LB-1084

A CARRIER ENERGIZED BI-STABLE CIRCUIT USING VARIABLE-CAPACITANCE DIODES

RADIO CORPORATION OF AMERICA
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A CARRIER ENERGIZED BI-STABLE CIRCUIT USING VARIABLE - CAPACITANCE DIODES

Approved

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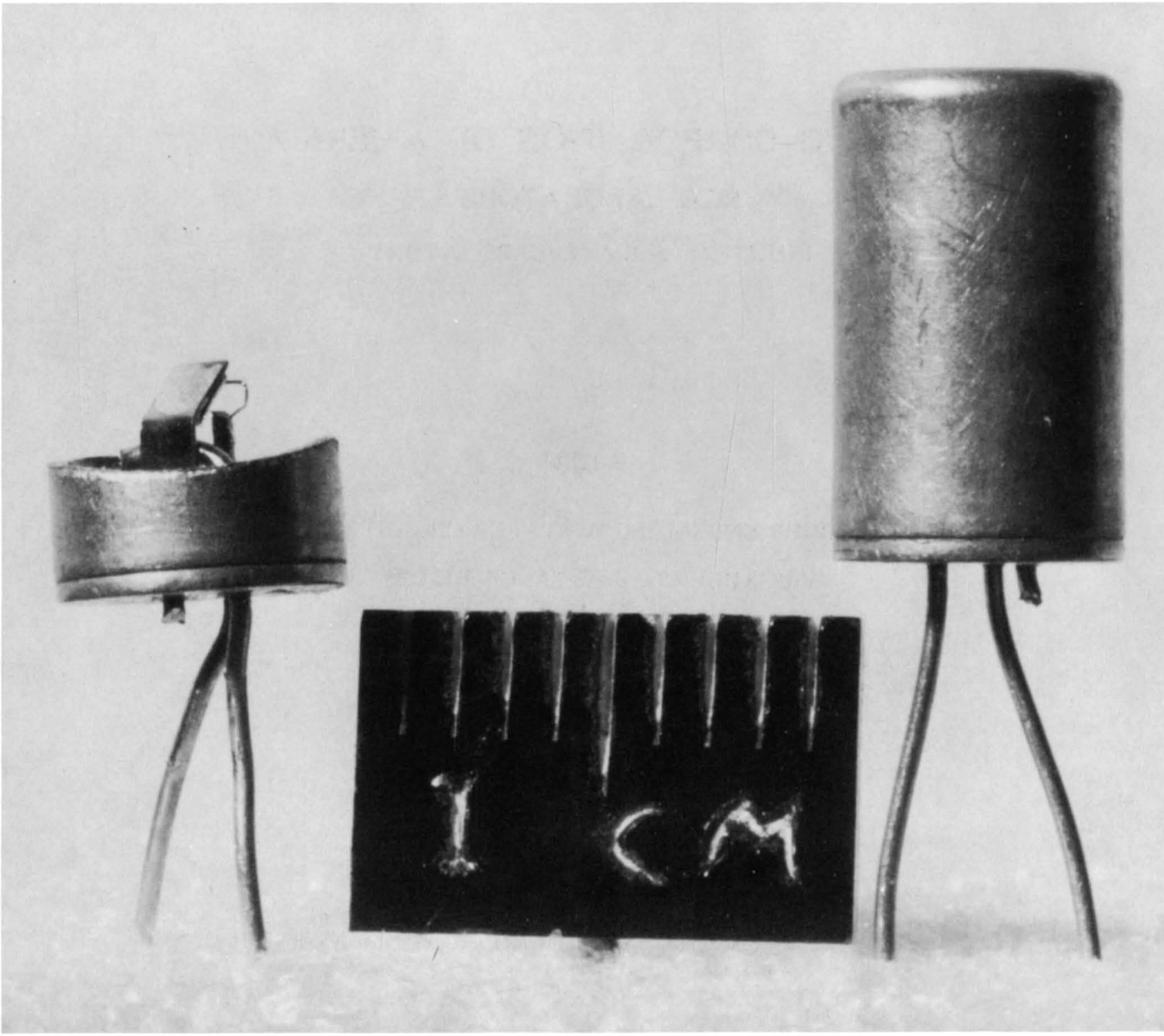


Fig. 1 – Experimental variable capacitance diode.

