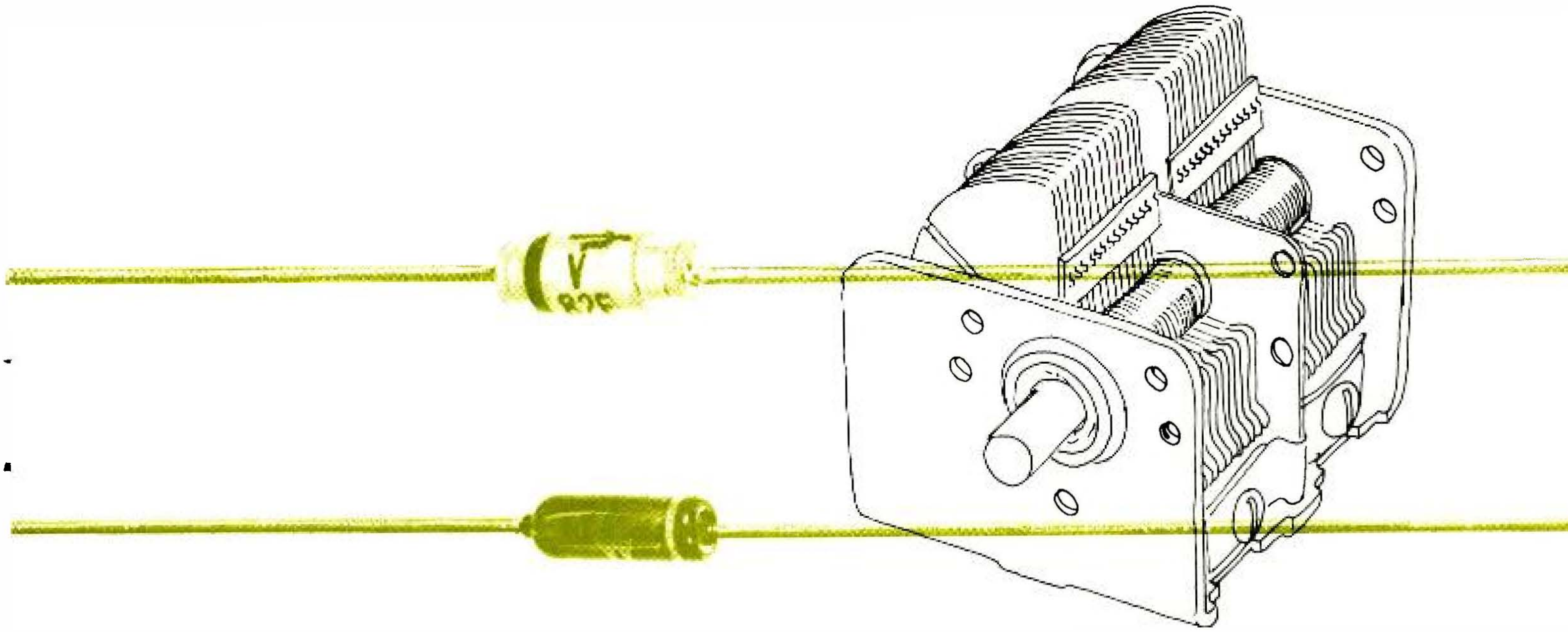


Varactor Diode Applications

By DONALD E. LANCASTER

These special semiconductor diodes, which operate as high-"Q" electronically variable capacitors, are finding increasing uses in a.f.c. circuits, FM modulators, harmonic generators, and parametric amplifiers over a wide range of frequencies.

WHENEVER any *p-n* semiconductor junction is reversed-biased, a depletion layer is formed in which there are no excess electrons or holes. No conduction takes place in this region. As the reverse bias varies, so does this depletion layer, the layer becoming thicker with increasing reverse bias. The net effect is a high "Q," electronically variable capacitor. Whenever junction characteristics are optimized to yield this variable capacitance effect, a varactor diode results.

Due to their remarkable properties, varactor diodes now find extensive use everywhere from the audio frequencies to the outer reaches of the extreme microwave frequencies. A varactor is a non-microphonic, compact, electronically variable capacitor whose capacitance can be readily changed at a high rate of speed. It can directly frequency-modulate a signal. It has a non-linear capacitance characteristic, allowing varactors to serve as harmonic generators and parametric amplifiers. Most important, it is a reactance and not a resistance. Because of this, it is nearly lossless and essentially noiseless. Varactors are only a fraction of the size of conventional mechanically variable capacitors yet perform many tasks far better.

