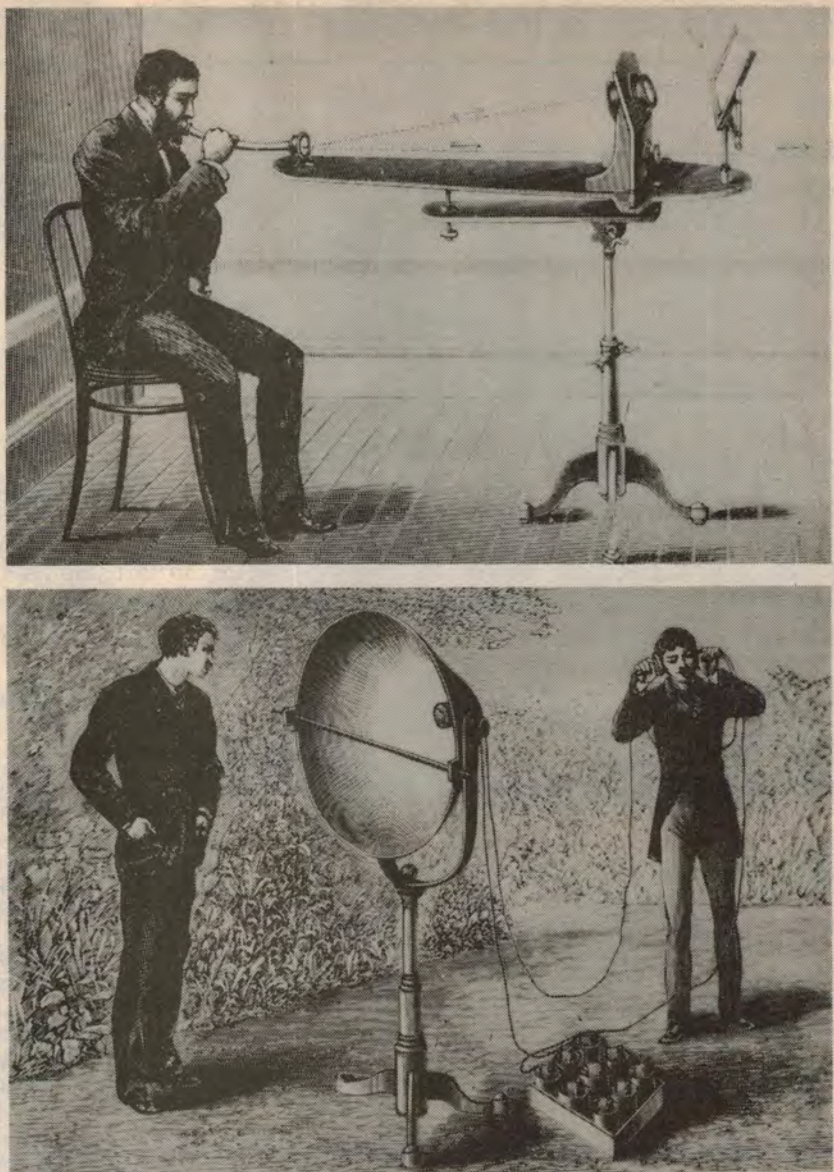


Fig. 2: these woodcuts from Bell's patent of December 1880 show the complete scheme for the Photophone. A selenium detector at the receiving end converted the light beam variations into electrical current to reproduce speech in a telephone handset. (Photos courtesy of Bell Labs).

Photo-acoustic spectroscopy

But in the course of seeking to understand more about the photophone, Bell also stumbled upon another very useful discovery which has taken even longer to be usefully applied but which has already yielded much of value. Bell set out to investigate, for all the wrong reasons, whether you could hear, without the aid of a telephone circuit, "the molecular disturbance" which he argued would take place when an interrupted light beam hit the selenium cell.

At first his efforts were not successful with selenium, but when he used a sheet of hard (and presumably black) rubber, he was rewarded with quite distinct sounds. These he intensified by making the hard rubber into a diaphragm and leading away the sound to his ear with a rubber tube.

He then substituted diagrahms of various other materials and found similar effects, except with white paper, mica and glass. Selenium in the form of a thin disc, gave a quite audible sound in this new apparatus as did virtually anything which Bell tried.

