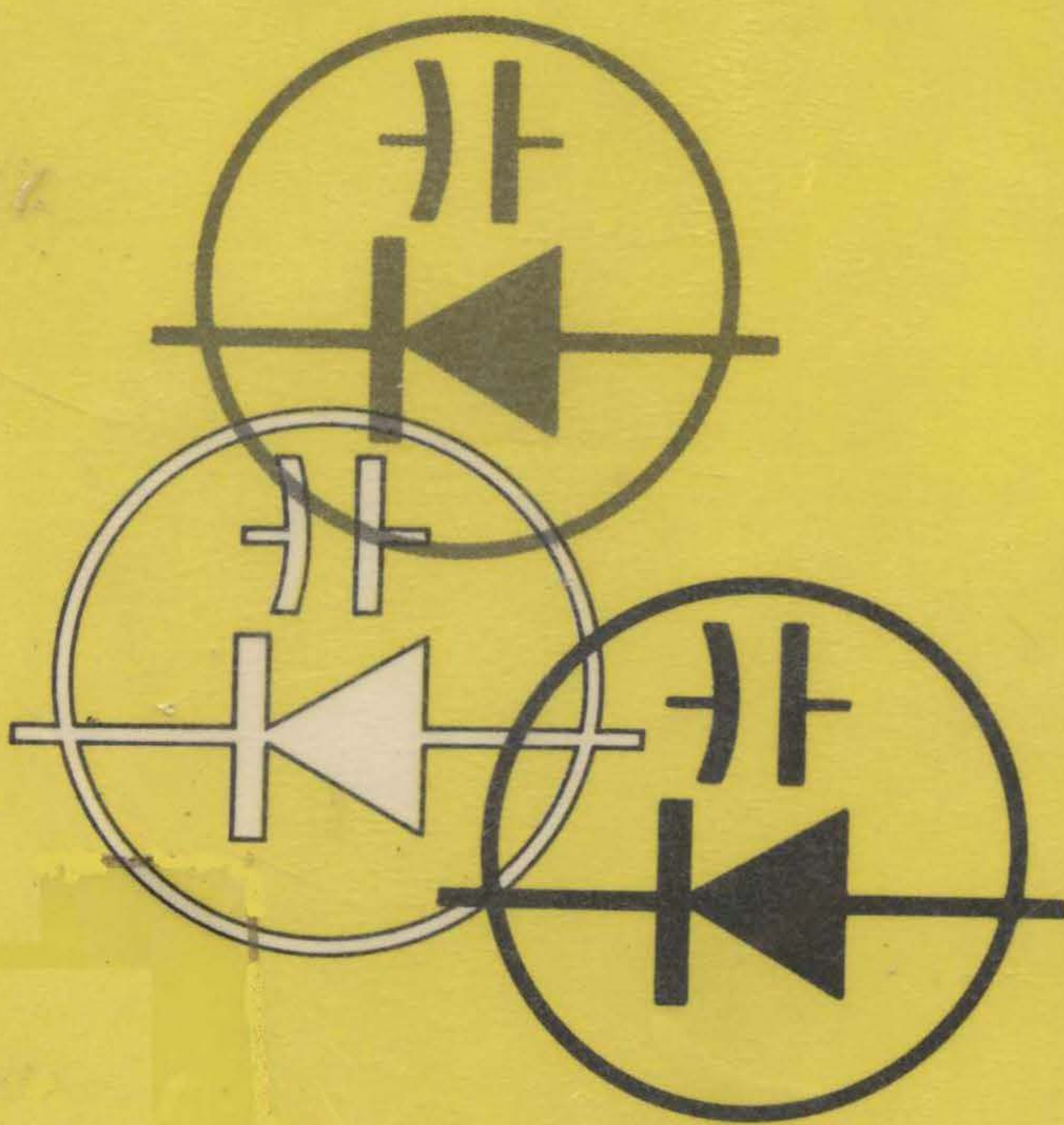


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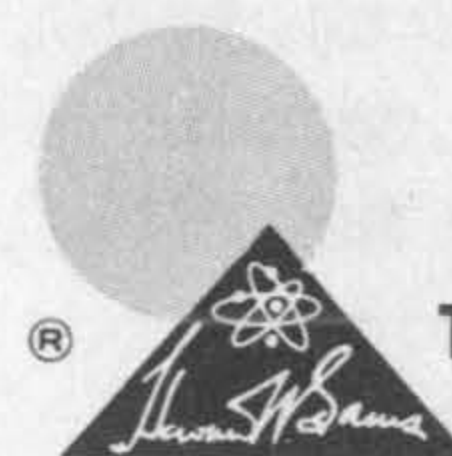
abc's of **Varactors**

by Rufus P. Turner



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This book attempts to explain the varactor and to describe some of its applications in essentially non-mathematical language. The author hopes that the discussion will help electronics people of all classes to understand this device and to use it advantageously.

RUFUS P. TURNER

Preface

The *varactor*, while no youngster, is a comparative newcomer to the semiconductor field. But with the vigor of youth it has already extended dependable solid-state operation into the microwave spectrum, and it has simplified and improved several types of electronic circuits. This is all the more remarkable because the varactor is a simple two-terminal device.

From one standpoint the varactor is the fulfilled hope of early workers that somehow the semiconductor diode might be made to amplify, multiply, and switch signals by itself—unaided by other electrodes or even by the property of negative resistance. It is also the answer to the long-felt need for a simple device which can convert voltage changes into useful amounts of capacitance change at high Q and with good temperature stability.

Despite its novel features and dramatic performance, the varactor is no laboratory curiosity. It has taken its place in the ranks of workhorse electronic components and promises to assume increased future importance. Research and development continue in varactor design and applications.

This book attempts to explain the varactor and to describe some of its applications, in essentially nonmathematical language. The author hopes that the discussion will help electronics people of all classes to understand this device and to use it advantageously.

RUFUS P. TURNER

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1

Basic Varactor Theory

The *varactor* is a relatively simple two-terminal solid-state device that utilizes the voltage-variable capacitance of a PN junction. It has provided new ways of tuning circuits, amplifying signals, generating oscillations, multiplying and dividing frequencies, automatically controlling frequency, and performing other tasks in electronics. In many instances the varactor does its job more efficiently, simply, and economically than other components.

Varactor operation is easily explained in practical terms and may readily be visualized by the reader who has an understanding of semiconductor behavior. To clarify varactor theory, a brief review of fundamental semiconductor and PN-junction theory will be given in this chapter. In addition, an explanation in practical terms of how capacitance occurs in a junction—and why it varies with voltage—is included.

WHAT IS A VARACTOR?

Every semiconductor diode has some internal capacitance. Usually, however, this parameter is insignificant; it is intentionally kept as small as practicable so that it will not

degrade normal diode operation. (The capacitance of a junction diode is higher than that of a point-contact diode mainly because the junction diode has the larger area.)

Basically, a varactor (its name is coined from the term *variable reactor*) is a special-purpose junction diode.¹ But it differs from other diodes in one important respect: it has been designed and fabricated expressly to make its junction capacitance useful. Thus, capacitance—which is an unavoidable nuisance in conventional diodes—is deliberately cultivated in the varactor.

It is both novel and useful that this capacitance can be varied at will by varying the voltage applied to the diode. This phenomenon enables a tiny varactor to do the work of a conventional variable capacitor that is many hundred times larger. Why a diode possesses capacitance and why the latter is voltage variable may be understood by closely examining the nature of the PN junction.

Although all semiconductor diodes and rectifiers (e.g., copper oxide, germanium, selenium, silicon) have inherent capacitance, which limits the highest frequency at which they will operate efficiently, most varactors are made from silicon. The reason for this choice is that this material has excellent temperature characteristics, and diodes made from it have extremely high back resistance. There is one notable exception: Varactors intended primarily for microwave and very low noise applications often are made from gallium arsenide. In external appearance, the varactor resembles a conventional diode or rectifier of the same power class. It may be as small as a 1/10-watt resistor or as large as a power transistor.

Fig. 1-1 shows circuit symbols for the varactor. In this book we will use the one at A.

VARACTOR SEMICONDUCTOR FUNDAMENTALS

The varactor differs from the conventional diode chiefly in internal features which result from special processing of

¹Besides being called by the familiar generic names of varactor, varactor diode, silicon capacitor, and voltage-variable capacitor, this component is also known by various trade names, such as *Capsil*, *Epicap*, *Paramp Diode*, *Semicap*, *Varicap*, and *Voltacap*.

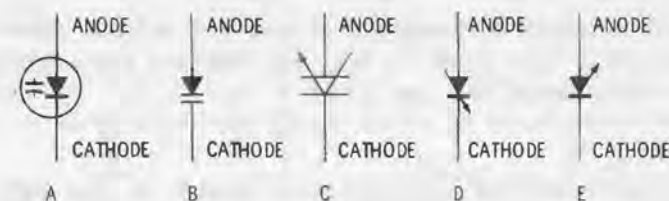


Fig. 1-1. Varactor symbols.

its semiconductor material and of its junction. This processing ensures usable internal capacitance, high parallel resistance, and low series resistance. The nature and electrical behavior of the semiconductor in the varactor must be examined at the atomic level.

Electricity in Semiconductors

The resistivity of semiconductors suitable for use in varactors lies somewhere between that of good conductors and of good insulators. For example, silicon suitable for this use may have a resistivity of 60,000 ohm-centimeters (ohm-cm) or higher, whereas a good conductor such as copper may show as tiny a value as 1 millionth ohm-cm, and the good insulator mica as high a value as 2×10^{17} ohm-cm.

The lone vehicle of electric current in common solids, whether conductors or insulators, is the free electron. Metals have enormous quantities of such electrons, insulators barely none. In semiconductors, the electron may not be the sole mobile carrier; current in these materials can be more complicated than in an ordinary conductor or insulator. Because a semiconductor can be processed to favor one or another type of carrier, conditions are obtainable which make diode and varactor operation possible.

Electrons and Holes

Electricity flows through a semiconductor via the drift of two kinds of current carriers: *electrons* (negative charges) and *holes* (equivalent positive charges). In semiconductor atoms, the electrons are the particles which orbit around the nucleus; a hole is a spot at which an expected electron is absent. In a suitably processed material, one type of carrier overwhelmingly predominates, hence is called the *majority carrier*. The other type is termed the *minority carrier* and

usually exists in inconsequential numbers only. A material is termed *N type* when its majority carriers are electrons, and *P type* when they are holes.

Doping

A highly purified semiconductor (which in that refined state is almost an insulator and is termed *intrinsic*) is deliberately made *N type* or *P type*, as desired, by "doping" it with a controlled trace of suitable impurity material (the *dopant* or *additive*). In this way, (1) the electrical conductance of the material may be closely tailored, and (2) the type of current carrier may be preselected. Intrinsic silicon, for example, may be made *N type* by doping it with arsenic or antimony, or *P type* by doping it with aluminum or boron. Depending on intended end use, a semiconductor may be lightly doped or heavily doped.

The effect of doping is more complicated than might be guessed from the surface appearance of simply mixing a suitable impurity material into a molten semiconductor. The impurity actually penetrates the semiconductor structure at the atomic level. To understand how this happens, visualize this picture: The atoms in an intrinsic semiconductor are believed to be arranged in an orderly, repetitive pattern called the *crystal lattice*. The lattice is held tightly together by means of bonds between the electrons of adjacent atoms. (These so-called valence bonds result from the sharing of orbits by electrons in the adjacent atoms.) Ideally, all of the electrons are tied up in these valence bonds, and at room temperature none are available as current carriers. The atoms of common semiconductors each have four orbiting electrons, each of which forms a bond with an electron in an adjacent atom (see the simplified, two-dimensional representation in Fig. 1-2). Now when an impurity atom is added, it can fasten itself into the semiconductor lattice and become a part of it only if the impurity electrons form bonds with electrons in the adjacent semiconductor atoms. If an impurity is added which has five valence electrons, each impurity atom will use four of its electrons to bond with adjacent semiconductor atoms, leaving its fifth electron unbonded and free to act as a current carrier. The semiconductor thus becomes *N type* (see Fig. 1-3). This is what hap-

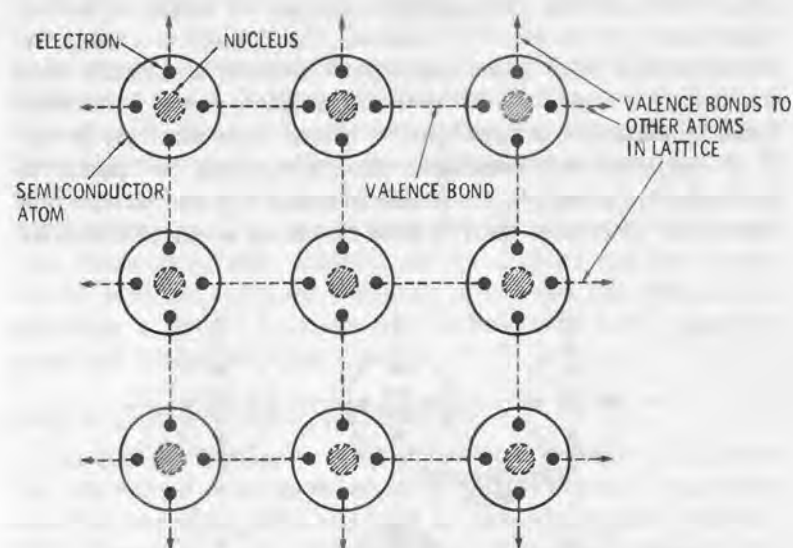


Fig. 1-2. Atoms in intrinsic semiconductor crystal lattice.

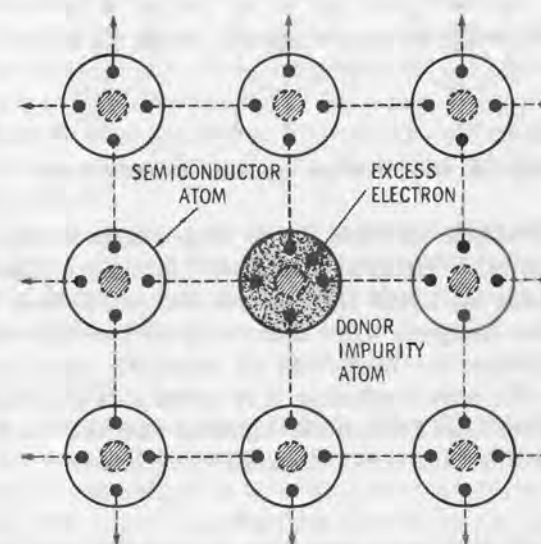


Fig. 1-3. Atoms in N-type semiconductor crystal lattice.

pens when arsenic (five-electron atoms) is added to silicon (four-electron atoms).² If, instead, the dopant is a material whose atoms each have only three valence electrons, each impurity atom will use all three of its electrons to bond with those in adjacent semiconductor atoms. One electron in one of the adjacent semiconductor atoms then has no "mate" in the impurity atom; hence a hole is created in the lattice (see Fig. 1-4). This hole then is free to act as a current carrier

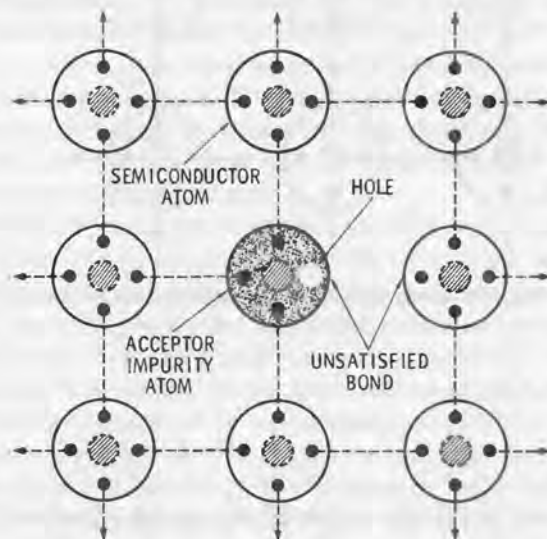


Fig. 1-4. Atoms in P-type semiconductor crystal lattice.

(i.e., an available electron from somewhere in the lattice will fall into the impurity-atom hole, leaving a hole where it came from, etc.) and the semiconductor becomes P type. This is what happens when aluminum or boron is added to silicon. Because the first kind of impurity contributes an electron to the semiconductor, it is called a *donor*. Similarly, because the second kind of an impurity can take an electron from the semiconductor, it is called an *acceptor*.

²In a typical case, one arsenic atom is added for each 100 million silicon atoms. Very few conduction electrons thus are provided, and this fact accounts for the high resistivity of the doped silicon.

THE PN JUNCTION

It is well known that the contact between an N-type semiconductor and a P-type semiconductor forms a rectifying "junction." That is, electric current passes through the combination very easily when an applied a-c voltage makes P positive with respect to N, and almost not at all when P is made negative. This shows that the resistance of the junction depends on the polarity of the applied voltage, being low in the first instance and high in the second. This action provides a simple diode—which is basically a PN junction provided with terminals.

Junction Voltage, Current, and Resistance

An applied voltage is termed *forward voltage* (V_f) when its polarity is such as to make P positive and N negative, and the resulting high current is termed *forward current* (I_f). Conversely, an applied voltage is termed *reverse voltage* (V_r) when its polarity is such as to make P negative and N positive, and the resulting low current is termed *reverse current* (I_r). (Reverse current is also called *leakage current*.) The corresponding junction resistances are *forward resistance* (equal to V_f/I_f) and *reverse resistance* (equal to V_r/I_r) (also called *leakage resistance*). In PN junctions suitable for varactors, reverse (leakage) current is extremely low—on the order of a few thousandths of a microampere. This is another way of saying that the leakage resistance is extremely high—on the order of several thousand megohms.

The P layer of the junction is termed the *anode*, and the N layer the *cathode*, from the conventional view that current flows through a diode readily when the anode is positive and cathode negative.

Junction Is Internal

Although we conveniently think of the PN junction as the junction between two pieces of semiconductor material, one N and one P, its nature is not so simple. An electrically efficient junction cannot be obtained merely by touching an N-type block to a P-type block, however flat their mating faces are polished and however tightly they are pressed together.

The contact must be a great deal more intimate than is afforded by such a simple arrangement. For that reason, the junction is processed into a single block, wafer, or chip of semiconductor material. For example, we can start with a wafer of N-type semiconductor and convert a portion of it to P type. Or, alternatively, we can start with P type and make a portion of it N type. An intimate junction then occurs naturally where the N-type material becomes P type, or vice versa. Finally, a lead may be attached to the N region and another to the P region, for external connection.

Alloyed Junction versus Diffused Junction

Two common methods of making the conversion in a single semiconductor are by *alloying* and *diffusion*. In the first, a suitable impurity is alloyed with the semiconductor to convert a part of the semiconductor into the opposite type. During this process, the impurity and the semiconductor both are molten, at least in the region of contact. In the second method, the impurity material is brought into contact with and diffuses into the semiconductor at high temperature but below the melting point (sometimes the dopant is gaseous), somewhat as a drop of ink diffuses into a blotter. Generally, the alloyed junction is abrupt (i.e., the N material quite suddenly becomes P material), whereas the diffused junction usually exhibits gradual transition from N to P.

Inside the Junction Diode

In a simple PN-junction device (diode, transistor, varactor), why do not the electrons in the N region drift across the junction and fill up the holes in the P region, thereby converting the entire mass into intrinsic semiconductor material and erasing the junction? The answer is that a small amount of this action (termed *recombination*) does occur when the junction first is formed—a few electrons move into the nearest holes across the junction (Fig. 1-5B). But then, as a result of this initial recombination, that portion of the P region which is at the junction becomes charged slightly negative because of the electrons it has gained, and this charge repels further electrons which try to drift across from the N region. The movement therefore stops. At the same time, that portion of the N region which is at the junction

becomes charged slightly positive because of the holes left in it by the electrons it lost in the brief recombination. This internal electrification is termed the *space charge* (Fig. 1-5C).

Space-Charge Region

The space charge amounts to a few tenths of a volt and can be imagined as a small battery inside the junction. This voltage (termed *contact potential*, ϕ) cannot be measured

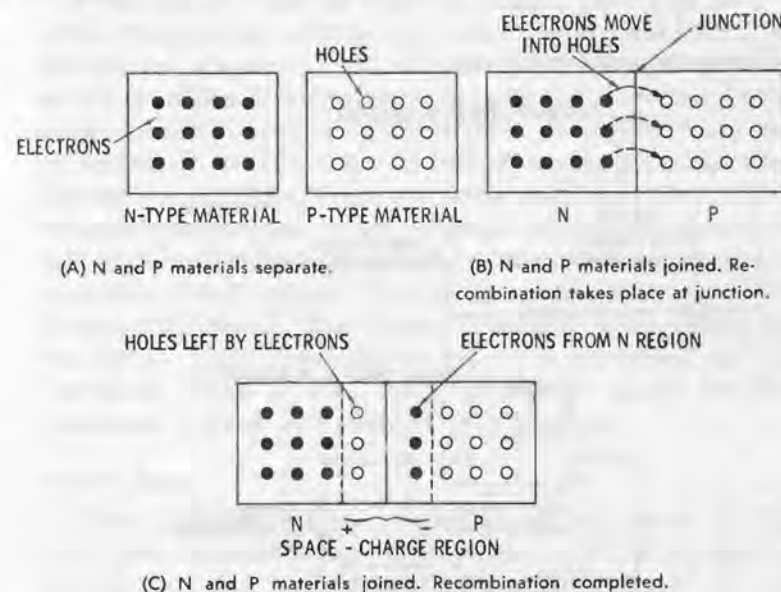


Fig. 1-5. Electron-hole relations at PN junction.

externally, but we know it is there, because it accounts for several aspects of diode behavior.

The space charge acts over a narrow section of the semiconductor on each side of the junction—the space-charge region—indicated by the dashed lines in Fig. 1-5C. When no external voltage is applied to the junction, the width of the space-charge region depends on the kind of semiconductor and the degree of its doping. Ideally, no free carriers exist in this region, so it effectively is an insulator, and for this reason is usually called the *depletion layer* (i.e., depleted of current carriers).

JUNCTION OPERATION

The behavior of a PN junction in response to applied voltage (bias), briefly previewed earlier under "Junction Voltage, Current, and Resistance," now may be visualized with the aid of Fig. 1-6.

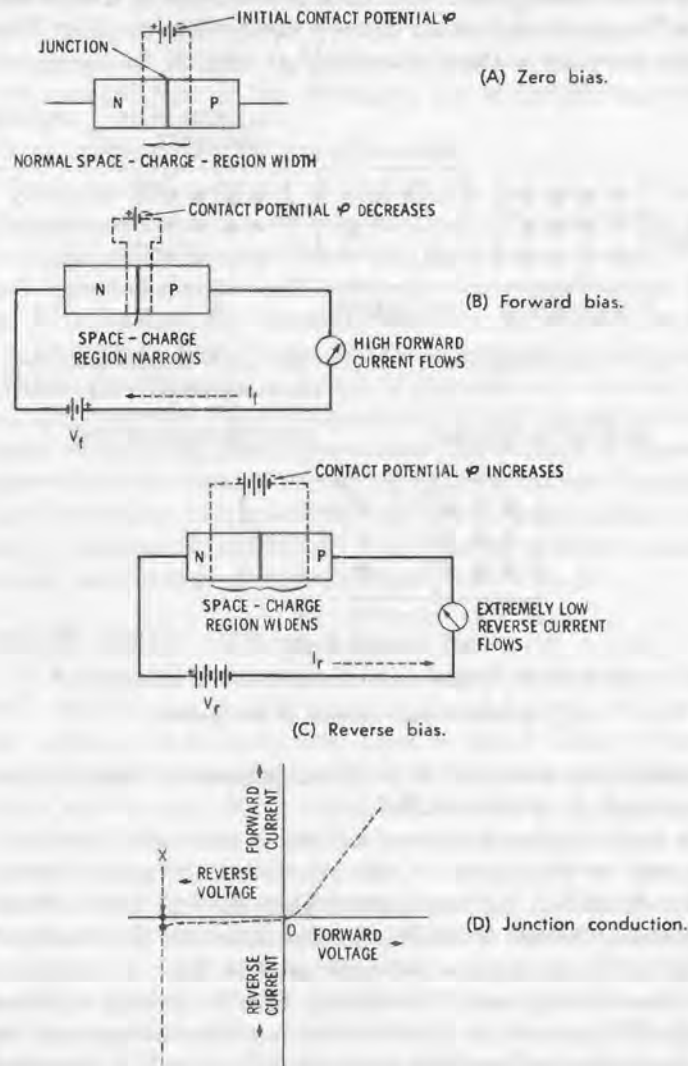


Fig. 1-6. PN junction operation.

