The Lenkurt® Demodulator

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The Varactor Diode

The total elimination of electron tubes from equipment is almost an obsession in some parts of the communication industry. More and more equipment is being "transistorized" or converted to "solid state" in the hope of reaching new levels of reliability or of reducing the space and power required. A new step in this direction has been made possible by the varactor diode, a device with some highly unusual characteristics. This article reviews some of the general properties and behavior of varactors and how they can be used in communications equipment.

The whole field of microwave communication was made possible by the invention of the klystron just before World War II. Despite great progress since then in almost every branch of electronics and physics, microwave communication still depends on the klystron. The extreme simplicity of the reflex klystron and its steadily growing life expectancy have made it hard to surpass as a source of easily modulated microwave energy.

The varactor diode, a relative newcomer in electronics, may eventually end the klystron's monopoly on the economical generation of microwaves suitable for communications. The varactor can be an extremely efficient — even irrepressible — generator of harmonics of the signals or waveforms applied to it. This particular characteristic lends itself particularly well to use in frequency multipliers.

The varactor is a simple *p-n* junction diode which is used as a voltage-controlled capacitor. The capacitance of the device can be made to vary not only with the applied bias voltage, but also with the instantaneous values of signal voltage. The result is a non-linear device which produces a wealth of harmonics of the applied signals, as well as a profusion of frequencies representing the sum and difference of the original signals and many of their harmonics. Although most diodes possess the re-

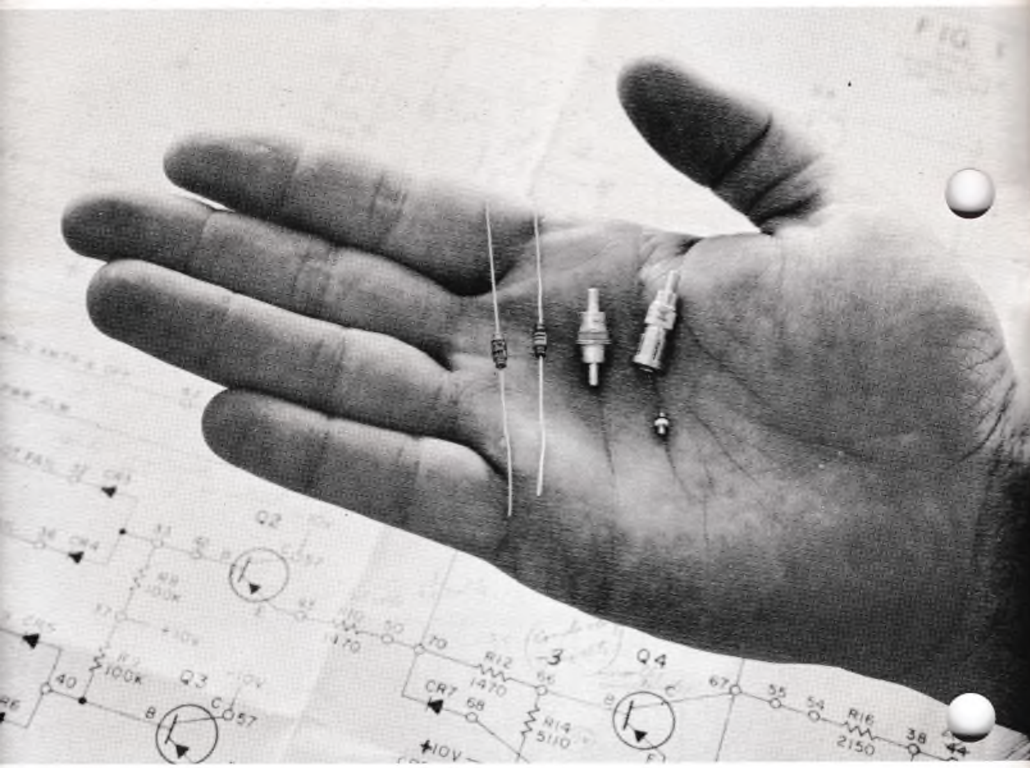

Figure 1. Varactor diodes take many forms, of which only a few are shown here. Diodes with leads are for low frequency circuits using "lumped" circuit elements. The tiny "pill" diode is used with stripline or waveguide circuits at very high frequencies. The cartridge types may be used for all frequencies, in both lumped-element or waveguide multipliers.

quired properties to some extent, diodes which have been designed to enhance certain characteristics provide the best performance.

