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CYCLOTRON WAVE AMPLIFICATION USING SELF GENERATED PUMP POWER

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RESEARCH REPORT NO 66

CYCLOTRON WAVE AMPLIFICATION USING SELF GENERATED PUMP POWER

By

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NONLINEAR MICROWAVE TUBE PHYSICS

Technical Note No 13 15 December 1966

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TABLE OF CONTENTS

ABSTRACT

This report describes measurements on an amplifier system consisting of two cascaded Adler tubes with a traveling wave tube (TWT) to amplify the pump signal. The latter was produced by the signal itself in the quadrupole of one of the Adler tubes. By so doing the pump voltage was phase locked to the signal.

Two cases were investigated. In one case the pump power was generated in the first Adler tube, amplified in the TWT and then used for pumping the second Adler tube. The dB gain of this system is a linear function of the input signal power. In the other case the pump power was taken from the second Adler tube, amplified in the TWT and then fed back to pump the first Adler tube. Now the dB gain becomes a linear function of the output power. A theoretically predicted hysteresis effect was experimentally verified.

I. INTRODUCTION AND SUMMARY

A cyclotron wave tube (Adler tube) with two quadrupoles can be used in an interesting nonlinear amplifier system. The characteristic feature of this system is that the pumping power is produced by the signal itself in one of the quadrupoles and, after external amplification, used in the other quadrupole to amplify or attenuate the signal.

The frequency and power conversion properties of the quadrupole and the behaviour of the nonlinear amplifier system have been theoretically studied by Nilsson [1]. The present report deals with experiments on this system. The results are in very good agreement with Nilsson's theory.

Two ordinary Adler tubes rather than one tube with two quadrupoles were used. The tubes (Zenith Radio Research Corporation, type ZD-11, signal frequency 1280-1320 MHz) were coupled according to Fig. 1.

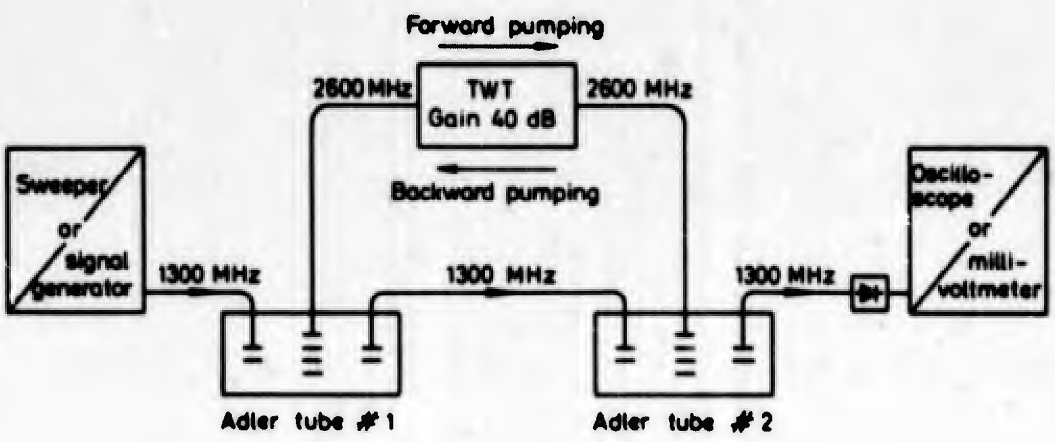

Fig. 1. Schematic of the cyclotron wave amplifier system with self generated pump power.

In the ordinary mode of operation of an Adler tube, pumping power is supplied to the quadrupole. However, in the system of Fig. 1, which uses two tubes, only one of the quadrupoles is pumped. In the other quadrupole the rotating beam induces a current of twice the signal frequency. This forms the source of the pump power which, after external amplification in a traveling wave tube, is fed to the pumped quadrupole.

Two different cases have to be considered. In the case of forward pumping the quadrupole of tube # 1 is the source while the quadrupole of tube # 2 is pumped. According to Nilsson [1] the signal gain G between the input of tube # 1 and the output of tube # 2 is, ignoring losses,

$$G \equiv \frac{P_{out}}{P_{in}} = e^{k P_{in}} \tag{1}$$

where k is a constant. It is assumed that the TWT is linear. Thus in this case the overall dB gain is proportional to the input power.

In the case of backward pumping the TWT is reversed so that tube # 1 is pumped while the quadrupole of tube # 2 becomes the pump source. The signal gain now becomes

$$G \equiv \frac{P_{out}}{P_{in}} = e^{k P_{out}} \tag{2}$$

which means that the overall dB gain is proportional to the output power. Eq. (2) is only valid when $\frac{d P_{out}}{d P_{in}} > 0$, i.e. when $k P_{out} < 1$ or, which is the same, $G < e$.

Since the pump voltage is produced by the input signal itself, the rotating field in the quadrupole is phase locked to the fast cyclotron signal wave. Thus, by adjusting the phase of the pumping voltage it is possible to either amplify or attenuate the cyclotron wave. This means that the constant k in Eqs. (1) and (2) can be made either positive or negative by changing the phase relation between the pump and the signal.