Zero Bias

At zero bias, the contact potential (voltage of the imaginary internal battery) has a characteristic value, and the depletion layer has a characteristic width, as shown in Fig. 1-6A. Both of these are determined by the semiconductor and its processing.

Forward Bias

When the junction is forward biased, as shown in Fig. 1-6B, the external voltage is in series with the contact potential, and electrons from voltage source V_f repel electrons in the N region, forcing them toward the junction. At the same time, the positive electrification from the other pole of source V_f repels holes in the P region, forcing them toward the junction. These electrons and holes meet and recombine continuously at the junction, as more electrons enter the N region from the voltage source, and more holes are moved in the P region. The result is the relatively heavy forward current I_f . The contact potential is decreased and the width of the space-charge region is narrowed as V_f is increased. When $V_f = \phi$, the space-charge region becomes extremely narrow and eventually disappears.

Reverse Bias

When the junction is reverse biased, as shown in Fig. 1-6C, the external voltage is in series with the contact potential, and the positive charge of the external voltage source, V_r , attracts holes in the P region away from the junction. Here, the result is a widening of the depletion layer, an increase of the contact potential, and a flow of tiny reverse current I_r .

Conduction Characteristic

Fig. 1-6D illustrates the typical forward and reverse currents in a silicon PN junction. From this plot, note that the forward current increases rapidly as the forward voltage is raised. And note that the reverse current is negligible and increases hardly at all as the reverse voltage is raised to a high value, until point X (reverse breakdown voltage V_{br}) is reached. At this point the reverse current then increases

sharply for a small further increase in reverse voltage. Although this point is termed "breakdown," the junction is not destroyed so long as the reverse breakdown current is limited to a safe value by the circuit in which the junction operates. Conduction, both forward and reverse, is nonlinear over a large part of its range.

Junction Capacitance

The question of how capacitance arises inside the PN junction now may be answered. From the foregoing discussion, it is evident that the junction actually consists of an N (negative) region and a P (positive) region separated by a depletion (intrinsic, insulating) layer. This structure is identical, then, to two flat conducting plates separated by a dielectric. This arrangement describes any two-plate capacitor.

In any two-plate capacitor, the capacitance is directly proportional to the effective area of the plates and to the dielectric constant of the dielectric, and is inversely proportional to the thickness of the dielectric. Expressed as a formula:

$$C = \frac{k A}{4.45d}$$

where,

- C is the capacitance in picofarads,
- k is the dielectric constant,
- A is the area in square inches,
- d is the thickness of the dielectric in inches.

In the semiconductor junction, A is the area of the N and P regions that face each other across the junction, d the thickness of the depletion layer, and k the dielectric constant of the depletion-layer semiconductor.

Since the thickness of the depletion layer varies with bias voltage (see Figs. 1-6B and 1-6C), the junction capacitance therefore varies with voltage. In effect, varying the bias voltage "moves" the capacitor "plates" toward or away from each other. That is, the varactor is basically a voltage-variable electronic capacitor—the capacitance varying according to the applied voltage.

INSIDE THE VARACTOR

As explained at the beginning of this chapter, the varactor is a special-purpose junction diode. Specifically, its junction has been processed to optimize capacitance, minimize series resistance, and maximize leakage resistance. Some varactors are fabricated primarily for tuning purposes, others for harmonic generation (frequency multiplication), and still others for parametric amplification and other applications.

Equivalent Circuit

In most applications, the varactor is reverse biased, since in this state it draws virtually no current and, therefore, is essentially voltage operated and consumes almost no power. The various parameters of the practical varactor are shown in their relation to each other by the equivalent circuit in Fig. 1-7A.

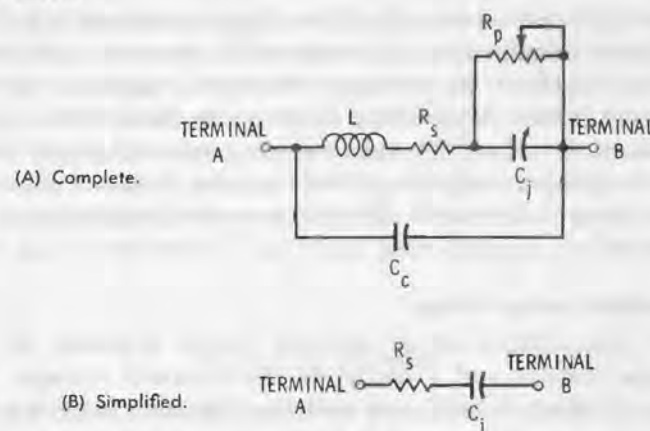


Fig. 1-7. Varactor equivalent circuit.

In Fig. 1-7A, L is the inherent series inductance due to leads and attachments, and to the semiconductor bulk; R_s is the series resistance due primarily to bulk resistance of the semiconductor, but also to leads and electrodes; C_c is the stray capacitance of the diode, due to leads, electrodes, attachments, and case; C_j is the internal voltage-variable capacitance of the junction; and R_p is the internal leakage re-

sistance of the junction. R_n is somewhat voltage variable, since the bias voltage changes the contact potential—see Fig. 1-6.

In practical varactors, L and C_c are reduced as far as practicable through efficient design and packaging. Series resistance R_s is minimized and leakage resistance R_p maximized through appropriate refinement of the semiconductor and careful control of its doping. Resistance R_p often is so high that it may be considered infinite, therefore being of no interest in the equivalent circuit. Junction capacitance C_j is optimized by junction processing and is proportioned by control of junction area, depletion-layer thickness, and semiconductor doping. Because R_p is extremely high and L and C_c extremely low, all three may be ignored in many lower-frequency situations. The equivalent circuit of the varactor then may be simplified to only two elements: junction capacitance C_j and series resistance R_s , as shown in Fig. 1-7B.

From the foregoing discussion, it is obvious that C_j is the desired parameter and all of the others undesirable but unavoidable. Maximizing R_p renders the varactor essentially voltage operated, by reducing resistive operating current virtually to zero. Minimizing R_s increases the Q of the varactor (here, $Q = 1/\omega R_s C_j$), thus reducing internal power losses and sharpening response of the varactor in tuned circuits.³ Minimizing L increases the self-resonant frequency of the varactor.

Capacitance versus Voltage

The capacitance of a varactor varies inversely as the reverse voltage and directly as the forward voltage. The reverse-voltage capacitance is of chief interest in most applications, since at forward voltages leakage current is high and Q low. Therefore, except where specifically designated otherwise, all references to varactor capacitance throughout this book mean reverse-voltage capacitance.

The capacitance varies nonlinearly. The exact manner in which it varies depends on the type of semiconductor and

³One of the methods employed to reduce R_s is to dope the semiconductor heavily, but to graduate the doping carefully so that it is light at the actual junction but heavy elsewhere.

how it has been processed. For example, in the silicon abrupt-alloyed junction:

$$C_r = \frac{K}{\sqrt{V + \phi}}$$

where,

C_r is the capacitance at the applied voltage,

K is a constant,

V is the applied voltage,

ϕ is the contact potential.

The constant (K) depends on the kind of semiconductor and its processing; it is related to reverse breakdown voltage and minimum capacitance of the junction (K is often 1, and ϕ 0.5 to 0.65 for silicon). In a deep-diffused junction:

$$C_r = \frac{K}{\sqrt[3]{V + \phi}}$$

Note that only the exponent is different in these two equations—the first denoting the square root of $V + \phi$, and the second the cube root. Through careful management of the diode processing, the exponent can be controlled, in order to tailor the voltage-capacitance curve to individual requirements. Fig. 1-8A shows a typical varactor capacitance curve. Note that in this instance the capacitance variation is approximately square law. Fig. 1-8B shows the capacitance curve for a particular varactor at both forward and reverse bias.

VARACTOR RATINGS

In their data sheets, varactor manufacturers give minimum, maximum, and typical values of various operating parameters. These include the following:

1. *Maximum Working Voltage (mwv)*—The maximum working voltage is the highest reverse voltage (d-c bias + peak a-c signal) at which varactor may be safely operated. Depending on type, this is from -9 to -700 vdc.
2. *Breakdown Voltage (V_{br})*—The breakdown voltage is the voltage at the point at which the reverse current in-

creases sharply to a higher level (X in Fig. 1-6D). Some manufacturers specify this voltage for the $10\text{-}\mu\text{a}$ point, others for $100\mu\text{a}$. Depending on type and make, this point will be from -17 to -100

3. **Maximum Reverse Current (I_r)**—The maximum reverse current is the current flow at the maximum reverse working voltage. Depending on type and make, this current ranges from 0.005 to $5\text{ }\mu\text{a}$.

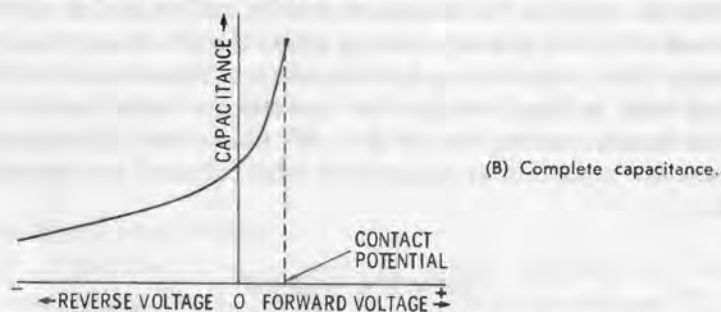
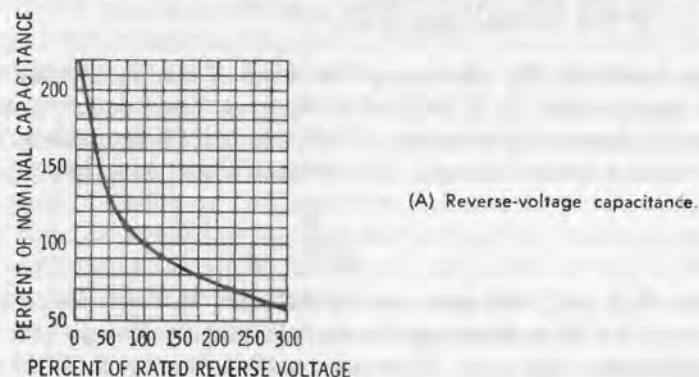


Fig. 1-8. Capacitance versus voltage characteristics.

4. **Power Dissipation (P_d)**—The power dissipation is the maximum power that can safely be dissipated by the varactor. Depending on type, it ranges from 200 milliwatts to 25 watts average at 25°C (up to 450-wa reactive power). For operations at ambient temperatures other than 25°C (-263°C to $+200^\circ\text{C}$, depending on type and make), various manufacturers recommend different derating factors, usually from 1.67 to $13\text{ mw}/^\circ\text{C}$.
5. **Nominal Capacitance (C)**—The nominal capacitance is

the rated capacitance of the varactor. It is usually stated for a specific voltage (e.g., -4 volts) and frequency (e.g., 1 MHz). Units are available with values from 0.1 to 2000 pf . The very low capacitances usually distinguish the microwave varactors. Chart 1-1 lists 48 standard nominal capacitances. These are the figures that appear in the varactor literature or on the varactor case. They are the capacitances obtained at the specified voltage. At lower voltages, the capacitance will be higher, and at higher voltages it will be lower.

Chart 1-1. Nominal Capacitances*

0.1	5.0	20	65
0.2	6.4	22	68
0.3	6.5	22.5	70
0.4	6.8	24	71
0.5	7.0	27	82
0.6	8.0	33	100
0.7	8.2	35	150
0.8	10	39	250
0.9	12	47	350
1.0	14	50	500
3.0	15	53	1000
4.0	18	56	2000

*All values are in pf.

6. **Capacitance Ratio or Range (ΔC)**—The capacitance ratio corresponds to a specified bias voltage range (zero, or a designated level such as -4 volts, to maximum working voltage, -1 to -50 volts, -2 to -100 volts, etc.) and specified test frequency (e.g., 1 MHz). Depending on type, capacitance ratios range from $0.233:1$ to $12:1$.
7. **Figure of Merit or Quality Factor (Q)**— Q is the ratio of reactance to series resistance (above 0.1 MHz , $Q = 1/\omega R_s C_j$ and decreases as the frequency increases). It is specified at a particular voltage (e.g., -4 volts) and

frequency (e.g., 50 or 100 MHz) and ranges from 3 to 600, depending on capacitance, voltage, type, and make. At low frequencies (i.e., below 0.1 MHz), Q reaches a value of several thousand. It increases with reverse voltage up to the reverse breakdown point (X in Fig. 1-6D), whereupon it decreases rapidly, approaching zero. Q also decreases rapidly with increasing forward voltage, again approaching zero.

8. **Series Resistance (R_s)**—The series resistance is primarily composed of the bulk resistance of the semiconductor and the resistance of contacts, leads, etc. However, it may also contain in-phase frequency-dependent components, such as constituents of skin effect. It is specified in ohms at a particular bias and extends from 0.14 to 14 ohms, depending on type and make.
9. **Cutoff Frequency (f_{co})**—The cutoff frequency is the frequency at which Q equals 1. It is generally specified with respect to a particular bias (e.g., -2 , -3 , -4 , or -6 volts, mwv, or $1/3V_{br}$) and extends from 10 to 350 GHz, depending on capacitance, voltage, type, and make.
10. **Self-Resonant Frequency (f_r)**—The frequency at which a varactor resonates without external components is the self-resonant frequency. It results from the inherent inductance and capacitance (junction and package capacitances) of the unit. The inherent series inductance is extremely small (typically less than 0.5 nh), so the self-resonant frequency accordingly is high. This frequency is not always specified by the manufacturer, but it ranges from 150 to 2000 MHz in lower-frequency models.
11. **Forward Current (I_f)**—The current resulting from forward bias of the junction is the forward current. This current is not always specified by the manufacturer, since the reverse characteristics are of prime interest. However, knowledge of its magnitude is important in some applications where the varactor becomes forward biased during part of a signal cycle, since this condition can, if forward current flows, lower the Q and increase power loss. A typical value for I_f is 100 ma at +1 volt (this is equivalent to a resistance of 10 ohms in parallel with the junction).

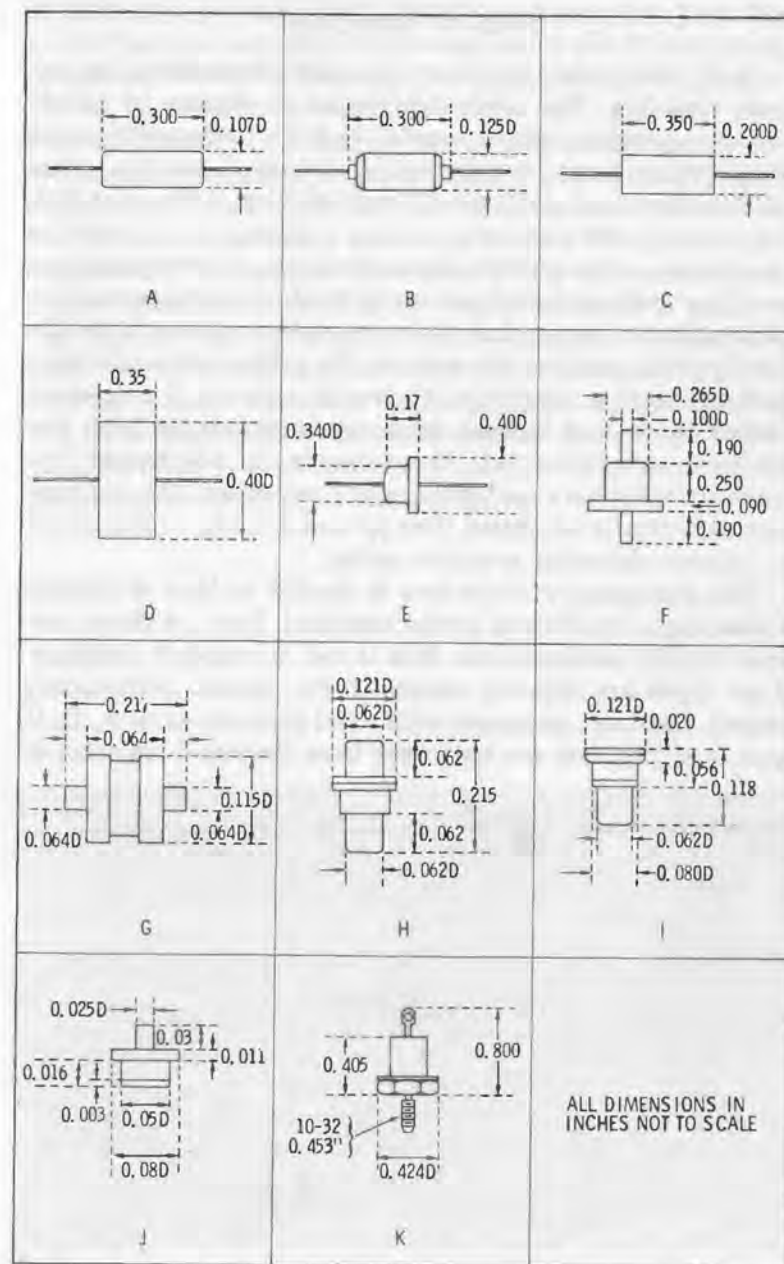
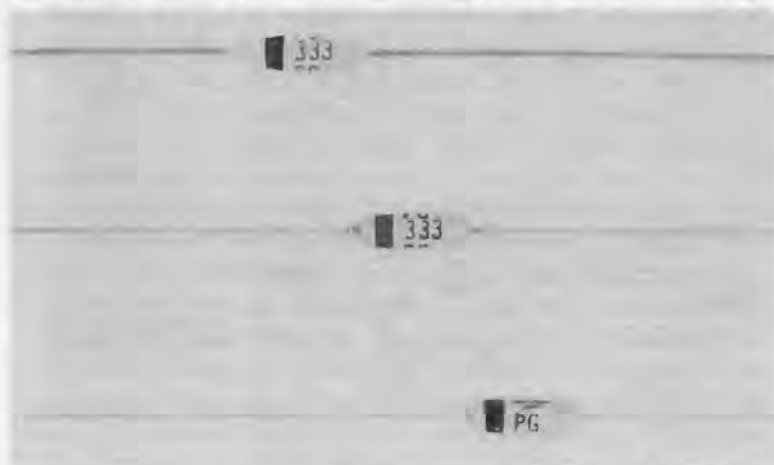


Fig. 1-9. Representative varactor packages.

TYPES OF VARACTORS

Most present-day varactors are made from silicon or gallium arsenide. The diode fabrication is chosen to satisfy various operating requirements. Various configurations are employed: alloyed junction, epitaxial alloyed junction, deep-diffused junction, shallow-diffused junction, diffused epitaxial junction, diffused mesa, planar epitaxial, etc. A detailed description of the physical characteristics of these structures or of the manufacturing processes would be extraneous here. It is sufficient to say that silicon varactors presently are the most widely used, but the more costly gallium-arsenide types find application where the highest Q and cutoff frequency, lowest noise, and highest efficiency at extremely high frequencies are demanded. For example, in microwave frequency multipliers and parametric amplifiers the gallium-arsenide type is employed. The epitaxial configuration seems to be most desirable in silicon units.

The packaging of varactors is similar to that of conventional signal diodes and power rectifiers. Fig. 1-9 shows several typical packages, but this is not a complete coverage. New types are steadily coming forth. Small, hermetically sealed, insulated packages with axial pigtails, as in A, B, C, and D of Fig. 1-9, are no longer than the small resistors or



Courtesy TRW Semiconductors

Fig. 1-10. Small-size varactors (TRW PG333).

tubular ceramic capacitors which they resemble (see Fig. 1-10). Various varactors of the type at A and B can handle power up to 500 mw. The one at C can handle 1 watt, and the one at D, 2 watts. A metal-cased, 115-volt unit with axial leads is shown at E. Double-ended ceramic-and-metal cartridges for convenient clipping into vhf and uhf fixtures are depicted at F and G, while H shows a similar double-ended cartridge for microwave use. Parts I and J of Fig. 1-9 show single-ended microwave cartridges of the type often called "pills" because of their shape. Finally, drawing K shows a high-power type. This DO-4 case is identical to that of a power rectifier. The threaded stud permits bolting to a heat sink for cooling. Varactors in this package (K) are rated up to 1 kv or higher, 25 to 30 watts average power, and at frequencies of up to 1200 MHz. Such units are useful in vhf-uhf frequency multiplication and switching.

2

Varactor Operation

Like other fully electronic components whose action simulates that of electromechanical devices, the varactor works faster and often more precisely and simply than its counterparts. In its basic role as a variable capacitor, for example, the varactor will operate at rates up to several million per second—faster than any motor-driven or hand-tuned capacitor could possibly function—and it can provide a wider range and higher efficiency than any comparable tube or transistor arrangement. In its more sophisticated functions, the varactor achieves with one component (or at most, only a few components in addition to itself) results which otherwise require numerous components and complicated circuitry.

VOLTAGE AND CURRENT RESPONSE

The control voltage for a varactor may be produced and adjusted directly for this purpose, or it may be a voltage obtained from an appropriate point in a circuit containing the varactor. Alternating current, direct current, or a mixture of the two may be used. In any event, the varactor has no way of knowing either source or intent but responds auto-

matically—and rapidly—to each value of voltage. This means that the a-c-operated varactor “sees” a succession of instantaneous voltages and responds to each of these as if it were a d-c voltage momentarily applied.

Steady D-C Voltage

When a steady d-c voltage is applied, the capacitance of the varactor assumes a value consistent with that voltage (see Fig. 1-8) and it holds to that capacitance as long as the voltage is maintained. The reverse d-c source sees the varactor as an infinite resistance, since the leakage current is negligible. This is a distinct advantage, as the loading of the source may for practical purposes be regarded as zero. Any d-c voltage applied to a varactor for control or bias purposes must be free of ripple, in order to obtain a nonvarying junction capacitance at each voltage setting.

