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MULTIPLE FREQUENCY PARAMETRIC DEVICES

by

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MULTIPLE FREQUENCY PARAMETRIC DEVICES

ABSTRACT

Three special purpose single stage parametric amplifiers and converters are described and analyzed. They are:

(1) Regenerative Up-Converter: a regenerative non-inverting up-converter with a power gain higher than the theoretical limit for conventional up-converter

(2) Upper Sideband Amplifier: a parametric amplifier for signal frequency higher than pump frequency

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(3) Tunable to Fixed Frequency Converter: a converter with a tunable input frequency but a constant output frequency.

These are all four frequency devices.

CONCLUSIONS

While conventional parametric amplifiers and converters all have three frequencies, parametric devices having more frequencies can be designed to perform special functions which either cannot be achieved with conventional devices or otherwise require multiple stages of conventional devices. The ideas and analyses expressed here are applicable to parametric devices in general, including, for example, the ferromagnetic and electron beam types although the experiments were performed only with the semiconductor diodes.

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MULTIPLE FREQUENCY PARAMETRIC DEVICES

INTRODUCTION

Conventional parametric amplifiers and converters usually have three frequencies, namely, a pump frequency, a signal frequency, and a sum or difference frequency. The purpose of this paper is to show that additional frequencies can be added to parametric devices in order to perform useful functions. In the following, I would like to present three particular examples:

1. Regenerative Up-Converter: a regenerative non-inverting up-converter with a power gain higher than the theoretical limit for conventional up-converters.

2. Upper Sideband Amplifier: a parametric amplifier for signal frequency higher than pump frequency.

3. Tunable to Fixed Frequency Converter: a converter with a tunable input frequency but a constant output frequency.

In each case we used only one semiconductor diode but all these devices have four frequencies. Without the additional frequency, we would need two or three diodes in several stages to achieve the same functions.

REGENERATIVE UP-CONVERTER

The four frequencies involved in this case are a pump frequency f_p, a signal frequency f_s, a sum frequency f_+, and a difference frequency f_-. If f_+ is absent, we get the parametric amplifier configuration. If f_- is absent, we get the up-converter scheme. Thus, the particular arrangement including all four frequencies is, in fact, a combination of parametric amplifier and up-converter. Referring to the energy-level diagram

(Figure 1) we see that a signal entering the device is at first amplified between levels 1, 2, and 3 and then converted to the sum frequency by the up-conversion action between levels 1, 3, and 4. The mechanism of such a device can be explained also by Figure 2. In this figure, the vacuum tube is considered as an ideal lossless nonlinear element. The input entering the signal circuit is at first mixed with the pump by the left half section of the mixer. The output at the difference frequency f_- can excite the f_- circuit. But the resonance of the f_- circuit will be mixed again with the pump by the right half section of the mixer. This time we get an amplified output at the original signal frequency. This amplified power at the signal frequency can be regarded as the regenerated power at the signal frequency. Its value is indicated at the anode of the right half section of the mixer. Notice that the regenerated power is proportional to the output at the difference frequency. Now the original signal and the regenerated signal can both mix with the pump and generate an up-converter output at the sum frequency. Thus we may say that the output P_+ now consists of two parts, as is shown in the power equations[(1)] of Figure 2. One part is due to a straight up-conversion. The other part is due to the up-conversion of the regenerative signal power.

Some interesting statements can be made at this time. First, the bandwidth of the regenerative up-conversion is usually smaller due to the negative resistance effect. Second, the regeneration due to the introduction of the difference frequency can greatly increase the gain. The amount of regeneration can be increased by absorbing power at the lower sideband frequency. Third, the regenerative up-converter gain can be very much larger than the frequency ratio. In fact, the circuit may become unstable when the lower sideband begins to oscillate. In this way, the up-converter becomes an oscillator which generates a higher frequency than the pump frequency. This type of oscillator also has been investigated by the Stanford University group(2).

These effects have all been confirmed experimentally in a single stage device using one semiconductor diode. Figure 3 shows the gain variation as displayed on a double trace scope. There are two sets of pictures. In each picture, the trace that starts at the lower left shows a sweep frequency response in the up-converter output. The inverted trace that starts at the upper left indicates the amount of regeneration corresponding to the output at the difference frequency. We can see from the lower picture that the up-converter output has a relatively small value when there is practically no regeneration. The output is greatly increased, as shown in the upper picture, when large regeneration is introduced. For example, a regenerative up-converter was operated with a frequency ratio of about 8, but an up-conversion gain of 25 db was measured.

