(Mr. Pai read his paper, marked No. 2.)
(Applause)

CHAIRMAN PENWELL: Are there any questions? If not, we will proceed.

Brian Jones, from Fairchild, is still with us. Come up, Brian. Brian is our next speaker. He was born and educated in England, and has worked for the Canadian Defense Research Board on transistor circuits. He has worked for Fairchild Semi-Conductor on high frequency transistor applications, Westinghouse Electric Corporation on integrated circuit design, and has worked for C-Cor Electronics on CATV and high frequency amplifier design. Presently he is with Fairchild in Palo Alto, California.

DISTORTION, VSWR and REVERSE TRANSMISSION IN BROADBAND TRANSISTOR AMPLIFIERS

by

BRIAN L. JONES

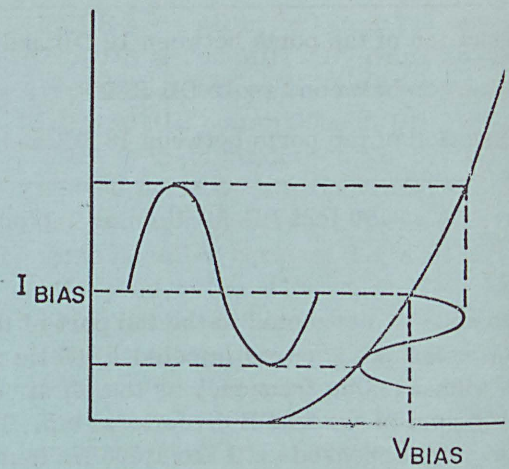
Transistor amplifiers produce distortion. This is a commonplace to everyone who is familiar with the cross-modulation of an overloaded CATV amplifier. Such amplifiers have a certain VSWR when introduced into a 75 Ω system and if this ratio is too high, reflections appear on the picture in the form of "ghosts". If an amplifier is inserted into a system backwards, that is, with the input signal to the output and the output signal to the input, the signal will be attenuated instead of amplified. The ratio of the input power to the output power under such circumstances is known as the reverse transmission. Similarly the gain of the amplifier is the forward transmission.

Now it may not be immediately obvious what connection these quantities may have and the purpose of this talk is to point out the inter-relationship between them. In order to do this I shall start by discussing some of the properties of transistors.

Figure 1 shows a typical curve of the relationship between collector current and base-emitter voltage of a transistor. This characteristic, a non-linear input voltage/output current relationship is the main source of distortion of transistors. This is illustrated by a sine-wave base emitter voltage which produces the distorted collector-current shown in the slide. It can be shown very easily mathematically that if the input signal voltage consists of two or more amplitude-modulated RF signals, cross-modulation will result. The forward transmission of the transistor is non-linear and shows distortion.

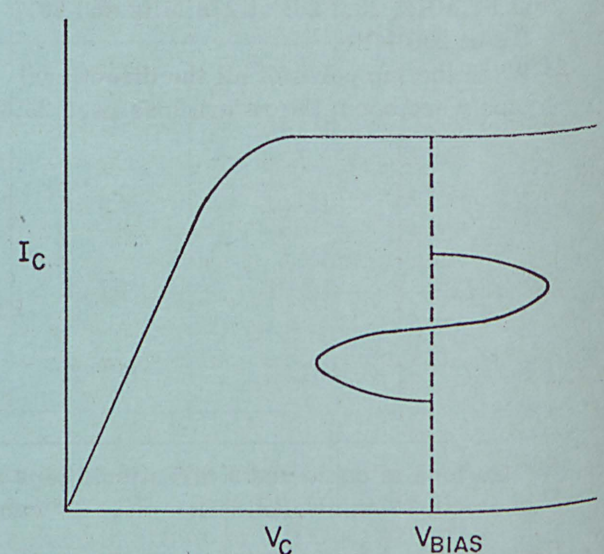
But what about the reverse transmission? If we apply a voltage to the collector of a transistor, will the resulting current show distortion? At first sight,