Inasmuch as varactor d-c control current is practically zero at reverse voltages, the voltage may be applied through a fixed high resistance, as shown in Fig. 2-1, without voltage loss across the resistor. This provides an isolation resistor which eliminates the effects of hand capacitance or of capacitance in the voltage source which would otherwise shunt the varactor. In Fig. 2-1, V is the adjustable, steady d-c voltage, $R1$ a high resistance (usually several megohms), and $X1$ the varactor. A variable capacitance, corresponding to the capacitance-voltage curve of the varactor used, is obtained at terminals X-X. If the circuit or device in which this variable capacitance is to be used contains a d-c voltage, the varactor must be protected from its effects (it too can tune the varactor or burn it out) by means of a

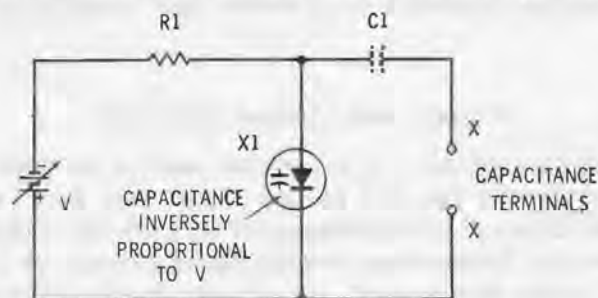


Fig. 2-1. D-c control of a varactor.

blocking capacitor, $C1$. The capacitance of the latter must be very much higher than the maximum capacitance of the varactor, so that $X1$ rather than $C1$ will determine the capacitance at terminals X-X. (A good rule of thumb is to make $C1$ approximately 1000 times the maximum capacitance of the varactor.)

With very-low-leakage varactors, there theoretically is no limit to the value of isolating resistor $R1$. A practical limitation is imposed, however, by the time constant (t) resulting from the series connection of this resistance and the varactor capacitance ($t = RC$, where t is in μsec , R in ohms, and C in mfd). The time constant is important when the varactor must respond to the control signal within some desired time after application of the signal. Thus, the time constant of a 100-megohm isolating resistor and 100-pf varactor is 10 msec. If the varactor must respond in a shorter period than that, a lower resistance must be used.

As explained in Chapter 1, the variation of capacitance in response to applied d-c voltage is nonlinear over most of its range. The graph in Fig. 1-8A, for example, shows that in one type of varactor a 2:1 voltage shift at one point (i.e., from 25 percent to 50 percent of rated reverse voltage) produces an inverse capacitance change of only 1.31:1, and at another point (i.e., from 12½ percent to 25 percent of rated reverse voltage) the 2:1 voltage shift produces an inverse capacitance change of 1.18:1. With most varactors, only a narrow sector of the response curve is linear.

Alternating Voltage and Current

While a varactor effectively blocks reverse direct current, it allows an alternating current to pass relatively freely. It is the reactive component of the varactor which transmits the alternating current. In most applications the reactance is capacitive because the inherent inductance component of the varactor is negligible. Since capacitive reactance is frequency dependent ($X_c = 1/\omega C$), the alternating current through a given varactor, for a constant a-c applied voltage, will increase as the frequency increases, and vice versa.

At a fixed frequency (reactance therefore constant), current increases as applied a-c voltage is increased. But it increases nonlinearly. It varies in this way because varactor

capacitance, upon which the reactance depends, itself varies nonlinearly with voltage. The varactor "feels" each of the instantaneous values of voltage in the a-c cycle and automatically adjusts its capacitance in accordance with each of these. (See Fig. 2-2.)

Because of the nonlinear a-c response of the varactor, the waveform of the varactor current differs from that of the applied voltage, in most instances. When a sine-wave voltage is applied, for example, the resulting current usually is non-

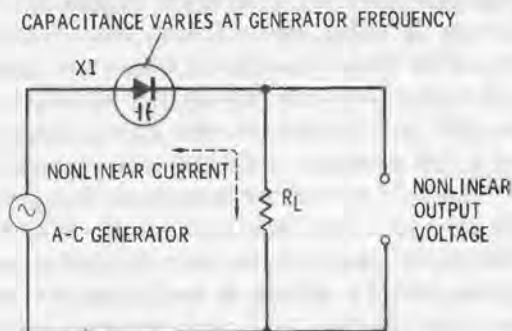


Fig. 2-2. Elementary a-c varactor circuit.

sinusoidal—that is, distorted. But it is this nonlinear a-c response which suits the varactor, as will be shown later, to such applications as harmonic generation and parametric amplification.

An a-c voltage presents the problem that its positive half-cycles forward bias the varactor (assuming the anode is positive); this will ordinarily increase leakage current and voltage-source loading, lower the Q , and broaden tuning. In many applications, therefore, care is taken to operate the varactor in such a way that it is never forward biased. Forward biasing by the signal is not always a detriment, however. At very high frequencies, for instance, an instantaneous positive half-cycle voltage higher than the contact potential will start current carriers flowing toward the junction. But at such a high frequency the voltage is in its negative half-cycle before normal d-c forward current can be established, and this negative voltage attracts the carriers back to their starting point. The effect is somewhat similar to charging and discharging a capacitor, so virtually no

power is consumed, and the reactive nonlinearity of the varactor is enhanced by the action.

The ability of the varactor to inhibit resistive current, while favoring reactive current, accounts for the high efficiency of this device in many applications. This follows from the fact that resistive current dissipates power in the resistance, and this power is lost, whereas reactive power ideally is lossless. To all practical intents and purposes, the varactor is a reactive-power device.

It must be remembered that the varactor is sensitive to *all* changes in applied voltage, intentional or accidental. Its capacitance therefore will vary with ripple, noise, hum, and transients. The varactor has no way of knowing that these are extraneous fluctuations. A d-c control signal or a d-c bias must be very clean. Because the varactor is a high-impedance device, hum and other interference may be accidentally capacitance-coupled into some of its circuits quite easily (as happens also in the high-resistance grid input circuit of a vacuum tube), and careful shielding may sometimes be required.

Operating Point

Through choice of a steady d-c voltage, the operating point of a varactor may be set anywhere along the capacitance-voltage response curve. Any control-voltage variation then may be accomplished by increasing the voltage above, or decreasing it below, this point. This is identical to setting the operating point of a tube or transistor by means of a d-c bias voltage.

When an operating point has been suitably chosen, an a-c signal may be superimposed on the bias; that is, it is applied to the varactor in series with the d-c voltage. This allows operation to be placed appropriately along the varactor curve to obtain linear, square-law, or other mode of response, since the a-c signal voltage swings the bias above and below its mean value wherever the bias value is located on the voltage axis. It also permits selection of operation such that the net positive swing of the a-c signal never drives the varactor into forward conduction. Again, the technique and results are similar to those associated with tube and transistor practice.

Fig. 2-3 illustrates the effect of shifting the operating point by changing the varactor d-c bias. The sinusoidal a-c signal shown here swings from +1 volt to -1 volt. In the first case, this signal is shown without d-c bias. As shown, the positive half-cycles then swing the varactor applied voltage up to -1 volt, and the negative half-cycles swing it across zero to +1 volt, forward biasing the varactor during this full, latter half-cycle. If, as shown in the second case, the operating point is moved to -4 volts, the positive half-cycles will swing the varactor voltage up to -5 volts, and the negative half-cycles down to -3 volts, safely outside the forward bias. If the operating point were set at -1 volt, the positive peaks of this same a-c signal would swing the varactor voltage up to -2 volts, and the negative peaks down to 0 volt, just escaping forward bias.

In the choice of operating point, there are other considerations than avoiding forward bias, however. Note from the shape of the reverse capacitance curve in Fig. 2-3 that the

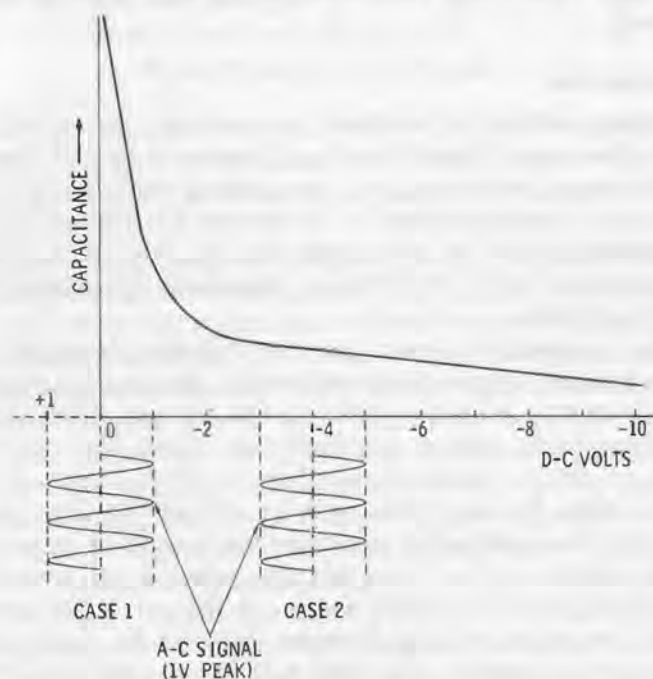


Fig. 2-3. Operating point.

slope of the curve is different at virtually each of the operating-voltage points. Accordingly, the waveform of varactor current will be different, since the reactance will vary at a different rate at each operating point.

In many applications which include combined alternating and direct current, the a-c component is kept much smaller than the d-c bias; otherwise, the a-c component will determine the varactor capacitance. In the circuit of Fig. 2-1, for example, terminals X-X normally are connected to some sort of a-c circuit in which the capacitance of the varactor will be utilized, and the a-c signal voltage in that circuit must be substantially lower than d-c control voltage V , or the direct current will be less effective than the alternating current in determining the varactor capacitance. It is well to restrict the peak value of the a-c voltage to not more than 1/10 of the d-c voltage. The sum of d-c voltage and peak a-c voltage must not exceed the maximum working voltage of the varactor.

Waveform

Alternating voltages applied to varactors are perhaps most often sine waves. But this is not mandatory. A signal voltage may also be a nonsinusoidal or pulse (square, rectangular, sawtooth, triangular, etc.) type. In general, the only precautions to be observed in the use of such signals are those which apply to use of the same signal with any capacitor of the same Q , capacitance, and voltage rating as the varactor, and/or the circuit in which it is connected.

MULTIPLE OPERATION

Large-capacitance varactors are not available at present. While a single varactor is seen in most circuits, the desire to connect two or more of these units in parallel to obtain higher capacitance for some applications may arise. Parallel operation is feasible if the following considerations are observed.

Total Capacitance

The total capacitance is the sum of the individual capacitances: $C_t = C_1 + C_2 + C_3 \dots + C_n$. The minimum (as well as

the maximum) capacitance is multiplied. Thus, three varactors, each of which covers the range 50 to 200 pf for a given voltage variation, will, in parallel combination, provide a capacitance range of 150 to 600 pf.

Voltage versus Capacitance

The voltage-versus-capacitance curve will be a composite of the curves of the individual varactors. This means that the shape of the curve for the parallel combination will depart from that of a single varactor to the extent that the capacitances of the individual units differ from each other at various voltage points. At a given voltage along the curve, the capacitance of the parallel combination will be the sum of the capacitances of the individual varactors. A special curve should be plotted for a parallel combination.

Total Reactance

The reactance of the combination is less than that of any one of the varactors:

$$X_c = \frac{1}{\omega C_t}$$

where,

C_t is the total capacitance.

If the individual reactances are known, the total reactance can be calculated by the formula:

$$X_t = \frac{1}{X_1} + \frac{1}{X_2} + \frac{1}{X_3} + \dots + \frac{1}{X_n}$$

Parallel Resistance

When varactors are connected in parallel, their parallel resistance (R_p) components, as well as their capacitance components, are effectively connected in parallel, as shown in Fig. 2-4. The total resistance of this combination is less than either of the individual parallel resistances. Using Ohm's law, it is computed:

$$R_{pt} = \frac{1}{R_{p1}} + \frac{1}{R_{p2}} + \frac{1}{R_{p3}} + \dots + \frac{1}{R_{pn}}$$

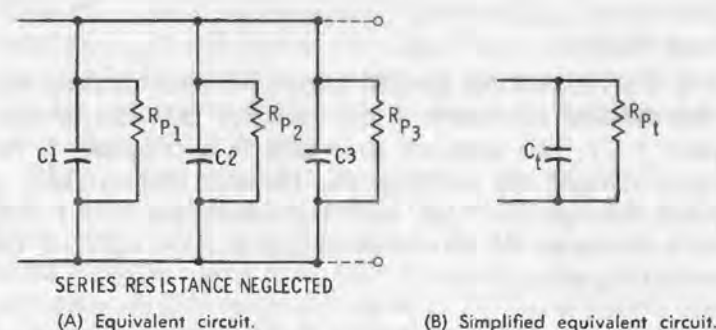


Fig. 2-4. Parallel connection of varactors.

Total Leakage Current

Since the parallel resistance of the combination is less than that of any one of the varactors, the leakage current at a given voltage must, by Ohm's law, be higher than that of any one of the varactors. The total leakage current is the sum of the individual currents:

$$I_t = I_1 + I_2 + I_3 + \dots + I_n$$

VARACTOR AND CONVENTIONAL CAPACITOR IN COMBINATION

A varactor often furnishes the total capacitance in a circuit. Occasionally, however, the varactor supplies only a part of the capacitance, the remainder coming from a conventional fixed or variable capacitor in parallel or series with the varactor.

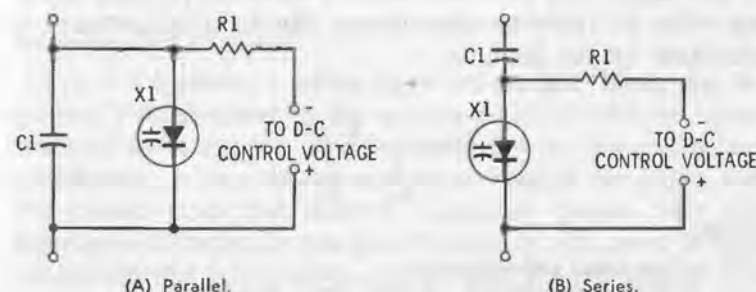


Fig. 2-5. Varactor and conventional capacitor in combination.

Parallel Circuit

Fig. 2-5A shows the parallel connection of a varactor and a conventional capacitor. Here, varactor X1 shunts fixed capacitor C1. The varactor thus acts as a trimmer. A d-c control voltage, for varying the varactor capacitance, is applied through the high isolating resistance of R1. The total capacitance of this combination at any value of the varactor capacitance is:

$$C_t = C_1 + C_d$$

where,

- C_t is the total capacitance,
- C_1 is the capacitance of the fixed capacitor,
- C_d is the capacitance of the varactor.

The minimum and maximum capacitances of the combination can be calculated by adding the minimum (or maximum) capacitance of the varactor to the fixed capacitance.

Capacitor C1 may also be variable. As such it may be used as a trimmer which is preset to limit the capacitance range of the varactor.

Series Circuit

Fig. 2-5B shows the series connection of the combination. As in the previous circuit, a d-c control voltage for varying the varactor capacitance may be applied through the high isolating resistance of R1. Here, the fixed capacitor acts as a padder for the varactor, or as a d-c-blocking capacitor, depending on the use to which the combination is put. The total capacitance of this circuit must be less than that of either of the capacitors (conventional or varactor). That is, at any value of varactor capacitance, the total capacitance is calculated by the formula:

$$C_t = \frac{1}{\frac{1}{C_1} + \frac{1}{C_d}}$$

where,

- C_t is the total capacitance,
- C_1 is the capacitance of the fixed capacitor,
- C_d is the capacitance of the varactor.

When C_1 is fixed and is equal to or less than the maximum value of C_d , it will reduce the capacitance range of the varactor. Capacitance C_1 may also be variable, whereupon it may act as a padder which may be preset to limit the capacitance range of the varactor.

When a fixed capacitor is connected in series with a varactor for protective purposes (i.e., to block direct current from an external circuit, as shown in Fig. 2-1), its capacitance is chosen very high with respect to the varactor capacitance. A fixed capacitor equal to $1000C_d$ is a good choice to ensure minimum effect on both varactor capacitance and the capacitance range.

VARACTOR-TUNED CIRCUITS

One of the basic uses of the varactor is the tuning of circuits. Figs. 2-6 and 2-7 show simple arrangements for d-c-tuning single-section LC and RC circuits. Such combinations as these may be used as building blocks for more complicated circuits.

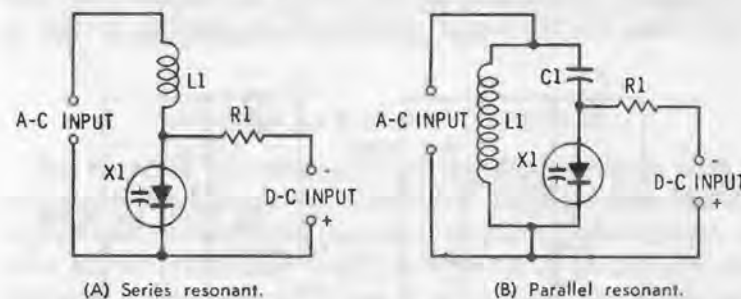


Fig. 2-6. Varactor-tuned LC circuits.

Series-Resonant LC Circuit

Fig. 2-6A shows a series-resonant circuit. Here, the frequency is determined by the inductance of L1 and the capacitance of the varactor. The varactor and d-c control voltage are chosen to provide the capacitance range needed to tune the circuit over the desired frequency range. The high resistance of isolating resistor R1 usually will serve to block r-f energy and prevent its passage into the d-c supply from the resonant circuit; however, a radio-frequency choke

sometimes is used instead. (An iron-core choke is used at audio frequencies.) As in other series LC circuits, a step-up voltage appears across the capacitor at resonance; this voltage must not be high enough to override the d-c control voltage or to exceed the mwv of the varactor.

Parallel-Resonant LC Circuit

Fig. 2-6B shows a parallel-resonant circuit. As in the series circuit, the frequency is determined by the inductance of L1 and the capacitance of the varactor. The varactor and d-c control voltage are chosen to provide the capacitance range needed to tune the circuit over the desired frequency range. The blocking capacitance must be very much higher than the varactor capacitance (usually 1000 \times) for lowest reactance, so that the varactor, rather than the fixed capacitor, tunes the circuit. At radio frequencies, isolating resistor R1 may be replaced with a radio-frequency choke, and at audio frequencies with a suitable iron-core choke.

Series RC Circuits

Fig. 2-7A shows a series RC circuit of the low-pass filter type. Here, the frequency response is determined by the re-

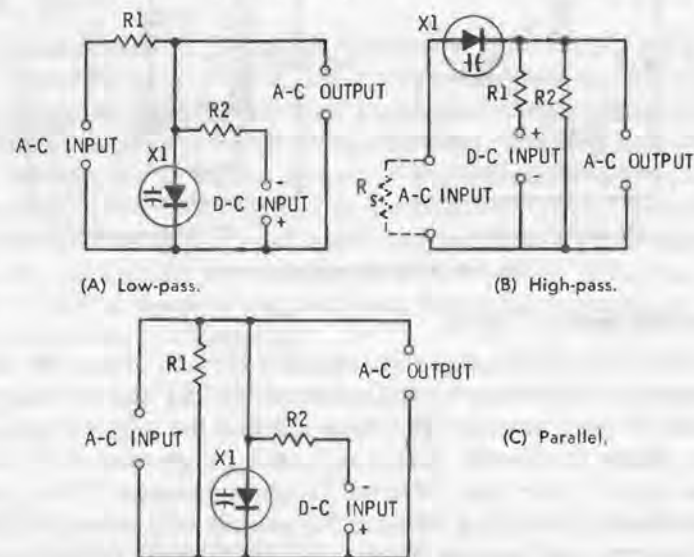


Fig. 2-7. Varactor in RC tuned circuits.

sistance of R1 and the capacitance of the varactor. The d-c control voltage is applied through isolating resistor R2, which must be very much higher in value than R1 (usually R2 is several megohms and R1 only a few kilohms).

Fig. 2-7B shows a series RC circuit of the high-pass filter type. The frequency response of this circuit is determined by the resistance of R2 and the capacitance of the varactor. The d-c control voltage is applied through isolating resistor R1, which must be very much higher in value than R2. The high-pass circuit requires that a d-c return path (for the control voltage) be provided by the a-c source, as indicated by the phantom resistor, R_s , in the illustration. When several such RC sections are operated in cascade, this path is automatically provided by the preceding output resistor (R2 in Fig. 2-7B).

Parallel RC Circuit

Fig. 2-7C shows a parallel RC circuit in which the frequency is determined by the capacitance of varactor X1 and the resistance of R1. Here, as in Fig. 2-7A, the d-c control voltage is applied through isolating resistor R2, which must be very much higher in value than R1.

VARACTOR AS FREQUENCY MULTIPLIER

The varactor has distinguished itself particularly well in frequency multiplication (harmonic generation). In this application, it performs doubling, tripling, quadrupling, or even higher frequency multiplication in transmitters and laboratory instruments more simply than do tubes and transistors.

Fig. 2-8 shows the basic arrangement of a varactor multiplier. Radio-frequency energy is fed into the stage at a frequency f . This frequency is transmitted to the varactor by pass filter 1 (often a simple, fixed-tuned, series-resonant circuit). Because of the nonlinear response of varactor X1, the current (I_i) due to the input voltage is distorted, containing a number of harmonics. The desired harmonic, a multiple nf of the input frequency, is selected by a second filter (pass filter 2) and transmitted (as harmonic current I_{nf}) to the output terminals. For doubling, the second filter is tuned to

twice the input frequency (i.e., $n = 2$); for tripling, to three times the input frequency, etc.

Because the varactor contains very little series resistance and thus handles reactive power principally, it dissipates little power—its losses are very low. It is this feature that gives the varactor multiplier its high efficiency (90 percent for the varactor doubler, compared with an ideal 50 percent

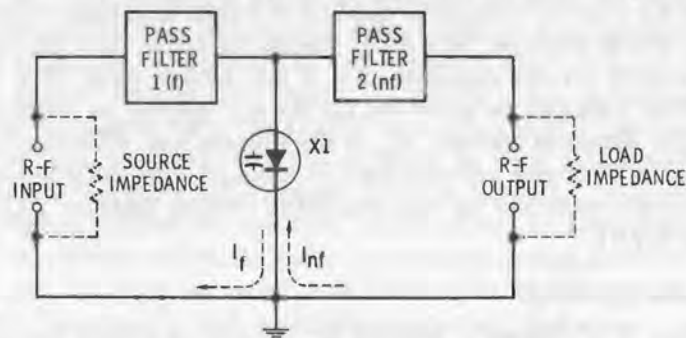


Fig. 2-8. Varactor frequency multiplier.

for tubes and transistors in the same function). A further advantage of the varactor multiplier is its freedom from the need for a power supply; the r-f signal itself is the only power required.

3

Receiver Applications

The ability of the varactor to tune an LC circuit suits it to various general- and special-purpose receiver applications. In fact, it is in this area that some of the earliest practical applications of the voltage-variable capacitor were devised.

Automatic corrective retuning processes, such as automatic frequency control (afc), are particularly benefited by the simplicity of the varactor. Vhf and uhf amplifiers employing varactors such as the one in Fig. 3-1, offer low-noise operation, high gain, and compactness.

The eventual development of small, multiple varactors doubtless will revolutionize receiver tuning by eliminating the ganged variable capacitor. In microminiature receivers, all front-end varactors could receive their d-c tuning voltage through a single miniature rheostat.

TUNING REQUIREMENTS AND CONSIDERATIONS

It is a comparatively simple matter to tune a coil, such as an r-f oscillator, amplifier, or detector coil or transformer winding, with a varactor. This was shown in the previous chapter (Fig. 2-6). However, sharp tuning demands a high-

Q varactor. The varactor capacitance—and capacitance range—must be sufficient to cover the desired frequency band with the available range of control voltage.

