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STUDY OF SHORT TERM PHASE STABILITY

SMITH ELECTRONICS, INC
Cleveland 41, Ohio

INTERIM REPORT

MARCH 17, 1965 THRU SEPTEMBER 5, 1965

CONTRACT NO NAS 8-11592

MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
HUNTSVILLE, ALABAMA

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George C. Marshall Space Flight Center
National Aeronautics and Space Administration
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ABSTRACT

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The theory of frequency-changing with the charge-storage diode is attempted using Fourier harmonic analysis.

Experimental work in the areas of frequency division, multiplication and mixing is reported. The applicability of the Manley-Rowe relationships to subharmonic operation of the charge-storage diode is suggested.

Matching and filtering techniques potentially useful for mixer and divider circuits using charge-storage diodes are discussed.

Author

INTERIM REPORT COVERING WORK DONE ON CONTRACT NAS 8-11592 MARCH 17, 1965 THROUGH SEPTEMBER 5, 1965

1. INTRODUCTION

The investigations conducted by Smith Electronics under Contract NAS 8-11592 during the period covered by this report have been in the areas of the theory of frequency division, the study of subharmonic generation and the study of frequency-changing circuits suited to synthesis applications. Specifically, the modified contract states:

a. "Theoretical investigation of the processes of frequency division shall be continued in an effort to derive an optimum method (of) frequency dividing.

b. The study of subharmonic generation shall be continued. A mathematical model and thorough theoretical treatment for the charge-storage diode as a subharmonic generator shall be sought.

c. A study of frequency multiplier, divider and mixer circuits shall be initiated to develop a method of frequency synthesis that obtains useful practical frequencies with the long term stability of a maser and the short term stability of a quartz crystal oscillator."

Early in this period, it became apparent that the subharmonic generator using the charge-storage diode is a very attractive solution to the frequency division problem in terms of simplicity and efficiency, and that the thorough study of this approach is a practical first step toward achieving objective (a) above. Moreover, charge-storage diode frequency changers should be peculiarly applicable to the frequency synthesis circuit problems of objective (c). Therefore, the major effort of the reporting period has been the theoretical and experimental study of charge-storage frequency changers and the design of practical circuitry employing these diodes.

2. CHARGE-STORAGE DIODE THEORY

2.1 Harmonic Analysis

The most common application of the charge-storage diode, other than high speed switching is high efficiency, high order frequency multiplication. Figure 1 shows a basic circuit for harmonic generation with a step-recovery diode in a series configuration, although the shunt configuration is also usable. The high efficiency of the charge-storage diode in frequency multiplication is generally attributed to the current waveform through the diode, shown in Fig. 2 as the solid line, and in particular the abrupt transition angle ψ. In Fig. 2, ψ is exaggerated; normally the transition is extremely rapid, being of the order of 100 nanoseconds. In early theoretical studies, this transition was assumed to be instantaneous and waveform analysis was carried out on this basis, leading to predicted efficiencies of 1/n, where n is the multiplication factor.

The dependence of the Fourier coefficients of the waveform upon the transition angle ψ for the two cases of linear transition and exponential transition were shown in the following manner. Referring to Figs. 1 & 2, the diode current in the three regions of the waveform for the linear decay case is

$$i_d = 0, \quad (\theta+\phi+\psi) \le \omega_1 t \le (2\pi+\theta) \tag{1}$$

$$i_d = \frac{E_p}{R_c}\left[\sin(\omega_1 t) - \sin\theta\right], \quad \theta \le \omega_1 t \le (\theta+\phi) \tag{2}$$

$$i_d = \frac{E_p}{R_c}\left[\sin(\theta+\phi) - \sin\theta\right]\left[\frac{\omega}{\psi}t\right], \quad (\theta+\phi) \le \omega_1 t \le (\theta+\phi+\psi) \tag{3}$$

Then the Fourier coefficients are

$$a_n = \frac{1}{\pi}\frac{E_p}{R_c}\left\{\int_{\theta}^{(\theta+\phi)}\left[\sin\omega_1 t - \sin\theta\right]\cos n\omega_1 t\, d\omega_1 t + \int_{(\theta+\phi)}^{(\theta+\phi+\psi)}\left[\sin(\theta+\phi) - \sin\theta\right]\left[\frac{\omega_1 t}{\psi}\cos n\omega_1 t\, d\omega_1 t\right]\right\} \tag{4}$$

and

$$b_n = \frac{1}{\pi}\frac{E_p}{R_c}\left\{\int_{\theta}^{(\theta+\phi)}\left[\sin\omega_1 t - \sin\theta\right]\sin n\omega_1 t d\omega_1 t + \int_{(\theta+\phi)}^{(\theta+\phi+\psi)}\left[\sin(\theta+\psi) - \sin\theta\right]\left[\frac{\omega_1 t}{\psi}\sin\omega_1 t\, d\omega_1 t\right]\right\} \tag{5}$$

For the exponential case, Eq. (1 & 2) remain unchanged, but Eq. (3) becomes

$$i_d = \frac{E_p}{R_c}\left[\sin(\theta+\phi) - \sin\theta\right] e^{-t/\psi}, \quad (\theta+\phi) \le \omega_1 t \le (\theta+\phi+\psi) \tag{6}$$

and the Fourier coefficients for the transition region alone become

$$a_n = \frac{1}{\pi} \frac{E_p}{R_c} \left\{ \int_{(\theta+\phi)}^{(\theta+\phi+\psi)} \left[\sin(\theta+\phi) - \sin\theta \right] e^{-t/\psi} \cos n\omega_1 t \, d\omega_1 t \right. \tag{7}$$

$$b_n = \frac{1}{\pi} \frac{E_p}{R_c} \int_{(\theta+\phi)}^{(\theta+\phi+\psi)} \left[\sin(\theta+\phi) - \sin\theta \right] e^{-t/\psi} \sin n\omega_1 t \, d\omega_1 t \tag{8}$$