A variable-capacitance junction diode, when used in a simple circuit driven from a high frequency a-c source, can cause that circuit to have a bi-stable characteristic suitable for dynamic memory, or to have a sensitive input-output characteristic suitable for control or detection purposes. This bulletin outlines the principles of operation of the basic bi-stable circuit, and describes several variations of it, including a transistor version where the two junctions of a transistor are used in place of two variable-capacitance diodes. A two-diode circuit is described for which the output-input characteristic is bi-stable for a range of nearly ten-to-one in input voltage amplitude. Using an energizing carrier level of about one-half volt, a d-c output change of several volts may be obtained. At an energizing frequency of 2 megacycles, transitions require about two microseconds. The input power per circuit is approximately one milliwatt.

Introduction

An experimental variable-capacitance diode having relatively high capacity and low series resistance (forming a low-loss, high-*Q* capacitive component) has been described in the literature.[1] Experimental diodes of similar type have since been a factor in circuit development. This bulletin described one result: a simple, carrier-energized, bi-stable circuit utilizing both the variable-capacitance and the non-linear conductance characteristics of such diodes. For purposes of discussion a specific experimental diode is used to illustrate the application, however, the treatment is sufficiently general to be applicable to other semiconductor diodes with somewhat similar characteristics.

The Basic Bi-Stable Circuit

Description of Experimental Diodes

The low-frequency electrical characteristics of the diodes used in the bi-stable circuit tests were quite semilar to those of the diodes described by Giacoletto and O'Connell. For a typical unit at five volts reverse bias, the capacity was about 50 mmf and the leakage current at room temperature was about 0.3 μa, while the series base resistance was about 0.5 ohm. Peak inverse voltage, limited by conduction in the reverse direction, was about 16 volts. The diodes were mounted in hearing-aid transistor type cases and had short flexible leads. The size and mounting are illustrated in Fig. 1. The capacitance of these germanium alloy-junction units varies inversely as the square root of the instantnaeous effective reverse bias voltage.

Basic Circuit

The variable-capacitance diode bi-stable circuit that is the subject of this bulletin is shown in basic form in Fig. 2. A high-frequency a-c voltage source drives a series combination of an inductance and capacitances (resistance, *R*, is at first to be considered large). The effective capacity of the variable-capacitance diode depends upon the amplitude of the a-c and d-c voltages across its terminals. Because the diode is a rectifier, the d-c voltage is essentially equal to the peak a-c volt-

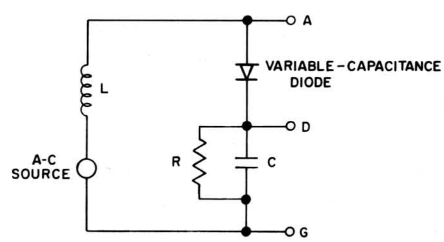


Fig. 2 – Variable-capacitance diode bi-stable circuit.

[1] *LB-1005, A Variable-Capacitance Germanium Junction Diode for UHF,* by J. H. O'Connell and L. J. Giacoletto.

age applied to the diode, which in turn depends upon the frequency and amplitude of the voltage source and upon the circuit components. When the frequency and component values are properly chosen, effective capacitance variation is such that the circuit may be tuned through series resonance from one side to the other by changing the amplitude of the source. If the effective Q of the circuit exceeds a minimum value, the change is abrupt, and a complete cycle of raising and lowering the input voltage amplitude traces out a pseudo-hysteresis curve. See Fig. 3, for example, in which the rectified d-c voltage measured between terminals D and G of the circuit of Fig. 2 has been plotted against the input amplitude. The segments of the characteristic will be traced out in the order 1-2, 2-3, 3-4, 4-5, 5-6, 6-7, etc., if the start of the input amplitude variation cycle is begun near zero input amplitude. The a-c voltage appearing between terminals A and D of Fig. 2 varies with input amplitude in a similar fashion. These pseudo-hysteresis characteristics pertain to the circuit not to the diode itself.