If a wide frequency band must be covered, a high d-c voltage may be required in order to reduce the capacitance sufficiently to tune to the high-frequency end. This introduces the additional varactor requirement of high maximum working



Courtesy TRW Semiconductors

3-1. A small high-*Q*, low-leakage varactor (TRW V947) in proprietary DO-7 package.

voltage (mwv). Another problem is posed by the fact that since *Q* decreases as voltage increases, the needed high-frequency selectivity may be sacrificed.

Tuning Range

In an LC tuned circuit, the frequency ratio varies directly as the square root of the capacitance ratio:

$$\frac{f_{\max}}{f_{\min}} = \sqrt{\frac{C_{\max}}{C_{\min}}}$$

Restated and illustrated, this means simply that a varactor must, for example, have a capacitance ratio of 4:1 if a frequency ratio of 2:1 is to be achieved.

Tuning the standard broadcast band in one sweep requires a capacitance ratio (C_{\max}/C_{\min}) of approximately 9:1, and with presently available coils and loops, C_{\max} must be 350 to 365 pf. A varactor for broadcast-band tuning must meet each of these requirements. There is little problem at higher frequencies, however. Standard varactors are easily adapted. The values of C_{\max} and of the ratio C_{\max}/C_{\min} of many presently available varactors easily permit complete coverage of bands higher than the broadcast band. For example, an inexpensive 47-pf varactor with a control voltage of 0–10 volts and an appropriate inductor will continuously tune any of the ham radio bands between 80 and 10 meters.

Balanced-Varactor Tuning

If a tuning varactor is forward biased by the signal during a part of the cycle, its leakage will increase momentarily and its *Q* may suffer. Moreover, significant harmonic energy is generated as the varactor is biased alternately positive and negative. The circuit shown in Fig. 3-2 avoids these dis-

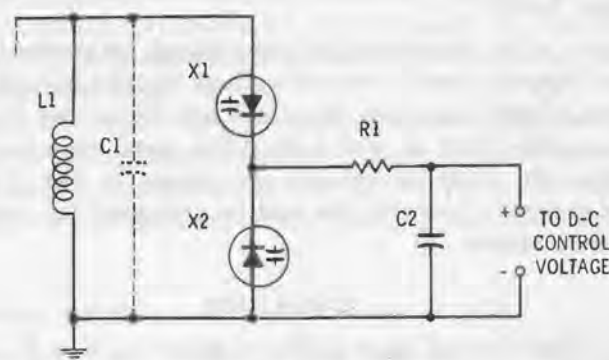


Fig. 3-2. A balanced-varactor tuned circuit.

advantages by employing two varactors connected back to back, in place of the simpler single-varactor tuned-tank circuit shown previously. The d-c control voltage is applied simultaneously to both varactors through the high resistance of R_1 . When the r-f signal is applied (Fig. 3-2), the identical varactors X_1 and X_2 are driven into high capacitance and low capacitance alternately. The net capacitance in the circuit is approximately constant and properly is determined by the d-c control voltage, rather than by the signal amplitude.

A disadvantage of the balanced circuit is the reduction of tank capacitance, due to series connection of the varactors; the total capacitance of the X_1 - X_2 combination is:

$$C_t = \frac{1}{\frac{1}{C_{x1}} + \frac{1}{C_{x2}}}$$

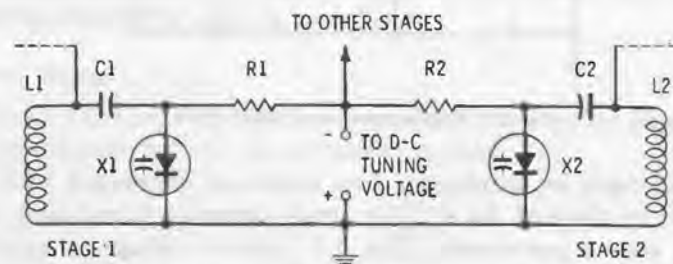
However, the reduction can be offset by choosing varactors with a value equal to twice the desired tank capacitance.

If varactor tuning is to cover only a portion of a frequency band, the varactor unit may be used as an incremental tuning section ("bandspreader") and a fixed trimmer installed, like C1 in Fig. 3-2.

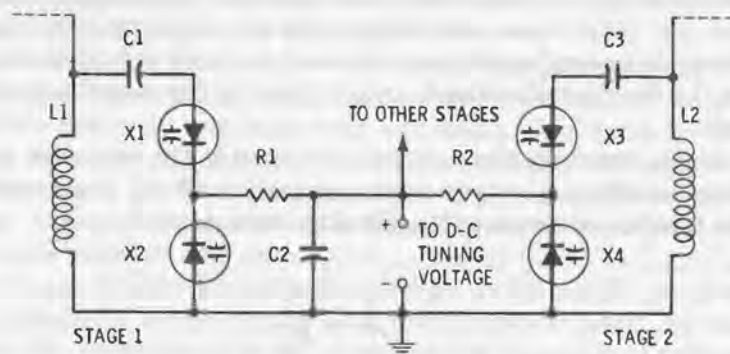
In this circuit, R1 is the usual high-resistance isolating resistor, and it acts in conjunction with C2 to form a radio-frequency filter.

Multistage Tuning

Two or more stages may be gang tuned, as shown in Fig. 3-3, by applying the d-c control voltage simultaneously to all of them. Closely matched varactors are demanded for each stage, in order that all will exhibit the same capacitance simultaneously. Only two stages are shown in Fig. 3-3, but the d-c control (tuning) line can be extended for use with other such stages.



(A) Single-varactor circuit.



(B) Balanced-varactor circuit.

Fig. 3-3. Ganged tuning.

Fig. 3-3A shows two gang-tuned r-f stages of the single-varactor type. Here, L1 and L2 are shown as single coils but may also be the secondary windings of r-f transformers. C1 and C2 are d-c-blocking capacitors which not only protect varactors X1 and X2 from any d-c component present in the receiver circuit, but also prevent a short circuit of the d-c control signal by L1 and L2. The d-c tuning voltage is applied to varactor X1 through isolating resistor R1, and to X2 through R2. Trimmers may be connected in parallel with L1 and L2, or these coils may be slug-trimmed, as desired, for range coverage.

Fig. 3-3B shows the corresponding two-gang tuning of r-f stages of the balanced-varactor type. Aside from the employment of matched varactors X1 to X4 in the balanced circuit, the arrangement is the same as that shown in Fig. 3-3A.

D-C Tuning Voltage

The d-c voltage used for tuning must be very clean; otherwise the frequency will be swept at a rate corresponding to the frequency of any ripple, hum, or other noise riding the d-c tuning voltage, and the sweep width will be governed by the peak amplitude of the interfering voltages.

The d-c voltage must also be constant; otherwise slow or abrupt detuning will occur, depending on how the voltage fluctuates. This means that it must be supplied by an excellently regulated source.

Correct polarity of varactor and of the d-c voltage must be preserved, to ensure proper operation and to prevent damage to the varactor.

Why Varactor Tuning?

A question might arise as to the feasibility of using varactor tuning in the first place:

"Is adjusting a potentiometer to control the tuning voltage very different from adjusting a variable capacitor?"

The answer depends on the circumstances. A miniature potentiometer, of course, is a great deal smaller than a plate-type variable capacitor, dramatically so when the capacitor has two to four sections. In some miniaturized equipment, there is no room for even the smallest tuning capacitor,

whereas a flat, miniature potentiometer can be fitted in. If a special tuning curve (such as logarithmic) is required, it sometimes can be obtained with an easily acquired potentiometer much more readily than a variable capacitor with specially cut plates. If a proportional d-c voltage (error signal, remote-tuning scheme, etc.) is already available, the varactor offers a way to use it without having to adopt motor-driven tuning. The varactor also provides a means of ganged tuning without mechanical coupling, which means that stages can be positioned on a chassis for maximum efficiency, convenience, and compactness, rather than having their location dictated by the shape and size of a multisection tuning capacitor.

An additional application which is simplified by the varactor is "scan tuning," in which a portion of the r-f spectrum is automatically swept repetitively. Band sweeping may be accomplished by applying a reverse-polarity sawtooth-wave tuning voltage to the varactor in any of the tuning circuits shown in Figs. 2-6, 3-2, or 3-3. The sawtooth voltage may be applied by itself or in series with a d-c bias. The frequency of the LC tank will be swept through the tuning range by each sawtooth, at a rate corresponding to the sawtooth frequency. A goodly number of voltage-variable capacitance diodes are catalogued as tuning varactors.

AUTOMATIC FREQUENCY CONTROL

In automatic frequency control (afc), a receiver which has drifted off frequency is returned automatically in accordance with a d-c error voltage developed by the detector. Afc is particularly useful in f-m tuners.

Fig. 3-4 shows a varactor afc circuit applied to an f-m receiver. Here, a small varactor, X1 (the nominal capacitance is immaterial), is connected in parallel with the oscillator tank (L1-C1) in the receiver front end, through blocking capacitor C2. As the d-c bias on this varactor is varied, the oscillator frequency, and therefore the receiver tuning, will be varied accordingly. The operating point of the varactor is set at 5 to 8 d-c volts by the bias voltage obtained through the voltage divider (R1-R4). This bias is obtained from a well-regulated point in the receiver power supply.

The d-c tuning voltage (a kind of error signal) is obtained from the discriminator stage of the receiver and is applied to the varactor through an r-f filter consisting of resistors R2 and R3, capacitors C4 and C5, and r-f choke L2.

After installation of the afc circuit, the receiver must be realigned to compensate for the presence of the varactor across the oscillator coil. Subsequently, as long as the receiver remains tuned to a station to which it has been set,

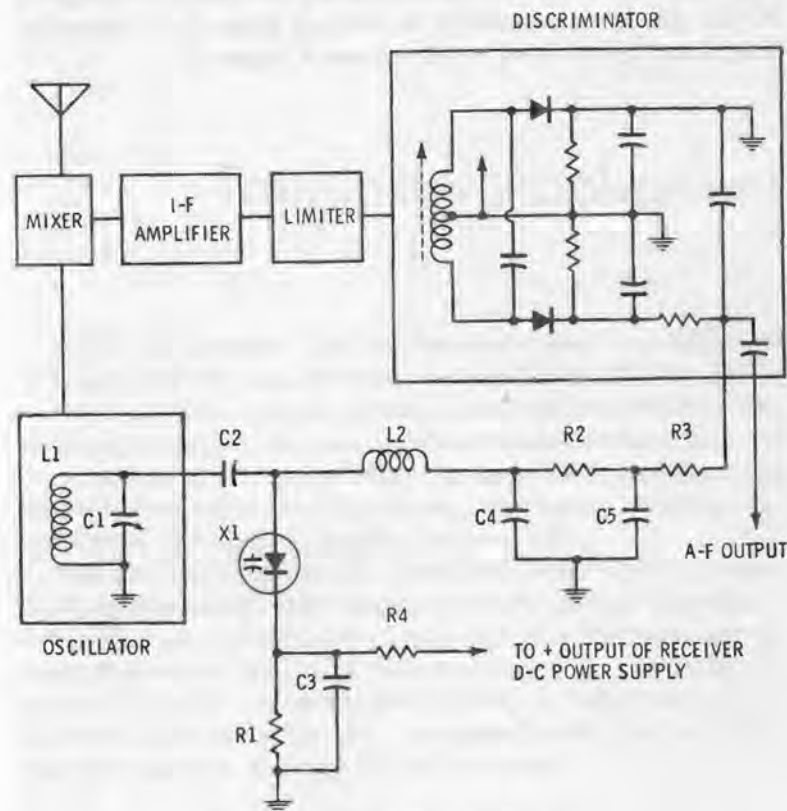


Fig. 3-4. Afc applied to an f-m receiver.

no d-c voltage is delivered by the discriminator to R3. If the receiver detunes, however, a proportional d-c voltage is applied to varactor X1 through the filter (C4, C5, R2, R3, and L2). This voltage changes the varactor capacitance in proportion to the amount of detuning, and this change in ca-

capacitance retunes the receiver by changing the oscillator frequency the proper amount.

R-F AMPLIFIER (PRESELECTOR)

In uhf and microwave receivers, low-noise r-f amplification may be provided by a varactor operated from a radio-frequency power supply (pump). Sensitive amplifiers of this type have been used in the deep-space tracking program of NASA and were prominent in Project Echo. For a description of the varactor r-f amplifier, see Chapter 5.

4

Transmitter Applications

While all varactor applications ultimately are based on voltage-sensitive capacitance, the particular ability of the varactor to tune circuits, provide adjustable reactance, and generate harmonics makes it useful in transmitters. Some of its practical functions include oscillator and amplifier-tank tuning, frequency multiplication, frequency modulation, amplitude modulation, and output control.

The varactor has greatly simplified some modern transmitters, especially lightweight, portable units and remote-controlled sets. In this role, it has also provided noteworthy economies—some in initial cost and others in operating expenses. In some instances, particularly in frequency multiplication, its high efficiency (compared with that of tubes and transistors) distinguish the varactor.

TANK TUNING

The varactor may be used in lieu of, or in conjunction with, a conventional variable capacitor for tuning the LC tank of an r-f oscillator or amplifier. In this application, the r-f signal impressed across the varactor must be maintained at a voltage that will not override the d-c tuning voltage and

which (if important in a particular case) will not cause excessive harmonic generation.

Single-Ended Tank, Single-Varactor-Tuned

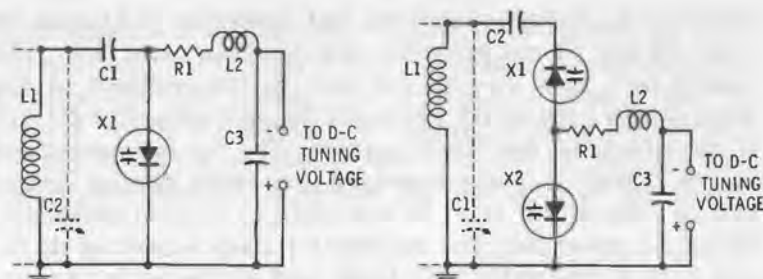
The basic LC tank-tuning circuits are shown in Fig. 4-1. Fig. 4-1A shows a typical single-ended tank. Only one varactor is used. Here, the frequency is determined by the inductance of coil L1 and the capacitance of varactor X1. If the varactor is to account for only part of the capacitance, bandset capacitor C2 may be used. C1 is a protective d-c blocking capacitor. Isolating resistor R1, radio-frequency choke L2, and bypass capacitor C3 form an r-f filter to isolate the d-c tuning-voltage source from the tank. If the tank is grounded directly, as shown in Fig. 4-1A, the positive terminal of the tuning-voltage supply likewise will be grounded. If, instead, the tank is r-f-grounded only (through a bypass capacitor), the tuning-voltage supply will be above ground and will require special insulation.

Single-Ended Tank, Balanced-Varactor-Tuned

Fig. 4-1B shows balanced (two-varactor) tuning of a single-ended tank. The merits of the balanced circuit were discussed in a previous chapter. Because the matched varactors X1 and X2 are connected in series, the total capacitance is one-half that of one varactor. The frequency is determined by the inductance of L1 and this total capacitance. If, however, the varactor pair is to account for only part of the capacitance, a bandset capacitor (C1) may be used. C2 is a protective d-c blocking capacitor. Isolating resistor R1, r-f choke L2, and bypass capacitor C3 form an r-f filter, as in the preceding circuit. Here, as before, if the d-c tuning-voltage circuit is above ground, it will need special insulation unless coil L1 is directly grounded, as shown.

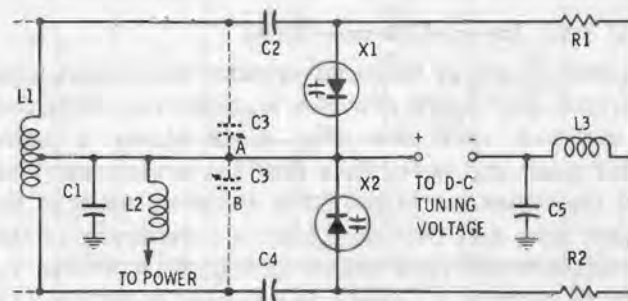
Push-Pull Tank, Single-Varactor-Tuned

Fig. 4-1C shows a push-pull tank, each half of which is tuned by a single matched varactor (X1 and X2). The varactors thus simulate a split-stator tuning capacitor, each receiving the d-c tuning voltage at the same time through resistors R1 and R2 and the r-f filter (C5-L3). If the varactors are to account for only part of the capacitance across

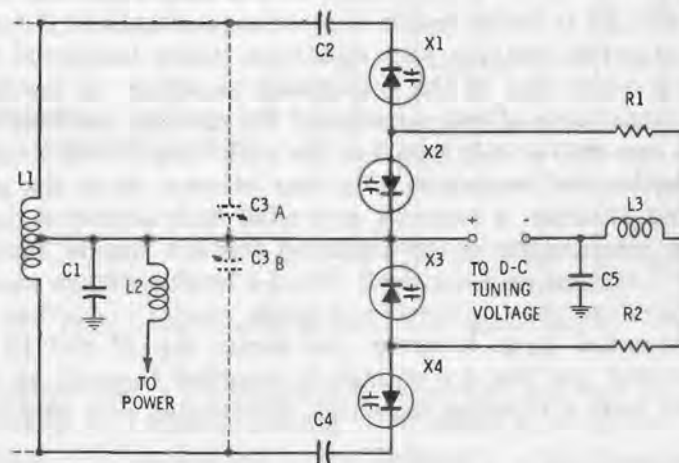


(A) Single-varactor, single-ended.

(B) Balanced-varactor, single-ended.



(C) Single-varactor, push-pull.



(D) Balanced-varactor, push-pull.

Fig. 4-1. Tank-tuning methods.

tank coil L1, a split-stator bandset capacitor (C3) may be used. C2 and C4 are protective d-c-blocking capacitors. The "series-fed" tank circuit, common in transmitters in the form shown here, is r-f grounded through capacitor C1 but is not grounded for direct current. The d-c tuning-voltage source therefore is above ground and needs special insulation. A "shunt-fed" tank, on the contrary, has the center tap of coil L1 grounded (the transmitter stage receiving its direct current through an r-f choke and delivering r-f energy to the tank through a blocking capacitor) and avoids this difficulty.

Push-Pull Tank, Balanced-Varactor-Tuned

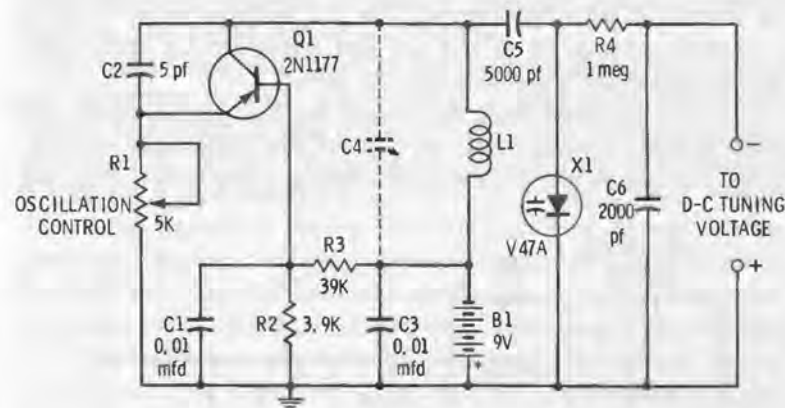
The advantages of balanced-varactor tuning are available also in push-pull tanks, provided no objection exists to using four matched varactors. Fig. 4-1D shows a balanced-varactor push-pull tank. Note that the arrangement on one side of the center tap of coil L1 is a mirror image of that on the other side, and that each side is a duplicate of the balanced single-ended tank shown in Fig. 4-1B, except for the sharing of a single r-f choke and bypass capacitor (L3 and C5 in Fig. 4-1D). In Fig. 4-1D, varactors X1 and X2 simulate one section of a split-stator variable capacitor, and X3 and X4 simulate the other section. The total capacitance of X1 and X2 in series equals the total capacitance of X3 and X4 in series; however, each total capacitance, because of the series connection of the constituent varactors, is one-half the capacitance of one varactor. If the varactor combination is to account for only a part of the tank capacitance, a split-stator bandset capacitor (C3) may be used. As in the preceding example, a common series-fed tank is shown here. This arrangement is r-f-grounded through bypass capacitor C1 but has no d-c ground. The d-c tuning-voltage source is therefore above ground and needs special insulation. In a shunt-fed tank, however, the center tap of coil L1 is grounded and the d-c voltage is supplied through an r-f choke past a blocking capacitor, eliminating this problem.

Oscillator Tuning

Fig. 4-2 is the circuit of a low-powered transistor r-f oscillator. Such units are used as master oscillators in multistage

transmitters, or as fleapower transmitters themselves. With the constants shown, the circuit is capable of approximately 100-mw d-c input power. Radio-frequency energy may be coupled out of the tank either capacitively or inductively.

Varactor X1 is shunted across tank coil L1, through protective d-c-blocking capacitor C5, and acts as the tuning



(A) Circuit.

(B) Voltage-frequency response with L1 equal to 0.4 microhenry.

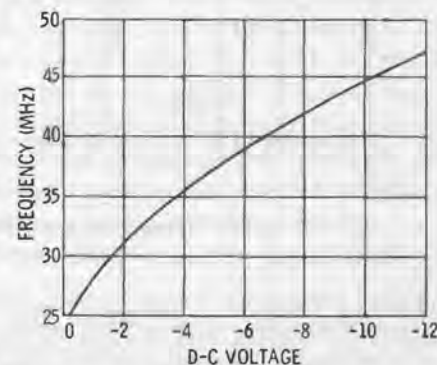


Fig. 4-2. Voltage tuning of low-powered transistor oscillator.

capacitor. But if the varactor is to account for only part of the tank capacitance, C4 may be inserted as a bandset capacitor. (Often, instead of this capacitor, a slug-tuned coil is substituted for the airwound one shown at L1.) Varactor X1 is chosen to supply the absolute capacitance and required capacitance range to tune L1 over the desired frequency

range with the available d-c control voltage. In some instances, the oscillator supply voltage (B1) will also supply the tuning voltage through a potentiometer, greatly simplifying the transmitter.

The circuit shown will operate at any frequency up to 100 MHz if L1 is chosen to resonate with the varactor. Fig. 4-2B shows how the operating frequency may be varied between 25 and 47.5 MHz by varying the d-c voltage from -0.5 to -12 volts, when L1 is 0.4 μ h and varactor X1 is a Type V47A (nominal capacitance = 47 pf).

Similar r-f oscillators are based on the tunnel diode for even greater simplicity than that of the transistor circuit; however, the power output and efficiency are lower. Fig. 4-3

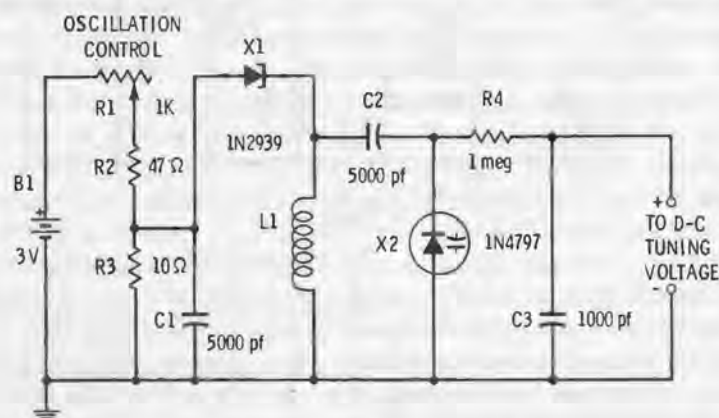


Fig. 4-3. Voltage tuning of tunnel-diode oscillator.

shows a varactor-tuned tunnel-diode oscillator. Here, tunnel diode X1 is operated at approximately 0.1 vdc, derived from 3-volt battery B1 through voltage divider R1, R2, and R3; the voltage is set for strongest oscillation by adjustment of R1. The frequency is determined by the inductance of coil L1 and the capacitance of varactor X2. With the 1N4797 varactor shown (nominal capacitance = 56 pf), a d-c voltage range of 0.5 volt to 6 volts, and L1 equal to 4.6 μ h, the frequency range is 7 to 11 MHz. This circuit will oscillate as high as 250 MHz if the inductance of L1 is properly chosen.