The bandwidth variation is shown in Figure 4 with a set of four similar pictures. The three upper pictures show the performances with various degrees of regeneration. The lowest picture shows the case with no regeneration. We can see that the up-conversion with no regeneration is basically a wideband process. The increased gain due to regeneration has a much narrower bandwidth.

Figure 5 shows the performance of an oscillating regenerative up-converter. The oscillation is at the sum frequency which is, of course, higher than the pump frequency. Near the oscillation threshold, the pump is off tuned. The device performs as a regenerative up-converter. This effect is shown in the four upper pictures. These pictures also show the beats between the oscillation and the up-conversion outputs.

UPPER SIDEBAND AMPLIFIERS

This case is related to the ferromagnetic amplifier proposed by Hogan, Jepsen, and Vartanian[(3)]. The scheme involves the same four frequencies as in the regenerative up-converter, but the input is at the upper sideband frequency.

The system proposed by Hogan, et al,[(3)] consisted essentially of multiple stages of three frequency parametric amplifiers and converters. By combining all the four frequencies together into a single stage, the system is very much simplified. We actually have used essentially the same circuit arrangements as in the regenerative up-converter and have achieved amplification at the upper sideband frequency with one diode only.

The mechanism of the upper sideband amplifier can be explained briefly as follows. The input is now at f_+. If we neglect f_-, there is down-conversion between f_+ and f_p to create f_s. This signal at f_s is then converted back to f_+ by the regenerative up-conversion. But, because the regenerative up-converter may be unstable at the upper sideband frequency, there is negative resistance at the sum frequency. Thus, the device is also capable of amplifying signals at the sum frequency.

The functions of the regenerative up-converter and the upper side-band amplifier can be clarified further by comparing the block diagrams of Figure 6. The regenerative up-converter is basically a combination of up-converter and parametric amplifier as explained earlier. The upper sideband amplifier has, in addition, a stage of down-converter. It is, of course, possible to use a cascade of converters and amplifiers to perform these functions, i.e. two diodes for regenerative up-converter and three diodes for the upper sideband amplifier. By introducing an additional sideband frequency, however, all these functions can be combined in one stage and using only one diode.

The experimental result of the upper sideband amplifier is shown in two sweep frequency pictures of Figure 7. The lower picture is taken without any pump power. The upward trace shows the input signal level. The upper picture shows the amplified signal with the pump on. The amount of regeneration is indicated by the small inverted trace. We can see that a signal which has a higher frequency than the pump frequency can indeed be amplified by this scheme.

TUNABLE PARAMETRIC DEVICES WITH FIXED OUTPUT FREQUENCY

This device has four frequencies arranged as shown in Figure 8. The pump frequency f_p is equal to the sum of the signal frequency f_s, idling frequency f_i, and output frequency f_o. The power equation in Figure 9 indicates that a positive pump power (P_p) requires the other powers (P_s, P_i, P_o) to be negative; i.e., there are negative resistances at all the other circuits. Thus, this device can be used as a parametric amplifier at frequencies f_s, f_i, and f_o or as a negative resistance converter between these three frequencies.

In the converter arrangement, the pump frequency and output frequency are both constant. The signal and the idling circuits are tuned together such that the sum of the signal and idling frequencies remains constant. Then the device becomes tunable for the signal frequency, but the output at f_o remains at a constant frequency.

Figure 10 shows the experimental result of such a four-frequency device. The top picture shows an amplified output of a sweep frequency input signal. The line below shows the very low input level when the pump power is turned off. The gain as an amplifier was about 20 db. Similar results have been obtained for frequency conversion between the three frequencies. In the particular experimental set up, we have varied successfully the input between 400 Mc/s and 500 Mc/sec, with a fixed frequency output at 2170 Mc/s.