Evaluating, the coefficients for the transition region alone are

$$a_n = \frac{E}{\pi R_c} \frac{e^{-\frac{\theta+\phi}{\psi}}}{\frac{1}{\omega_1\psi} + n^2\omega_1\psi} \left[\sin(\theta+\phi) - \sin\theta \right]$$

$$\times \left[\frac{1}{e} \cos n\omega_1 (\theta+\phi+\psi) - \frac{n}{e} \sin n\omega_1 (\theta+\phi+\psi) \right.$$

$$\left. - \cos n\omega_1 (\theta+\phi) - n \sin n\omega_1 (\theta+\phi) \right] \tag{9}$$

and

$$b_n = \frac{E}{\pi R_c} \frac{e^{-\frac{\theta+\phi}{\psi}}}{\frac{1}{\omega_1\psi} \quad n^2\omega_1\psi} \left[\sin(\theta+\phi) - \sin\theta \right]$$

$$\times \left[\frac{1}{e} \sin n\omega_1 (\theta+\phi+\psi) - \frac{n}{e} \cos n\omega_1 (\theta+\phi+\psi) \right.$$

$$\left. - \sin n\omega_1 (\theta+\phi) + n \cos n\omega_1 (\theta+\phi) \right] \tag{10}$$

These equations show strong dependence of the harmonic coefficients on ψ. It may be worthwhile to carry out the indicated calculations for numerical values and plot the results, although this has not been done during the reporting period.

2.2 Low Frequency Model

It was felt that much could be learned about the behavior of the charge-storage diode in frequency changing operations, if a model were available for operation at very low frequencies. Such a model would be a single-port device with voltage-current relationships identical to the diode, and with adjustable impedance, storage time, and transition time. It would be sensitive to biassing and could generate self bias and it could be used in either shunt or series circuits just like the charge-storage diode.

Figure 3 shows such an audio frequency model in block diagram form. A design was completed for a solid state version, shown in Fig. 4. However, this device was not fabricated, since it was not clear at the time that this was the most efficient procedure.

2.3 Diode Parameters

Preliminary measurements of charge-storage diode characteristics have been made with rather unexpected results. Measured ac resistance values exceeded 90 ohms and some indication of negative resistance was obtained in the low microampere forward bias region. Moreover, a smooth capacitance-voltage characteristic was observed in the reverse bias region, while abrupt or discontinuous reactance changes were observed in low current forward bias region.

It is important to note that these results are only preliminary and not necessarily representative because of the very limited number of observations. They are reported here because they show the possibility of more than one mechanism contributing to frequency-changing operations based on the charge-storage diode. Subharmonic generation in particular could very well depend on both a Manley-Rowe type of parametric characteristic and the abrupt transition characteristic.

3. EXPERIMENTAL CHARGE-STORAGE FREQUENCY-CHANGERS

3.1 Harmonic Generation

Figure 5 shows the schematic of a high order frequency multiplier using a charge-storage diode. Using a MA4373C snap-off diode, a 20 mw intput at 175 Mc produced 4 mw output at 2280 Mc. In addition to verifying the high-order efficiency capability of the diode as a harmonic generator, the circuit is of interest because of the input matching technique used. Output decoupling is achieved by the large value of capacitance at the low frequency side of the diode, and a section of transmission line is used in the input π network. The bandwidth limitation is principally the passband of the output resonator, and stable output is achieved over a fairly wide range of input frequencies.

3.2 Subharmonic Generation

Successful use of the charge-storage diode in a $\div$ 13 subharmonic generator circuit was reported in the Interim Report covering the period March 16, 1964 through March 16, 1965. The circuit used operated with an input of 35 mw at 2280 Mc and produced an output at 175.4 Mc of 2.1 mw. An idler at 2104.6 Mc was employed.

Early in the period covered by this report, a similar circuit was fabricated and successfully operated for dividing a 575 Mc signal by five to produce 115 Mc, using a 460 Mc idler. The frequencies were selected for ease of separation, ease of fabrication, the availability of filters, and because of the need to measure frequency and power of the idler. Figure 6 is the schematic. Of great interest is the fact that significant amounts of power were developed at both the subharmonic and idler frequencies simultaneously. 36 mw input at 575 Mc yielded 6 mw at 115 Mc, and 3.5 mw at 460 Mc. The tuneup could be optimized for either output at the expense of the other.

This configuration was useful also because of the capability of introducing power at the idler frequency to produce mixing; in fact, this proved to be the easiest way to obtain subharmonic operation. The circuits were tuned in the driven-idler condition and then the drive reduced until self-oscillation and finally locked oscillation occurred.

The intriguing possibility of using idler output for non-integral division was further explored by revising the $\div$ 13 circuit operating at 2280 Mc input. Figure 7 shows the layout. It should be noted that external matching networks, (not shown) were used at the 2280 Mc and 2105 Mc frequencies. With this arrangement, 1.2 mw was obtained at 2105 Mc from an input 12 mw at 2280 Mc. No attempt was made to measure the 175 Mc output in this case. It was also found possible to achieve locked divider operation with a similar circuit at 1.3 mw input at 2280 Mc. The efficiency in this case was better than 7%.

3.3 Mixing and Upconversion

From the remarks in Para. 3.2 on tuning a subharmonic generator by injecting the idler frequency, it is apparent that the charge-storage diode is capable of a mixing operation. If the mechanism involved follows the

Manley-Rowe relationships, it should be possible to obtain upper-sideband upconversion with gain. The circuit of Fig. 8 was used to check this possibility. A 170 Mc input at -54 dBm,with a 2280 Mc local oscillator input at 0 dBm produced an output at 2450 Mc of -48.5 dBm, or a signal conversion gain of 5.5 dB. The frequencies were selected to avoid harmonic relationships which would cause instability. Conversion gain was also achieved at -93 dBm input level.