The experimental results for the forward pumping case are described in Section II while Section III is concerned with the backward pumping case. In both cases the extremes of maximum amplification and maximum attenuation are studied by varying the phase of the pumping voltage from fully in phase to fully out of phase with the signal. Some measurements, essentially concerned with power conversion in the quadrupole, are described in the Appendix.

II. EXPONENTIAL AMPLIFICATION AND ATTENUATION WITH FORWARD PUMPING

In this case the pump power is generated in tube # 1 and, after amplification in the TWT, fed to tube # 2 (Fig. 1). The

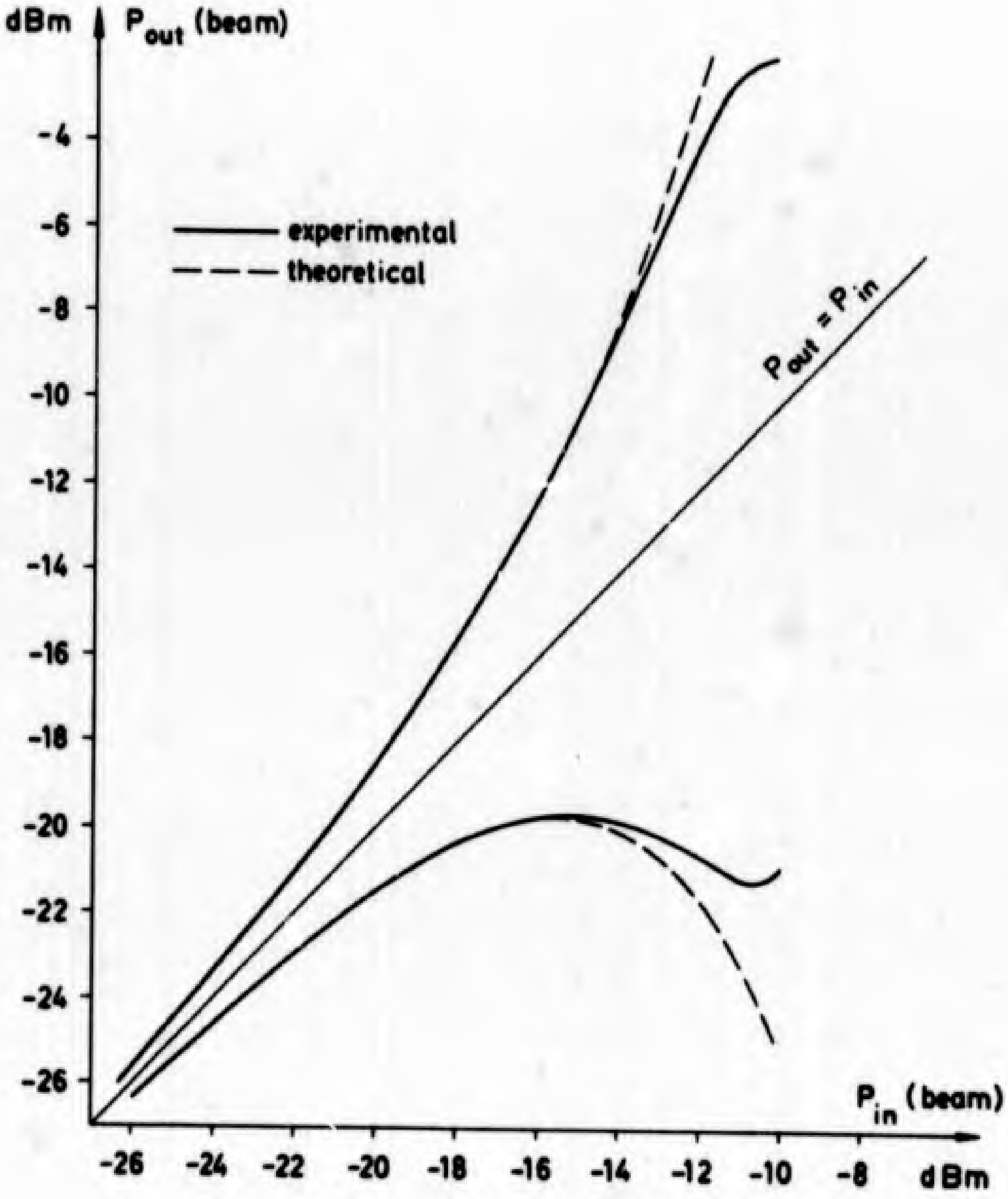

Fig. 2. P_{out} versus P_{in} (both refer to the signal power carried by the beam) with fully in phase and fully out of phase forward pumping.

experimental and the theoretical results for fully in phase and fully out of phase pumping, respectively, are shown in Fig. 2. P_{in} (beam) is the input power referred to the beam (i.e. after input coupling losses) in tube # 1 while P_{out} (beam) is the output power referred to the beam (i.e. before output coupling losses) in tube # 2, increased by the coupler and transmission losses between the two tubes. The expected theoretical result is described by Eq. (1), Section I. The experimental conditions are such that k takes the values $+4.0 \cdot 10^4\ W^{-1}$ (fully in phase pumping) and $-4.0 \cdot 10^4\ W^{-1}$ (fully out of phase pumping). The same results are shown in Fig. 3 in the form of dB gain

