Some milestones in electronics

An interview with Professor Bernard Tellegen

by Arthur Garratt

In this article Professor Bernard Tellegen, inventor of the pentode, discoverer of the Luxembourg Effect, pioneer of the gyrator and great figure in the history of radio talks to Arthur Garratt, a British scientific and industrial consultant now living in France.

BEFORE the invention of the transistor, the three most significant inventions in radio were the diode (Ambrose Fleming, 1904), the triode (Lee de Forest, 1906) and the pentode by Bernard Tellegen in 1926.

The pentode originated in the Philips Research Laboratories, the *Natuurkundig Laboratorium* or *Nat Lab* as it is generally called, at Eindhoven in the Netherlands.

The Nat Lab was set up in January 1914 under the directorship of Dr Gilles Holst, who had previously worked in Leyden with Kamerlingh Onnes – one of the great figures in low temperature research. Holst soon had an assistant, Dr Ekko Oosterhuis, who became Holst's second-in-command. (Oosterhuis, incidentally, was the grandfather of the British golfer, Peter Oosterhuis.) After the first world war the Nat Lab grew apace and among other well-known members of its staff were Balthasar van der Pol who published some two hundred papers on theoretical aspects of radio, with particular emphasis on relaxation oscillations, and Klaas Posthumus who, as we shall see, was a co-discoverer of negative feedback and also carried out pioneer work on split-anode magnetrons. Apart from Bernard Tellegen, a prolific generator of ideas who still comes to the Nat Lab regularly to "work on things which interest him" and Klaas Posthumus, the other men we have mentioned are now dead.

Arthur Garratt visited the Nat Lab at Eindhoven and recorded an interview with Bernard Tellegen who explained how the pentode and gyrator came into being and also traced the history of wave interaction in the ionosphere, the so-called Luxembourg Effect.

Bernardus Dominicus Hubertus Tellegen, to give him his full name, was born in 1900 and trained as an electrical engineer at Delft Technical University, graduating in 1923. After completing his military service he joined the Nat Lab in May 1924 and spent his entire working career with Philips. Arthur Garratt asked him if he immediately joined Van der Pol's radio group:

TELLEGEN Not immediately, this happened a few years later. When I first joined Philips I worked with Oosterhuis. One of my first assignments was a tungsten arc lamp which had recently been developed in the Nat Lab. This operated well on d.c. and we tried to make it work on a.c. by using some kind of transformer – unfortunately this was not successful. After that I worked on the development of a battery eliminator; this was taken over by someone else who carried it through to production.

It was after this that I joined Van der Pol. From the beginning I was more theoretically than practically minded and this naturally caused me to gravitate towards Van der Pol, and I started in the field of radio about which I didn't know a great deal at that time. However, I studied a paper of Van der Pol's – a general paper on electron paths; this was my introduction to radio. I then began to study amplification. W. Schottky had written some papers on screen grid tubes (tetrodes) and these interested me very much. I also read papers on the use of triodes as output tubes and I observed that the triode should have a low internal resistance in order to get the maximum output. Then I put the two tubes together in my mind – I realised that with the tetrode you move the anode-current/grid voltage characteristics over to the left and this was clearly a desirable thing to do. I did some calculations – nothing about secondary emission at this stage – and I came to the conclusion that a screen grid tube, notwithstanding its high internal resistance, was very well fitted to the role of an output tube. You must remember that these were the days when the anode supply was from dry batteries and we wanted the maximum output from a given battery voltage. From this starting point I saw that one should not only get a higher output but also greater stage gain and less frequency distortion because the current in the loudspeaker should then be proportional to the control grid voltage. Putting all these things together led me to the conclusion that a tetrode should make an excellent output tube.

Professor Bernard Tellegen, now aged 79, at the Natuurkundig Laboratorium in Eindhoven, Netherlands

Of course, when you try this out you immediately come up against the problem of secondary emission. Secondary electrons are always emitted when primary electrons strike an electrode with an energy above about 10eV. In a triode they have no effect because they are drawn back to the electrode from which they are emitted, but in a screen grid tube secondary electrons emitted from the anode are attracted to the screen grid when the anode potential falls below that of the screen. This produces impossible distortion if the tube is driven hard – as an output tube must be. So I introduced a suppressor grid between the screen grid and the anode – this prevented the exchange of secondary electrons between the anode and the screen grid.