Commercially available varactors are amazingly diverse. They range in price from a little over a dollar each for a.f.c. varactors intended for FM receivers to exotic matched sets of parametric amplifier diodes costing thousands of dollars a pair. Low-frequency varactors are available with capacitances as high as .002 microfarad; some microwave devices have a maximum capacitance of only 0.4 picofarad. The power-handling capability ranges from 100 milliwatts or so for the small varactors to stud-mounted versions that can accept over a hundred watts of input r.f. power. Some are strictly low-voltage units having a breakdown voltage in the reverse direction of only −6 volts, while other, high-voltage, units may be rated as high as −300 volts and may have a maximum capacitance ratio on the order of 20:1 or higher.

Varactor Operation

A varactor is always operated somewhere between forward breakover and reverse breakdown. As the reverse bias increases, the junction capacitance *decreases*, but not in a linear manner. Many varactors will have their junction capacitance vary inversely as the square root of the reverse bias. This non-linearity is a two-edged sword. It means that bias-shaping circuitry is required to obtain large linear capacitance *vs* voltage control regions. This is highly desirable for frequency modulators and receiver-tuning applications. On the other hand, the two most important varactor applications—frequency multiplication and parametric amplification—*must* have a non-linear capacitance *vs* voltage characteristic. Both these applications are fundamentally impossible in a linear, time-invariant system.

The depletion layer is then the dielectric of a capacitor. As such, the varactor has a capacitance value and a "Q." Both are determined in the conventional manner, the capacitance being a function of the junction area, the thickness of the depletion layer (as determined by the reverse bias), and the dielectric constant. "Q" is defined as the ratio of reactance to resistance at a given frequency. To obtain high "Q," very low leakage is required. Because of this, silicon is used exclusively

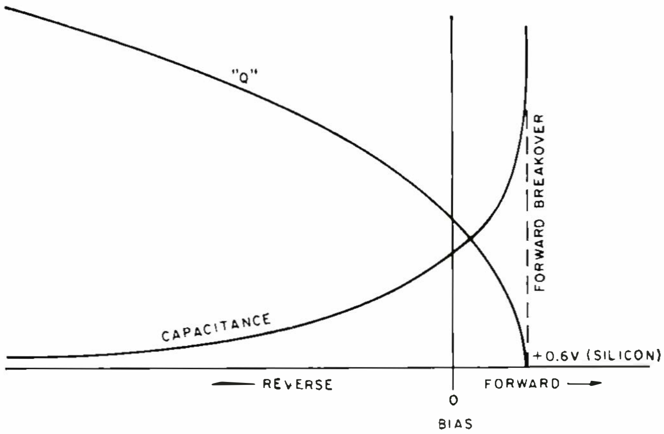


Fig. 1. Varactor capacitance and "Q" vary with bias voltage.

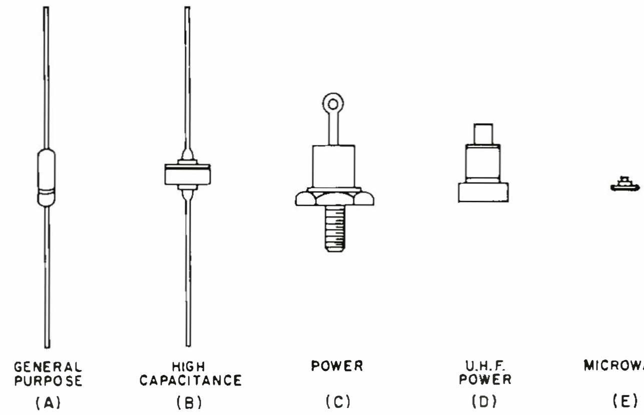


Fig. 2. Various types of varactor packages are shown here.

Table 1. A directory of manufacturers of varactor diodes.