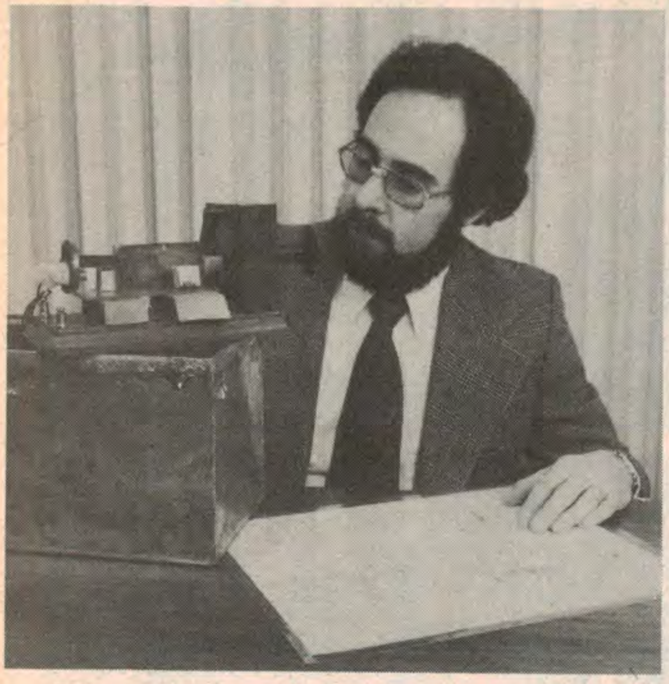
It was this discovery that has spawned the new science of photo-acoustic spectroscopy.

Bell reasoned that the sound was due to a rearrangement of molecules in the specimen, and, as this sound had to be transmitted through the substance in the apparatus he was using, it would be better to lead to the ear air that is in direct contact with the illuminated surface. So he used tubes of vulcanised rubber, brass and wood into which chopped sunlight was focused. Very perceptible musical notes were heard.

The logical next step was to focus the light directly into his ear. This he did in the very best traditions of intrepid investigators! Sunlight was chopped and some of the heat was filtered out of it by a filter comprised of an alum solution, but as Bell said, "a considerable amount of heat was of course perceptible, and the experiment was only continued for a sufficiently long period of time for me to satisfy myself of the reality of the phenomenon".

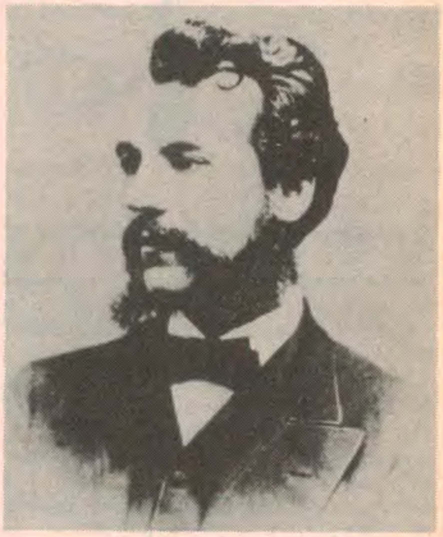
This latter discovery, called the non-electric photophone effect, excited more interest at the time than did the photophone itself. A number of eminent scientists of the time worked on the effect. At the Royal Institution, the Director Prof Tyndall, most famous for the Tyndall Effect (or the scattering of light by small particles), quickly took up Bell's discovery.

Spectroscopy & the invention of the photophone



"I have heard a ray of sun laugh and cough and sing", wrote Alexander Graham Bell in 1880 after inventing the Photophone. Here, Jim Lowell of Bell Labs examines the original photophone developed by Bell. (Photo courtesy of Bell Labs).

Alexander Graham Bell from a photograph taken in 1876, the year in which the telephone was patented. Bell once defined an inventor as a "man who looks upon the world and is not content with things as they are".



Tyndall had done considerable work on the absorption of infra-red light by gases, most of which had been greeted with disbelief. So he extended Bell's experiments to gases and vapours of liquids in a flask with a rubber tube leading to the ear. Chopping sunlight, limelight, a Siemens lamp, candle light and radiation from a red-hot poker, he found that quite intense sounds could be heard. In fact, he claimed that under some circumstances a sound as loud as an organ pipe could be obtained!