I talked with Holst about other means of suppressing secondary emission and he proposed some methods which were put into the patent – this was the reason that the patent itself is under the names of both Holst and me. In fact Holst's suggestions were never put into practice, the suppressor grid was successful and that was that.

GARRATT When you first constructed a tube with a suppressor grid, did it work right away or did you have to do more experiments?

TELLEGEN We had to do some experiments to measure anode current as a function of anode voltage at various values of suppressor voltage. You can find these in the original paper together with some of the results. The optimum dimensions for the suppressor grid were later studied by Jonker in the Nat Lab, but at the beginning we did not have much difficulty in finding a reasonable construction for the suppressor grid.

GARRATT When you found this was a satisfactory tube, had you any realisation at that time of the implications of the pentode to the radio industry?

TELLEGEN Well the effect it would have on the industry was too big a world for me! As far as I was concerned it was a tube which could be used practically in a radio receiver. It was just at this time that the first receivers that Philips had decided to build were under construction and new ideas were coming in from every side. Not only was there the pentode, but also the indirectly heated triode as a detector and what was called the 'Hull tube' (named after A. W. Hull who had studied a screen grid tube designed to, have a very low anode/grid capacitance). Hull had stated in the paper describing this tube that it was purely experimental and was not intended as a production tube. It was Posthumus who developed the idea into a practical tube. So our first commercial mains set had a screen grid r.f. amplifier tube with a very low anode/grid capacitance, an indirectly heated triode and a pentode output tube.

GARRATT Was the pentode indirectly heated as well?

TELLEGEN No, the pentode was directly heated off a.c. There were actually two sets, a battery version which was, of course, d.c. throughout and the a.c. mains version.

GARRATT This was the a.f. péntode. How did the r.f. pentode come into being?

TELLEGEN I think the first r.f. pentodes were constructed by Bell Telephones who needed rather high r.f. voltages. They realised the importance of the pentode for r.f. amplification – this was also covered by the original patent.

GARRATT The patent is interesting. Philips patented the pentode in eighteen countries, but it was never patented in the Netherlands – why was this?

TELLEGEN The reason was that some date was overlooked. When you apply for a patent in the Netherlands you get a letter back saying, "We have such and such objections and we want certain information" before a certain date. Because of some administrative error, the expiry date was overlooked. Despite efforts to get permission from the Dutch Patent Office to extend the time, they refused and this is why the patent was not granted in the Netherlands.

GARRATT This was a patent immense importance to Philips. It raised a great deal of money . . .

TELLEGEN Yes, and it opened doors – the doors of other important electronics firms.

GARRATT It was about this time that your colleague, Posthumus, was working on negative feedback. Negative feedback is generally attributed to H. S. Black of Bell Telephones, but Posthumus was working on it almost simultaneously.

TELLEGEN You can say "simultaneously" and quite unknown to each other.

GARRATT In fact there was an interesting difference. Black used a bridge circuit while the circuit Posthumus developed was much more like the feedback circuitry used in radio today.

TELLEGEN Yes, Black concentrated largely on telephone applications where a bridge was necessary, while Posthumus was interested in radio sets – so the two men had rather different points of view.

GARRATT Negative feedback took some time to get into commercial practice.

TELLEGEN It was used in radio sets because there were objections that pentode output tubes gave third harmonic distortion due to the impedance of the loudspeaker rising with frequency. This could be overcome by applying negative feedback but it took a number of years before it was used generally in radio receivers.

GARRATT What about its use in telephony?

TELLEGEN At that time Philips were not in the telephone business while Bell, on the other hand, were primarily interested in telephones and, I believe, they used negative feedback commercially before Philips.

GARRATT At that time, at the end of the twenties and beginning of the thirties, the Philips Nat Lab was very much in the front row. In electronics, you had produced the pentode, Posthumus had produced negative feedback simultaneously with Black and he had also done pioneer work on the magnetron, Van der Pol was doing a great deal of important theoretical work – this must have been a remarkable time and place to be doing research?