3.4 Matching and Filtering

In the case of high order harmonic generation as in Para. 3.1, it is often desirable that the bandwidth of matching networks and filters be as great as is consistent, with adequate rejection of harmonics adjacent to the desired output frequency. Some attention was therefore given to the broadbanding of high-transformation-ratio impedance matching networks. The input network of Fig. 5 is an example.

On the other hand, subharmonic generators with three frequencies present in the diode require some narrow banding to separate closely adjacent frequencies. For example, when an idler is loaded, it is important not only that the other frequencies be attenuated in the output, but that means be provided to prevent wasted power at these frequencies. Therefore, one or more of the ports may have broadband matching, but at least one may require narrow band filtering.

Three approaches have been considered; high- or low-pass filters, selective bandpass filters, and notch filters. Pi-network matching networks can be designed for low or high pass properties, and frequent use has been made of this approach at SEI. Coaxial resonators as bandpass filters are extremely useful at 1 Gc and higher, and will be seen in circuits such as that of Fig. 8.

The extension of the coaxial resonator to lower frequencies through the use of the helical resonator is attractive. Figure 9 is an example of a helical bandpass filter having a loaded Q of about 60 at 575 Mc. Figure 10 shows the same principle applied to a double resonator notch filter. With both resonators of this particular filter at 575 Mc, nearly 30 dB rejection is obtained; with the resonators tuned to different frequencies, the individual rejections will be 10 to 20 dB, depending on frequency.

These filters and matching networks should find considerable application in the mixer and divider circuits using charge-storage diodes.

4. SUMMARY

The theory of frequency-changing with the charge-storage diode has been approached through harmonic analysis, with particular reference to exponential decay during the transition time. A low frequency model has been designed to permit control of parameters and the observation of their effect. No clear cut understanding of the effect of parameters on the subharmonic operation has resulted, although the possibility of the applicability of the Manley-Rowe relationships has been demonstrated, both by the three-frequency subharmonic generator circuit and by upconversion with gain. Also, preliminary measurement of diode characteristics hint at the possibility of unexpected mechanisms.

Fabrication and testing of circuits based on the charge storage diode has not only contributed to the understanding of charge-storage diode frequency changers, but has resulted in useful devices such as non-integral dividers and multipliers and the upconverter with gain. Operation of the subharmonic generator at 1 mw input level was demonstrated. Various matching and filtering techniques were explored and found to be potentially useful for future designs.

5. PUBLICATION

Some of the results of the application of the charge-storage to subharmonic generation were published in the correspondence columns of the July 1965 issue of the Proceedings of the IEEE, pp. 735-736.