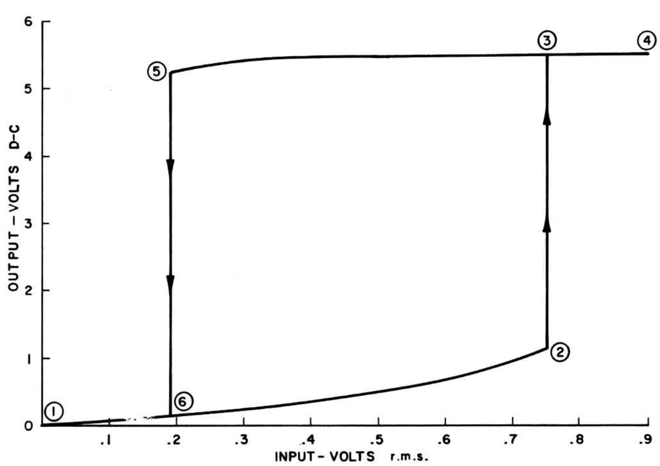


Fig. 3 – Pseudo-hysteresis characteristic obtained by varying the amplitude of the input voltage.

As Fig. 3 shows, the characteristic is bi-stable over a considerable range of input voltage amplitude. Within this range the two states may be easily distinguished by the substantial difference in output amplitudes. The input may be varied within this range (for example, 0.2 to 0.7 volts) and the output will continue to trace along one segment of the characteristic without forming minor loops or affecting the critical voltages which bound the bi-stable region.

If the frequency of the input voltage is varied, rather than its amplitude, the *output voltage* vs *frequency* characteristic will also have a bi-stable region. This is illustrated in Fig. 4. In this case the peak-to-peak a-c across the diode and the fixed capacitor was taken as the output.

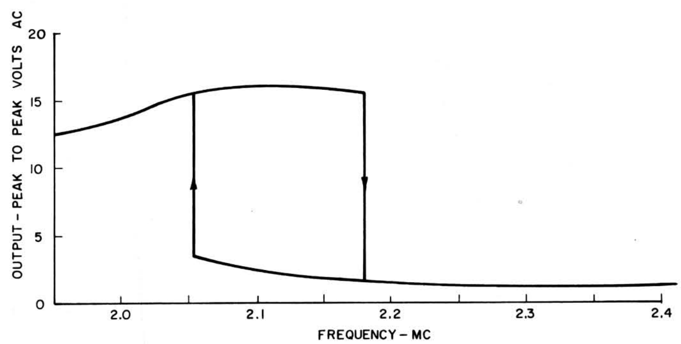


Fig. 4 – Pseudo-hysteresis characteristic obtained by varying the frequency of the input voltage.

Elementary Principle of Operation

If the variable-capacitance diode were replaced in Fig. 2 with a hypothetical variable capacitance element sensitive to bias voltage and the bias were varied by external means, the output vs. bias curves for three different inputs might be represented approximately by the three dotted response curves in Fig. 5. Then consider the action of a rectifying diode shunted across the bias-sensitive capacitance when the external bias is removed. The diode will rectify the a-c voltage appearing across the variable-capacitance, resulting in a self-bias appearing across both the variable-capacitance and the fixed capacitance, C. The magnitude of this bias will equal the peak of the a-c voltage across the variable-capacitance, the relation being simply a linear one as shown by the solid straight line on Fig. 5. For all levels of input volt-