Figure 1



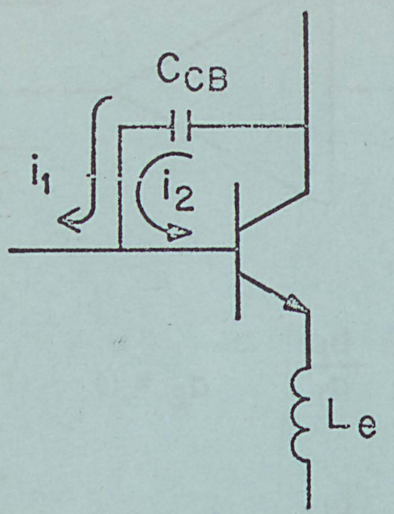
it would appear not. The low frequency collector characteristics are shown in Figure 2. It would appear that the collector current remains nearly constant regardless of the voltage swing on the collector. The transistor is a good constant current source at low frequencies; that is, it's output current depends only on the base voltage. It is also clear from this figure that what happens at the output has very little effect on the input, i.e., the transistor has a low reverse transmission.

Figure 2



At high frequencies, however, none of the foregoing remains true. There are certain undesirable properties of the transistor, known as parasitics, which give the transistor considerable reverse transmission. Figure 3 shows the two main parasitic resistances: the emitter inductance and the

Figure 3



collector base capacitance. The emitter inductance increases the reverse transmission because it is common to input and output circuits. The collector-base capacitance provides a direct path from output to input. Although the emitter inductance can be quite important in some transistors, I will only consider the collector base capacitance which is usually dominant.

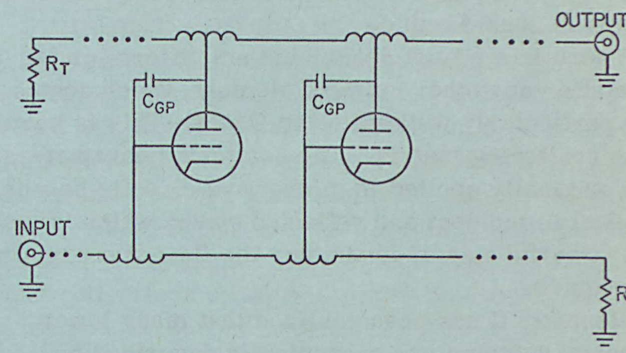
This capacitance is rather peculiar, inasmuch as it's value varies with voltage -- it is non-linear; thus the reverse transmission of the transistor is non-linear. This means that if a signal voltage is applied to the collector there will be a distorted current flowing out of the base. Part of this current will flow into the external circuitry, but part of it will flow back into the transistor base where it will be amplified, causing a distorted collector current to flow. The new result of all this is that the output impedance appears non-linear and contributes cross-modulation and other distortion to the amplifier characteristics.

Let us now suppose that the transistor is driven from a high impedance source. If this is the case i_1 will be zero and the whole of the feedback current will flow back into the transistor. The distortion will thus be greatest in this case and will be less if the transistor is fed from some finite impedance.

The important point is that the distortion resulting from a signal at the output is dependent on the conditions in the input. Everyone who has worked with transistors at high frequencies knows that what is done at the output affects the input and this is also true of distortion.

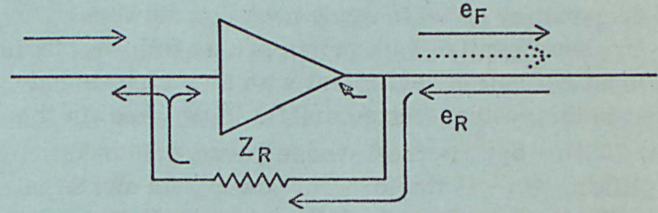
Let us leave transistor amplifiers for a moment and consider an old fashioned tube amplifier of the distributed type. Part of a typical circuit is shown in Figure 4. Two differences from the transistor amplifier are immediately noticeable. These are (1) the output impedance is matched to the 75 Ω cable by a resistor, not by the output impedance of the tube and (2) the tube amplifier also has feedback capacitance but it does not vary with the output voltage. It is a constant capacity determined only by the tube electrode geometry and it is included in the artificial transmission line; thus reflected waves are terminated in R_T the terminating resistor and do not modulate the tube characteristic significantly.

Figure 4



The importance of this point can be seen in Figure 5. The amplifier in this diagram is assumed to be perfect, that is, it has no reverse transmission. All real amplifiers have some reverse transmission however and this is simulated by the green resistor. We can see that if there are reflections on the output cable, the effect of these reflections will be felt at the amplifier input and amplified, resulting in a change at the output.