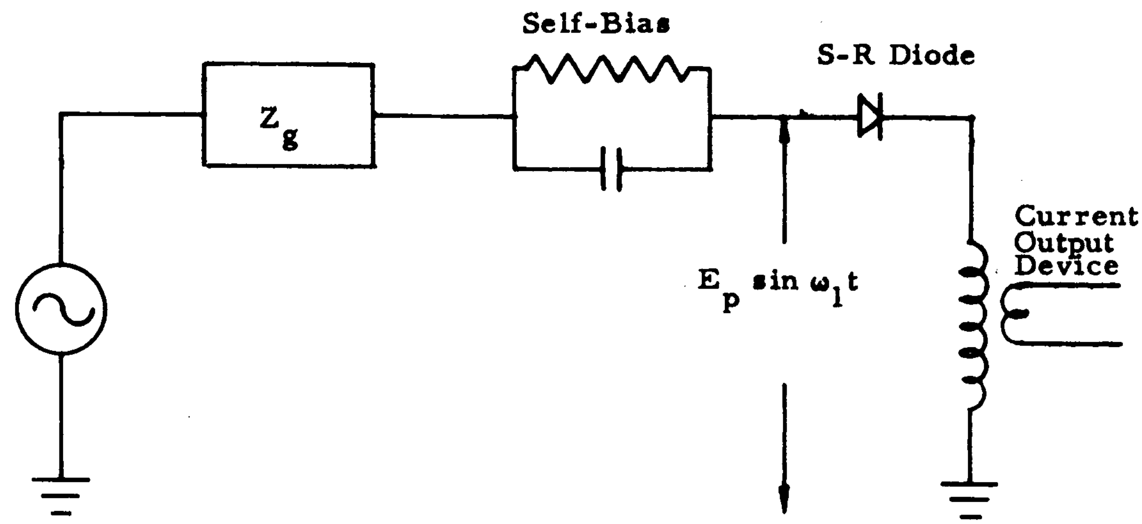

FIG. 1 BASIC STEP-RECOVERY HARMONIC GENERATOR CIRCUIT

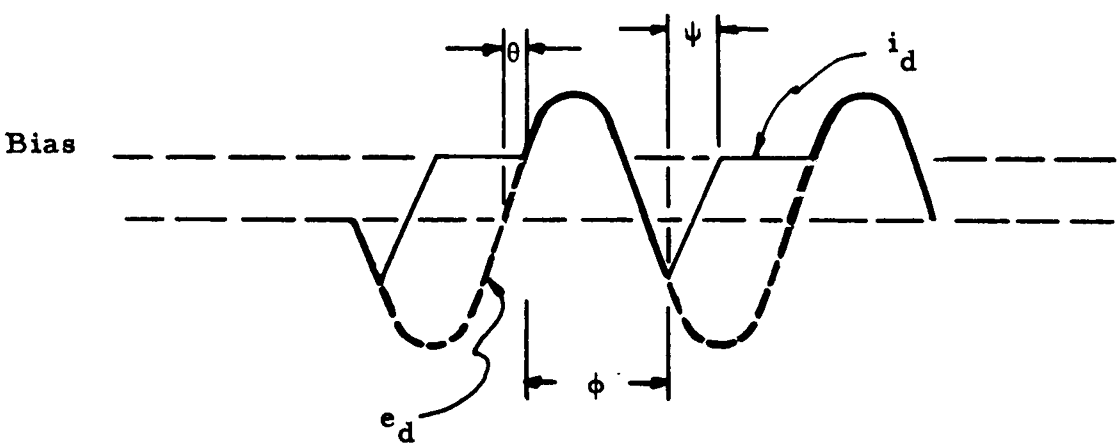

FIG. 2 STEP-RECOVERY DIODE CURRENT AND VOLTAGE WAVEFORMS