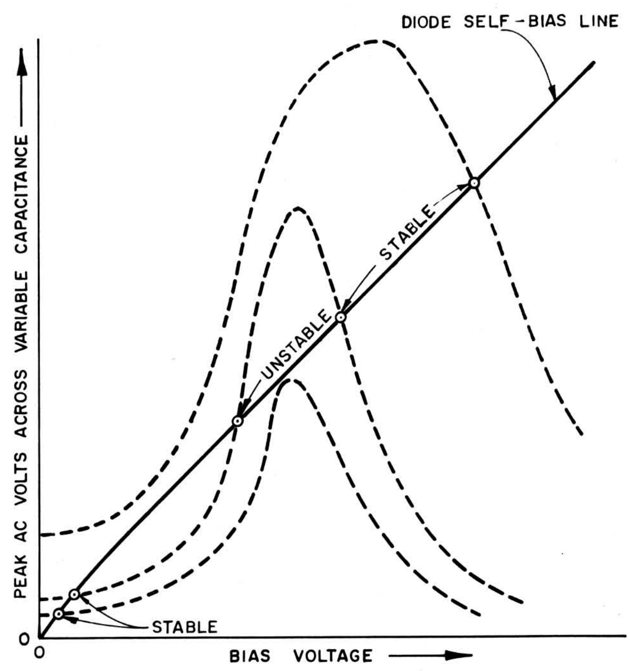


Fig. 5 – Curves showing responses, self-bias line, and operating points.

age, the steady state operating point will remain on this straight line. Since the operating point must also be on the a-c response curve corresponding to the particular level of input being used, it must be where the two curves, i.e. the response curve and the self-bias curve, cross. For small amplitudes of input, there is only one crossing. For somewhat larger input amplitudes, however, there are three crossings. For still larger input amplitudes there is again only one crossing. At any point where the response curve exceeds the self-bias curve, there will be additional self-bias generated, so the operating point will shift to one of higher bias, continuing to shift until a point of coincidence of the two curves occurs, i.e., until the peak a-c is just enough to maintain the self-bias necessary to tune the circuit to maintain that amount of peak a-c. At any point where the response curve falls below the self-bias curve, there will be no diode conduction, and the self-bias will leak away, moving the operating point toward lower bias, until a point of coincidence of the curves is again reached. The center point of crossing, in cases where there are three, is not a stable operating point, since any perturbation away from it will result in a shift to one of the other points of crossing. However, all of the other points are stable, since any perturbation about them is countered by a restoring action.

We may define the largest input voltage for which the response curves still cross the self-bias line in three places as the upper critical input voltage; and similarly the smallest such as the lower critical input voltage. These correspond to the input voltages at point 2 and point 5 of Fig. 3. The effective Q of the response curves and their position along the bias axis affect the location and separation of these voltages. If the series inductance or the input frequency is increased, the response will be moved toward a higher bias condition (assuming higher bias means less capacitance), increased input will be needed, and the back voltage limitation of the diode may be reached before the bi-stable region is reached.

If the Q of the circuit is made lower, as for example by decreasing R, the separation of the upper and lower critical levels will decrease, and a point may be reached where the circuit is no longer bi-stable, although a steep S-shape remains in the output-input amplitude characteristic.

Practical Operation

In practice there are some further considerations. The capacity of actual variable-capacitance diodes follows the instantaneous total reverse bias, resulting in considerably flattening of one half of the a-c voltage waveform and peaking of the other half. It also results in some effective broadening and shifting in the frequency of the response curves as a function of the amplitude of the input. Also, in the case of the experimental diodes used for most of the tests, conduction in the reverse direction limited the peak-to-peak a-c voltage to about 16 volts; this flattened the self-bias line at slightly under six volts. (The peak amplitude of the half cycle of the a-c wave that opposed the average bias was about 6 volts and the peak amplitude of the other half cycle about ten volts). Reverse-bias conduction contributes to the flatness of the top portions of the curves of Figs. 3 and 4. Still another practical effect encountered under certain conditions of operation is a tendency for a spontaneous modulation or sub-frequency generation to occur. It occurs over a certain range of inputs when the circuit is in the upper or high-level state and the output is just below the reverse-conduction-limited level.[2] By operating the circuit with sufficient input that the level of the upper bi-stable state is limited by reverse conduction, or with a small input, the tendency to generate sub-frequencies can be avoided.