Figure 5



Now consider the case where the reverse impedance Z_R is non-linear, which is the case in transistor amplifiers. The reflected wave will be distorted as it travels back through the amplifier and the resulting amplified wave will show cross-modulation and other forms of distortion. If we look into the output impedance of the amplifier it appears non-linear.

The other important point to make here is that the output impedance and VSWR depends on the source impedance connected to the input of the amplifier. Usually amplifiers have their input and output VSWR specified when the other part is well matched. Sometimes, however, this is not the case in practice. If the output part is connected to a short length of cable which is terminated in a component of poor VSWR then not only will there be reflections at the output if the reverse transmission of the amplifier is considerable, there will be reflections at the input also.

This is a simple test of the reverse transmission of an amplifier. If the VSWR at the input is different, depending on whether the output is terminated in 75 Ω or not then you can conclude that the reverse transmission is considerable.

There is a way of describing amplifiers, or for that matter any other network element, which seems to be particularly well suited to CATV. This is known as the scattering matrix. The scattering parameters were originally applied in microwave circuits because they deal in incident and reflected waves which is the most powerful way of describing the flow of energy in a waveguide.

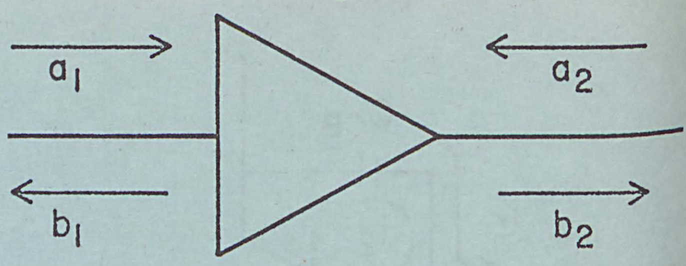
Recently it has been realized that many lower frequency systems are conveniently described by scattering parameters. CATV systems being coaxial throughout are usually considered as having incident and reflected waves and the scattering parameters include a measure of the forward and reverse transmission.

In Figure 6 the scattering parameters are defined. The waves a_1, b_1, a_2, and b_2 differ from voltage waves in that they have the dimensions of the square-root of power. That is, if you square them you will get power. They are also normalized to some impedance level, which is usually 1 Ω. In the present case it would be more useful to normalize to 75 Ω.

There is not time for a full discussion of scattering parameters and anyone who is interested in delving deeper may do so in many books on network theory; however the main points are as follows: S_1 is the input reflection coefficient with the output terminated in the system characteristic impedance (in this case 75 Ω). $|S_r|^2$ is the reverse power gain of the amplifier, $|S_f|^2$ is the forward power gain and S_o is the reflection coefficient of the output with the input terminated properly.

It can be seen that these four scattering parameters give all the information necessary to evaluate the performance of an amplifier, with the exception of distortion. In particular, a knowledge of S_r enables one to calculate the input VSWR when the output is terminated on a non-ideal load. The calculation is shown in Figure 7.

Figure 6



$$S_{11} = \frac{b_1}{a_1} \qquad a_2 = 0$$

$$S_{12} = \frac{b_1}{a_2} \qquad a_1 = 0$$

$$S_{21} = \frac{b_2}{a_1} \qquad a_2 = 0$$

$$S_{22} = \frac{b_2}{a_2} \qquad a_1 = 0$$

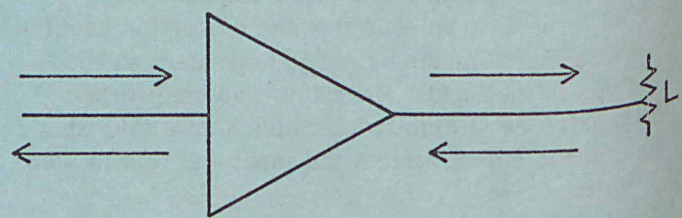
This equation:

$$\rho_{in} = S_i + \frac{S_r S_f \rho_o}{1 - S_{22}\rho_o}$$

is easy to solve if the scattering parameters are given.