How it Works

A junction diode consists of two layers of semiconductor material (such as silicon) which has been "doped" with impurities so that one layer has a deficiency of electrons, and the other a surplus. These layers are usually designated as the *p* and *n* layers, respectively. (For a fuller description of *p-n* junctions, see DEMODULATOR, May, 1960). In the *n* layer, the surplus electrons are free to migrate under the influence of a field or applied voltage, thus leaving a net positive charge. Similarly, in the *p* layer, the deficiency of electrons leaves "holes" which behave as though they were mobile positive charges. Holes also are free to leave the area under the influence of external fields, thus leaving a negative charge.

Where the two materials meet, their respective charge fields extend across the junction and influence the current carriers (mobile electrons or holes) in the opposite material. The positive charge from ions in the *n* crystal tends to repulse the holes in the *p* material, and the negative charge of the *p* material pushes back the free or loosely-bound electrons in the *n* material. By thus removing the current carriers from the junction area, a *"depletion zone"* is created through which current cannot flow until the mutual repulsion of carriers is overcome by the application of a suitable voltage of the correct polarity. As shown in Figure 3, the depletion zone behaves as though it were a battery of a certain voltage. In order for current to flow through the diode, it is necessary to overcome this voltage or "contact potential" by a greater voltage of the opposite polarity.

If the external voltage is connected so as to *reinforce* the contact potential rather than oppose it, the depletion zone is made larger as the current carriers in both layers are drawn even farther from the junction. Such a reverse-biased diode behaves just like a capacitor. The depletion zone becomes the dielectric, and the boundaries of the current carriers simulate the two plates or electrodes of the capacitor. The capacitance value will vary with the area of the junction, the nature of the semiconductor material and — most important of all — the applied voltage. As the reverse bias increases, the two capacitor "plates" are pushed farther apart, thus reducing the effective capacitance across the junction. As bias is lowered, the two plates draw closer together, and capacitance increases. The result is a new class of "capacitor" in which capacitance can be varied by changing the applied voltage. Figure 5 shows a typical voltage-versus-capacitance curve for a varactor diode.

This unique electrical control of capacitance opens the door to a great number of applications. Perhaps the simplest and most obvious is the electrical control of tuned circuits for automatic frequency control. Another is a "parametric" amplification. Still another use is harmonic generation. Unlike a simple capacitor, the varactor capacitance varies continuously as the signal wave itself changes value. The effect on the signal is very complex. Not only does the changing signal value cause the circuit

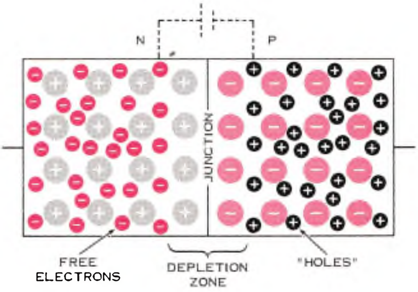

Figure 3. P-n junction consists of semiconductor material which has been suitably "doped" with donor atoms. Field from charged donors extends across junction to repulse similarly charged current carriers (electrons and "holes"). Simulated battery represents the "contact potential" which must be overcome before current can flow. Current carriers act as capacitor plates, depletion zone serves as dielectric.

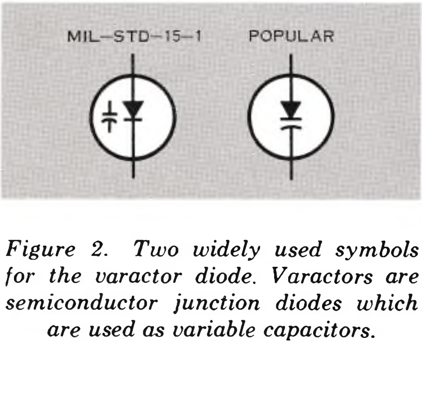

Figure 2. Two widely used symbols for the varactor diode. Varactors are semiconductor junction diodes which are used as variable capacitors.