FREQUENCY MULTIPLIERS

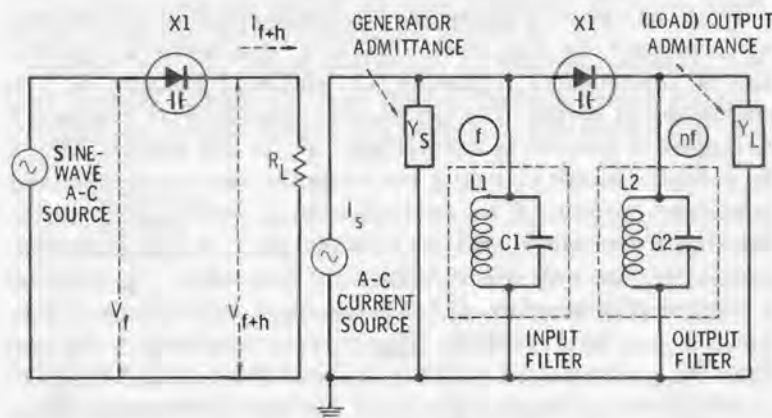
Harmonic generation is the most important large-signal property of the varactor. It arises as a result of the pronounced distortion occurring when the varactor is operated over its entire range of nonlinear response. This property, which was introduced in Chapter 2, is utilized in modern, high-efficiency passive frequency doublers, triplers, quadruplers, and higher-order multipliers.

How the varactor generates harmonics may be understood by reference to Fig. 4-4A. Here, a sine-wave a-c power source (generator), varactor X1, and load resistor R_L are connected in series. The generator, operating at frequency f , applies a sine-wave a-c voltage, V_t , to the circuit. When V_t is high enough to swing the varactor over enough of the nonlinear portion of its current-voltage curve, the current through the varactor and load resistance is highly distorted, containing not only the fundamental frequency (f) but also a number of harmonics (h). This current accordingly is designated I_{t+h} in Fig. 4-4A. The current produces a voltage drop V_{t+h} across load resistor R_L , and this voltage likewise is a mixture of fundamental and harmonic frequency components. Now, because the varactor is a reactive device, it consumes very little power (i.e., its losses are low), so most of the generator power appears in the output (load)—indicating high efficiency. We might have connected a battery, properly poled, in series with the generator and varactor to ensure that the varactor always operates at reverse voltage, but frequency multiplication is enhanced by allowing the varactor to be driven momentarily into the forward conduction mode.

The load current (I_{t+h}) and resulting load voltage (V_{t+h}) are mixtures of many frequencies. In transmitter practice, we are interested in single frequencies; therefore, the operation illustrated by Fig. 4-4A is of little interest other than in accounting for the ability of the varactor to generate harmonics. A single desired harmonic frequency can be extracted from the mixture by means of a suitable filter. It is to illustrate this possibility that the next two circuits are given (Figs. 4-4B and C). Fig. 4-4B is termed a *series-type* multiplier from the fact that the varactor is in series with

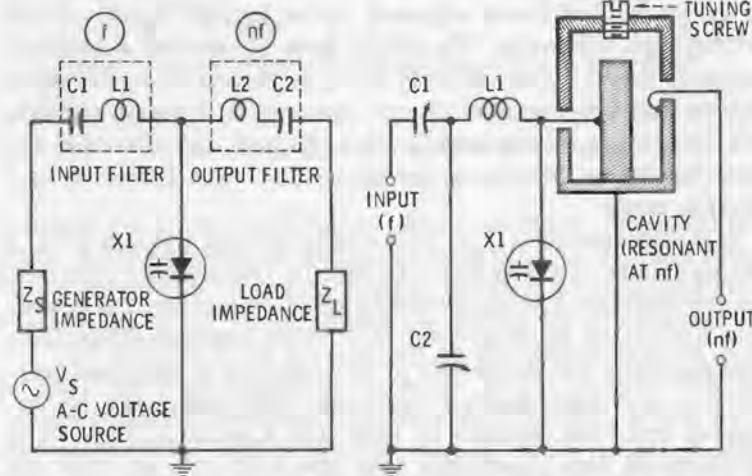
the input (generator) and the output (load). Fig. 4-4C is termed a *shunt-type* multiplier because the varactor is in parallel (shunt) with the input and the load. In both circuits, the proper harmonic is selected by means of two selective circuits: an *input filter* and an *output filter*.

In Fig. 4-4B, the filters are high- Q parallel-resonant circuits. The input filter (L1-C1) is tuned to the fundamental frequency (f), and the output filter (L2-C2) to the de-



(A) Rudimentary.

(B) Series-type.



(C) Shunt-type.

(D) Microwave-type.

Fig. 4-4. Varactor frequency multipliers.

sired harmonic—or multiple of f (i.e., to nf). The generator is thought of as a current source (I_s) with internal admittance Y_s , and the output device as a load admittance, Y_L . Each of the filters offers maximum impedance at the frequency to which it is tuned; therefore, maximum voltage is developed across the filter at that frequency.

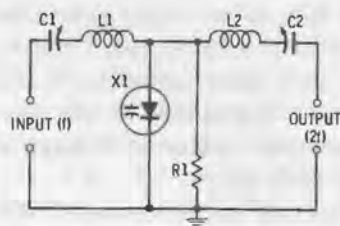
In Fig. 4-4C, the filters are high- Q series-resonant circuits. The input filter (L1-C1) is tuned to the fundamental frequency (f), and the output filter (L2-C2) to the desired harmonic—or multiple of f (i.e., to nf). The generator is thought of as a voltage source (V_s) with internal impedance Z_s , and the output device as a load impedance, Z_L . Here, each of the filters offers minimum impedance at the frequency to which it is tuned; therefore, each allows maximum current through itself at that frequency.

Fig. 4-4D shows one version of a microwave varactor frequency multiplier. Here, capacitors C1 and C2 facilitate matching the circuit to the driving source. C1 also combines with L1 to form a series-resonant filter to pass the fundamental frequency (f) to varactor X1. The cavity is resonant at the desired harmonic (nf) and, like the parallel-resonant filters in Fig. 4-4B, develops maximum output at that frequency. Some microwave frequency multipliers dispense with lumped constants, such as C1, C2, and L1. Instead, they employ a transmission line between the input terminals and the varactor. This line is provided with tuning stubs for resonating at frequency f .

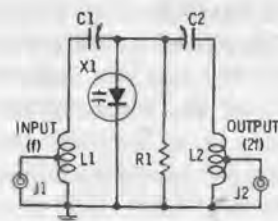
Every varactor multiplier is some adaptation of the circuits given in Fig. 4-4. The varactor multiplier is not only efficient (i.e., P_o/P_i approaches 100 percent for doublers, where P_o is the output power, and P_i is the input power, both r-f), but it also requires no local power supply. The only power required for its operation is supplied by the input signal itself.

Doublers

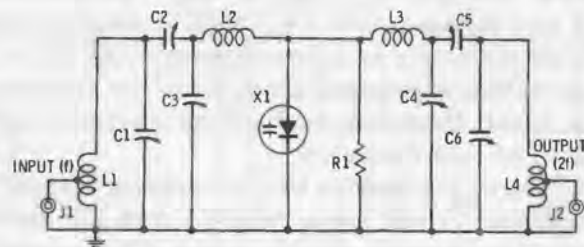
The basic circuits of Figs. 4-4B and C may be used as frequency doublers simply by making n equal to 2 wherever it appears. That is, the output filter in either instance must be tuned to twice the frequency of the input signal. Fig. 4-5 shows five typical doubler circuits.



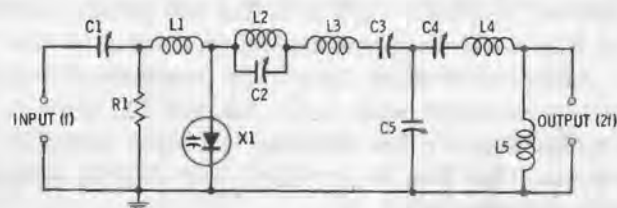
(A) Simple arrangement.



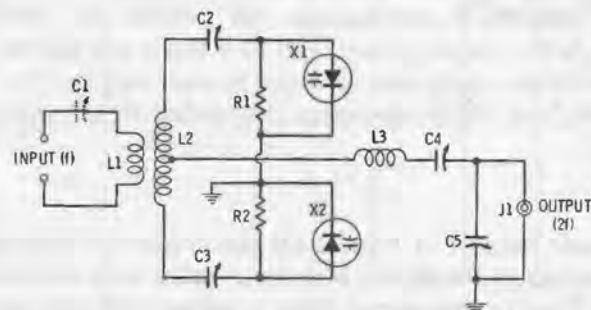
(B) Self-contained, single-tuned.



(C) Self-contained, double-tuned.



(D) Series-resonant input and output with wavetrap.



(E) Push-push doubler.

Fig. 4-5. Typical doubler circuits.

Fig. 4-5A is a simple arrangement. Here, the L1-C1 filter is tuned to f , and L2-C2 to $2f$. Noninductive resistor R1 provides self-bias (the varactor acts as a shunt-diode rectifier). The circuit is adapted to individual conditions by providing it with suitable input and output coupling and impedance matching.

Fig. 4-5B shows a more self-contained arrangement. In this circuit, coils L1 and L2 not only supply the inductances for the input and output filters, respectively (in conjunction with capacitors C1 and C2), but also act as impedance-matching input and output autotransformers. As before, the input filter (L1-C1) is tuned to f , and the output filter (L2-C2) to $2f$. Self-bias is provided by noninductive resistor R1 (60K to 270K, depending on varactor type).

In Fig. 4-5C, double tuning is employed for increased efficiency and more complete rejection of unwanted frequencies. For example, parallel-resonant circuit L1-C1 is tuned to transmit input frequency f , and parallel-resonant circuit L4-C6 to transmit output frequency $2f$. Also, series-resonant circuit L2-C2 is tuned to pass f , and series-resonant circuit L3-C5 to pass $2f$. Coils L1 and L4 also act as input and output autotransformers, respectively. Noninductive resistor R1 provides self-bias.

A somewhat different filtering arrangement is shown in Fig. 4-5D. Here, C1 and L1 form a series-resonant circuit which passes input frequency f to varactor X1. Following the varactor is a wavetrap—the parallel-resonant circuit, L2-C2—which serves to suppress frequency f from the output. The output circuit contains a second-harmonic bandpass filter, the first section of which is composed of the wavetrap (L2-C2), capacitors C3 and C5, and inductor L3; and the second section of which is composed of capacitor C4 and inductors L4 and L5. Self-bias is provided by noninductive resistor R1.

The push-push doubler is well known in tube and transistor practice and is characterized by (1) its use of two components to obtain double the output afforded by one, and (2) its push-pull input and parallel output. (This connection doubles power but circumvents some of the difficulties, such as increased strays and spurious responses, occasioned by straight parallel connection.) Fig. 4-5E shows a varactor

push-push doubler circuit. Here, C2 and the upper half of L2 serve as a series-resonant filter to pass input frequency f to varactor X1 during one input half-cycle; C3 and the lower half of L2 perform the same function during the opposite half-cycle. Input energy is coupled into L2 through primary coil L1, which provides an impedance match to the signal source. In the output circuit, the series-resonant filter, L3-C4, passes frequency $2f$ while rejecting f . Capacitor C5 aids in matching the output impedance to that of the load. Noninductive resistors R1 and R2 provide varactor self-bias.

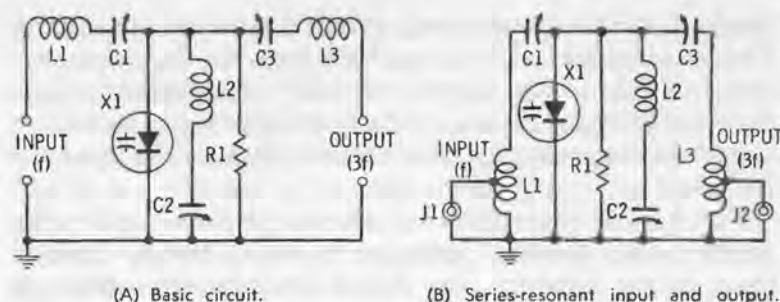
Whereas the theoretical efficiency of tube-type doublers is given as 50 percent, this figure is obtained only through excellent design and adjustment. But the efficiency of the varactor doubler, depending on varactor type and input power, has been reported above 90 percent at frequencies as high as 100 MHz, dropping to 20 percent at 20 GHz.

Triplers

In the varactor tripler, the output filter is tuned to the third harmonic of the input signal frequency. Aside from this particular, the tripler circuit differs from the doubler circuit chiefly in its use of an auxiliary tuned circuit—the idler—to reinforce the triple-frequency output.

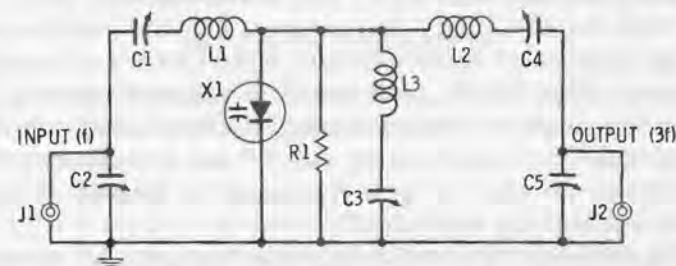
The basic tripler circuit is shown in Fig. 4-6A. Here, the input series-resonant filter, L1-C1, is tuned to pass input frequency f to varactor X1, and the output series-resonant filter, C3-L3, is tuned to pass the tripled frequency ($3f$) to the output terminals. Noninductive resistor R1 provides self-bias. The idler consists of the L2-C2 leg which is tuned to the second harmonic, $2f$. Second-harmonic current (I_{2f}), which flows readily through the idler, adds to the fundamental (I_f) to form third-harmonic current (I_{3f}). This idler action results in higher tripler efficiency.

In Fig. 4-6B, coils L1 and L3 serve as series-resonant input and output filter inductors (with capacitors C1 and C3, respectively), and also as input (L1) and output (L3) autotransformers for input and output coupling and impedance matching. Here, as in the preceding example, the idler circuit is comprised of L2 and C2. Filter L1-C1 is tuned to input frequency f , L2-C2 to second-harmonic frequency $2f$,

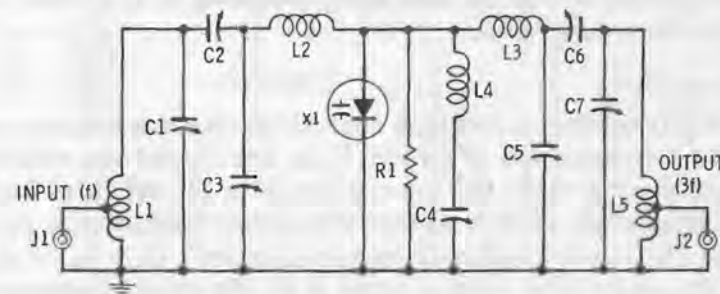


(A) Basic circuit.

(B) Series-resonant input and output.



(C) Series-resonant with tapped capacitances.



(D) Double-tuned circuit.

Fig. 4-6. Typical tripler circuits.

and L3-C3 to output frequency $3f$. Noninductive resistor R1 provides self-bias.

The only difference between Fig. 4-6C and Fig. 4-6B is the use of a tapped capacitor arrangement in Fig. 4-6C (C1-C2 at the input, and C4-C5 at the output) to provide an impedance match from the generator to the input of the tripler, and from the output of the tripler to the external load. Autotransformers are used, instead of this capacitor arrangement, in Fig. 4-6B. Coil L1 and capacitor C1 form

the input series-resonant filter tuned to pass input frequency f to varactor X1, while L2 and C4 form the output series-resonant filter to pass output frequency $3f$ to output jack J2. Inductor L3 and capacitor C3 form the idler tuned to second-harmonic frequency $2f$. Noninductive resistor R1 provides self-bias.

Fig. 4-6D shows a more complicated tripler circuit using double tuning to avoid spurious responses and to improve input-output isolation. The double-tuned input consists of parallel-resonant filter L1-C1 and series-resonant filter L2-C2, both tuned to input frequency f ; and the double-tuned output consists of series-resonant filter L3-C6 and parallel-resonant filter L5-C7, both tuned to output frequency $3f$. The idler, tuned to second-harmonic frequency $2f$, consists of L4 and C4. Capacitors C3 and C5 aid in adjustment of the circuit for peak output. Noninductive resistor R1 provides self-bias for varactor X1.

The efficiency of varactor triplers, depending on varactor type and power input, has been reported at 60 percent at frequencies as high as 100 MHz, dropping to 5 percent at 20 GHz.

Quadruplers

All frequency multipliers beyond the doubler require an idler for maximum efficiency. If in any one of the tripler circuits (Fig. 4-6) the idler is tuned to $3f$, the third-harmonic current (I_{3f}) it passes will add to fundamental current (I_f) to produce fourth-harmonic current ($I_f + I_{3f} = I_{4f}$). If the output filter then is tuned to $4f$, the output frequency of the stage becomes four times that of the input, and a quadrupler results.

The efficiency of varactor quadruplers, depending on varactor type and input power, has been reported at 60 percent at frequencies as high as 100 MHz, dropping to 5 percent at 20 GHz.

Higher-Order Multipliers

Quintuplers ($5\times$), sextuplers ($6\times$), septuplers ($7\times$), octuplers ($8\times$), etc. may be made from the tripler circuits shown in Fig. 4-6, by changing the output filter to resonate at the desired harmonic, nf , and changing the idler to reso-

nate at the frequency $f(n-1)$. Thus, the idler frequency is $4f$ in a quintupler, $5f$ in a sextupler, $6f$ in a septupler, and $7f$ in an octupler, etc.

Efficiency decreases in high-order multipliers below that of the doubler, tripler, and quadrupler. Sometimes, better results are obtained when high-order multiplication is required, by cascading successive lower-order stages; for example, two doublers for quadrupling, a doubler and a tripler for sextupling, etc.

FREQUENCY MODULATION

Because a varactor will tune an oscillator tank circuit, it will frequency modulate the oscillator if an audio voltage is used instead of d-c voltage to vary the varactor capacitance.

Fig. 4-7 shows a frequency modulator circuit. Here, the varactor X1 is connected in parallel with the tank (L2-C4)

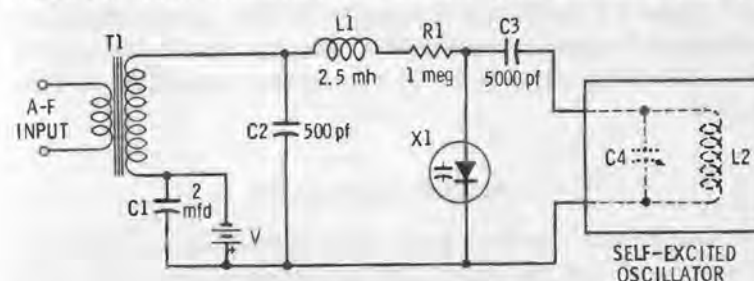


Fig. 4-7. Frequency modulator.

of a self-excited oscillator through a protective d-c-blocking capacitor, C3. With the d-c bias voltage, V , adjusted to place the operating point of the varactor within a straight portion of its response curve, C4 is tuned to set the oscillator to the desired carrier (center) frequency, f_c . If an audio signal then is applied to the a-f input terminals, the a-f voltage at the secondary of transformer T1 will alternately aid and buck the d-c voltage, increasing and decreasing the net varactor voltage. Thus, on one a-f half-cycle, when the lower secondary terminal of T1 is positive, the varactor voltage will increase, the varactor capacitance will decrease, and the oscillator frequency will increase from its center value

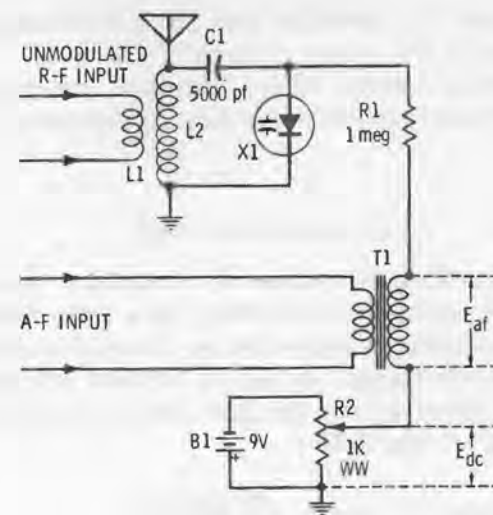
(f_h) to f_c . When the a-f cycle passes through zero, only the d-c voltage (V) will be present at the varactor, and the oscillator frequency will return to f_b . On the opposite a-f half-cycle, when the lower secondary terminal is negative, the varactor voltage will decrease, the varactor capacitance will increase, and the oscillator frequency will decrease from the center value (f_h) to f_a . As the a-f signal continues to go through its alterations, the oscillator frequency will swing above and below the carrier value and frequency modulation of the oscillator output will occur. If the d-c operating point is within the straight portion of the varactor response curve, the frequency upswing will equal the downswing. For linear modulation, the linear portion of the curve must be used.

The modulation rate (number of frequency swings per second) is identical with the audio modulating frequency, while the sweep width (total kHz or MHz covered in the sweep) is proportional to the peak amplitude of the a-f voltage. By properly proportioning the a-f voltage with respect to a given r-f oscillator frequency, either narrow-band or wide-band frequency modulation may be obtained. Any of the small varactors (20- to 68-pf nominal capacitance) may be used.

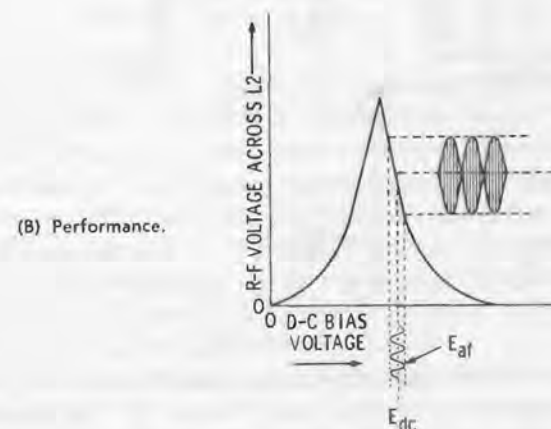
AMPLITUDE MODULATION

A c-w transmitter may be amplitude modulated externally by means of the varactor-tuned antenna coupler (L1, L2, C1, and X1) shown in Fig. 4-8A. This coupler is tuned to the carrier frequency by varactor X1, the capacitance of which may be varied by adjusting potentiometer R2 to control the varactor d-c bias. The inductance of L2 and the bias voltage are chosen so that the operating point is within the straight portion of the r-f voltage *vs.* d-c bias curve (Fig. 4-8B) for the particular varactor used. Blocking capacitor C1 keeps L2 from short circuiting the d-c bias, and its reactance is negligible in the circuit. L1 is a link-coupling coil.