MANUFACTURER	A	B	C	D	E
AIRBORNE ELECTRONIC LABS Richardson Rd., Colmar, Pa.	•			•	•
AMPEREX ELECTRONIC CORP. 230 Duffey Ave., Hicksville, L.I., N.Y.	•			•	
BENDIX CORP, SEMICONDUCTOR DIVISION South Street, Holmdel, N.J.	•		•	•	
COMPUTER DIODE CORP. 250 Garibaldi Ave., Lodi, N.J	•				
EASTRON CORP. 25 Locust Street, Haverhill, Mass.	•	•	•		
FAIRCHILD SEMICONDUCTOR 545 Whisman Rd., Mountain View, Cal.	•				
HUGHES AIRCRAFT CO., SEMICONDUCTOR DIV. 500 Superior Ave., Newport Beach, Cal.	•	•			
ITT FEDERAL LABS 500 Washington Ave., Nutley, N.J.	•				
MOTOROLA SEMICONDUCTOR Box 955, Phoenix, Arizona 85001	•		•	•	•
MICRO STATE ELECTRONICS 152 Floral Ave., Murray Hill, N.J.				•	•
MICROWAVE ASSOCIATES Northwest Park, Burlington, Mass.		•	•	•	•
NUCLEONIC PRODUCTS CO. 3133 E. 12th St., Los Angeles, Cal.	•				
PHILCO SPECIAL PRODUCTS Lansdale Div., Lansdale, Pa.	•		•		•
RADIO CORPORATION OF AMERICA 415 S. Fifth St., Harrison, N.J.			•	•	•
RAYTHEON CO., SEMICONDUCTOR DIV. 350 Ellis St., Mountain View, Cal.	•				
SOLITRON DEVICES INC. 256 Oak Tree Rd., Tappan, N.Y.	•	•	•		
SYLVANIA ELECTRIC, SEMICONDUCTOR DIV. 100 Sylvan Rd., Woburn, Mass.			•	•	•
TEXAS INSTRUMENTS, SEMICONDUCTOR DIV. Box 5012, Dallas, Texas 75222	•		•		•
TRW/PSI SEMICONDUCTORS 14520 Aviation Blvd., Lawndale, Cal.	•	•	•		
VARIAN SOLID STATE Beverly 34, Mass.	•			•	•

A = General-purpose, low-frequency control varactors.
B = High capacitance, low-frequency varactors (68 pF or more).
C = High-power, low-frequency varactors (1 watt or more).
D = High-power, high-frequency varactors (1 watt or more; 100 MHz and higher).
E = Microwave devices (1 gigahertz and higher).

for all varactors, except for a few gallium-arsenide microwave devices. The finite "Q" implies a loss or a resistive component. This occurs due to the bulk resistivity of the semiconductor and appears as a small series resistance.

A figure of merit of any varactor is its *cut-off frequency*. This is the frequency at which "Q" = 1. Put mathematically, "Q" $= X/R = 1/2\pi fCR$ and $f_{cut-off} = 1/2\pi RC$ where f = frequency in Hz, C = capacitance in farads, and R = series resistance in ohms for some specified bias value.

Low-frequency "Q's" are at least 50, typically 200 to 400 for many units. Many microwave varactors have "Q's" so high they cannot be readily measured. Some manufacturers guarantee "Q's" of several thousand.

Fig. 1 shows how capacitance and "Q" vary with changing reverse bias. The junction capacitance tends to become infinitely great at the forward breakover voltage, for here the depletion layer approaches zero thickness. Unfortunately, the junction is conducting heavily at this point and has ceased being a capacitor. Because of this, the useful "Q" rapidly diminishes as forward breakover is approached. Obviously, if reverse breakdown is ever reached, the "Q" will also suddenly vanish. The greater the reverse bias, the greater the "Q" and the smaller the capacitance.

The choice of a reverse-bias operating point depends upon the application. For maximum capacitance swing, the varactor is normally biased halfway between zero and a value safely under reverse breakdown. For maximum capacitance *change* and greatest non-linearity, the varactor is biased near the forward region. In fact, some harmonic multipliers actually are momentarily driven into forward conduction briefly each cycle to produce strong harmonics. Operation at zero bias has an advantage in many circuits—no d.c. bias source is required. Finally, for maximum "Q" and greatest linearity, the varactor can be biased well out on the curve, perhaps within a few volts of reverse breakdown.

The actual biasing techniques will become apparent as we discuss applications. Since the varactor is always operating in the *reverse*-bias region, negligible current, and hence, negligible bias power are required. In this sense, a varactor is an extremely "high-gain" device, providing many control functions with only a few microwatts of control power.