EXPERIMENTAL SETUP

I have presented some of our experimental results. Now I would like to describe briefly the experimental setup. Figure 11 is a picture of the particular cavity arrangements used for the regenerative up-converter study. Basically, we have used separate cavities and orthogonal modes of each cavity for microwave frequencies. The coaxial resonant circuits are used for low frequencies around UHF. Here, for the four resonant frequencies, two of the frequencies are supplied by the rectangular cavity, one by the additional cavity shown at the center of the picture, and the fourth frequency supplied by the coaxial circuit. Essentially the same type of arrangements has been used for other experiments. The setup is very convenient because the circuits can be adjusted or changed easily. We can monitor the input and output signal levels of all resonant circuits. Thus, the same setup can be operated as a parametric amplifier and a converter often at the same time. In order to provide common coupling to the diode and still to avoid perturbation of the resonant frequencies, the diode is located in a loop inside the rectangular cavity. The loop is coupled loosely to all circuits. Figure 12 shows the method of mounting the diode inside the rectangular cavity. The diode itself forms the coupling loop.

SUMMARY

Single stage parametric amplifiers and converters can be designed to perform functions of multi-stage devices by introducing additional side-band and idling frequencies. Several examples were just described and analyzed. They included regenerative up-converter having higher gain than frequency ratio, parametric amplifiers for signal frequency higher than pump frequency, and tunable devices with fixed output frequencies. The technique we used can be extended to introduce other multiple-frequency devices if desired.

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3. C. L. Hogan, R. L. Jepsen, and P. H. Vartanian: "New Type of Ferromagnetic Amplifier", J. Appl. Phys., Vol. 29, No. 3, pp. 422-423; March, 1958.

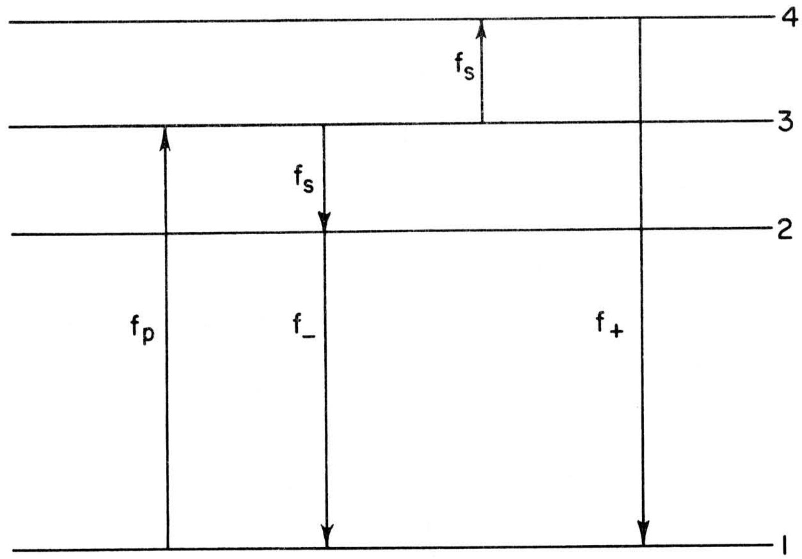
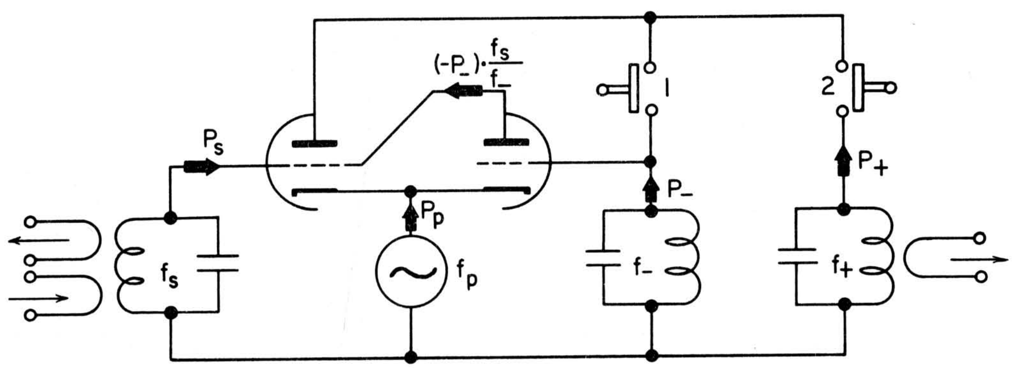


Figure 1: Energy Level Diagram of Regenerative Up-Converter and Upper Sideband Amplifier



$$\Sigma P = 0; \qquad f_- = f_p - f_s \; ; \quad f_+ = f_p + f_s$$

$$\text{PARA. AMP.}: \quad (-P_s) = \frac{f_s}{f_-} \cdot (-P_-)$$

$$\text{UP-CONV.}: \quad (-P_+) = \frac{f_+}{f_s} \cdot P_s$$

$$\text{REG. UP-CONV.}: \quad (-P_+) = \frac{f_+}{f_s}\left[P_s + \frac{f_s}{f_-} \cdot (-P_-)\right]$$