The a-f modulating voltage is applied in series with the d-c bias, by means of transformer T1, which has a 2:1 or 3:1 step-up turns ratio. Because of the extremely high resistance of the varactor, virtually no audio power is required, and the modulating voltage accordingly may be ob-



(A) Circuit.



(B) Performance.

Fig. 4-8. Amplitude modulator.

tained from a one- or two-stage transistor speech amplifier or directly from a carbon microphone.

Fig. 4-8B shows operation of the circuit. Note that the circuit is tuned to the high-frequency side of resonance, by adjusting the d-c bias to the level E_{dc} . The a-f voltage (E_{af}) is superimposed on E_{dc} . This causes the bias to swing above and below E_{dc} at the audio-frequency rate. The resulting

voltage across L2 therefore has the amplitude-modulated shape shown by the output pattern in Fig. 4-8B.

For correct operation, R2 is set for best linearity of modulation, and the a-f amplitude for desired percentage of modulation.

R-F OUTPUT CONTROL

The d-c-variable reactance of a varactor may be used conveniently to vary the r-f output of a transmitter or exciter. The varactor is connected as a variable coupling capacitor between stages, as shown between the plate tank (L1-C1) of one stage and the grid tank (L2-C3) of the following stage in Fig. 4-9.

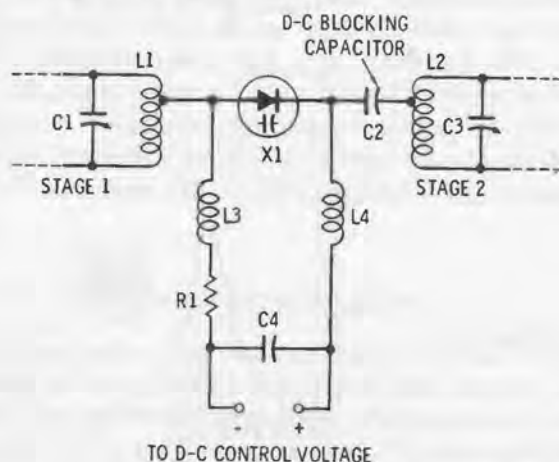


Fig. 4-9. R-f output control.

A d-c-control voltage is applied to varactor X1 through a radio-frequency filter, consisting of r-f chokes L3 and L4, isolating high resistance R1, and capacitor C4. Increasing the voltage decreases the capacitance (increases the reactance) of the varactor, and this action reduces the r-f power coupled by the varactor.

This control system has the advantage that, being reactive, it consumes little or no power (either d-c or r-f power).

Varactor Amplifiers

The voltage-variable nonlinear capacitance of the varactor may be used to amplify a signal. The kind of amplifier that results belongs to that class of devices known as *reactance amplifiers*. Other types of reactance amplifiers are the magnetic amplifier and the electrostatic amplifier. The distinguishing peculiarity of every reactance amplifier is its need of a high-frequency a-c power supply. It differs in this respect from tube and transistor amplifiers, which are operated from a d-c supply.

As an electrostatic device, the varactor amplifier offers the advantages of high input impedance, very low noise, circuit simplicity, instant operation (no warm-up), physical ruggedness, and small size (in most instances). The idea of electrostatic amplifiers was not introduced by the varactor, however; such amplifiers based on nonlinear (ferroelectric) ceramic capacitors have been known for a number of years.

BASIC PRINCIPLES

How the variable reactance of a varactor is exploited for amplification may be understood by reference to the simple

demonstration circuit in Fig. 5-1. In this arrangement, the a-c power source excites varactor X1 through isolating transformer T1 and blocking capacitor C1. Current resulting from this a-c excitation flows through load resistor R_L , the output device. Now, if a d-c voltage of correct polarity is applied to the signal input terminals, it will shift the operating point of the varactor, changing the latter's capacitance and reactance and shifting the current through R_L to a new level. Because very little signal current is needed to obtain a large change in the current through R_L , amplification results.

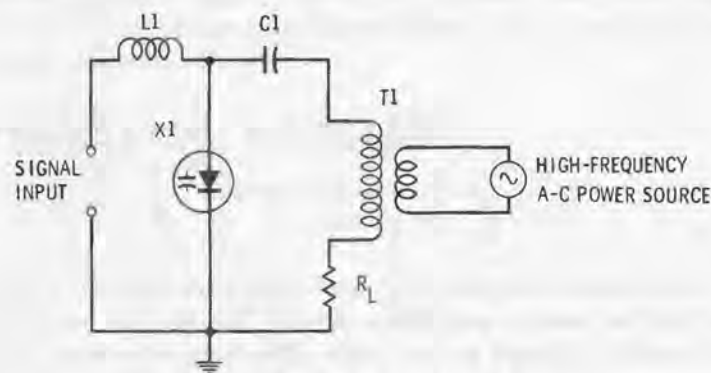


Fig. 5-1. The basic varactor amplifier.

Choke coil L1 blocks the a-c power from the signal input terminals. If, instead of direct current, an a-c signal is applied to the signal input terminals, the R_L (output) current will vary in sympathy with the input-signal alternations (for best results, the power-supply frequency must be at least ten times the highest signal frequency). If a d-c voltage is applied in series with the a-c signal, the former will permit the operating point to be set along the steepest part of the varactor response curve. This results in maximum amplification.

Even this rudimentary circuit is capable of appreciable gain, especially if the output circuit is tuned to the power-supply frequency. Practical varactor amplifiers are somewhat more sophisticated in configuration, however, and are of two types: *resonant-slope* and *parametric*.

RESONANT-SLOPE AMPLIFIERS

This type of amplifier is so named because it utilizes the steep slope of a resonant LC circuit in which the varactor is the signal-variable capacitor. It is also known as a *carrier amplifier*, *capacitor amplifier*, and *dielectric amplifier*.

A-C Amplifiers

Fig. 5-2A shows the circuit of a single-ended a-c amplifier. Here, varactor X1 resonates inductor L1 at the frequency of the h-f power supply which is coupled to this inductor through L2. The resonance curve is shown in Fig. 5-2B. Protective blocking is provided by capacitor C1, which must be chosen for low impedance at the power-supply frequency.

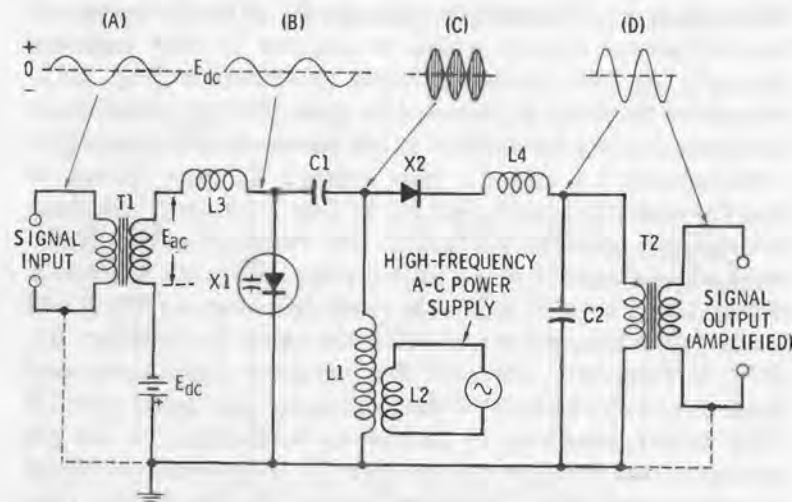
Inductance L1 and d-c bias voltage E_{dc} are chosen so that the operating point (see E_{dc} in Fig. 5-2B) will fall along the steepest *straight* portion of the response curve, somewhat off resonance.¹ When an a-c signal, E_{ac} (see pattern A in Fig. 5-2A) then is applied through transformer T1, it will fluctuate the bias above and below the value E_{dc} (pattern B). This, in turn, will fluctuate the varactor capacitance and cause the L1-X1 tank to be detuned above and below point X (Fig. 5-2B), resulting in amplitude modulation of the h-f voltage across the tank (see pattern C). Note, however (from pattern C and from "amplified signal" in Fig. 5-2B), that this signal is several times larger than input signal E_{ac} , showing that amplification has taken place. We need only to demodulate this signal to recover E_{ac} amplified, and this is done by means of the conventional diode (X2), which delivers the amplified output signal shown in pattern D.

In this circuit, radio-frequency choke L3 keeps h-f supply current out of transformer T1 and the battery, and radio-frequency choke L4 and C2 in combination remove the h-f component from the modulated signal (pattern C). For audio-frequency signals, T1 and T2 are iron-core transformers; for radio-frequency signals, they are air core.

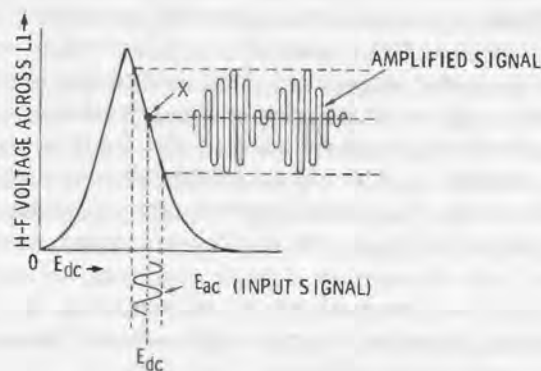
Like tubes and transistors, varactors may be operated push-pull for increased output and reduced harmonic dis-

¹Note that "straight" here does not mean linear, but uncurved. The sector must be straight although *nonlinear*, for without nonlinearity there is no amplification.

tortion. Fig. 5-3 shows a push-pull a-c amplifier circuit. Note that the upper and lower halves of this circuit are identical with the single-ended circuit in Fig. 5-2A and operate in the same manner. For symmetrical operation, the similar components must be matched electrically (i.e., $C1 = C2$, $C3 = C4$, $X1 = X2$, $X3 = X4$, $L3 = L4$, and $L5 = L6$). Also for symmetry, transformers T1 and T2 and inductor L1 are center tapped.



(A) Circuit.



(B) Performance.

Fig. 5-2. A single-ended varactor a-c amplifier

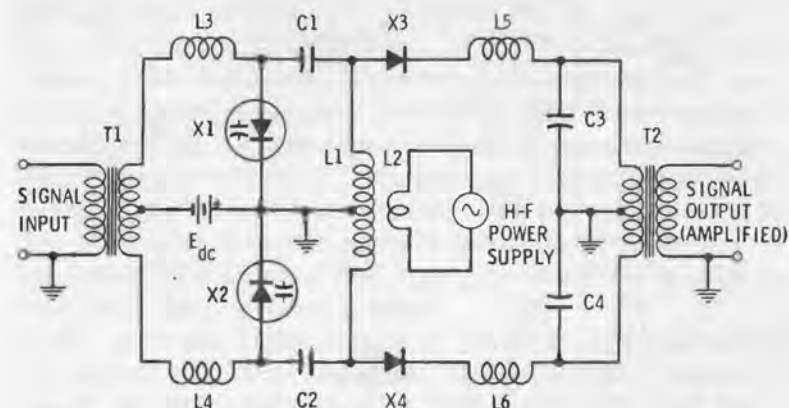


Fig. 5-3. Push-pull varactor amplifier.

PARAMETRIC AMPLIFIER

The *parametric* uhf and microwave amplifier has figured prominently in the space exploration program, largely because the low-noise properties of this amplifier (superior to those of any tube or transistor) make it usable at very low signal levels. It also provides high gain.

In the resonant-slope amplifier described in the preceding section, the varactor offers reactance to the power supply, and the signal varies this reactance at a lower-frequency rate. In the parametric amplifier, on the contrary, the varactor offers reactance to the signal, and the power supply varies this reactance at a higher-frequency rate while at the same time it adds power to the signal. It is as if a weak signal in the resonant-slope amplifier switches the higher power from the power supply into the load, and in the parametric amplifier the power supply switches the signal into the load while simultaneously adding power to it. In the parametric amplifier, the power supply is said to "pump" the varactor; hence it is called the *pump*.

Fig. 5-4A shows the functional arrangement of the parametric amplifier (Fig. 5-4C is a practical amplifier employing a resonant cavity). The pump voltage is a reversed voltage (e.g., only negative half-cycles), so when it is maximum it minimizes the capacitance of the varactor. Now, if the signal and pump are applied in such a way that the varactor

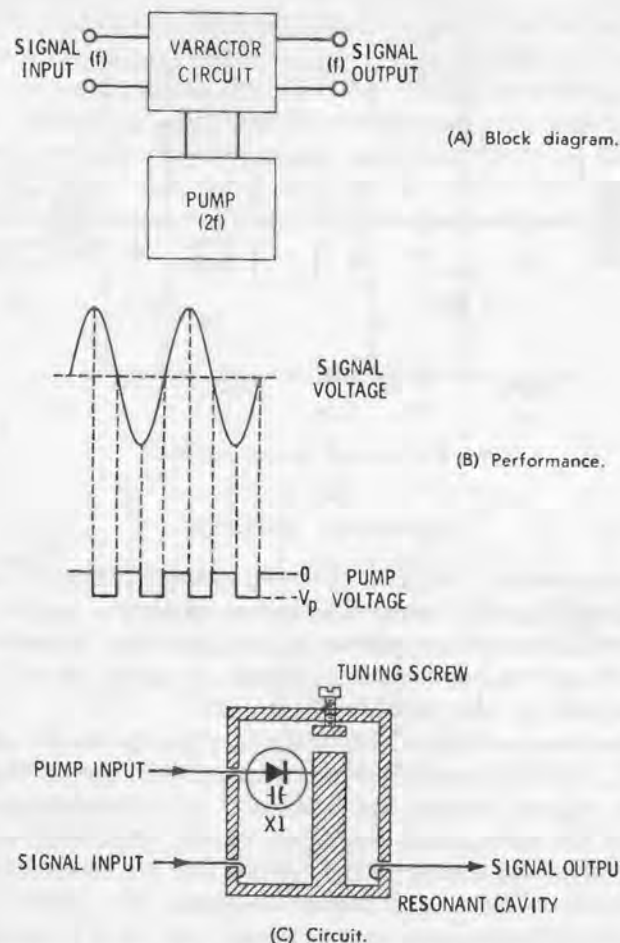


Fig. 5-4. Principle of the parameter amplifier.

is already fully charged by the signal when the pump-pulse peak arrives, the charge (Q) remains constant but the varactor voltage (V) increases because the capacitance (C) has been pushed down ($V = Q/C$). This increases the power in the varactor circuit, i.e., power is delivered to the load when the varactor capacitance is lowest. For this action to take place, a pump-voltage peak must occur at the instant that the signal voltage on the varactor is at its positive peak and again when it is at its negative peak. This requires that the pump be both properly phased with respect to the signal,

and also that its frequency be twice the signal frequency. Fig. 5-4B shows these relations. When the phase relations are as shown, minimum varactor capacitance occurs at positive and negative peaks of the signal cycle, and maximum capacitance at the zero-signal points. (If we could mechanically open and "close" a two-plate capacitor in the same sequence at the signal frequency, we could get amplification in the same way that the pumped varactor provides it.) A parametric amplifier of the type just described is said to operate in the *degenerate mode*.

The need for tight control of phase in the degenerate parametric amplifier has given rise to another design in which the pump operates at a frequency other than twice the signal frequency. This involves the use of an idler. Fig. 5-5 shows the functional arrangement of this type, with the

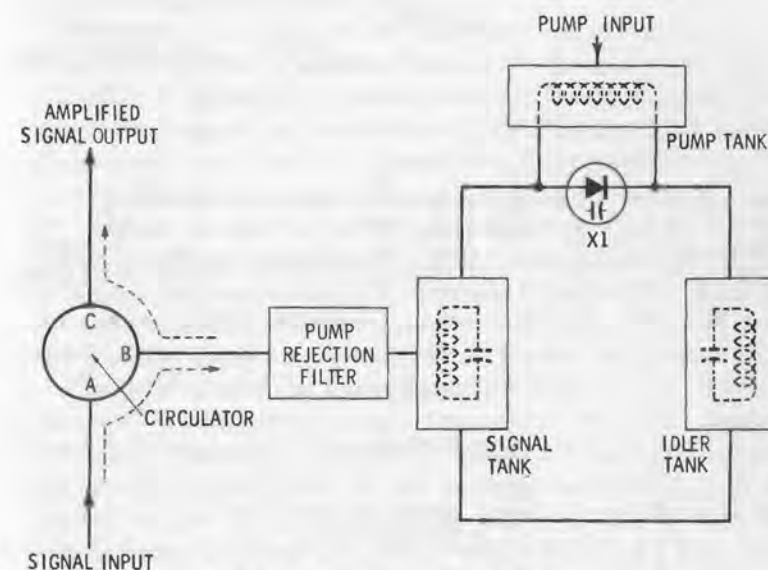


Fig. 5-5. Parameter amplifier with idler.

signal tank, pump tank, and idler tank represented as lumped LC circuits (dotted lines). In this arrangement, a three-port microwave circulator is used for input and output coupling. With the system in operation, a third frequency—the *idling frequency*—is produced, which is equal to the difference between signal and pump frequencies. Varactor

X1 couples the three tanks in the circuit which handle these frequencies.

The signal to be amplified is applied to port A of the circulator, and the latter transmits this signal, through port B, to the signal tank. A mixture of the amplified signal and an idler-frequency signal then would appear at port B, but the idler frequency is removed by the pump rejection filter, so only the amplified signal remains, and it is transmitted, through port C, to the load.

D-C AMPLIFIER

Fig. 5-6A shows the circuit of a curious d-c varactor amplifier of the resonant-slope type. With d-c input and output

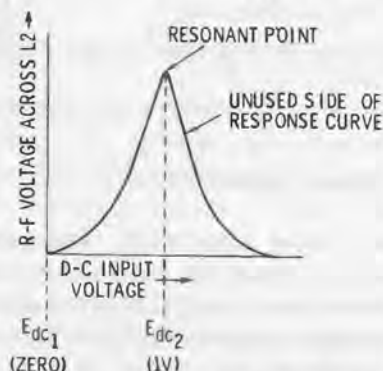
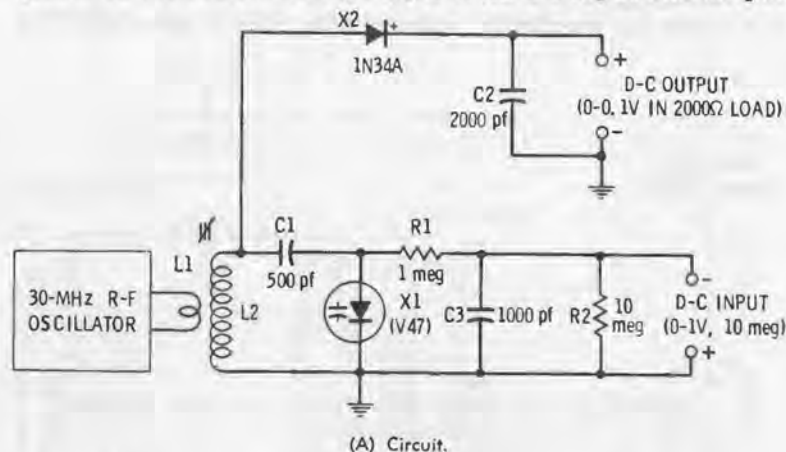


Fig. 5-6. The d-c amplifier.

signals, this circuit provides a current gain of 500, power gain of 50, and voltage gain of 0.1. In its transformation of high input resistance (10 megohms) to low output resistance (2000 ohms) at power gain and voltage loss, it resembles a d-c cathode follower and is useful as such whenever its 10:1 voltage reduction can be tolerated.

When powered from a 30-MHz power supply (transistor crystal oscillator operated at 3 volts, the circuit can employ a 47- or 56-pf varactor. At 1-volt d-c input, the amplifier circuit draws 0.1 μ a from the signal source (d-c input power equals 0.1 μ w). This input current is due entirely to current through input resistor R2, which is provided for the purpose, since the varactor draws only a leakage current of approximately 0.02 μ a. With 1-volt signal input, the amplifier delivers an output of 0.1 volt and 50 μ a into a 2000-ohm load (d-c output power equals 5 μ w).

The tank coil (L2) of the amplifier circuit is tuned entirely by varactor X1. Protective d-c blocking is provided by capacitor C1. Radio-frequency energy is transmitted into this tank through link-coupling coil L1. The varactor capacitance (and thus the tank frequency) is proportional to the d-c signal voltage, applied through isolating resistor R1. The r-f voltage across L2 is therefore proportional to the d-c signal voltage. The r-f voltage is rectified and filtered by diode X2 and capacitor C2 to provide a d-c output. Resistor R1 and capacitor C3 serve as a radio-frequency filter to block power-supply r-f energy from the d-c input terminals.

Fig. 5-6B shows the response of the circuit. Note that the choice of a high power-supply frequency (30 MHz) enables the L2-X1 tank to be completely tuned and detuned by varying the d-c input signal voltage between zero and 1 volt. As shown in this illustration, when input signal voltage E_{dc} equals zero, the circuit is completely detuned. At this time, the r-f tank voltage is zero and so is the d-c output. But when E_{dc} equals 1 volt, the r-f tank voltage and d-c output are maximum (this is ensured by adjusting the slug on L2 for resonance when E_{dc} equals 1 volt). Because of the curvature of the varactor response, the d-c output voltage varies nonlinearly with respect to the d-c input voltage.

6

Instrument Applications

As a unique variable capacitor, the varactor is often invaluable in special-purpose test instruments. In such applications, it replaces hand-tuned and motor-driven capacitors or more complicated tube or transistor circuitry used to simulate these capacitors. As in its other applications, the varactor in instrumentation requires little or no attention after installation, and it offers simplicity, compactness, and ruggedness.

ABSORPTION WAVEMETER

A d-c-controlled varactor can tune an absorption wavemeter satisfactorily. This is very convenient when, for reasons of compact construction, very high frequency operation, or elimination of strays, even a small variable capacitor is undesirable.

Fig. 6-1 shows a d-c-tuned wavemeter circuit. The basis of any wavemeter is a plug-in coil and variable capacitor; here L1 is the plug-in coil and varactor X2 is the variable capacitor. The capacitance of the varactor is adjusted by means of a continuously variable d-c voltage obtained by setting potentiometer R2. The inductance of L1 is chosen

so that the varactor capacitance range will afford coverage of the desired frequency band. In this circuit, d-c blocking capacitor C1 prevents coil L1 from short circuiting the d-c supply. Isolating resistor R1, r-f choke L2, and bypass capacitor C3 form an r-f filter to block r-f tank voltage from the d-c input terminals.

Increasing the d-c tuning voltage by advancing potentiometer R2 decreases the varactor capacitance and increases the resonant frequency of the L1-X2 tank. (When L1 is loosely coupled to the r-f signal source, resonance is indicated by peak deflection of the d-c microammeter, which receives rectified current from the conventional diode, X1.) A dial attached to the potentiometer accordingly may be calibrated to read directly in megahertz. If a direct indication of resonance is not needed (i.e., resonance will be indicated instead by the effect of the wavemeter on the circuit to which it is coupled), the meter circuit (X1, C2, and the meter) may be omitted.

The d-c tuning voltage must be well regulated, otherwise the frequency calibration of the potentiometer will be disturbed and the instrument will be unstable in operation. (A simple zener-diode regulator with battery or a-c supply is adequate in most cases.) Also, the amplitude of the r-f signal picked up by the wavemeter must be low enough to prevent overriding the d-c tuning voltage. Loose coupling will afford the needed protection.