He also found that he could obtain audible signals from a poker which had cooled down to a temperature below the boiling point of water!

He had Bell at his side when he conducted his first experiments on chopped light passing through gases in November 1880, as he was convinced they would work, and support (as they did) his previous controversial results on absorption of heat rays in gases. Quite correctly he predicted that the absorption of heat rays would warm the gas, increase its pressure and, with intermittent heating due to absorption of chopped light, emit a note of the same frequency as the chopping.

In particular, he noted the high sensitivity of this technique with marsh gas (methane) and predicted a use for the effect in determining the concentration of this dangerous gas in coal mines. Independently, in Germany, Rontgen of X-ray fame, was also working on the effects of the absorption of heat rays in gases, in what might be called the "DC mode". He used a manometer to measure the increase in pressure of ammonia gas when it was exposed to infrared light.

So, the increase in pressure in gases when they absorb light is therefore known as the *Tyndall-Rontgen Effect*, as distinct from the sound produced when light is absorbed in a solid, which is called the *Bell Effect*. Rontgen soon found his X-rays and Tyndall became interested in other matters, and so this field of study lapsed until 1939 when it was revived in Russia by Veingerov. It was later refined by Luft in Germany after the war, and turned into a very useful tool for analysing gases. It masquerades under various names, spectrophone, opto-acoustic effect and photophone being the most common.

Today, it is used throughout industry to detect methane, carbon dioxide, carbon monoxide and many other gases. It can detect down to levels of parts per billion, and has been sent aloft in satellites. It is also widely used in medical environments to measure anaesthetic and natural gases and is the basis of some alcohol vapour detecting "breathalysers".

Incidentally, in the course of these experiments Tyndall discovered another effect which has been the subject of much post-war work. He observed in a footnote to a paper he read to the Royal Society in London that "when I stand with open eyes in a flashing beam, at a definite velocity of recurrence, subjective colours of extraordinary gorgeousness are produced. With slower or quicker rates of rotation the colours disappear. The flashes also produce a giddiness sometimes intense enough to cause me to grasp the table to keep myself erect."

He was stimulating his brain at its dominant frequency, and this technique, and associated electrical signals from the brain, has led to a greater understanding of epilepsy and to how the brain works. Probably Tyndall was the first to observe this effect, which can be aroused at the appropriate frequency for the individual in all normal subjects, and which can trigger fits in epileptics.

Meanwhile Bell, Lord Rayleigh, William Preece (the President of the Society of Telegraph Engineers of London), and Mercadier in France all concentrated on solids. All found that black samples were the most effective and while almost anything they tried produced the effect to some degree, it was minimal in transparent materials. However, there was much confusion about the reason for the phenomenon.

Lord Rayleigh, one of the most powerful mathematical physicists of all time, produced a theory based on expansion of the surface exposed to light buckling the disc and thus producing mechanical motion at the frequency of the chopping of light. Bell believed it to be due to the noise of the rearrangement of "molecules" in the solid. Preece set to work to investigate the effect systematically, and came closest to the modern explanation — "any absorbent surfaces placed inside a transparent vessel will, by first absorbing and then radiating heat rays to the confined gas, emit sonorous vibrations."

He tested his theory by making a very fine spiral of platinum wire in a kind of earphone, through which he passed a current broken intermittently by a commutator switch. He heard a note at the chopping frequency. Professor Stokes nudged him greatly in the right direction by suggesting that the major effect was due to contact of gas atoms pinging on the solid surface and carrying away heat.

The modern phase of the Bell effect, now called the photo-acoustic effect (although variant names are also used) started, ironically enough, in the Bell Telephone Laboratories, when Alan Rosencwaig and his colleagues published the results of their work on photo-acoustic spectroscopy in 1973. The initiated now call it PAS.

PAS has a number of decided advantages over traditional spectroscopic methods. The most important is the fact that almost any kind of specimen will do. In the traditional methods the specimen has to be prepared in the form of a parallel-sided slab or film, and light is passed through it. The absorption is measured via the diminution of light passing through the specimen.

If the specimen is highly absorbing, then it has to be very thin indeed in order that a measurable amount of light can pass through it. Thus a small pinhole in the specimen can pass more light through it than the rest of the sample, in highly absorbent specimens, and lead to false results.