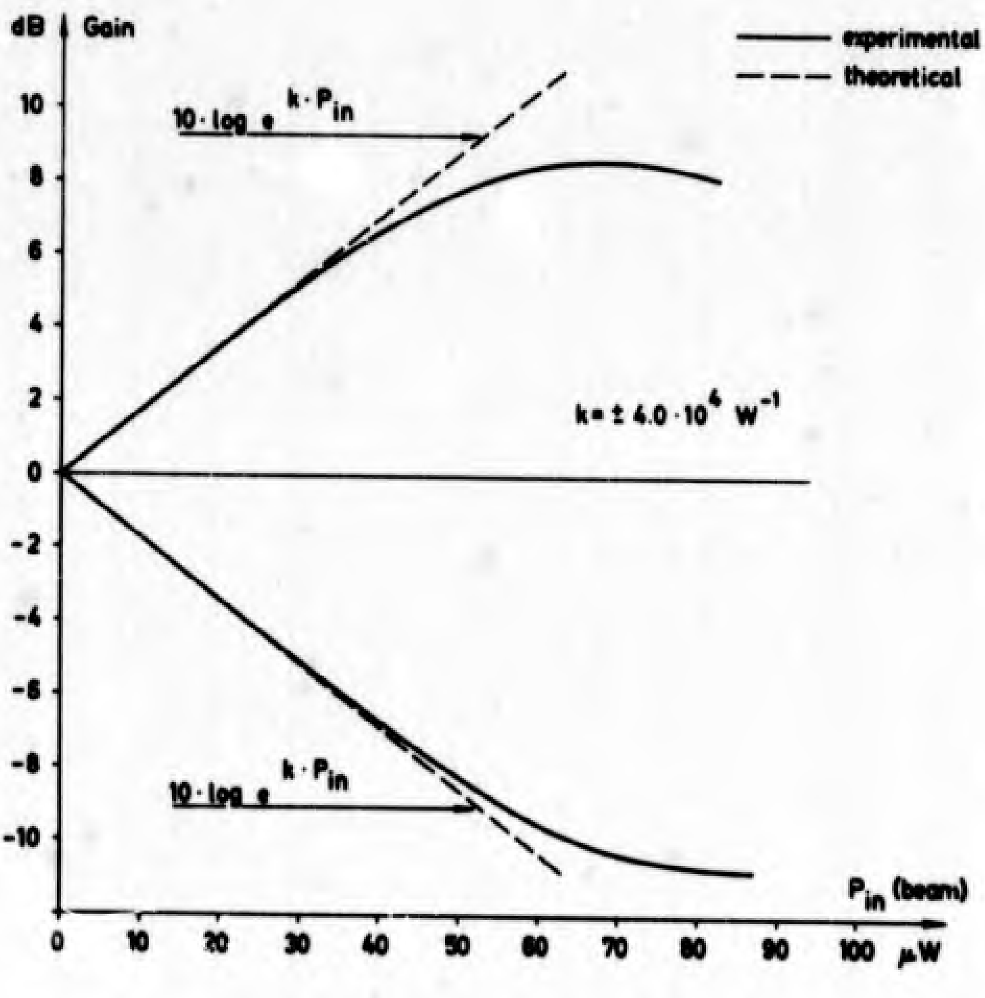

Fig. 3. Gain versus input power with fully in phase and fully out of phase forward pumping.

versus input power. [$G_{dB} \equiv 10 \log \frac{P_{out}\ (\text{beam})}{P_{in}\ (\text{beam})} = 4.34\, k\, P_{in}\ (\text{beam})$].

Fig. 3 demonstrates the linearity between gain (attenuation) and input power, for small input signals. The deviation from linearity at higher input power levels, in the out of phase pumping case, is caused by saturation effects in the TWT. In the case of in phase pumping, beam interception in tube # 2 (see Appendix) as well as TWT saturation spoil the linearity at high input power levels. With tubes particularly designed for the purpose it would be possible to considerably extend the linear gain range.

III. EXPONENTIAL AMPLIFICATION AND ATTENUATION WITH BACKWARD PUMPING

The pump power is now generated in tube # 2, amplified in the TWT and fed back to the quadrupole of tube # 1 (Fig. 1). The experimental results (solid curves) are shown in Fig. 4 together with Eq. (2), Section I, (dashed curves) where $k = \pm 4.0 \cdot 10^4 W^{-1}$. The definitions of P_{out} (beam) and P_{in} (beam) are the same as in Section II.