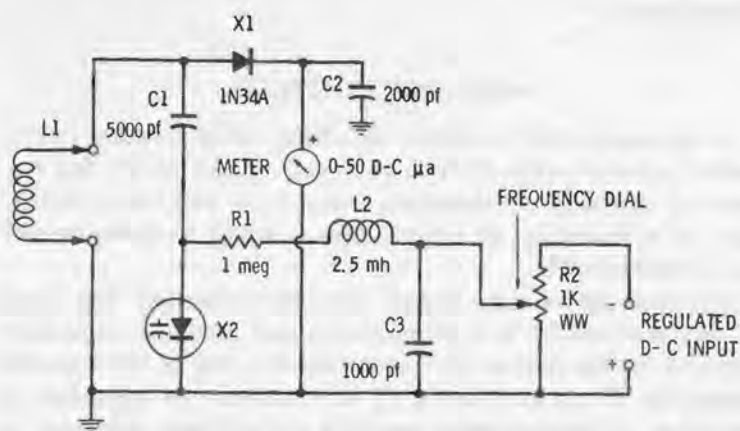


Fig. 6-1. Absorption wavemeter.

REMOTE-TUNED FIELD-STRENGTH METER

Somewhat similar to the absorption wavemeter just described is the simple diode-type field-strength meter. Like the wavemeter, the latter also consists of an LC tank followed by a diode-rectifier-type meter. At resonance, the deflection of the meter is proportional to the strength of the received signal.

The varactor makes it possible to tune a field-strength meter at a distance. This is important when the instrument must be located in close quarters or when the presence of the operator's body would distort the measurements—as in the immediate field of an antenna. Both the tuning adjustment and the indicating meter may be placed at a remote station connected to the pickup unit of the instrument by a shielded cable.

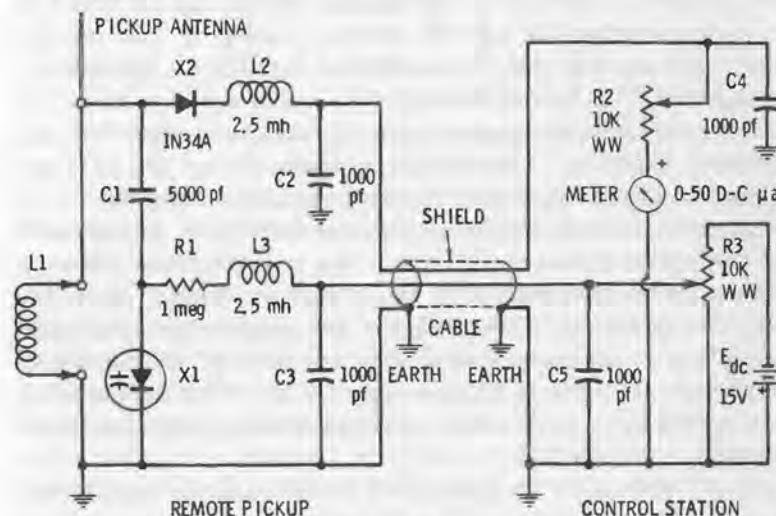


Fig. 6-2. Remote-tuned field-strength meter.

Fig. 6-2 shows the circuit of a remote-tuned field-strength meter. As in the wavemeter, the tank consists of a plug-in coil and varactor (L1 and X1). the inductance of the coil is chosen so that the varactor capacitance range (with the available d-c voltage spread) will provide coverage of the desired frequency band. Capacitor C1 provides d-c blocking, to prevent the coil from short circuiting the varactor d-c

voltage. The r-f tank voltage is rectified by conventional diode X2, whose output is fed through the cable to the d-c microammeter at the distant control station.

The shielded cable connecting the remote pickup unit to the control unit (station) has two inner conductors. One of these conducts direct current from diode X2 to the meter; the other conducts direct current from tuning potentiometer R3 to varactor X1. The shield provides the common (ground) connection between the two units and must be connected to an earth ground at both ends.

There are two r-f filters in the pickup unit. One of these (comprised of isolating resistor R1, r-f choke L3, and bypass capacitor C3) keeps radio frequencies out of the tuning-voltage source, and the other (comprised of r-f choke L2 and bypass capacitor C2) removes radio frequencies from the d-c output of rectifier diode X2. Radio-frequency bypassing is provided at the control station by C4 and C5.

Potentiometer R3 affords smooth tuning of the remote tank, and its dial may be calibrated directly in megahertz, if desired. The 15-volt battery (E_{dc}) will serve in most instances to tune the general run of varactors used for this purpose (nominal capacitances between 12 and 100 pf), but a higher voltage is needed for very-wide-band tuning.

At resonance, the meter gives peak deflection. Adjustment of the series rheostat, R2, keeps the pointer from pinning. The scale of this meter may be graduated directly in microvolts or millivolts, if desired, but the response is nonlinear, crowding at the low end of the scale because of the combined nonlinearity of diode X2 and varactor X1. This necessitates an individual calibration for each instrument and the drawing of a special scale.

The r-f signal voltage applied to the varactor should not exceed 0.1 volt peak, to circumvent its overriding the d-c tuning voltage. This can usually be managed successfully by correctly positioning the pickup unit in relation to the signal source, and/or gauging the pickup antenna.

HARMONIC INTENSIFIER FOR FREQUENCY STANDARD

Secondary frequency standards employing 100-kHz crystal oscillators are widely used. With or without multivi-

brators, such oscillators supply harmonics for calibration points far into the r-f spectrum.

Unfortunately, however, the output of the simpler 100-kHz oscillator is almost a pure sine wave, which means that the harmonics beyond about 1000 or 2000 kHz are too weak to use. Some designers have inserted a germanium diode in the oscillator output circuit and used its nonlinear low forward current to distort the 100-kHz wave and thus produce stronger harmonics. But, because the diode is a power-

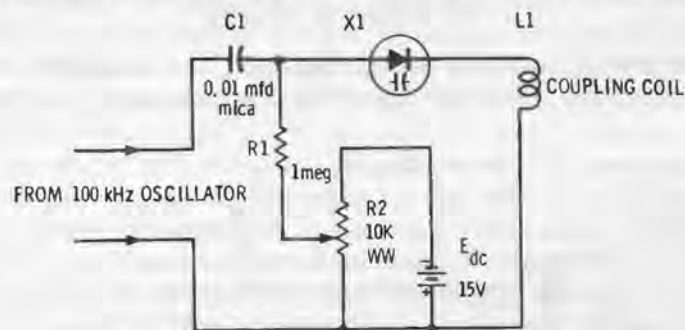


Fig. 6-3. A harmonic intensifier for frequency standard.

consuming resistive component, a better course is to use a varactor—a high-Q reactive component which consumes virtually no power.

Fig. 6-3 shows the circuit of a harmonic intensifier for use with a standard-frequency oscillator. Here, varactor X1 is in series with the standard-frequency oscillator output and coupling coil L1 (which is a few random turns of insulated wire for coupling the signal into a receiver or other device under test). Capacitor C1 provides d-c blocking; i.e., it protects the intensifier circuit from any direct current in the oscillator output, and prevents coil L1 from short circuiting the intensifier bias, E_{dc} . Varactor X1, because of its nonlinear response, delivers a distorted (harmonic-rich) current to coil L1.

A varactor bias circuit is provided: 15-volt battery E_{dc} , potentiometer R2, and isolating resistor R1. This allows biasing the varactor at will to the particular operating point at which a desired harmonic will be accentuated. Some high-order harmonics, especially when the oscillator output am-

plitude is high, will be strengthened most when the varactor d-c bias is zero (potentiometer R2 turned all the way down). The proper bias value—or even the need of any bias—for a particular desired harmonic is determined by experiment.

In individual cases, some improvement in operation is obtained by shunting coil L1 with a variable capacitor to form a tank at the desired harmonic frequency.

R-F SWEEP OSCILLATOR

A swept-frequency r-f oscillator or signal generator is required for visual display of the response curve of a tuned

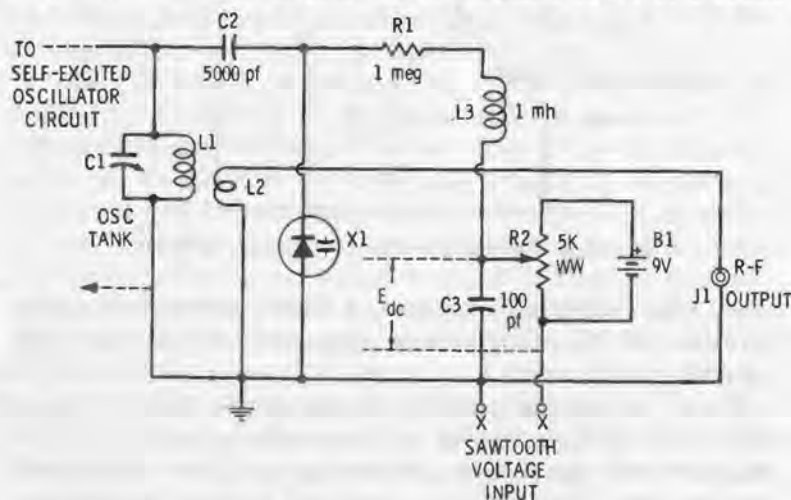


Fig. 6-4. An r-f sweep oscillator.

circuit. This instrument is a type of frequency-modulated oscillator. A straight c-w oscillator which lacks this feature may be provided with swept output by means of the circuit shown in Fig. 6-4. (An explanation of frequency modulation via a varactor was given in a previous chapter.)

In Fig. 6-4, L1 is the tank coil of the r-f oscillator, and C1 is the oscillator tuning capacitor. L2 is the output coupling coil. (In an individual oscillator, the arrangement may be somewhat different: the output may be capacitance-coupled, rather than inductive-coupled, and some type of attenu-

ator is inserted ahead of output jack J1.) Varactor X1 is connected across the tank, through d-c-blocking capacitor C2, and thus can tune the oscillator some distance above and below the frequency determined by L1 and the setting of C1. A sawtooth wave applied to terminals X-X will sweep the varactor bias, E_{dc} , repetitively over a range determined by E_{dc} and the peak amplitude of the sawtooth voltage. This, in turn, will sweep the varactor capacitance and the oscillator frequency. Bias E_{dc} is adjusted by means of potentiometer R2, to tune the oscillator to the desired resonant frequency when the sawtooth is at one-half of its peak voltage. A single rise of the sawtooth then sweeps the oscillator output from zero (or "practical zero") through the resonant peak and back to zero.

For radio and television alignment and the testing of many components, the sawtooth frequency may be 60 or 120 Hz. Sawtooth waves may be obtained from a special signal generator, from a transistor oscillator built for the purpose, or from a special pair of output terminals on some oscilloscopes used for visual testing. Because the varactor response is nonlinear, the frequency axis of the displayed resonance pattern will be nonlinear. This will require a special, corresponding frequency calibration of the horizontal axis of the oscilloscope used; otherwise, a nonlinear sawtooth wave must be used to compensate for the nonlinearity of the varactor.

SIGNAL CONVERTER

In scientific and industrial instrumentation, high-gain d-c amplification often is obtained by means of a three-step process: (1) the d-c signal to be amplified is first changed into a proportionate a-c voltage by means of a converter, then (2) this a-c voltage is amplified by a high-gain a-c amplifier which can be made more stable than a comparable d-c amplifier, and finally (3) the amplified a-c voltage is rectified to give an amplified d-c output. Some of the converters used for this purpose are vibrator-type choppers, transistor-type choppers, photoelectric choppers, magnetic modulators, Hall-effect modulators, magnetoresistive modulators, and diode-bridge modulators.

Fig. 6-5A shows a three-step amplifier system in which the converter is a varactor bridge. This bridge changes the d-c input signal into a proportionate a-c voltage which then is presented to the input of the a-c amplifier. Finally, the amplified a-c output is rectified by conventional diode X3, and the resulting amplified d-c output voltage developed across resistor R2.

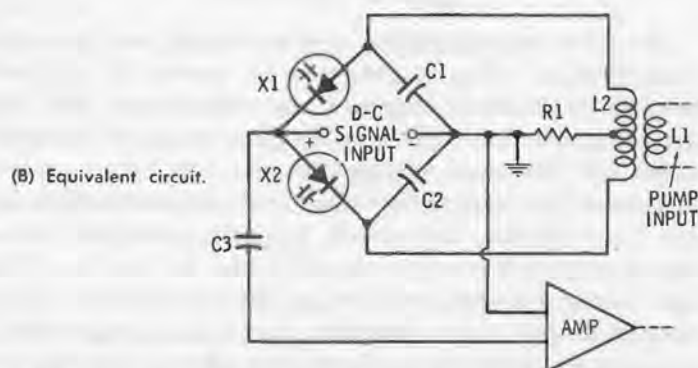
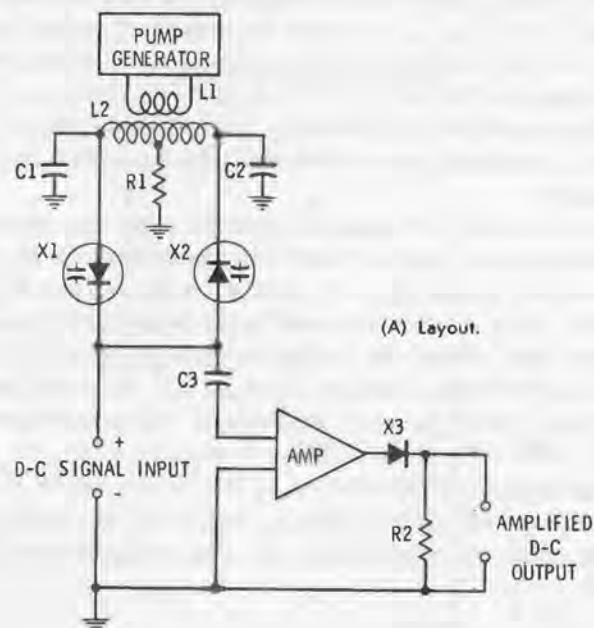


Fig. 6-5. Varactor signal converter for an instrument amplifier.

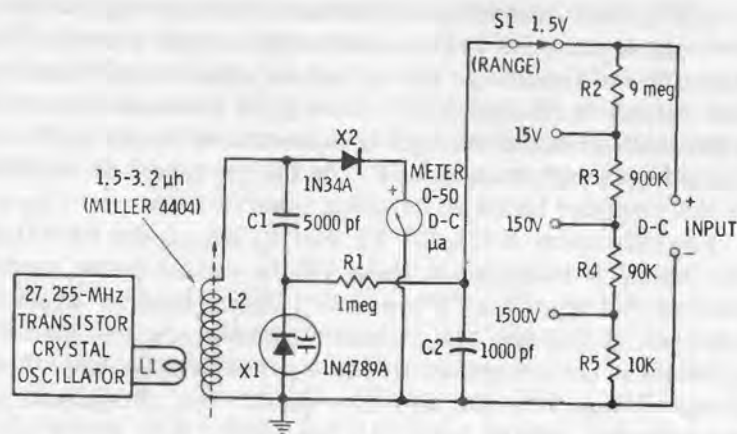
In Fig. 6-5B, the converter portion of the circuit has been redrawn to show its bridge configuration more clearly. The four arms of the bridge are formed by capacitors C1 and C2 and varactors X1 and X2. The bridge is powered by an h-f pump voltage delivered by the balanced secondary (L2) of the bridge input transformer. The bridge output is coupled to the amplifier input by blocking capacitor C3.

The reactances of C1, C2, X1, and X2 are chosen such that the bridge is balanced at these values and no pump signal reaches the amplifier. When a d-c input signal is applied, however, it changes the varactor capacitance and thereby unbalances the bridge, switching a proportionate amount of pump voltage into the amplifier input. The advantages of the varactor bridge are: (1) practically zero power consumption, (2) extremely high input resistance offered to the d-c signal, (3) extremely low noise, and (4) conversion gain. The pump frequency is not critical, so long as it can be accommodated by the amplifier. The gain supplied by parametric amplifier action in the bridge reduces the gain requirement of the amplifier somewhat.

ELECTRONIC D-C VOLTMETER

The resonant-slope d-c varactor amplifier discussed in a previous chapter is utilized in Fig. 6-6A to provide an electronic d-c voltmeter circuit. This instrument behaves in a manner similar to the vacuum-tube voltmeter and its transistorized counterpart. Its input resistance is 10 megohms, and its d-c ranges are 0-1.5, 0-15, 0-150, and 0-1500 volts. Unlike the vtm and transistor voltmeter, this instrument has no zero adjustment.

The h-f power supply is a transistor oscillator operated from a 27.255-MHz Citizens Band crystal and link-coupled to the tank comprised by coil L2 and varactor X1. The tank is operated on the low side of resonance, so that a 1.5-volt d-c input tunes the circuit exactly to resonance (trimmed initially by means of the L2 tuning slug) and deflects the meter to full scale. The selectivity of the tank is high enough that the circuit detunes completely when the d-c voltage is removed, and the meter reads zero. Initial adjustment consists merely of applying an accurately known 1.5-volt d-c



(A) Circuit.

(B) Performance.

INPUT (dcv)	METER READING (μa)
0	0
0.25	2
0.50	3
0.75	7
1.00	16
1.25	32
1.50	50

Fig. 6-6. Electronic d-c voltmeter.

input (with range switch S1 set to its 1.5-volt position) and adjusting the slug on L2 for exact full-scale deflection of the meter. The coupling between L1 and L2 must be rigid and the oscillator d-c power supply must be well regulated (a zener diode with battery supply suffices), for the instrument to be stable.

Because of the nonlinear response of varactor X1 and diode X2, the voltmeter scale is nonlinear, crowding at the low end. Fig. 6-6B shows the meter readings for various input voltages; hence, a typical calibration.

If a very-low-leakage varactor is used, the input resistance of the instrument can be increased to 100 megohms by multiplying the values of each resistor (R2 through R5) by ten.

One might question the use of this varactor circuit when the transistor and its d-c power supply might be removed from the crystal oscillator and used directly as a "vtvm." The answer is that the high input resistance of 10 to 100 megohms would not be obtained unless a more expensive field-effect transistor were used.

7

Supplementary Applications

This chapter describes some additional applications of varactors, which are not included in the preceding categories. The ideas are intrinsically useful and they may also suggest further applications.

There is no intent to suggest that the varactor is a universal component or that it is a panacea. But it is applicable to a number of circuits where it can perform a task more efficiently or simply than devices formerly or presently used for the purpose. Thus, only a few possibilities are explored in this chapter.

FREQUENCY DIVIDER

Now well known as a frequency multiplier, the varactor will also operate as a frequency divider. It has been used in several ways to achieve subharmonic operation. Fig. 7-1 shows a typical circuit.

In the shunt-varactor circuit of Fig. 7-1, the configuration is essentially the same as that of the frequency multiplier; the chief difference is the tuning of the output filter, L2-C3, to a submultiple (f/n) of the input frequency. Specifically

here, the circuit is a frequency halver, i.e., the input is f and the output $f/2$. Another difference is the noninductive internal load resistor, R_2 .

The input filter (series-resonant circuit L_1 - C_2) is tuned to the fundamental frequency, f ; the output filter (series-resonant circuit L_2 - C_3) is tuned to $f/2$. Capacitors C_1 and C_4 are impedance-matching units for input and output, respectively.

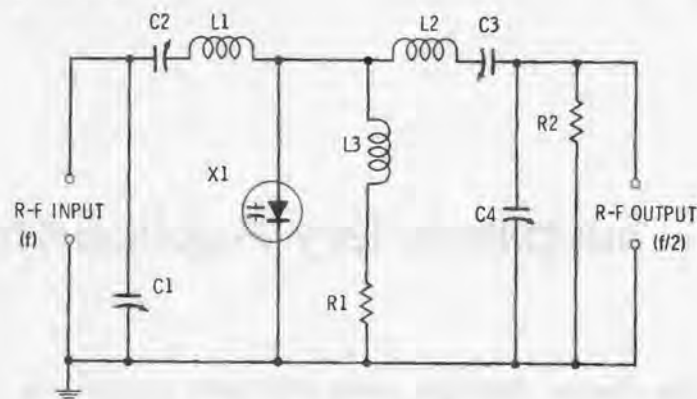


Fig. 7-1. Frequency-divider circuit.

The divider requires a lower self-bias resistance (R_1) than is used in multiplier circuits—usually of the order of $1/10$ of the multiplier value. In some instances, this (and the presence of R_2) precludes efficient operation of the simple circuit shown here alternately as a multiplier or divider simply by interchanging input and output.

Efficiency figures between 80 and 90 percent have been reported for frequency halvers of this type operated with 125-watt input at 50 MHz ($f_{out} = 25$ MHz).

Other configurations (such as parallel-resonant filters, autotransformer input and output, and double tuning) may also be used (see Fig. 4-4.)

MICROWAVE LIMITER

Fig. 7-2 is the block diagram of a relatively simple setup for microwave voltage limiting (compression). A varactor doubler, of any desired configuration, is used with its out-

put terminated by a nonradiating, noninductive resistive load, R_L .

The limiting action afforded by this arrangement is based on an inherent operating characteristic of the varactor doubler: As the applied r-f input is increased from zero, no doubler operation occurs until a characteristic threshold voltage is reached. The doubler then goes into operation, delivering to the load device output power proportional to the input power as the input is further increased. But there is no further increase in r-f input *voltage* (which levels off at the threshold value), since the high efficiency of the doubler

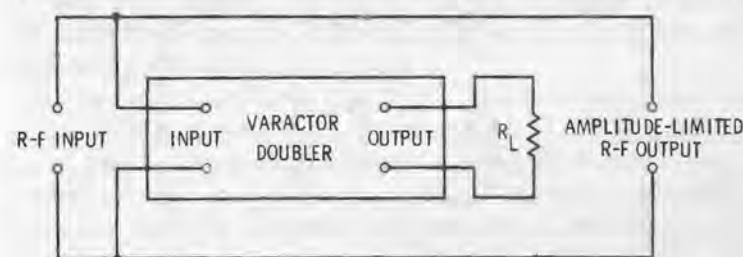


Fig. 7-2. Microwave-limiter circuit.

causes nearly all of the input power to be converted into output power. The r-f voltage at the output terminals (which are merely extensions of the input pair) therefore is quite constant in amplitude.

This arrangement makes a convenient method for amplitude-limiting microwave and uhf voltages in certain parts of transmitters and signal generators when other schemes prove inadequate.

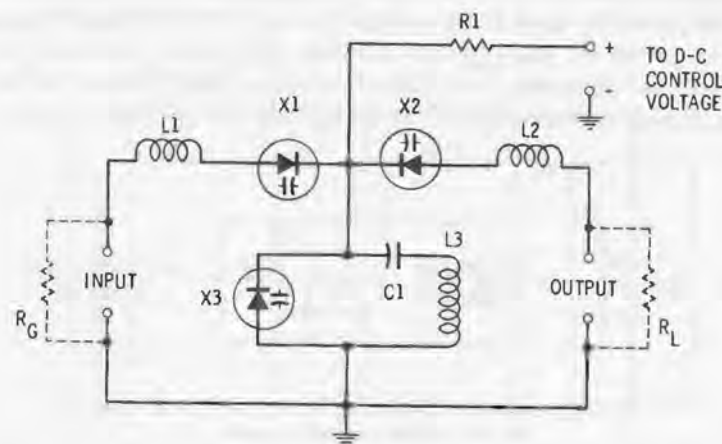
WAVE FILTERS

The voltage-variable capacitance of the varactor provides an efficient method of tuning several capacitors simultaneously in a constant- K or m -derived filter, using only one control (such as a potentiometer) to do the job. Representative single-section RC filters were shown earlier in Fig. 2-7.