Where a d.c. bias is used, a stable reference source must be obtained. If not, the junction capacitance will faithfully follow any drift or noise present with the bias source. A zener diode is often employed in order to provide a stable reference source when this is required.

Types of Varactors

There are five basic types of varactors, each with a fundamentally different package. These are shown in Table 1 and Fig. 2. The ordinary diode package of Fig. 2A finds use for general-purpose, low-power, low-frequency varactors. These are usually low-cost devices, rated at a few hundred milliwatts of power dissipation and having junction capacitances between 1 and 100 pF. These are used for any frequency where case and lead stray inductance and capacitance are not important, which usually restricts their use to under 500 MHz. For some low-frequency applications, more junction capacitance is required than will fit in this package. To increase junction capacitance, either a larger junction or multiple junctions may be employed. Both techniques find use. This results in the "fat" package of Fig. 2B. These devices range from 68 to 2000 pF and go as high as one or two watts of dissipation. Their main use is in low-frequency applications, such as audio phase shifters, AM broadcast-band applications, and delay lines.

The dissipation rating of any varactor is simply how much heat it can safely dissipate. In an ordinary diode, substantial heat is produced only in the forward-biased and reverse-breakdown regions. This heat is determined by multiplying the diode voltage by the d.c. diode current, producing the internal heat loss in watts. But no d.c. current can flow in a reverse-biased varactor (except for a trivial leakage current measured in nanoamperes). This is not true of an a.c. signal, since it will readily travel through the junction capacitance and series resistance of the reverse-biased varactor. The a.c. current traveling through the series resistance produces the heat loss that is the basis for the dissipation rating of the diode. The loss is given by I^2R_s where I is the instantaneous a.c. signal current and R_s is the equivalent series resistance. The peak values of this particular power can be substantial in some cases.

For applications where high r.f. signal levels are a problem, the power varactor package of Fig. 2C finds use. Some of these power varactors are rated at 25 watts and can easily handle r.f. power inputs of 100 watts. These are important in high-power multiplier chains, v.h.f. transmitters, and u.h.f. frequency multipliers. The practical upper frequency limit of this package is about 500 MHz of r.f. input. Heatsinking is usually provided by bolting the varactor to an aluminum or copper plate of reasonable size.

Above 500 MHz, the power varactor has to be streamlined to eliminate stray capacitance, residual inductance, and other parasitics, resulting in the u.h.f. power varactor package of Fig. 2D.

For microwave work, the least amount of circuit strays can drastically alter performance. Lead inductances of 5 nanohenrys can be intolerable, as can 0.1 pF of capacitance. Thus, the microwave "package" of Fig. 2E is not a package at all but merely a means of protecting the semiconductor and making contact with the circuit. These devices are used exclusively in stripline and waveguide circuitry. Some varactors have cut-off frequencies in excess of 500 GHz and find use at frequencies of 80 to 100 GHz. These varactors are truly tiny—some will fit in an ⅛-inch cube with room to spare.

Circuit Applications

One obvious application consists of using a varactor as a replacement for a conventional variable capacitor in a resonant circuit, as shown in Fig. 3. To allow proper biasing, a blocking capacitor (C) is added in series with the varactor. Biasing is by way of a high-value resistor and an r.f. bypass. As the d.c. bias on the varactor is changed, the depletion layer capacitance changes, which in turn changes the resonant frequency. If capacitor C in Fig. 3B is much larger than the junction capacitance, the series equivalent capacitance will essentially be that of the varactor itself.

There is a defect in this simple circuit. At any instant, the varactor sees a voltage that is the sum of the instantaneous signal and the d.c. bias value. If the signal is quite small, this is immaterial. But if the signal is large, it will itself bias the varactor differently on positive and negative cycles and cause severe distortion. This is eliminated by the balanced varactor circuit of Fig. 3C. Here, two varactors are used back to back. As the signal swings positive, it decreases the capacitance of