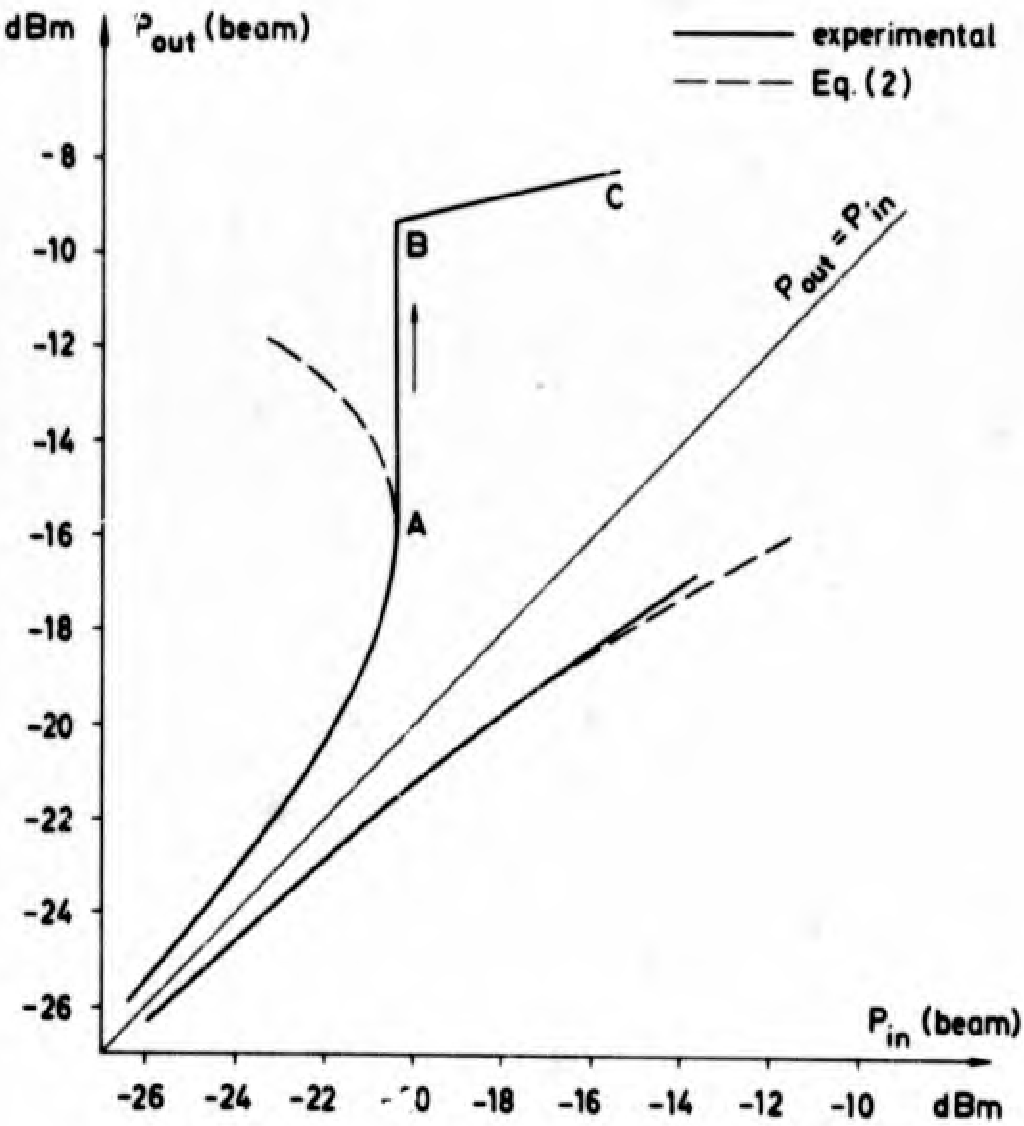

Fig. 4. P_{out} versus P_{in} (both refer to the signal power carried by the beam) with fully in phase and fully out of phase backward pumping. Upper curve is obtained for increasing input power only.

In the case of in phase pumping (positive k) there is an abrupt, step-like increase in P_{out} which occurs at the point A where $\frac{d\,P_{out}}{d\,P_{in}} = \infty$. According to Eq. (2) this corresponds to the condition $k\,P_{out} = 1$ or $k\,P_{in} = \frac{1}{e}$. When $k\,P_{in}$ is made larger than $\frac{1}{e}$, Eq. (2) is no longer valid and the output power is limited by the TWT in the external pumping loop [Ref. 1, p. 29]. It should be noted that the upper curve of Fig. 4 is obtained only when the input power is increasing.

Fig. 5 depicts the result shown in Fig. 4 as dB gain versus output power demonstrating that gain and attenuation, respectively, vary linearly with output power, for small output signals.