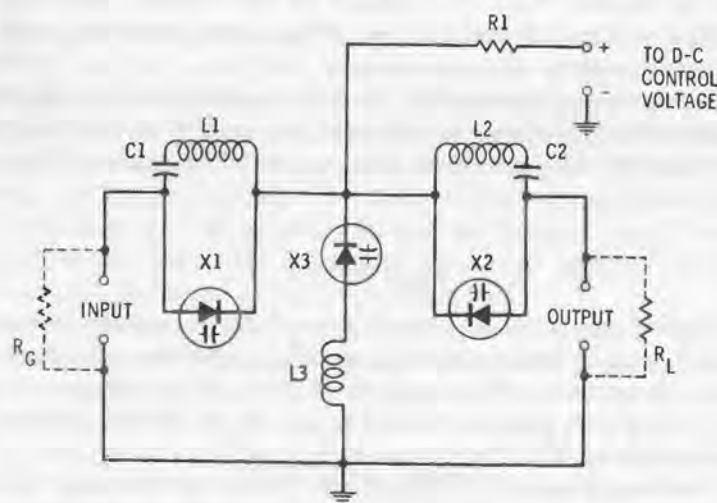
The two types of LC filters for which continuously variable tuning most often is desirable are the *bandpass* and *bandstop* (band-suppression or band-elimination) circuits. These are shown with varactor tuning in Fig. 7-3. Both are

T filters containing appropriate series- and parallel-tuned sections with varactors as the tuning capacitors.

In the bandpass filter (Fig. 7-3A), the two series arms are the series-resonant elements ($L1-X1$ and $L2-X2$) and the shunt arm is the parallel-resonant element ($L3-X3$). The d-c control voltage is applied to all three varactors simultaneously through the isolating high resistance, $R1$.



(A) Bandpass.



(B) Bandstop.

Fig. 7-3. Wave filters.

taneously through the isolating high resistance, $R1$. The return path for this control voltage must be supplied through the output resistance (R_G) of the signal source, for varactor $X1$; and through the load resistance (R_L), for varactor $X2$. If these resistances are absent, comparable resistors must be connected in shunt with the input and output terminals. In the shunt arm, d-c-blocking capacitor $C1$ prevents $L3$ from short circuiting the control voltage and must be very much higher in capacitance than $X3$, so as not to tune the shunt arm.

The capacitance ($X1$, $X2$, and $X3$) and inductance ($L1$, $L2$, and $L3$) values required for a desired pass frequency and bandwidth may be determined with the aid of standard filter-design formulas or tables.

In the bandstop filter (Fig. 7-3B), the two series arms are the parallel-resonant elements ($L1-X1$ and $L2-X2$) and the shunt arm is the series-resonant element ($L3-X3$). The d-c control voltage is applied to all three varactors simultaneously through the isolating high resistance, $R1$. The return path for this control voltage must be provided by the output resistance (R_G) of the signal source, for varactor $X1$; and by the load resistance (R_L), for varactor $X2$. If these resistances are absent, comparable resistors must be connected in shunt with the input and output terminals. In the series arms, d-c-blocking capacitors $C1$ and $C2$ prevent $L1$ and $L2$, respectively, from short circuiting the control voltage. The capacitance of $C1$ and $C2$ must be very much higher than that of $X1$ or $X2$.

The capacitances ($X1$, $X2$, and $X3$) and inductances ($L1$, $L2$, and $L3$) required for a desired notch frequency and bandwidth may be determined with the aid of standard filter-design formulas or tables.

VOLTAGE-TUNED PI NETWORK

The CLC pi network is used in many ways: antenna coupler in transmitters, low-pass wave filter, power supply filter, and phase-shift transmission line are several examples. Both of the capacitors in the network may be d-c tuned simultaneously from a single potentiometer if they are varactors as shown in Fig. 7-4.

The transmission and impedance characteristics of the network are determined by the inductance of coil L1 and the capacitances of the two varactors, X1 and X2. The inductance and capacitance values required for a desired mode of operation may be determined with the aid of standard filter-design and phase-shift formulas or tables.

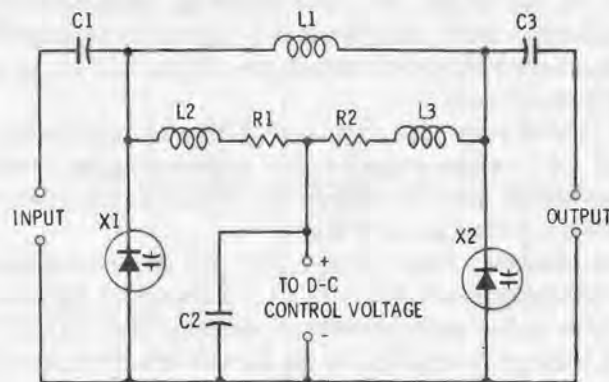


Fig. 7-4. Voltage-tuned pi filter.

The d-c tuning voltage is applied to the two varactors simultaneously—to X1 through r-f filter L2, R1, and C2 and to X2 through r-f filter L3, R2, and C2. R1 and R2 are isolating high resistances. C1 and C3 are d-c-blocking capacitors; C1 prevents the input signal source from short circuiting the d-c control voltage on varactor X1, and C3 prevents the external load from short circuiting the d-c control voltage on varactor X2. Each of these capacitances must be very much higher than the capacitance of X1 and X2, so that the varactors and not the capacitors will determine the network characteristics.

BALANCED MODULATOR

Balanced modulators are used principally in wave analyzers, spectrum analyzers, and sideband transmitters. Fig. 7-5 shows a bridge-type modulator circuit in which two of the bridge arms are varactors (X1 and X2) and the two other arms are conventional capacitors (C1A and C1B, the two sections of a split-stator variable capacitor). The varac-

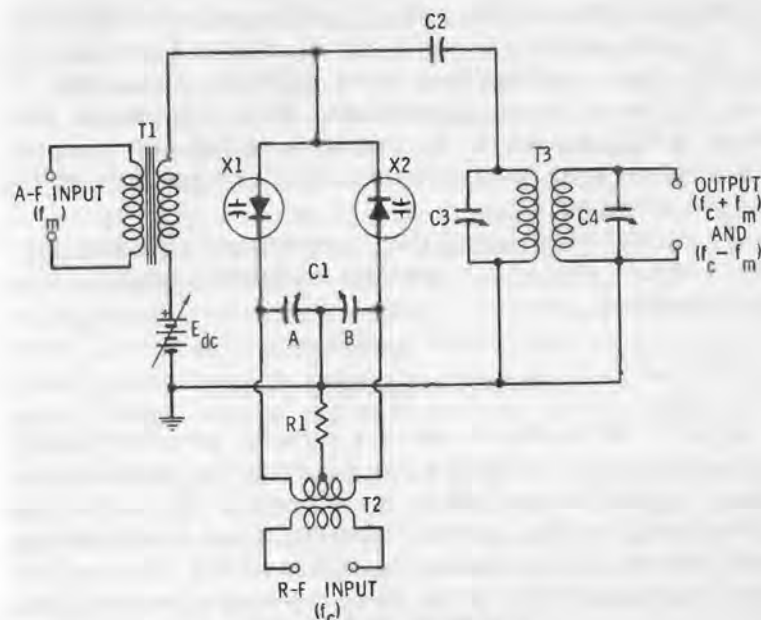


Fig. 7-5. Balanced modulator.

tor arrangement is similar to the signal converter shown earlier.

The varactors are biased by adjustable d-c voltage E_{dc} to a favorable point for lowest distortion. Direct-current-blocking capacitor C2 prevents the primary of transformer T3 from short circuiting the bias. A radio-frequency carrier (f_c) is presented to the bridge through air-core transformer T2. If X1 and X2 are capacitance matched and if the sections of the variable capacitor (C1) track and are equal, this capacitor may be adjusted to balance the bridge, whereupon the carrier will be suppressed at the output terminals. If, then, audio-frequency modulation (f_m) is applied through transformer T1, the a-f voltage will be superimposed on the d-c bias voltage, E_{dc} , and will fluctuate the capacitance of the varactors, balancing and unbalancing the bridge at the audio-frequency rate. Each time the bridge is unbalanced, the carrier is switched through transformer T3 to the output terminals (the a-f signal cannot pass through this air-core transformer); and each time the bridge is balanced, the carrier is cancelled in the output. The output wave

therefore contains the sum ($f_c + f_m$) and the difference ($f_c - f_m$) of carrier and audio, but no carrier; i.e., it consists of the upper sideband and lower sideband. Capacitors C3 and C4 permit tuning transformer T3 to the desired sideband. Additional selectivity may be provided with a crystal filter resonant at the desired sideband and operated at the output of the circuit.

By careful matching of the varactors and critical adjustment of bias voltage E_{dc} , spurious modulation products may be minimized.

ULTRAHIGH-RESISTANCE SWITCH

Fig. 7-6 shows the circuit of a varactor switch which offers an ultrahigh resistance to a d-c switching-signal source. An r-f signal is switched by a d-c voltage. The circuit delivers output as long as the switching signal is maintained, and thus simulates a spst spring-return switch. This application is an adaptation of the basic resonant-slope amplifier.

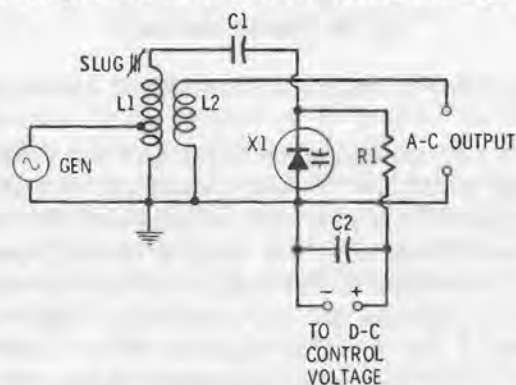


Fig. 7-6. Ultrahigh-resistance switch.

The r-f signal is supplied by the generator and is coupled into coil L1 through an impedance-matching tap. L1 forms a tank with varactor X1, resonant at the generator frequency. Capacitor C1 provides d-c blocking, to prevent L1 from short circuiting the d-c control voltage. R1 is an isolating high resistance, and C2 an r-f bypass capacitor.

With the d-c control (switching) voltage applied to the circuit, the tuning slug of coil L1 is adjusted to resonate the

circuit at the generator frequency, as indicated by maximum voltage at the a-c output terminals (this voltage is coupled out of the tank by means of L2). When the d-c control voltage is removed, the a-c output voltage falls to zero, because the tank completely detunes (if the frequency is high enough, e.g., 20 MHz or more). Thus, the output may be switched on and off by making and breaking the d-c voltage. Current drawn from the d-c source, which may have as low as 1 volt output, is of the order of nanoamperes; the input resistance of the switch accordingly is of the order of gigohms. If desired, the switching voltage may be a positive-going square wave or pulse. To use a negative switching signal, simply reverse the varactor and the d-c input terminals.

The r-f output may be rectified with a single germanium diode (or diode bridge) to give d-c output. The d-c output obtained in this way will close a sensitive d-c relay.

CAPACITIVE POTENTIOMETER

A compact, small-sized a-c potentiometer (attenuator, voltage divider) may be obtained with a series connection of capacitor and d-c-controlled varactor (see Fig. 7-7). A capacitive potentiometer is called for when power consumption must be held to a minimum and resistive elements are prohibited.

The a-c input voltage to be controlled is applied across capacitor C1 and varactor X1 in series. The varactor ca-

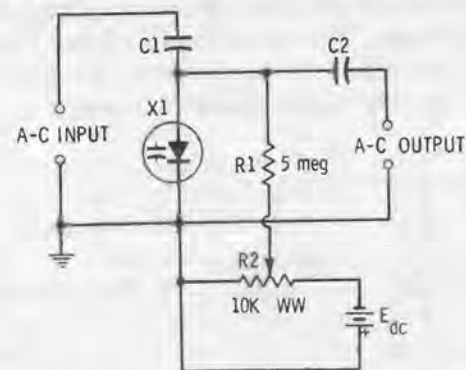


Fig. 7-7. Capacitive potentiometer (attenuator).

capacitance is varied by means of a d-c control voltage obtained through potentiometer R2 from d-c source E_{dc} . Resistor R1 serves as isolator and a-c choke. The capacitance of C1 must be chosen with respect to the minimum and maximum capacitances of varactor X1 so that the desired output voltage range will be obtained as the varactor is "tuned" through its capacitance range.

Capacitor C1 automatically provides d-c blocking, to prevent the input-signal source from short circuiting the varactor d-c voltage and to protect the varactor from any direct current present in the input signal, while it acts as the upper arm of the capacitive potentiometer. A separate capacitor, C2, must be provided, however, to protect varactor X1 and its d-c voltage from the external load device. The capacitance of C2 must be very much higher than that of the varactor, so that the varactor capacitance, rather than C2, determines the attenuation.

LIGHT-CONTROLLED CAPACITOR

In Fig. 7-8, a varactor receives a variable d-c control voltage from a self-generating photocell or solar battery (PC) through the usual isolating high resistance, R1. A high-output solar battery will vary the varactor capacitance over a significant range as the cell experiences illumination from total darkness to bright light. Blocking capacitor C1 protects the varactor from any direct current present in the circuit in which this variable capacitor is used, and it prevents the external circuit from short circuiting the varactor d-c control voltage. The capacitance of C1 must be very much higher than that of the varactor, so that the capacitance "seen" at the "capacitance" terminals is principally

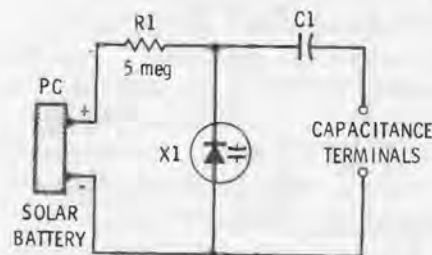


Fig. 7-8. Light-controlled capacitor.

that of the varactor. Because the varactor draws virtually no current from the cell, the cell output voltage will be its maximum no-load value at each level of illumination.

The variable capacitance available at the "capacitance" terminals may be used in a variety of ways. For example, a telemetering transmitter may be tuned by it, to communicate light changes to a distant observer. Or it may be used to shift the frequency of a beat-frequency oscillator in response to the interruption or variation of light. In any application, the amplitude of an a-c signal applied to the varactor by the external circuit must be very much less than the photocell d-c voltage to prevent overriding the latter.

NEGATIVE REACTOR

Negative reactance (the a-c counterpart of negative resistance) has been observed in varactors. This may be seen in a series-resonant circuit comprised by a varactor and conventional inductor and operated with an adjustable a-c input. Such an arrangement is shown in Fig. 7-9A.

That part of the circuit within dotted lines may be regarded as the negative reactor. Here, the series-resonant circuit is composed of coil L1 and varactor X1. Capacitor C1 provides d-c blocking, and its capacitance must be very

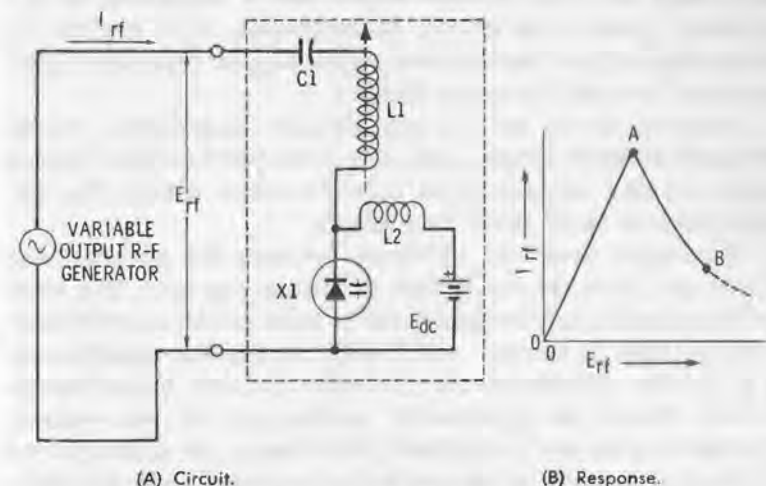


Fig. 7-9. Negative reactor.

much higher than that of X_1 , so that this capacitor does not tune the resonant circuit.

At a given value of reverse bias (E_{dc}), the inductance of L_1 is set by means of its slug to tune the series-resonant circuit to resonance when the generator voltage, E_{rf} , is one-half of maximum. When the generator voltage then is reduced to zero, the circuit current (I_{rf}) also drops to zero, as shown in Fig. 7-9B. Increasing E_{rf} then causes I_{rf} to increase, this current reaching a maximum at point A where the signal voltage has tuned the series-resonant circuit to resonance. Increasing E_{rf} further produces a decreasing I_{rf} , since the signal voltage now detunes the circuit above resonance. Current I_{rf} consequently decreases, as from A to B .

The negative slope, AB , indicates negative reactance—voltage increases; current decreases. This negative reactance is available at the input terminals and may be used in various r-f circuits for monostable switching, generation of lower-frequency oscillations, and similar applications common in negative-resistance practice.

VARACTOR EFFECTS IN CONVENTIONAL DIODES

The sensitivity of capacitance to reverse voltage was first observed in conventional semiconductor diodes. This is a secondary property in such diodes and is minimized to the greatest practicable extent. Nevertheless, it is present in some degree in all such diodes, depending on type and make, and can be exploited when desired.

Junction diodes exhibit the highest capacitance, chiefly because of their larger area, but even point-contact diodes show a small amount. Most manufacturers specify the capacitance in their diode data sheets.

The major practical difference between the conventional diode and the varactor is that of leakage current. The level of this current can be significant in some of the conventional diodes (such as zeners) which give the highest capacitance, e.g., a few microamperes. In spite of this shortcoming, which results in appreciable loading of the d-c control-voltage source and in internal diode losses, the conventional diode can function as an emergency varactor or as an interesting (and often inexpensive and readily available) unit

for demonstrating the d-c dependence of junction capacitance.

A diode must be carefully picked from a good sampling if best varactor simulation is desired. Criteria for selection are lowest reverse leakage current throughout the projected range of d-c control voltage, and best capacitance for the projected application. (Note that "best" capacitance does not always mean highest capacitance.) The conventional diodes which most nearly meet all of the requirements for varactor substitution are the silicon units. The reverse leakage of germanium diodes totally unsuits them for *voltage-controlled* applications, although they can afford d-c control of capacitance if one is willing to expend a certain amount of d-c power.

Appendix

ABBREVIATIONS USED IN THIS BOOK

A —area	d - c —direct-current (adjective)
a - c —alternating-current	E —voltage
a - f —audio-frequency	E_{ac} —alternating-current voltage
afc —automatic frequency control	E_{af} —audio-frequency voltage
B —battery	E_{dc} —direct-current voltage
C —capacitance	$e.g.$ — <i>exempli gratia</i> (for example)
C —capacitor	E_r —radio-frequency voltage
C_c —stray case capacitance	$etc.$ — <i>et cetera</i> (and so forth)
C_d —capacitance of diode or of varactor	f —frequency
C_j —junction capacitance	f —fundamental
CLC —capacitance-inductance-capacitance	f_c —carrier frequency
C_{max} —maximum capacitance	f_{co} —cutoff frequency
C_{min} —minimum capacitance	f_{in} —input frequency
C_t —total capacitance	f - m —frequency-modulated (adjective)
C_v —capacitance at applied voltage v	f_m —modulation frequency
c - w —continuous-wave	f_{max} —maximum frequency
d —thickness	f_{min} —minimum frequency
D —diameter	f/n —frequency divided by a number n

f_{out} —output frequency
 f_r —resonant frequency
GHz—gigahertz (1 GHz = 1000 megacycles per second)
h—harmonic
h-f—high-frequency
Hz—Hertz (1 Hz = 1 cycle per second)
I—current
i.e.—id est (that is)
 I_f —current at frequency *f*
 I_r —current at the fundamental frequency
 I_f —forward current
i-f—intermediate-frequency
 I_r —reverse current
 I_{rf} —radio-frequency current
 I_s —current source
 I_s —source current
 I_t —total current
 I_{2r} —second-harmonic current
 I_{3r} —third-harmonic current
 I_{4r} —fourth-harmonic current
J—jack
k—dielectric constant
k— $\times 1000$
K—a constant depending on kind of semiconductor and its processing

kHz—kilohertz (1 kHz = 1000 cycles per second)
kv—kilovolt(s)
L—inductance
L—inductor (coil)
LC—inductance-capacitance
M—meter
ma—milliampere(s) (1 ma = 0.001 ampere)
max—maximum
mc—megacycle(s) (1 mc = 1,000,000 cycles)
meg—megohm(s) (1 meg = 1,000,000 ohms)
mfd—microfarad(s) (1 mfd = 1,000,000 picofarads)
mh—millihenry(s) (1 mh = 0.001 henry)
MHz—megahertz (1 MHz = 1 megacycle per second)
min—minimum
msec—millisecond(s) (1 msec = 0.001 second)
mw—milliwatt(s) (1 mw = 0.001 watt)
mwv—maximum working voltage
N—electron-rich semiconductor
nf—frequency *f* multiplied *n* times
nh—nanohenry(s) (1 nh = 10^{-9} henry)

ohm-cm—ohm-centimeter(s)
P—hole-rich semiconductor
PC—photocell
 P_d —power dissipation
pf—picofarad(s) (1 pf = 1 micromicrofarad)
 P_i —input power
PN—junction of P-type and N-type semiconductor materials
 P_o —output power
Q—electrical charge
Q—figure of merit (quality factor)
Q—transistor
R—resistance
R—resistor
RC—resistance-capacitance
r-f—radio-frequency (adjective)
 R_L —load resistance
 R_p —internal leakage resistance
 R_p —parallel resistance
 R_s —series resistance
 R_s —source resistance
 R_t —total resistance
t—time
t—time constant
T—transformer
uhf—ultrahigh frequency

V—voltage
va—volt-ampere(s)
 V_{br} —breakdown voltage
 v_{dc} —volts, direct-current
 V_f —forward voltage
 V_r —voltage at the fundamental frequency
vhf—very-high frequency
 V_p —pump voltage
 V_r —reverse voltage
 V_s —voltage source
ww—wirewound
x—times (multiply by)
 X_c —capacitive reactance
 X_t —total reactance
Y—admittance
 Y_L —output admittance
 Y_s —source admittance
Z—impedance
 Z_L —load impedance
 Z_s —source impedance
 Δ —change or ratio (such as ΔC)
 μa —microampere(s) (1 μa = 10^{-6} ampere)
 μh —microhenry(s) (1 μh = 10^{-6} henry)
 μsec —microseconds (1 μsec = 10^{-6} second)
 ϕ —contact potential
 Ω —ohm(s)
 ω — 2π times frequency
 $^{\circ}C$ —degrees centigrade (Celsius)

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abc's of VARACTORS

by Rufus P. Turner

The varactor—also known as a silicon capacitor, voltage-variable capacitor and varactor diode—is really just a PN junction, the same as a semiconductor diode. However, in the normal semiconductor diode efforts are made to minimize inherent capacitance, while in the varactor, this capacitance is emphasized. Also, since the capacitance varies with the applied voltage, it is possible to amplify, multiply, and switch with this simple two-terminal device.

The first two chapters are devoted to basic varactor theory and operation. Only simple mathematics is used in the easy-to-follow explanation of the factors essential for an understanding of the subject. The remaining chapters contain typical circuits, showing applications where varactors are used in receivers, transmitters, amplifiers, test instruments, and other areas. Microwave applications—for which the varactor is especially well suited—are included.

abc's of Varactors is intended for anyone interested in learning more about these novel units. The experimenter, student, or technician will find the simple, straightforward explanations of the units and the circuits invaluable in obtaining an understanding of this comparative newcomer in the semiconductor field.

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