Figure 2. Tube Circuit Analogy of Regenerative Up-Converter

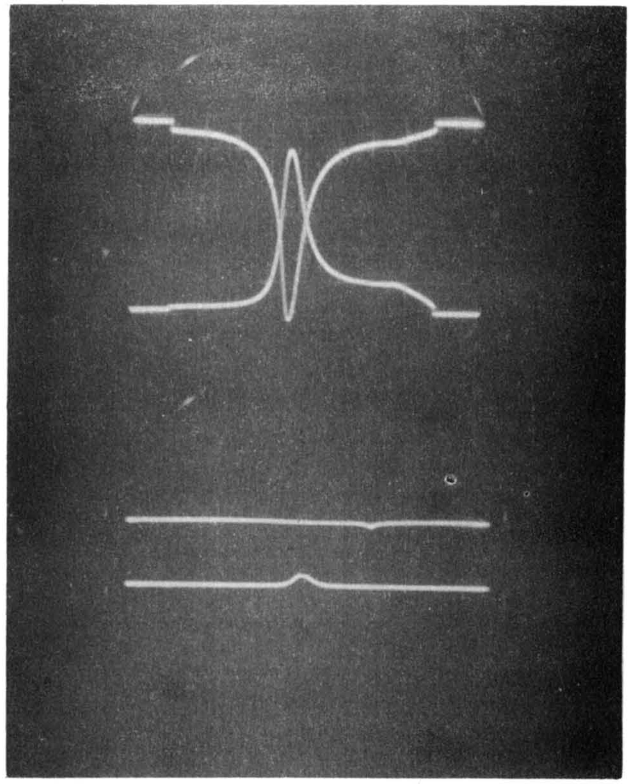


Figure 3. Sweep Frequency Performance of Up-Converter **With and Without** Regeneration

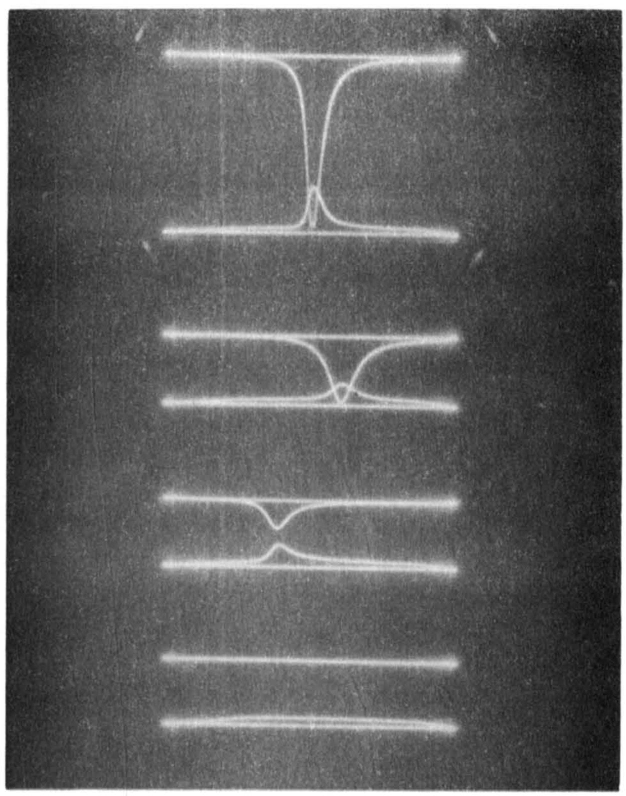


Figure 4. Sweep Frequency Performance of Up-Converter **with Various Degrees of Regeneration**