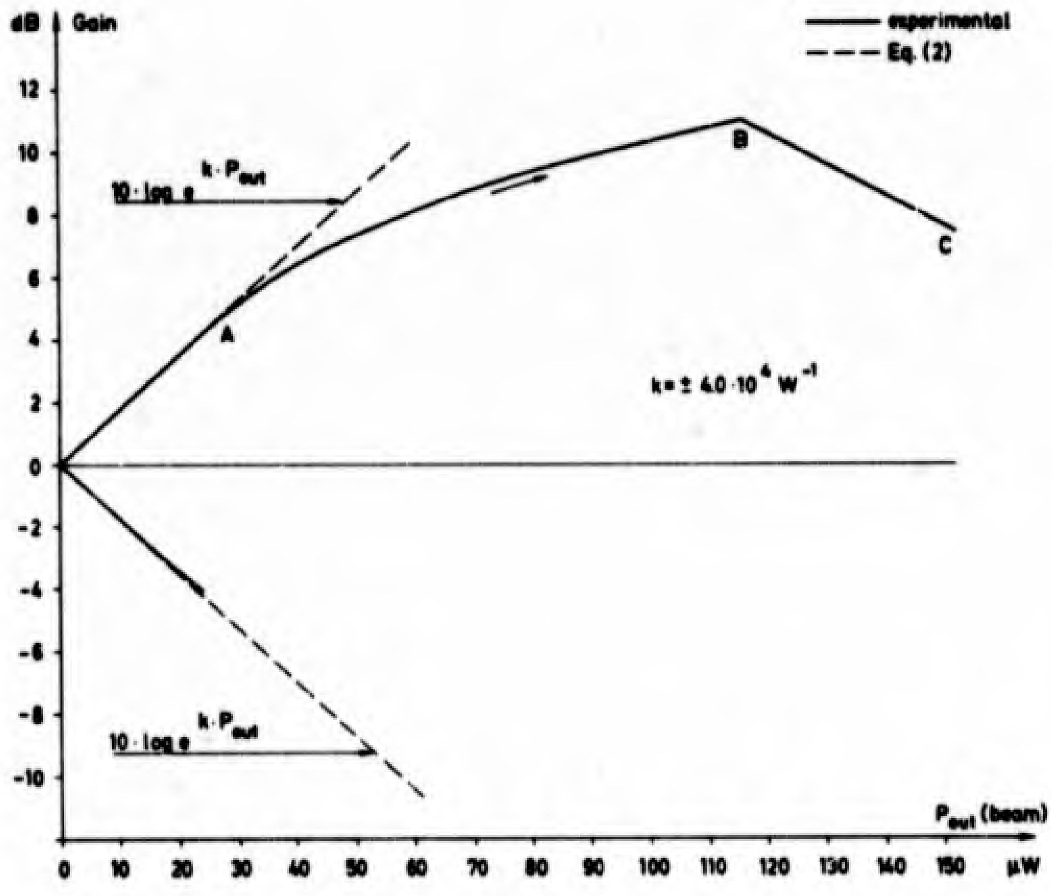

Fig. 5. Gain versus output power with fully in phase and fully out of phase backward pumping. Upper curve is obtained for increasing input power only.

Nilsson [Ref. 1, pp. 27-28] has pointed out that the abrupt change in output power, in the case of in phase backward pumping, occurs at different input power levels depending on whether the latter is increasing (as in Figs. 4 and 5) or decreasing.

An experimental recording of this hysteresis effect has been made. The result is presented in Fig. 6, which shows the fully in phase backward pumping case for increasing as well as decreasing input power.

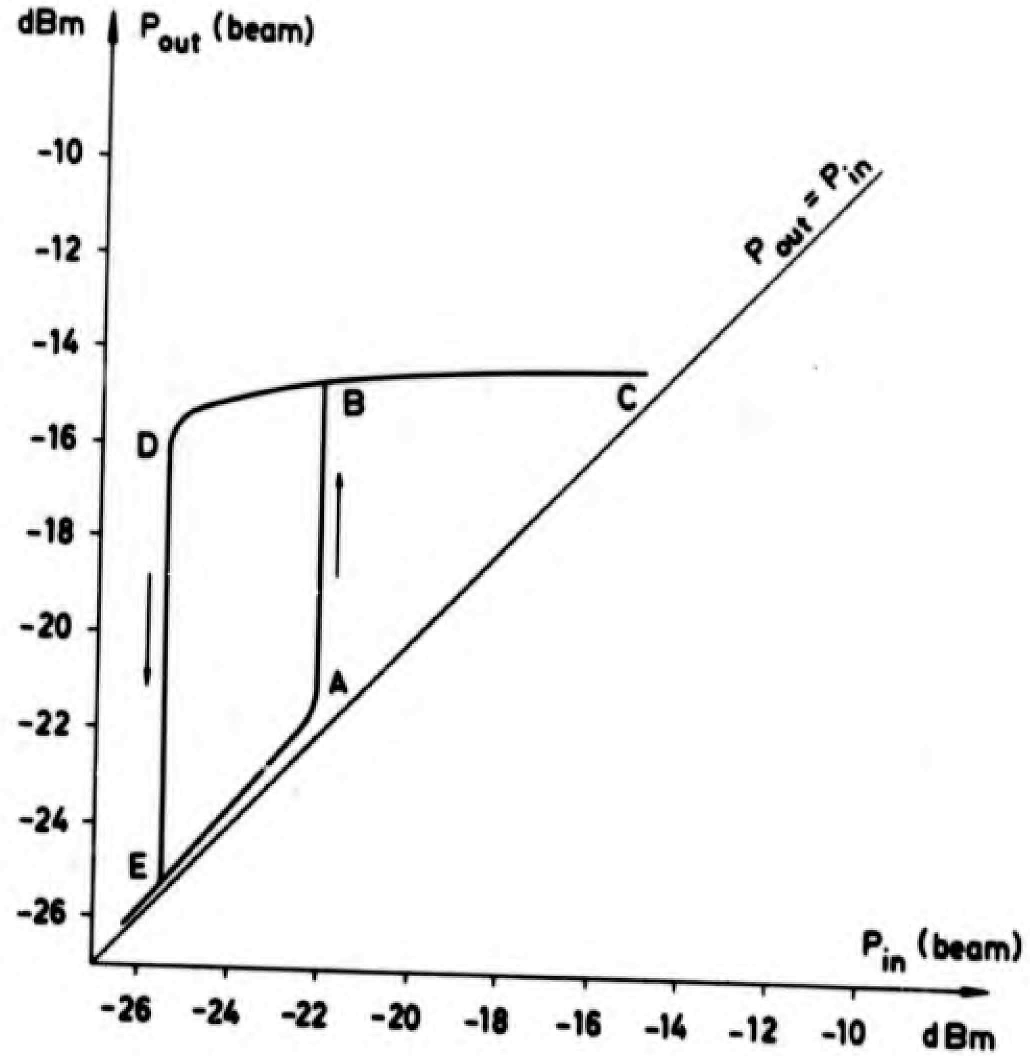

Fig. 6. Demonstrating the hysteresis effect in the case of fully in phase backward pumping.