Triggering

In the bi-stable region, operation may be triggered between states by several means. As already indicated, the input amplitude may be momentarily changed beyond the critical amplitude, or it may be changed in frequency. By changing the d-c bias from an external source stiff enough to override the self-bias, the same effect may be achieved. The tuning of the circuit may be changed by using an additional variable-capacitance diode or a saturable inductance. Under proper conditions light energy falling on the junction area of the diode can also be used to control or trigger the output.

The output pulse or bias change derived from a transition usually will be more than enough to trigger or switch another similar circuit. Depending on the kind of coupling used, two of these circuits may be interconnected to achieve either flip-flop or multi-vibrator action. Coupling means include use of a common input impedance, coupling between the outputs, or a combination of the two.

Transition Characteristic

The transition characteristics are illustrated in the photographs of Fig. 6. A sine-wave amplitude modulated 2.2 mc input was applied to the circuit of Fig. 2; C was 330 mmf., R was 50,000 ohms, and L was a 64-105 μh tunable inductance tuned to give the bi-stable responses shown. Oscilloscope probes, each having a capacitance

[2]A frequency-dividing circuit making use of this phenomenon has been developed, and will be included in a forthcoming paper.

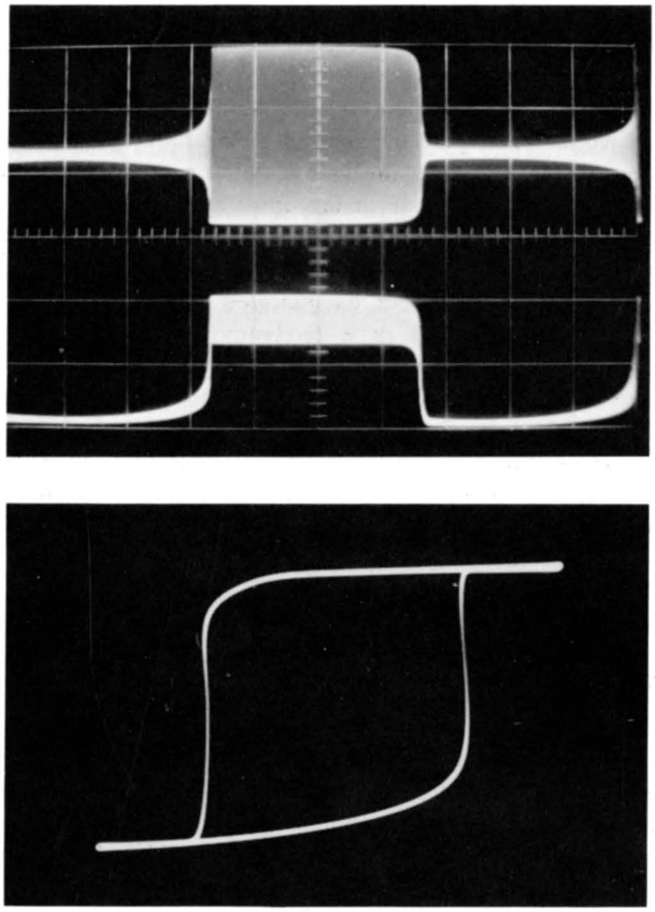


Fig. 6 – (a) and (b) Waveforms observed at terminals A and terminals D of circuit of Fig. 2. (c) Output-input characteristic of circuit of Fig. 2.

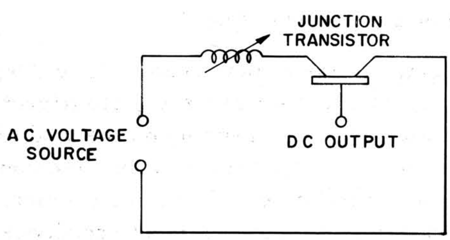


Fig. 7 – Series diode version for maximum sensitivity and response speed.

of approximately 15 mmf to terminal *G*, were connected to terminal *A* and to terminal *D*. The waveform shown in Fig. 6(a) is that seen at terminal *A*, and the waveform shown in Fig. 6(b) is that seen at terminal *D*. Each centimeter of horizontal trace represents 20 microseconds in these figures; the transitions take about 2 microseconds. Figure 6(c) is another photograph taken under the same circuit conditions, but where the filtered output from *D* was applied to the vertical deflection input of the oscilloscope and the generator output was rectified, filtered, and applied to the horizontal deflection input.