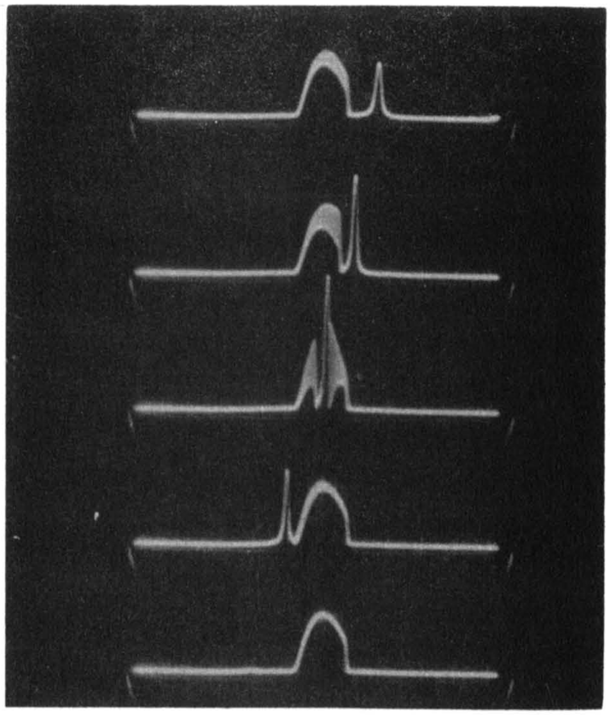
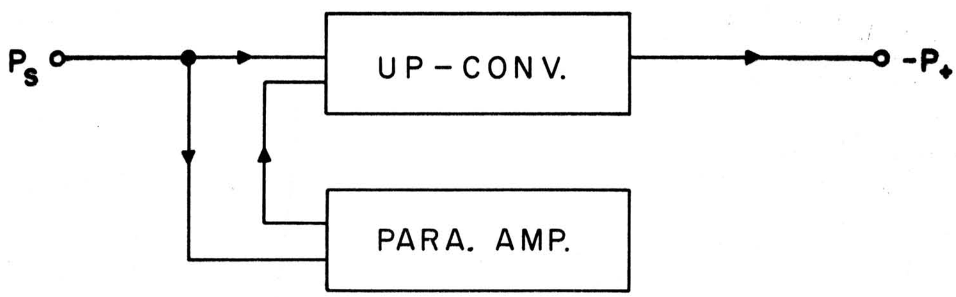
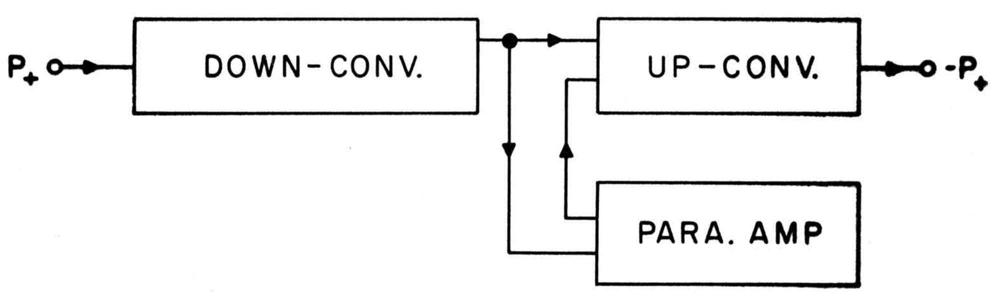


Figure 5. Sweep Frequency Performance of Oscillating **Regenerative** Up-Converter



REGENERATIVE UP-CONVERTER



UPPER SIDEBAND AMPLIFIER

Figure 6: Block Diagrams of Regenerative Up-Converter **and Upper** Sideband Amplifier