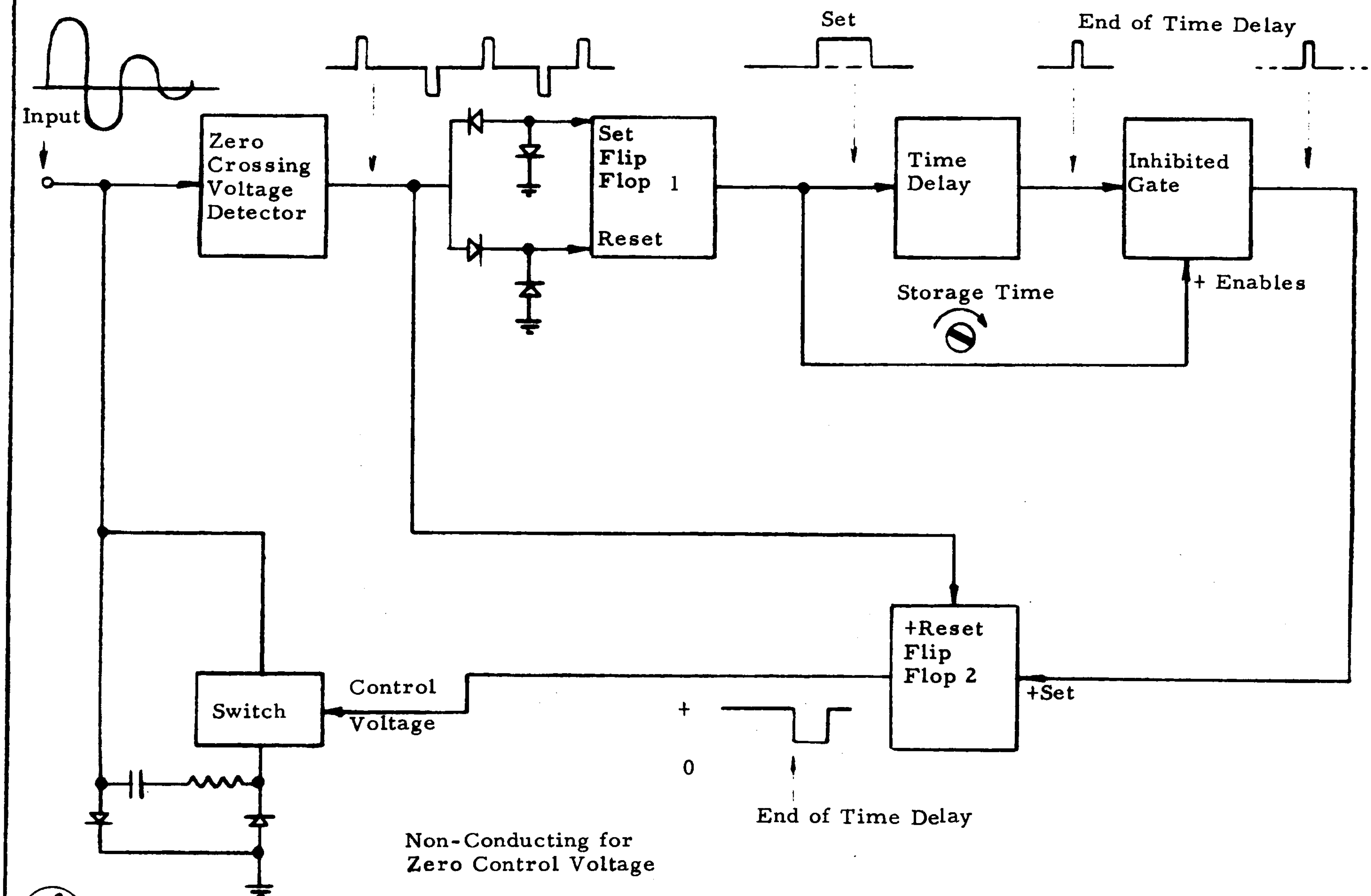

FIG. 3 PROPOSED LOW-FREQUENCY MODEL OF STEP-RECOVERY DIODE

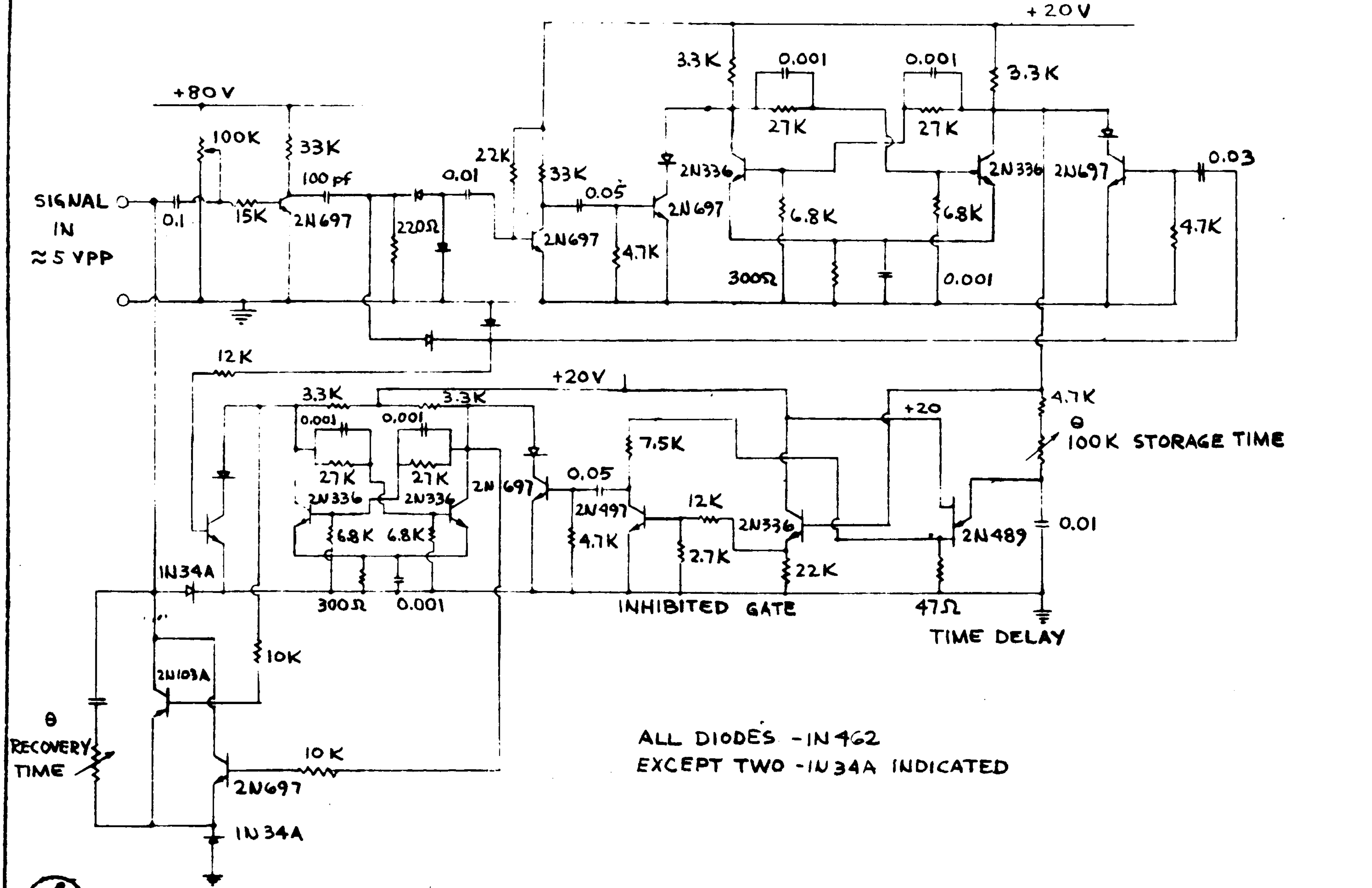

FIG. 4 LOW FREQUENCY MODEL OF CHARGE STORAGE DIODE