Decreasing *C* or increasing the input frequency (smaller *L* needed) shortened the rise time, but had little

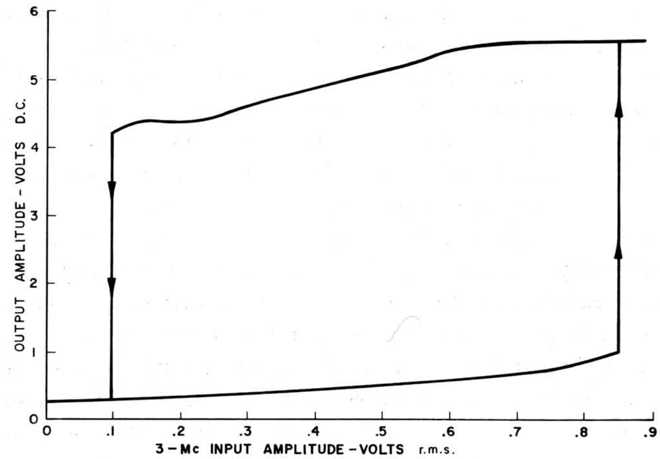
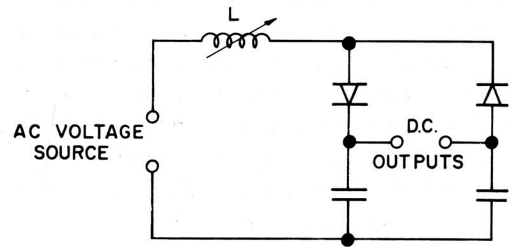
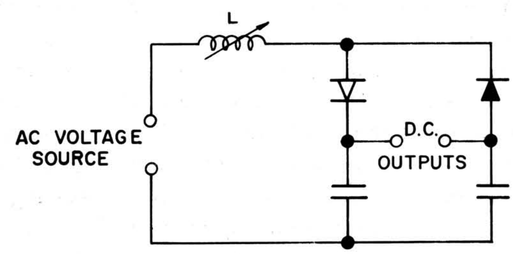


Fig. 8 – Typical characteristic obtained with circuit of Fig. 7.



(a) Two variable-capacitance junction diodes.



(b) One variable capacitance and one rectifying diode.

Fig. 9 – Circuits showing use of two diodes to provide both polarities of d-c output.

effect on the fall time. On the other hand, a very large *R* results in a short, sharp transition, followed by a long slow decay. The value of C may be decreased, but as it approaches the value of the variable-capacitance diode, much of the width of the bi-stable region and the amount of output decreases.

Other Versions of the Circuit

Series Diode Version for Maximum Sensitivity

As just stated, reducing *C* to a very low value may restrict the operating range of the circuit. This occurs because a small value of fixed C places a relatively large fixed reactance in series with the variable-capacitance diode. This reduces the range of tuning of the circuit that can be brought about by changes of capacity of the diode. It also results in division of the a-c voltage so only a portion of it appears across the diode. The circuit of Fig. 7 shows how these effects may be overcome. A second variable-capacitance diode may be used in place of the fixed capacitor to maintain a highly bi-stable characteristic while at the same time providing a minimum of capacity across R. The capacitances of both diodes, varying together, result in a maximum range of tuning of the circuit and in full utilization of the a-c voltage. A typical output-input characteristic for this circuit is shown in Fig. 8. A bi-stable characteristic extending over a ten-to-one ratio of input voltages is not uncommon with this circuit if R can be kept large.

d-c Outputs of Different Polarity

The circuit shown in Fig. 9(a) shows how another variable-capacitance diode may be connected to provide two d-c outputs of different polarity. Typical output-input characteristics are similar to those shown in Fig. 3, except that there will be two, one of each output polarity.