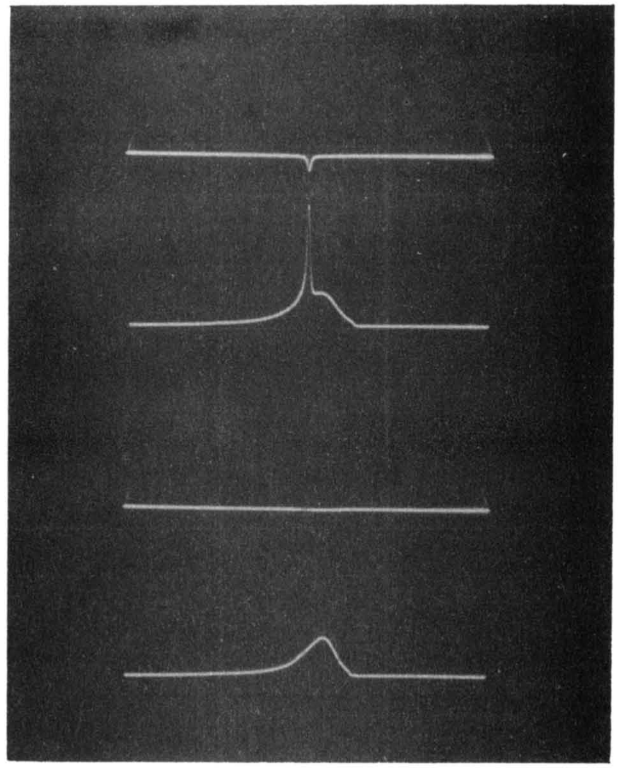


Figure 7: Sweep Frequency Performance of Upper Sideband **Amplifier**

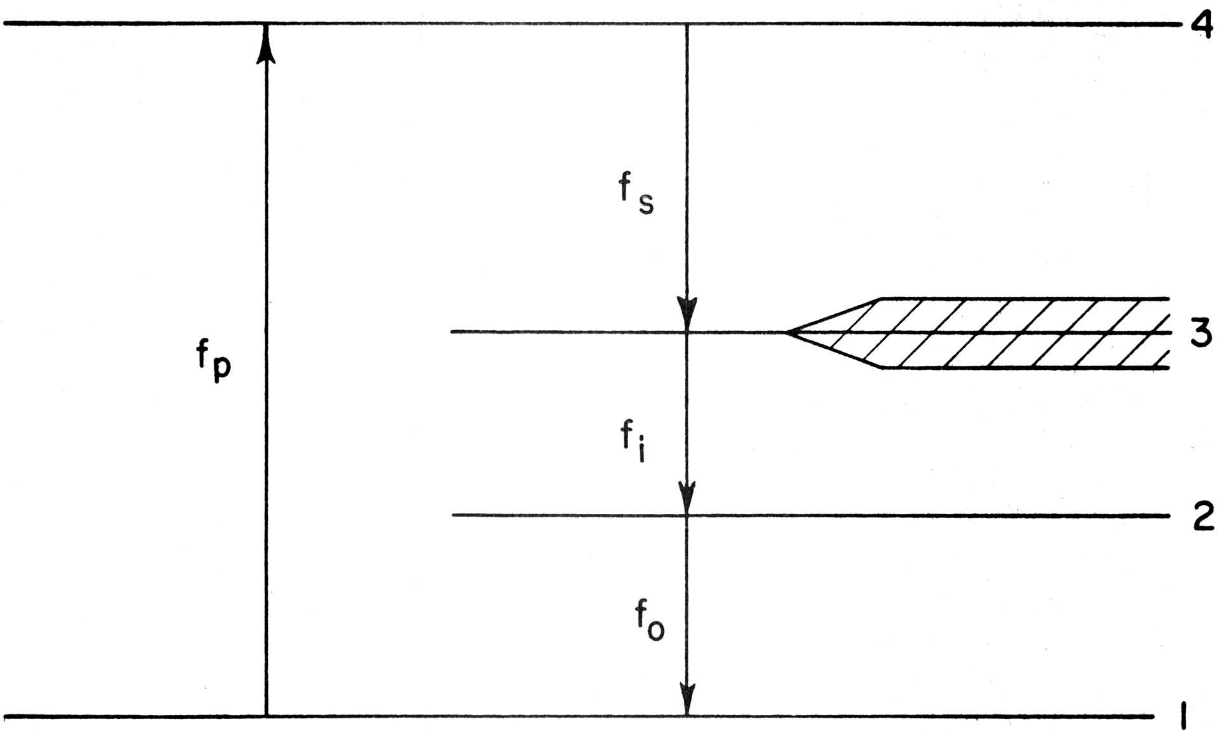


Figure 8. Energy Level Diagram of Constant Output **Frequency Converter**

$$f_p = f_s + f_i + f_o,$$

f_p = CONSTANT PUMP FREQUENCY,

f_s = VARIABLE SIGNAL FREQUENCY,

f_i = TUNABLE IDLING FREQUENCY,

f_o = CONSTANT OUTPUT FREQUENCY,

$$\frac{P_p}{f_p} = \frac{-P_s}{f_s} = \frac{-P_i}{f_i} = \frac{-P_o}{f_o}$$