In order to make the hysteresis effect more pronounced, i.e. to move the abrupt P_{out} changes further apart, the TWT was operated at a higher than normal helix voltage. This changed the TWT characteristics so that with increasing input power to the TWT its gain increases. Now the coefficient k in Eq. (2), instead of remaining constant, increases with increasing output power (in the P_{out} range -22 to -16 dBm).

IV. CONCLUDING REMARKS

Adler tube behaviour has been experimentally studied in two cases (Sections II and III), both characterized by the fact that the pump voltage is produced by the signal itself. A fraction of the signal is extracted, frequency-doubled and then, upon amplification, used as the pump voltage. Thus the pump voltage is phase locked to the signal and no idler signal is produced in the amplifying quadrupole.

In the first case (Section II) the pump voltage is generated (in the first quadrupole) by the signal cyclotron wave before the latter enters the amplifying quadrupole. In this case, called forward pumping, the signal gain is

$$\frac{P_{out}}{P_{in}} = e^{k P_{in}}$$

i.e. the gain varies exponentially with the input power (dB gain proportional to P_{in}). The coefficient k depends on the phase relation between the signal cyclotron wave and the pump field in the quadrupole. One can easily vary the phase of the pump field by varying the electrical length of the pump circuit. The coefficient k can also be made negative. In the experiments k could easily be varied in the range $-4.0 \cdot 10^4\ W^{-1} \leq k \leq 4.0 \cdot 10^4\ W^{-1}$ by varying the pump voltage phase. The simply controllable exponential gain-attenuation property of the system should be useful in certain modulator applications. One should then, of course, take measures to avoid beam interception, which limited the dynamic range of the system in the present experiments.

In the second case (Section III) the pump voltage is generated by the signal cyclotron wave after the latter has been amplified. In this case, called backward pumping, the signal gain is

$$\frac{P_{out}}{P_{in}} = e^{k P_{out}}$$

i.e. the gain varies exponentially with the output power (dB gain proportional to P_{out}). The coefficient k can be varied as already described. However, this expression is valid only when $P_{in} < \frac{1}{ek}$. For higher P_{in} values the gain becomes high and is limited by nonlinearities in the pump voltage circuit. The behaviour of the backward pumping system is complicated since in certain ranges the gain depends on whether P_{in} is increasing or decreasing and discontinuities appear in the gain characteristics.

The experiments described in this report are in excellent agreement with Nilsson's [1] theoretical predictions.

APPENDIX

This appendix gives some measured data for the Adler tubes used in the experiments. There was no significant difference between the two tubes so the data refer to both.

The signal power transmitted through a single tube in the absence of pumping ($P_{out\ 1300\ MHz}$) is shown in Fig. A1 versus the power input to the first Cuccia coupler ($P_{in\ 1300\ MHz}$). For small values of $P_{in\ 1300\ MHz}$ ($\lesssim -12$ dBm) the $P_{out\ 1300\ MHz}$ curve is parallel to and 1.4 dB below the line $P_{out} = P_{in}$. Thus the transmission loss is 1.4 dB. This loss is equally divided between the input and output Cuccia couplers (0.7 dB each).