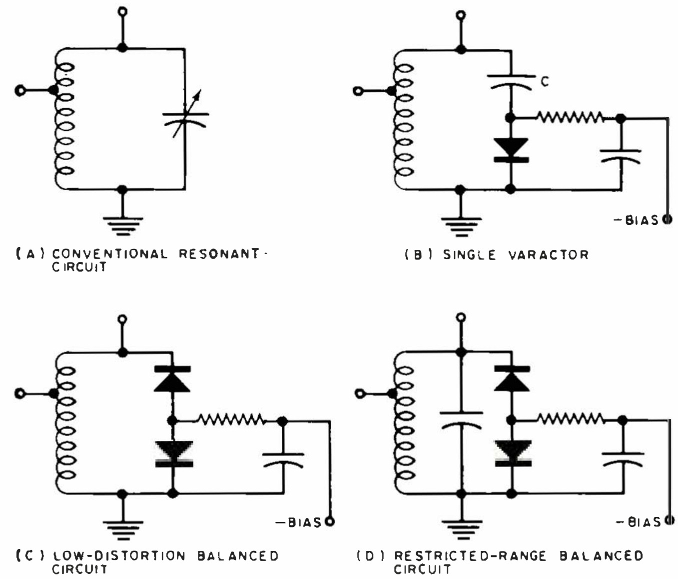


Fig. 3. The use of varactors in various tank circuits.

one varactor and increases the capacitance of the other one. The sum of the two series capacitors remains nearly constant, determined almost entirely by the bias and not the signal. Note that two series varactors have only half the junction capacitance of a single unit.

Sometimes it is desirable to just trim a resonant circuit instead of permitting the varactor to assume full frequency control. A shunt capacitor may be added as in Fig. 3D to give any desired control range. The ratios of shunt to junction capacitance determine the swing the varactor can produce.

The circuit in Fig. 3C is used for radio-receiver tuning. For a conventional AM receiver, the 365-pF tuning capacitor is replaced by two 700-pF varactors in the balanced connection. A d.c. source and potentiometer provide the tuning. In more elaborate circuits, a saw-tooth signal may be used for tuning, producing either a signal-seeking tuner or a spectrum analyzer, depending upon the rest of the circuit. Obvious advantages of this circuit are mechanical stability, small size, and ease of remote control.

Fig. 4 shows how a varactor is used to provide a.f.c. for an FM receiver. The varactor is normally biased at −4 volts with no input signal due to the base bias on the transistor. The input signal is derived from the d.c. output of the FM discriminator. If the local oscillator frequency is low, a positive d.c. output is produced at the discriminator which increases the reverse bias on the varactor, decreasing its capacitance and raising the local oscillator frequency. Similarly, a high oscillator frequency produces a negative error which is also corrected, thus locking the local oscillator to the input FM signal. This same technique is used in radar to provide signal-tracking filters, devices that follow an input signal regardless of its frequency drift or change. Voltage-tunable i.f. amplifiers work in much the same manner.