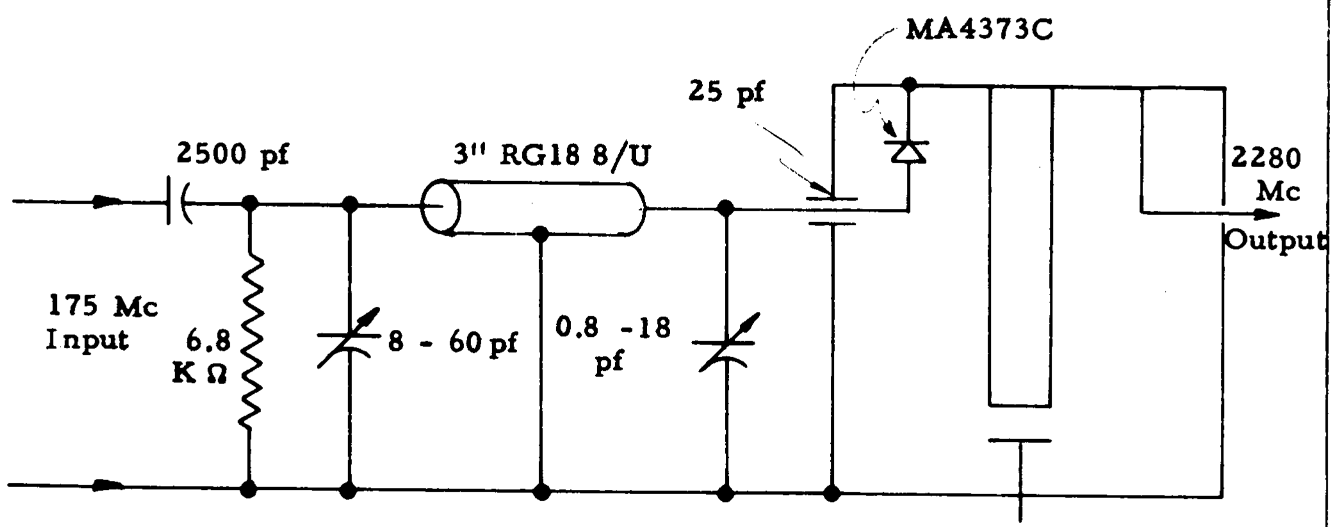

FIG. 5 HIGH-ORDER STEP-RECOVERY MULTIPLIER

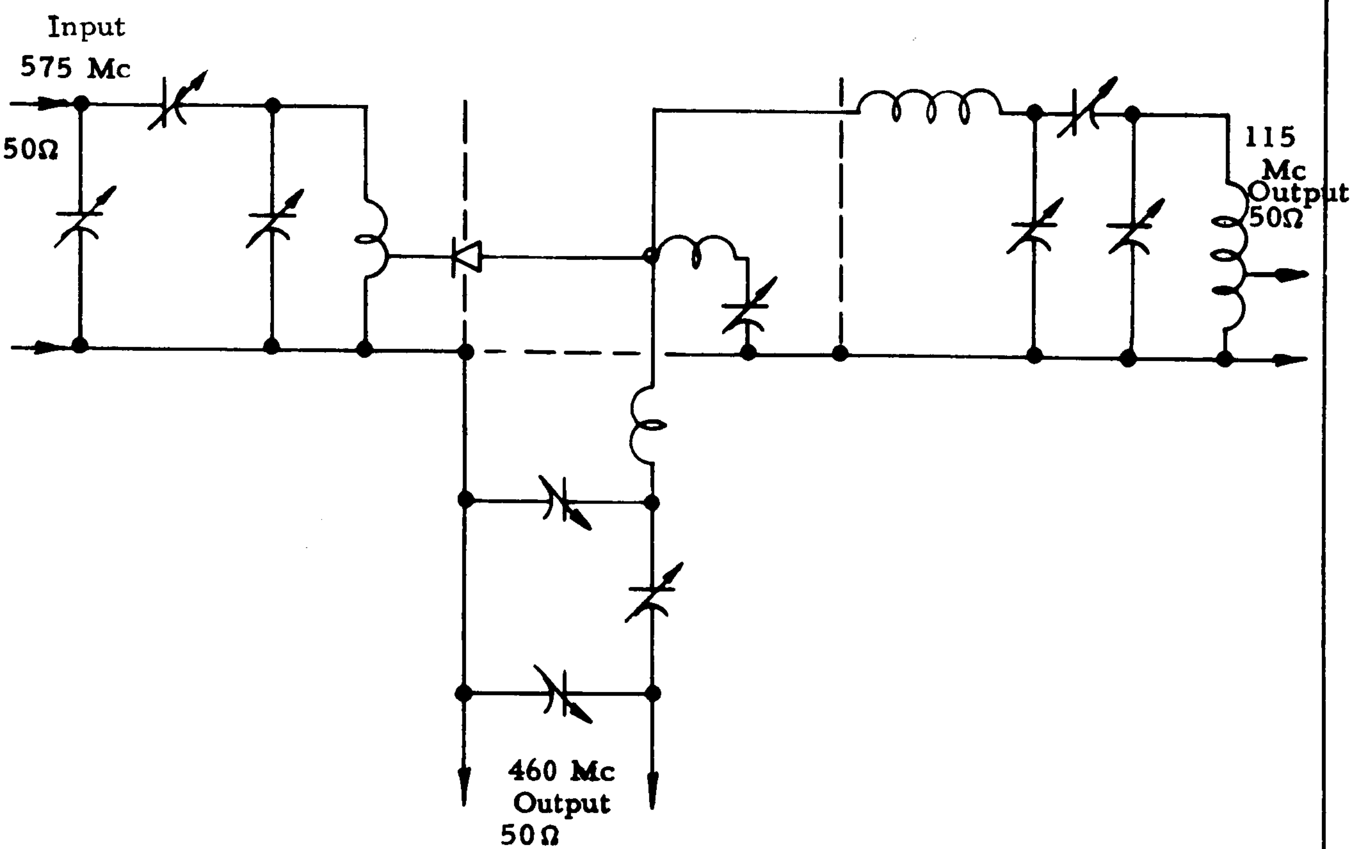

FIG. 6 STEP RECOVERY ÷ 5 SUBHARMONIC GENERATOR WITH IDLER OUTPUT MATCHING