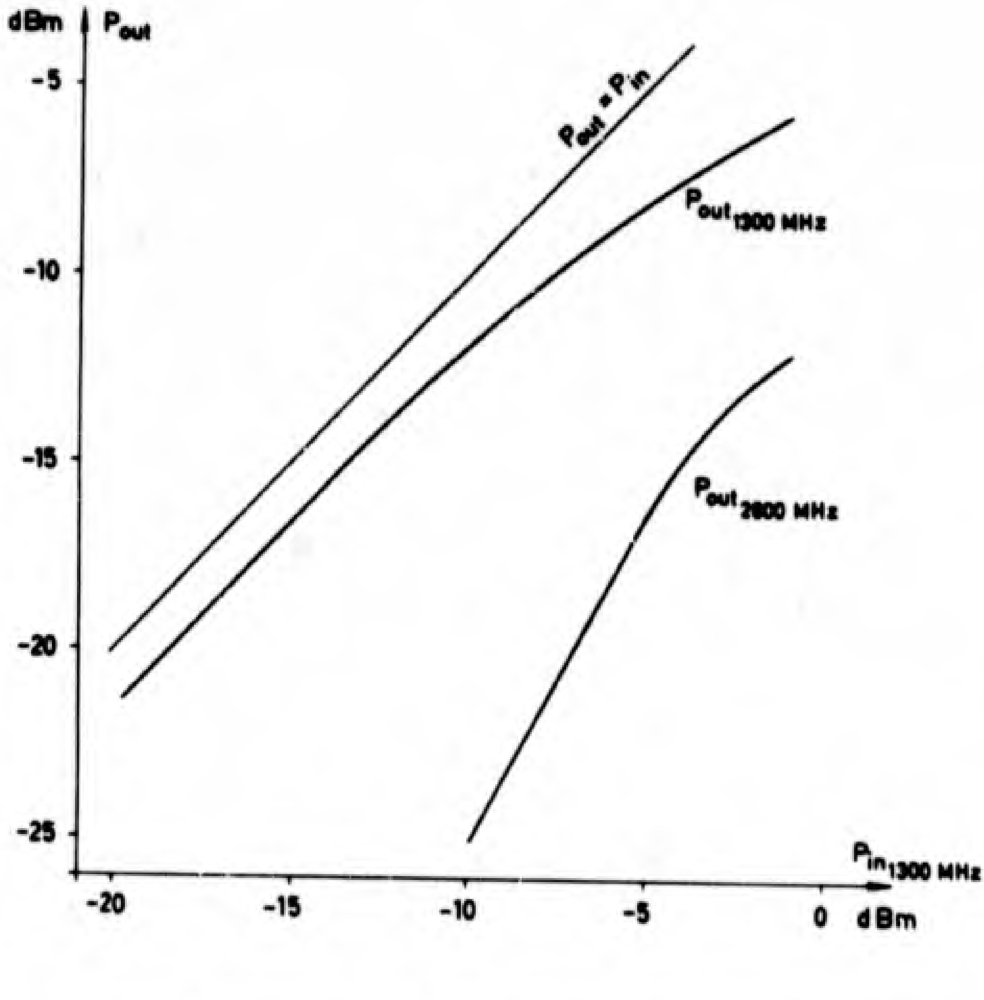

Fig. A1. Signal power transmitted through the Adler tube (1300 MHz) and frequency converted power delivered by the quadrupole (2600 MHz) versus signal input power.

The curve $P_{out\ 2600\ MHz}$ shows the frequency converted power delivered by the quadrupole to an external matched load. The source of this power is the signal power in the beam. The conversion process is nonlinear - for small enough $P_{in\ 1300\ MHz}$ ($\lessapprox$ -12 dBm), $P_{out\ 2600\ MHz} \propto P^2_{in\ 1300\ MHz}$. For higher $P_{in\ 1300\ MHz}$ it is expected that

$$P_{out\ 2600\ MHz} \propto P_{in\ 1300\ MHz} \cdot P_{out\ 1300\ MHz} \qquad \text{(A1)}$$

which corresponds to Eq. (45) in Reference [1]. From Eq. (A1)

$$\frac{d \log P_{out\ 2600\ MHz}}{d \log P_{in\ 1300\ MHz}} = 1 + \frac{d \log P_{out\ 1300\ MHz}}{d \log P_{in\ 1300\ MHz}} \qquad \text{(A2)}$$

which relates the slopes of the two curves in Fig. A1. An investigation shows that the slopes of the measured curves agree with Eq. (A2) when $P_{in\ 1300\ MHz} \lessapprox$ -4 dBm (400 μW). Beam interception spoils the agreement at higher input powers.

Knowing the input and output Cuccia coupler losses (0.7 dB each) and the terminal powers shown in Fig. A1, it is possible to obtain both $P_{out\ 1300\ MHz}$ and $P_{in\ 1300\ MHz}$ referred to the beam. These are shown as $P_{out\ 1300\ MHz}$ (beam) and $P_{in\ 1300\ MHz}$ (beam) in Fig. A2.

The vertical difference between the line $P_{out} = P_{in}$ and $P_{out\ 1300\ MHz}$ (beam) is the rf power lost by the beam between the two Cuccia couplers. At small input powers this lost power should simply be the power converted to 2600 MHz in the quadrupole. For $P_{in\ 1300\ MHz}$ (beam) $\lessapprox$ 330 μW the power lost is found to be 3.6 times the measured quadrupole output power [$P_{out\ 2600\ MHz}$ (measured)]. Consequently the quadrupole loss