TELLEGEN That's right. It was very stimulating to work on these problems and it was not very difficult to make progress in different directions and to find new applications for one's ideas. It was very exciting for all of us.

GARRATT A little later on came the beam tetrode output tube, another way of avoiding the effects of secondary emission . . .

TELLEGEN And a way of avoiding the patents!

The Luxembourg Effect

GARRATT You were also a pioneer i the discovery of what was originall called the 'Luxembourg Effect'.

TELLEGEN Yes, it's now called "wav interaction". After some time with Va der Pol I had moved to work in th group headed by Oosterhuis. Van de Pol and I looked at things from a dif ferent point of view. He was a physicis I am an engineer. Van der Pol wa almost exclusively interested in under standing things, I thought understan ding was no use if you didn't *apply* th results in the right way – that's th point of view of an engineer. This is wh after some years I joined Oosterhuis group which was busy developing radi receivers. One problem we faced wa cross-modulation, so we built straigh sets with two tuned circuits in front o the first tube – by increasing the sele tivity before the first tube we reduce the cross-modulation. We had buil such an experimental receiver in whic we were quite certain we had eliminate all cross-modulation and I tested thi out at home. I found that when I wa listening to the Swiss station Ber münster I could hear another statio faintly in the background. This puzzle me a lot. I thought to myself this can' be cross-modulation as we had take every possible measure to eliminate it. could only hear the second station whe there was silence in the Beromünste programme. I tuned around and foun that the interfering programme wa being broadcast by Radio Luxembour

GARRATT Which was a long-wave sta tion.

TELLEGEN Yes, a long-wave station. called my friend Rinia and told him t listen in. He did so and got the sam effect. At first we thought it migh perhaps be something complex hap pening in the electric light mains. So w went outside the town and repeated th experiment . . . and got the same result I then realised that Luxembourg wa just about half way between Eindhove and Beromünster and was a ver powerful station transmitting a lot energy into the ionosphere and som thing must be happening in th ionosphere that affected the signal fro Beromünster on its way to Eindhove and this was the reason for the inte ference.

The ionosphere was outside my fiel but when people reported similar e periences with other receivers it becam obvious that the effect was not cause by something in the receiver but mu occur in the ionosphere. So I wrote letter to *Nature* which was du published. G. W. O. Howe wrote a editorial about it in the *Wireless Engi eer* and he called it the "Telleg Effect", but that didn't stick and became known as wave interaction. was V. A. Bailey in Australia, a ma working on the ionosphere, who eve

...ually explained exactly what was happening – the mean-free path of the electrons in the ionosphere was being influenced by an external field, the r.f. field, and so one transmission was modulated by the other.

GARRATT What did you do during the war, when there were Germans in the Nat Lab?

TELLEGEN Having worked on circuit problems in connection with radio receivers, I had become interested in circuit theory. We used to run courses for each other in the laboratory – I gave a course on circuit theory, one of my colleagues took notes and it was later reproduced and I eventually extended it into a book. The notes came into the hands of one of the professors of electrical engineering at Delft Technical University. He suggested to me that I should come to Delft and lecture in this field. As a result I became an Extraordinary Professor there in 1947 – Extraordinary in this sense means part-time. It was the policy of Delft University to have some specialists from industry to lecture on their particular specialities to the students in order to establish closer ties between the university and industry. This was how I first came to Delft and I continued there for twenty years.

GARRATT And you received a doctorate from Delft?

TELLEGEN I retired from Delft in 1968 and the following year I was awarded a doctorate in electrical engineering. Needless to say this pleased me very much.

The Gyrator

GARRATT As though the pentode and the Luxembourg Effect were not enough for one man, you worked in several other areas?

TELLEGEN Yes, first of all on receiving tubes, then on complete receivers and later, on circuit theory which led to the gyrator.

GARRATT How did the concept of the gyrator arise?