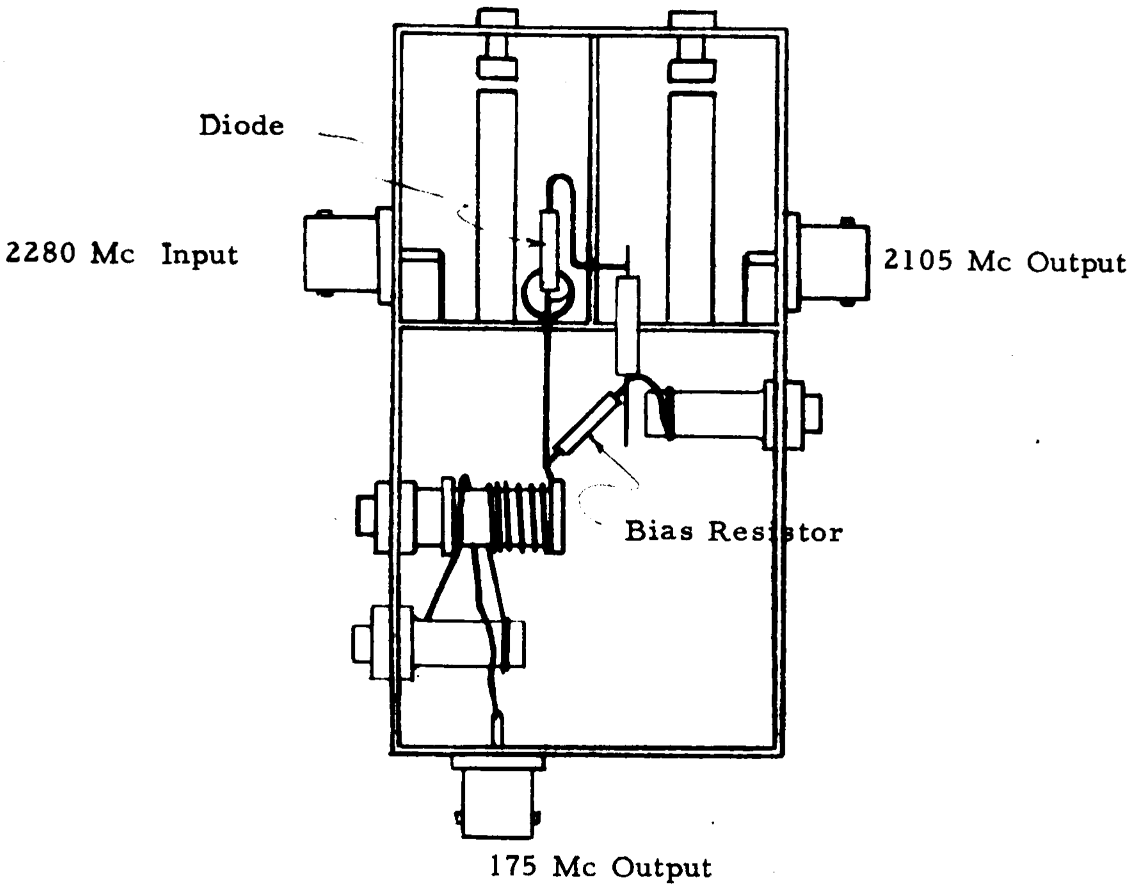

FIG. 7 NON-INTEGRAL STEP-RECOVERY DIVIDER

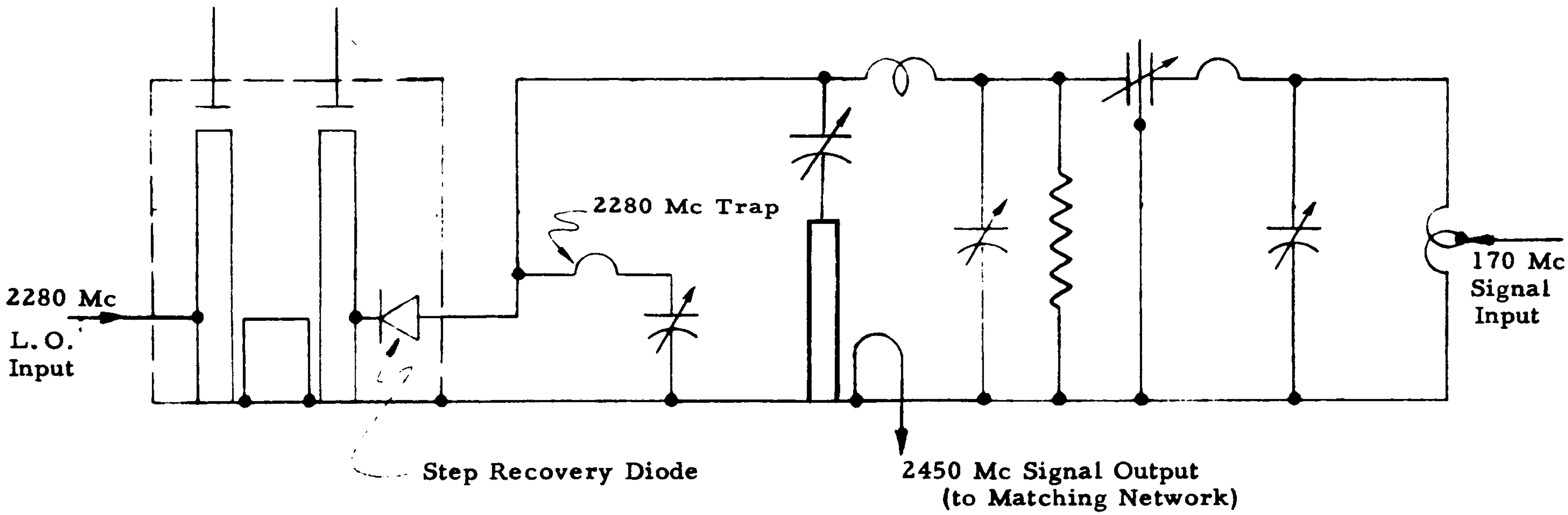

FIG. 8 UPCONVERTER WITH STEP RECOVERY DIODE