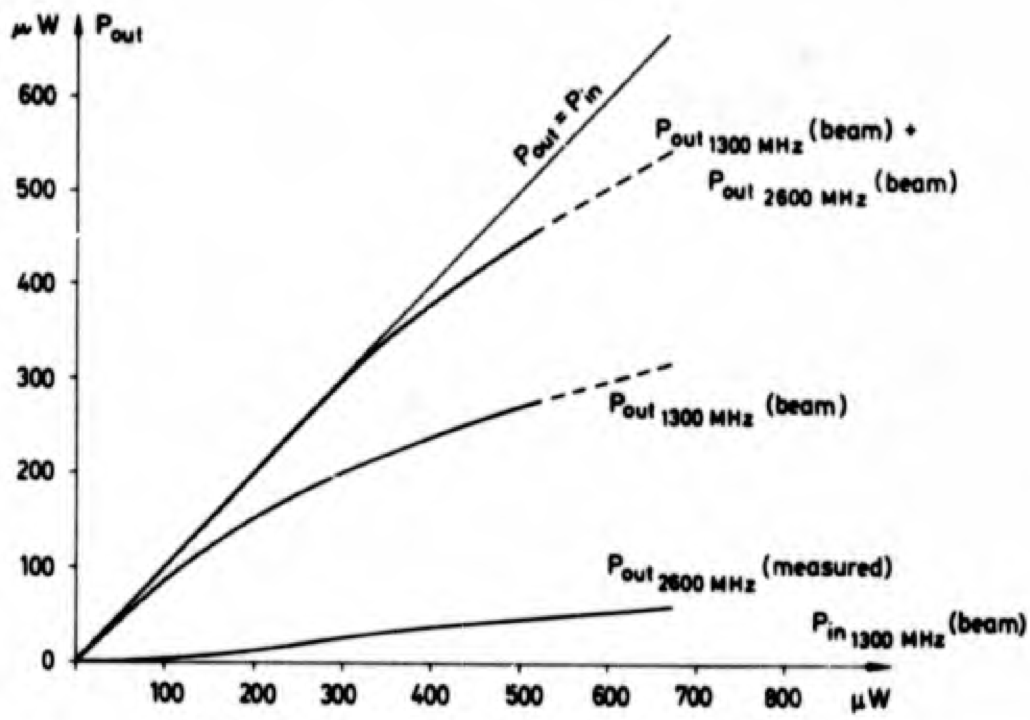

Fig. A2. Various output powers as functions of signal input power to the electron beam (see text).

is 3.6 (power ratio) or 5.5 dB. Thus,

$$P_{out\ 2600\ MHz}\ (beam) = 3.6\ P_{out\ 2600\ MHz}\ (measured)$$

For $P_{in\ 1300\ MHz}$ (beam) $\geq$ 330 μW Fig. A2 shows that

$$P_{in\ 1300\ MHz}\ (beam) > P_{out\ 1300\ MHz}\ (beam) + P_{out\ 2600\ MHz}\ (beam)$$

As already mentioned this power loss can be attributed to beam interception.

Finally the gain of one of the tubes in the ordinary degenerate mode of operation was measured using an external pump source.

The result, which includes the idler output power, is shown in

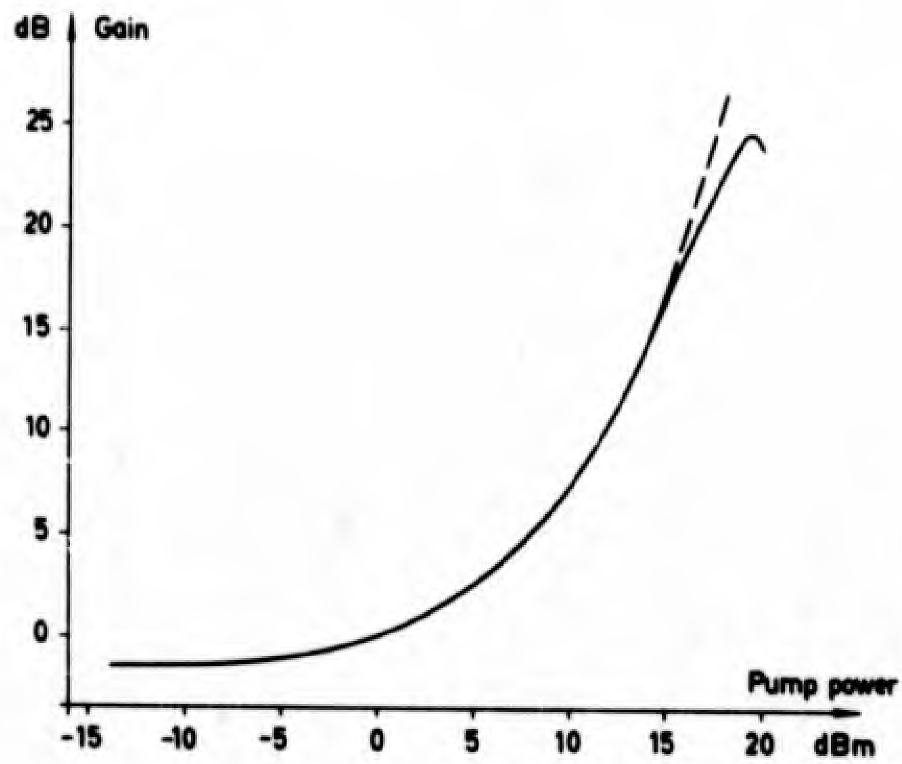

Fig. A3. Gain of tube # 1 (ordinary degenerate mode of operation) versus pump power (external pump source).

Fig. A3. The measured curve is compared to the theoretical expression

$$G_{dB} = 10 \log(\cosh 2A \sqrt{\text{pump power}}) - 1.4$$

where the number 1.4 accounts for the transmission loss and where the constant A has been chosen as 12.7 $W^{-\frac{1}{2}}$. The deviation between the two curves becomes noticeable when the gain exceeds 18 dB and is due to beam interception probably caused by orbit pumping [2].

ACKNOWLEDGEMENTS

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[2] R.Adler, A.Askin, and E.I.Gordon: Excitation and Amplification of Cyclotron Waves and Thermal Orbits in the Presence of Space Charge, J. Appl. Phys., 32, 4, 672-675, April 1961.

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13. ABSTRACT

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