TELLEGEN Around 1930 I was studying the properties of loudspeakers. The first equations concerning loudspeakers and telephones were developed by Poincaré. They are electro-mechanical systems, that can be described as systems with two ports – an electrical one and a mechanical one, which are related to each other by the telephone system. When you write down the equations something very curious happens depending on how you relate the electrical and mechanical quantities. If we say a current corresponds to a velocity and a voltage corresponds to a force and you write the two-port equations in these quantities for an electromagnetic telephone, you get a set of equations which don't obey reciprocity, but if you do this for an electrostatic telephone the equations *do* obey reciprocity. Reciprocity, which is a property of a two-port, can be expressed as a mathematical relationship between the equations which link the current through one port to the voltage across the other port when the two-ports consist of standard circuit elements, namely resistors, capacitors and inductors.

Reciprocity is one of the important general properties in electrical networks – of course I was aware of these properties – but the telephone introduced equations which were of a different type. I realised that you could combine an electromagnetic and an electrostatic telephone in such a way that you have an electrical input and an electrical output; in principle, at least, you could imagine an electrical two-port which did not obey reciprocity. This led to the concept of two sets of equations; one pair defined an ideal transformer, which is a separate network element, the other pair defined another separate network element which I called a *gyrator*. In the transformer there is a proportionality between primary and secondary voltages and also between primary and secondary currents. In the gyrator there is a proportionality between primary voltage and secondary current and also between primary current and secondary voltage. The gyrator is thus defined but I had no means of realising it in the field in which I was working, i.e. radio receiver design. But I kept it in mind and during the war I pondered over the possibility of trying to find some means of actually realising it without mechanical means – I had been carrying the equations around for some years on a small piece of paper. Well eventually I found a means by using the gyromagnetic effects in ferrites and I carried out some experiments. When the war was over I wrote a paper about it – the time was then ripe for publication. During the war I had written a number of laboratory notes about the gyrator and I remember that when the Germans came around I collected all these notes and put them away so that they wouldn't get into Nazi hands.

The gyrator is connected in a way with a very famous book, *A Treatise on Natural Philosophy*, by Thomson and Tait, which was very well known among physicists at the end of the nineteenth century. It was Thomson and Tait's book which had everything about mechanics in it. It discussed vibrations of small amplitude which are described by linear equations. In these equations special terms may occur, called by the authors "gyroscopic" or "gyrostatic" terms because they occur when flywheels in a state of rapid rotation form part of the system by being mounted on frictionless bearings connected through a framework with other parts of the system, and because they occur when the motion considered is motion of the given system relative to a rigid body revolving with a constrained constant angular velocity round a fixed axis. What I did was related to this and, as a result, I found a good name for the element – *gyrator*, the *gyra* from *gyroscope* and the final *tor* from many other electrical words like *capacitor*, *inductor* and *transformator* (Dutch). Gyrator is a practical word and can be used equally well in English, German and French – it's short and the *tor* implies that it is electrical. If you want to popularise a concept it is very important to have a good name for it. This did a lot to arouse interest in the concept of the gyrator.

GARRATT So you were the inventor of the gyrator as well as the pentode?

TELLEGEN It depends what you mean by inventor. The gyrator has been the subject of some patent applications. As I said before, I realised in 1930 that by combining electrostatic and electromagnetic loudspeakers you can, at least on paper, find pairs of equations that are non-reciprocal. I didn't publish it at the time; it was published by E. M. McMillan in the United States some years before my paper on the gyrator. So whether you call me the inventor is up to you, but certainly I invented the name.

GARRATT When was the gyrator first used practically?

TELLEGEN It was first put into practice by Bell Telephones. They realised before I did that you could use gyromagnetic effects in microwave technology – Casimir (one of the Directors of the Nat Lab at the time) was not very happy about this! I had missed the point, but then I was always thinking more about the frequencies used in ordinary radio receivers than about microwaves – these were not my special field. Perhaps it was stupid of me not to have looked into this. I had realised that the gyromagnetic effect could be very much greater at high frequencies than at lower ones, but they took this very much farther at Bell and introduced ferrites and waveguides and various other things related to gyrators. There are several things you can do with gyrators in waveguides and so introduce non-reciprocal effects.

Gyrators are now very popular and can be realised in an extremely efficient manner using solid-state components. This did not interest me at first because the gyrator itself is a passive element. With active networks the field is very much broader and, at first, there is very little reason to limit yourself to producing a passive element by active means. But it turns out that it is valuable even in active networks; for filters, for example, it has proved very useful.