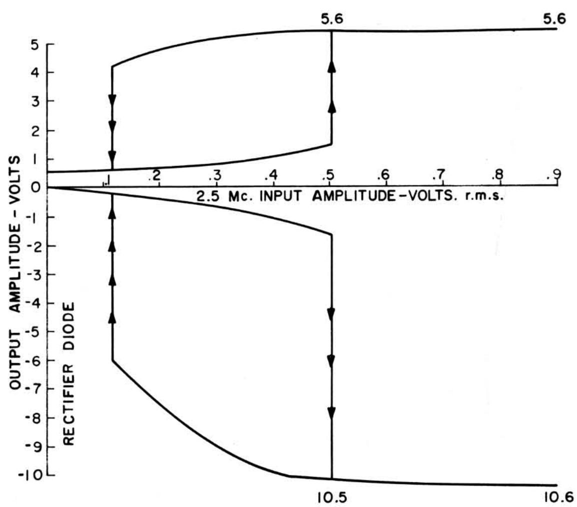


Fig. 10 – Output-input characteristic for double-diode circuit of Fig. 9(b).

A point contact diode can be substituted for one of the variable capacitance diodes, as shown in Fig. 9(b). Figure 10 shows typical output-input characteristics for this connection. It will be noted that the output from the point contact diode is greater than that from the variable-capacitance diode. As explained earlier, there is considerable flattening of one side of the a-c waveform, and

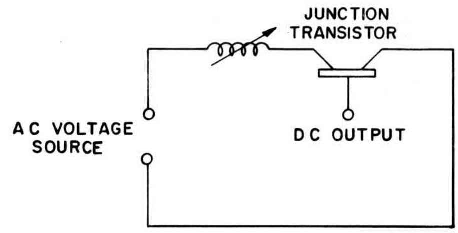


Fig. 11 – Transistor version of bi-stable circuit.

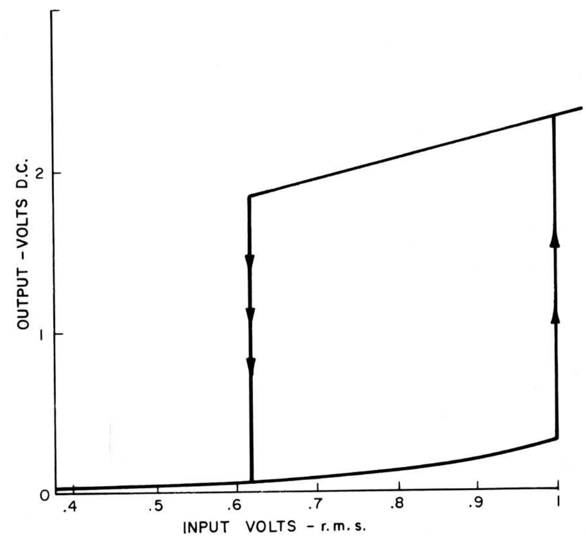


Fig. 12 – Bi-stable characteristic of transistor version.

peaking of the other. The variable-capacitance diode develops bias determined by the flattened half of the cycle, while the point contact diode develops bias on the peaked half of the cycle. There is about a two-to-one difference in outputs.

Transistor Version

A transistor version, one in which a junction transistor is used to replace both of the variable-capacitance diodes in the series diode version, is shown schematically in Fig. 11. This circuit uses the emitter-base junction capacity and the base-collector capacity in series to form a circuit that appears to be like the series variable-capacitance diode circuit of Fig. 7. It is not exactly similar, however, because there is the possibility of transistor action during conduction. When the transistor is used in this manner, the resistance of its base and base lead are not normally part of the r-f circuit, and therefore do not lower the Q. The bi-stable output-input characteristic obtained with a 2N109 transistor is shown in Fig. 12.

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