$$f_s + f_i = f_p - f_o \quad \text{CONSTANT}$$

Figure 9. Power Equation of Constant Output Frequency **Converter**

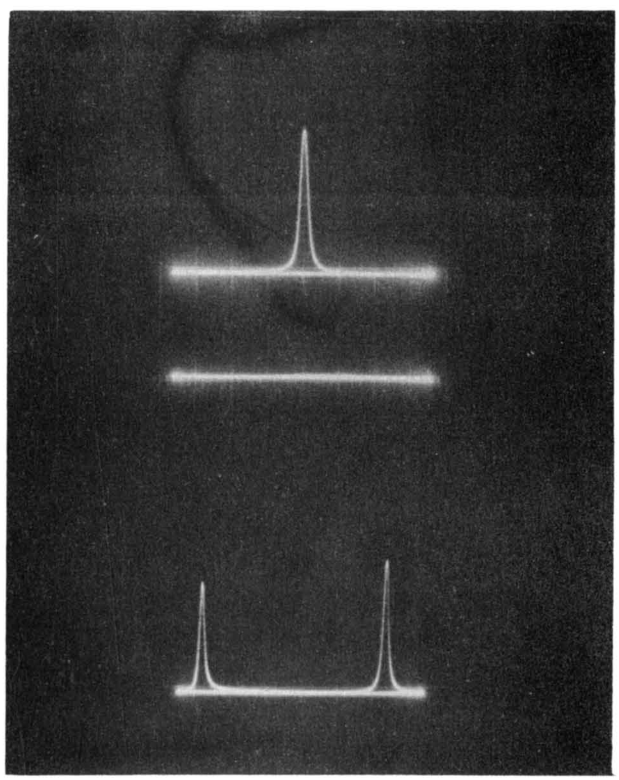


Figure 10. Sweep Frequency Performance of Constant Output **Frequency** Converter

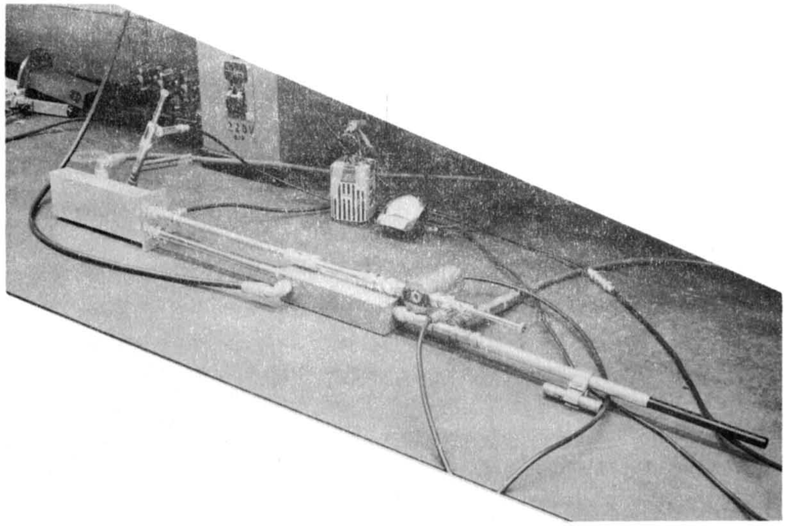


Figure 11. Experimental Cavity Arrangement for Regenerative Up-Converter

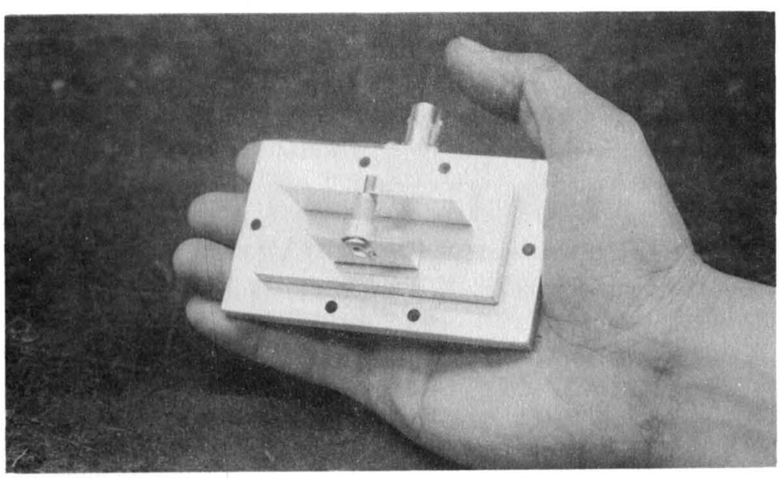


Figure 12. Experimental Diode Mounting Structure