PAS only measures true absorption and is not at all choosy about the form of the sample. For example, biological samples contain cells which cannot be dragooned into appropriate traditional samples, and powder samples of solids are quite acceptable. Moreover, quite opaque samples may be used, so that the spectroscopy of a corrosion film on a metal surface can easily be examined, for example.

Another very valuable property of PAS is that it ignores scattered light which is not absorbed. It can thus measure the absorption in opal glass, which can be opaque due to scattering. Also smoke can be studied, as again only the light truly absorbed is measured.

Yet another stirling attribute of PAS is its ability to ignore the fraction of light which is absorbed, stored for a while and then re-emitted. This is called luminescence. When re-radiation takes place, it is always at a longer wavelength than the absorbed light – in other words some heat at least is left behind in the solid. When the chopping frequency is slow compared with the average storage time, or the re-radiation decay time, the effect of this residual heat input is observed. When the chopping is fast, the residual heat input is only minimally co-related with the phase of the chopping.

Thus, a study of the PA effect as a function of chopping frequency yields information about the average delay between absorption of light and radiation of luminescent light.

It also has a few bonuses which are of more interest to the solid state physicist than the spectroscopist. In order to look at this, we need to look at the form that modern PAS equipment takes, shown in Fig. 3. Light from an appropriate source, usually a high powered xenon lamp, is passed through a monochromator, so that light of a narrow wavelength band only emerges. Some of this is sampled by a PA cell which has in it a total absorber, such as carbon black, to monitor the intensity of the source at that wavelength, and the rest passes into another PA cell containing the specimen.

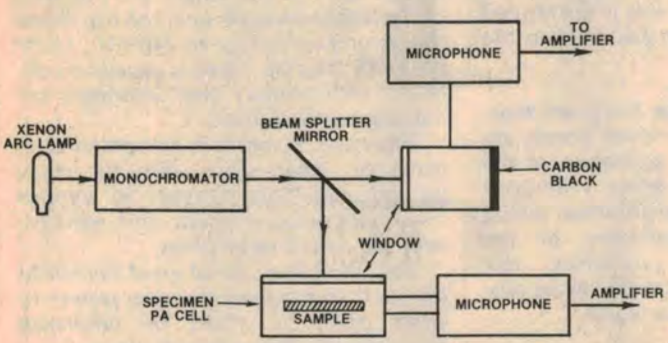


Fig. 3: basic scheme for a PAS spectrometer. PAS measures only true absorption and is not fussy about the form of the specimen.

The PA cells have a transparent front window and contain a built-in microphone, usually a small electret device, to pick up the intensity of the sound produced at the chopping frequency. Light absorbed by the sample turns into heat and raises the temperature of the front surface of the specimen. Some of this heat is conducted inwards into the bulk of the sample and some is conducted away by the gas in the PA cell.

The gas in immediate contact with the surface heats, expands and acts as a piston, pushing outwards while the light is being absorbed in the surface. When the light is cut off, the supplement of heat to the gas is cut off and the gas pressure falls as the additional heat is lost to the outer walls of the cell and to the absorbing solid.

A modern photo-acoustic spectrometer from Princeton Applied Research Corp, USA. Photo courtesy Technico Electronics.

Thus, PAS can be used to study the thermal conductivity of a powder sample, for example, in which it would be almost impossible to measure the thermal conductivity accurately otherwise.

What a hotch-potch of accidental discovery, human emotions, curiosity, sheer good luck and perseverence all this is, just like so many other stories in science! Berzelius puzzled by a queer smell arising from a sulphur specimen, Mr May perplexed by the variability of the resistance of his selenium insulator, Alexander Graham Bell riding on the crest of a wave of fame generated by his telephone a few years before, Tyndall annoyed by detractors who contradicted his earlier results on the absorption of infra-red light in gases, the amiable and verbose Preese bringing matters to a head, Rayleigh making a rare blunder, and Rontgen performing a characteristically simple experiment.

The applications of PAS to solids are rapidly multiplying. The analysis of gases via opto-acoustic techniques is well established. Communication via modulation of light beams seems set to revolutionise our lives.

The beginning of all this was signalled by a wave of Alexander Grahame Bell's hat one hundred years ago.

Mr Bell, we take our hats off to you!