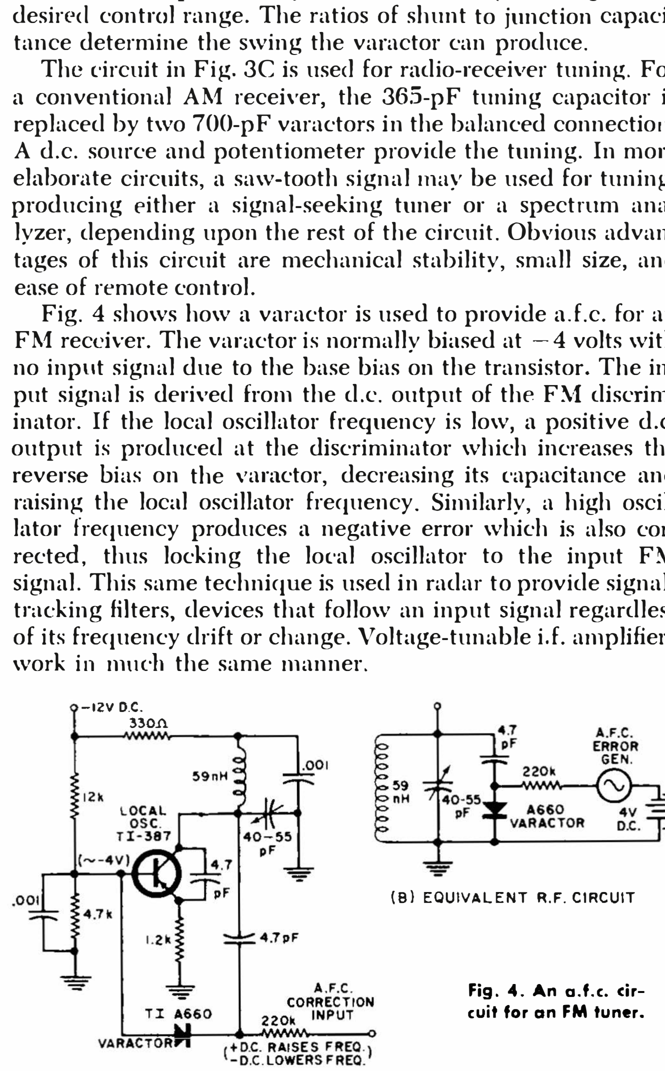


Fig. 4. An a.f.c. circuit for an FM tuner.

The basic resonant circuit becomes a sweep oscillator if a saw-tooth bias voltage is applied to the varactor. The output will be a swept frequency that follows the saw-tooth input. Distortion of the input saw-tooth will produce either a linear or a logarithmic sweep, useful in many test instruments.

Fig. 5 is a varactor v.c.o. (voltage-controlled oscillator) circuit. It produces a 25- to 35-MHz r.f. output in tune with a d.c. bias input of - 2 to −39 volts. Distortion circuitry added to the bias input has produced a v.c.o. with better than 1% linearity over a 30% bandwidth.

Varactors can produce frequency modulation in an oscillator simply by being driven with audio. The choice of shunt capacitance, d.c. bias point, and modulation amplitude will determine the modulation index. This method is much simpler and more effective than conventional reactance modulators. It also produces very little residual AM, has a very high "Q," and requires only a tiny amount of modulation power.

Varactors can replace ordinary capacitors in many conventional networks, resulting in electrically variable phase shifters, delay lines, and low-pass filters, as well as high-pass, bandpass, and band-rejection networks. These may have operating frequencies anywhere from audio to microwave.

An efficient microwave switch, shown in Fig. 6, uses a single varactor series-connected in a coaxial transmission line. To turn the switch *off*, enough *forward* bias is introduced to cause the diode to conduct heavily. This places the internal lead inductance in *parallel* with the case capacitance, producing a high "Q" parallel-resonant circuit that blocks the band of frequencies of interest. *Reverse*-biasing the varactor puts the junction capacitance and the internal lead inductance in *series*, producing a *series*-resonant circuit that easily passes the frequencies of interest. Note that this circuit appears to be "backwards" from what a casual look at this circuit would reveal; the switch is "off" when the diode is conducting heaviest. Shunt diode circuits also find use for varactors. Both circuits will readily switch in a fraction of a nanosecond with very little amount of control power.

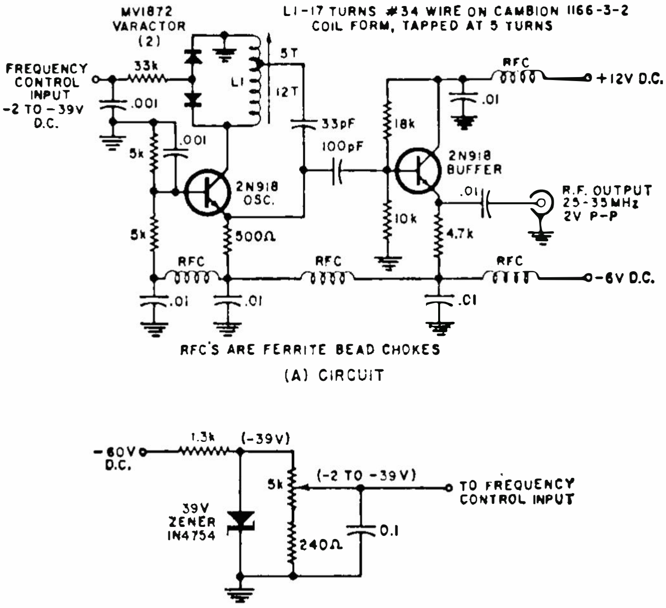


Fig. 5. Dual-varactor voltage-controlled oscillator circuit.