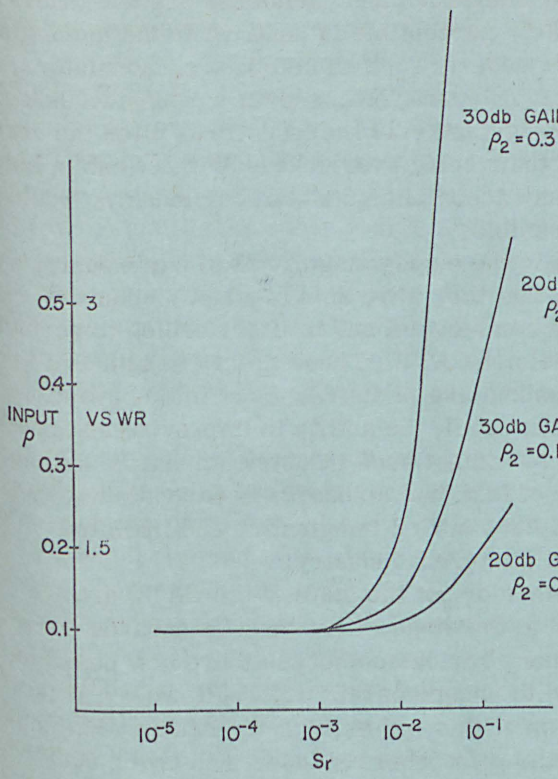
Figure 8 shows the variation of input reflection coefficient versus reverse transmission. Notice the importance of forward gain. As the gain of an amplifier is increased the reverse loss must be

Figure 7



$$\rho_{IN} = S_i + \frac{S_r \; S_f \; \rho_L}{1 - S_o \rho_L}$$

Figure 8



correspondingly increased, otherwise the input will become too sensitive to output reflections.

The ordinate of this graph is plotted as S_r and since $|S_r|^2$ is the reverse power transmission we can simply take

$$20 \log \left| \frac{1}{S_r} \right|$$

if we wish to know the reverse loss in dB. Thus if S_r is 0.1 the reverse loss is 20 dB. You can see from the curve that the amount of S_r that be tolerated depends on the forward gain or S_f. 40 dB reverse loss would be a good figure for an amplifier with 20 dB gain but if the amplifier gain is raised to 30 dB the reverse loss must be raised to 50 dB to give the same isolation of input from output.

These transistor characteristics impose a heavy burden on the amplifier designer. At Fairchild we are trying to improve the devices used for linear broadband amplifiers and one of the most important things is to reduce the reverse transmission. The preliminary results of this work indicate that considerable improvement is possible over currently available devices. The improvement can be expected to be passed on to the amplifier designers in the near future.

In some transistors there is a distortion cancellation effect which arises because the phase of the S_r distortion. When the load VSWR is poor, the distortion may be disturbed and there is a dramatic increase of cross-modulation. If the reverse transmission of the amplifier is reduced the cross-modulation becomes nearly independent of the load.

(Mr. Jones read his paper, marked No. 3.) (Applause)

CHAIRMAN PENWELL: Are there any questions?

MR. BERNARD EVANS (Malibu): I am curious about whether this reverse transfer characteristic is feeding back through an amplifier. I can see where this would be quite a factor on, say, a one-transistor extender, where you had virtually no isolation; but on a practical amplifier, say three or four devices, is this not quite minimized by the time it gets back through all these four stages, or do your reflections occur within the coupling of the last stage and the second before the last stage?

MR. JONES: In a well-designed amplifier I think you are right. If the forward gain were 20 db and the reverse loss were 60 db, for example, you probably would be quite well off. But, as you say, there are reflections which occur at the input to the last stage.

MR. EVANS: This is the most troublesome spot, then, I presume?

MR. JONES: Yes.

CHAIRMAN PENWELL: Thank you, Brian. I have learned a new parameter today, reverse gain. Maybe we will see that on the spec sheets some day.

During the course of this convention a lot of interest and activity has developed over the mounting chaos in standards of the CATV business. People in the business session have their own brand of chaos. We have wrestled with some of our problems. Archer Taylor, who is Chairman of the Engineering Subcommittee of the NCTA Standards Committee, has asked that we present Mr. Sidney A. Mills at this time, to talk about the problem of cable standardization.

Sid is Vice President of Production and Engineering of Ameco Cable, Inc., Phoenix, Arizona. He graduated in 1949 from Syracuse with his EE. He was in the U.S. Signal Corps following graduation for two years, and from 1952 to 1966 he was Senior Product Engineer for Rohn Cable. Presently he is with Ameco. Sid Mills.