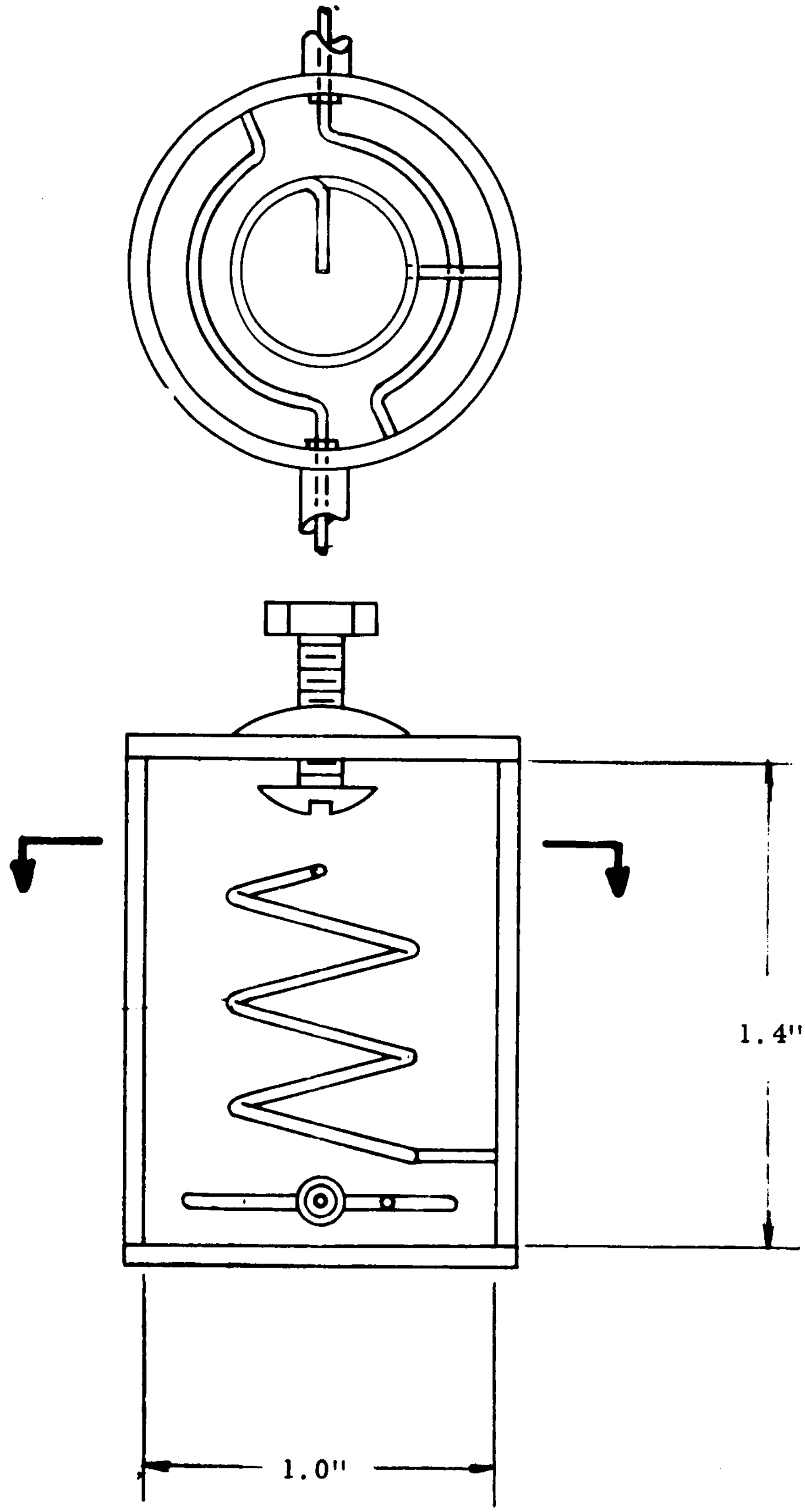

FIG. 9 HELICAL BANDPASS FILTER, TUNABLE 560 - 590 Mc

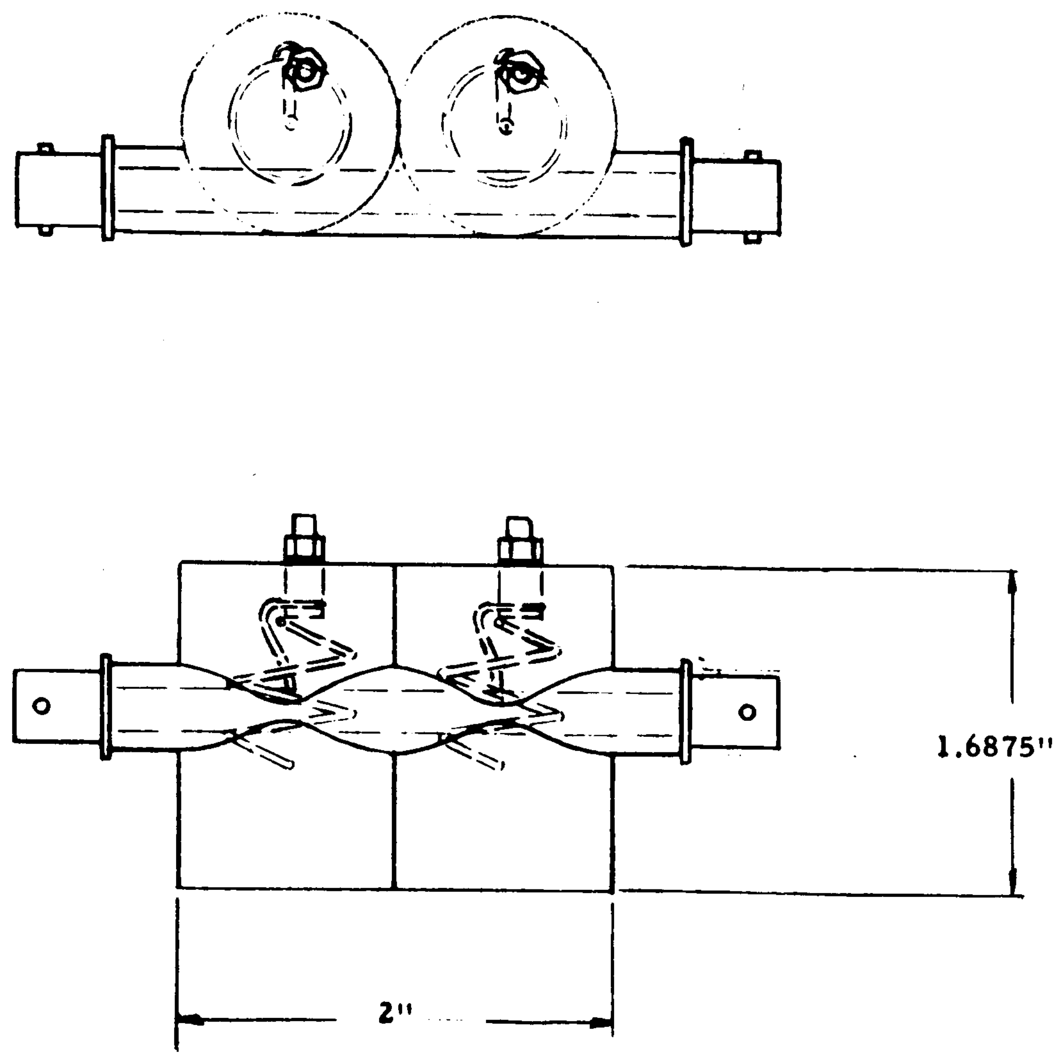

FIG. 10 TWO-STAGE HELICAL NOTCH FILTER, TUNABLE 365 - 620 Mc