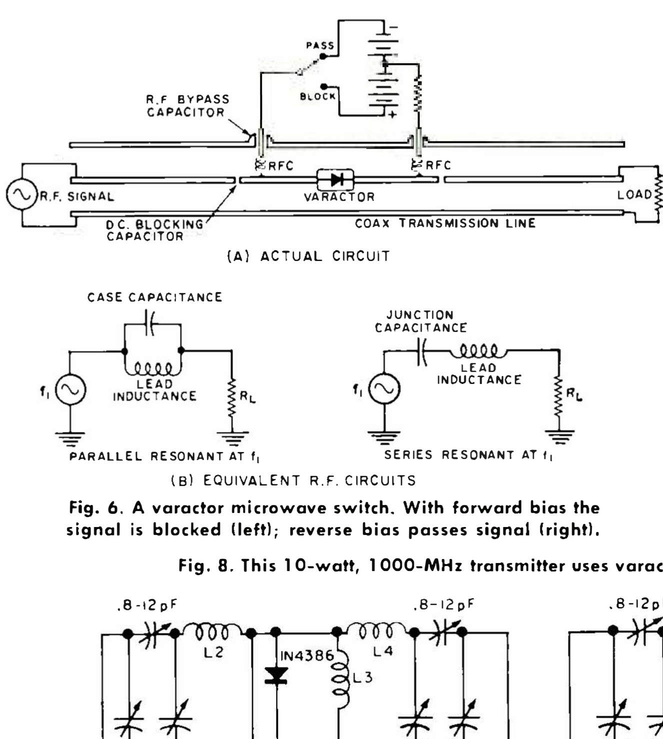


Fig. 6. A varactor microwave switch. With forward bias the signal is blocked (left); reverse bias passes signal (right).

Non-Linear Applications

None of the applications discussed so far have made use of the capability of a varactor to produce strong harmonics of an r.f. signal. The two most important applications make specific use of the varactor as a non-linear, time-varying reactance. These applications are frequency multipliers and parametric amplifiers.

Consider the frequency doubler of Fig. 7. This circuit consists of a signal source at frequency f_1, an ideal series-resonant circuit that will pass *only* f_1, a varactor, a second ideal series-resonant circuit that will pass *only* the second harmonic of f_1, and a load resistance. An input signal is delivered to the varactor at a frequency f_1. The varactor will change its junction capacitance as it is self-biased by f_1, producing a strong harmonic waveform that is time-varying to the tune of f_1. The only harmonic that is allowed to flow by the filter is the second. Therefore, practically all the power that goes into the input must be converted into second harmonic power at the output. The only losses are incurred in the small series resistance of the varactor and the finite "Q" of the filters.

Frequency multipliers of this type do not have an efficiency limitation nearly as severe as the $1/n$ efficiency limit that is rarely, if ever, achieved with non-linear resistance tube and transistor multipliers. Doublers (*Continued on page* 70)

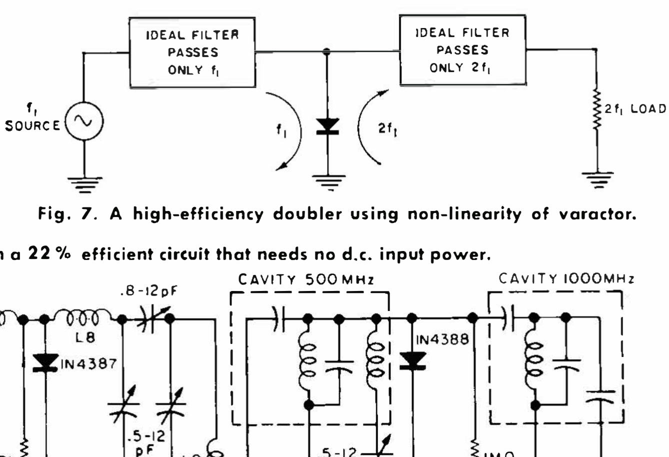
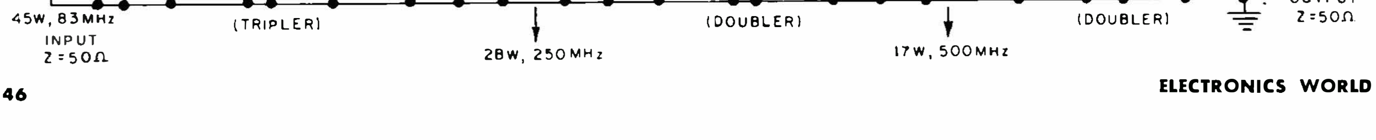


Fig. 7. A high-efficiency doubler using non-linearity of varactor.

Fig. 8. This 10-watt, 1000-MHz transmitter uses varactors in a 22% efficient circuit that needs no d.c. input power.



Varactor Diode Applications

(Continued from page 46)

with over 90% efficiency and 50% efficient octuplers are readily achieved and require no power except the input signal. Any order harmonic may be produced by proper filtering. By allowing certain other harmonics to flow and then multiply each other, efficiencies may be markedly increased.

The present practical limitations of this technique are about 25 watts of r.f. output at 1 GHz and 2.5 watts at 10 GHz. Useful harmonic power may be obtained at 100 GHz in special circuits.

Fig. 8 is a typical circuit. It is a 1-GHz, 10-watt transmitter driven from a 45-watt, 83-MHz source. This gives a 22% efficiency after a multiplication of twelve. The three varactors have a total cost of around $125. This is considerably more economical than any other present solid-state technique. Note that no d.c. power is required by the circuit as the varactors derive a self-bias from the r.f. input. The size, power, and reliability advantage over tube circuits is obvious.

This type of circuit finds use in v.h.f. and u.h.f. solid-state transmitters and signal sources. A second type of circuit uses higher order multiplication to allow a low-frequency (25 to 50 MHz) crystal to produce a stable reference microwave frequency, perhaps at 10 or 24 GHz. This is often used to phase-lock klystrons, backward-wave oscillators, and other tubes, producing substantial, precisely controlled microwave power.

A mutation of the multiplier produces an interesting circuit. Suppose we ignore the second harmonic power and look at the *input* to the multiplier. There is a sharp, well-defined threshold below which a varactor multiplier will not operate. Above this threshold, the input voltage remains constant, *independent of the input power*. This is because all power above the threshold is immediately converted into the second harmonic. This results in an effective microwave limiter with over 20 dB of dynamic range. Fig. 9 gives details. By using high "Q" circuits (usually cavities), the limiter's output is essentially flat.

Parametric amplifiers have purposely been saved for last. To attempt to cover these amplifiers in a few lines would be, to say the least, a gross oversimplification. Interested readers are urged to look up "Semiconductor Diode Parametric Amplifiers" by Blackwell & Kotzebue, published by *Prentice Hall*, Englewood Cliffs, New Jersey (1961) for details. Suffice it to say that parametric amplification is a means of using a readily available signal to reinforce a much weaker one. This is accomplished by interaction of the two signals in the time-varying reactance of a varactor diode or two. One form of paramp uses a local "pump" signal of precisely twice the input signal frequency to increase the amplitude of the input. This is in exactly the same manner as a child on a swing will "pump" the swing twice each cycle to increase its amplitude.

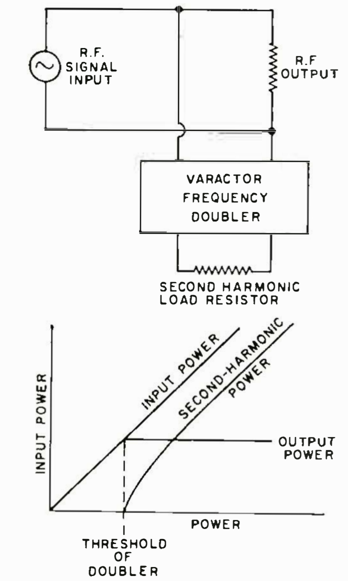


Fig. 9. R.F. limiting with varactor circuit.

The big advantage is low noise. Paramps have room-temperature noise figures that are well below any conventional devices; a one- or two-decibel noise figure is typical. This is possible because the varactor is a reactance and not a resistance. A pure reactance produces no thermal noise, but all resistances, biasing networks, transistors, and tubes do. This is of utmost importance when dealing with weak radar returns, miniscule satellite TV signals, radio astronomy, and many other applications where the last ounce of signal must be obtained without further degrading an already low signal-to-noise ratio.

Varactor paramps are useful from 200 MHz to the outer reaches of the extreme microwaves. They are now the only practical means of forming extremely low noise amplifiers at reasonable temperatures over this entire freqnency range. ▲

"Please, Doc, don't tell me I'm color blind! I just paid $800 for a color-TV set!"