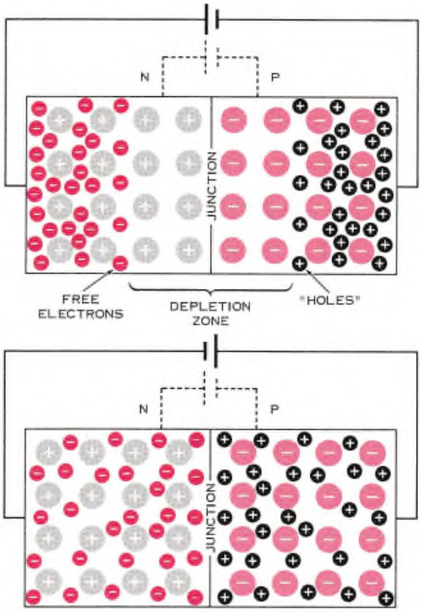

Figure 4. If contact potential is reinforced by external voltage, carriers are forced back from junction area. This enlarges depletion zone, lowers capacitance. If external voltage opposes contact potential, current carriers are forced closer to junction, changing its capacitance.

reactance to vary continuously, but the amount of signal energy absorbed and then returned to the circuit by the capacitance also changes. The result is a highly distorted output wave that is extremely rich in harmonics.

The extreme non-linearity of the varactor diode lends itself admirably to use in frequency multiplying circuits similar to those long used in FM transmitters for mobile communications and broadcasting. An important difference between conventional amplifier - type multipliers and varactor multipliers, however, is that the latter are entirely "passive." That is, they require no power other than the input signal to be multiplied. Not only that, they are often remarkably efficient, converting as much as 90% of the input signal into the desired higher harmonic. By contrast, conventional multipliers rarely exceed 30-40% efficiency.

Figure 6 illustrates a typical varactor frequency doubler. It consists essentially of two resonant circuits coupled together through a common impedance, the varactor itself. The input circuit is series resonant to the fundamental frequency, *F*, which is to be multiplied, thus assuring maximum energy transfer to the diode. Similarly, the output circuit is tuned to the 2*F* harmonic, thus assuring maximum output. Series resonant frequency "traps" block the flow of *F* currents in the output circuit or 2*F* currents in the input circuit. It is also possible to tune the circuits to obtain the third, fourth, or higher harmonic to achieve higher - order multiplication. However, this tends to complicate the circuit and lower efficiency. Figure 7 shows a typical tripler circuit, one that multiplies the input frequency by three. Note that it is necessary to provide an

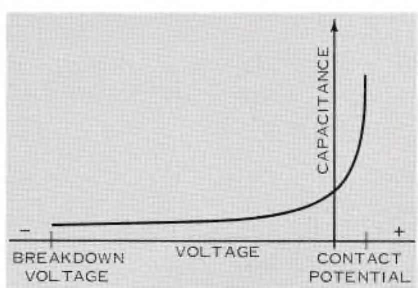

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Figure 5. A typical varactor diode voltage-capacitance relationship. Note that capacitance increases very rapidly as applied voltage approaches the contact potential. Diode conducts above contact potential or below breakdown voltage.

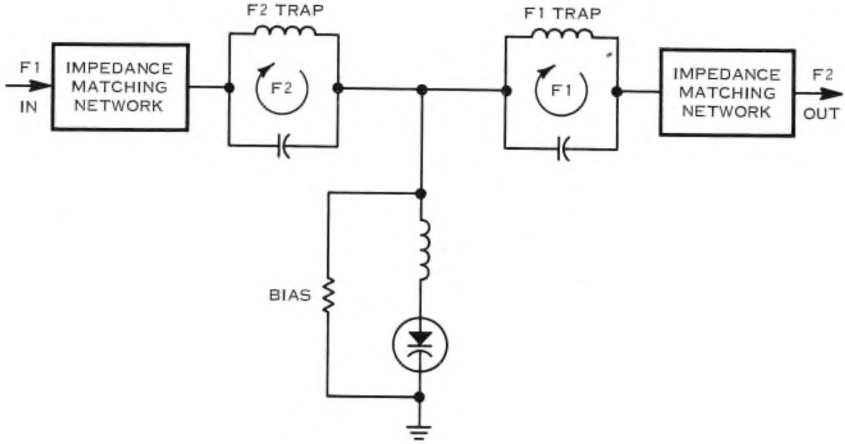

Figure 6. Typical varactor frequency doubler circuit. Frequency F is coupled to diode by series resonance of diode, inductor, and 2F frequency trap elements. The 2F harmonic is coupled efficiently to output, but blocked from input by trap.

additional shunt-resonant "idler" circuit which is resonant at 2*F*, followed by the circuit resonant at the desired 3*F* harmonic.

Efficiency

The very high efficiency that may be attained in a varactor multiplier is achieved because the device is essentially reactive rather than resistive. Theoretically, a purely reactive (in this case, capacitive) frequency multiplier will be 100% efficient. In reality, however, small losses inevitably occur in the conductors and circuit components and in the series resistance of the diode itself.

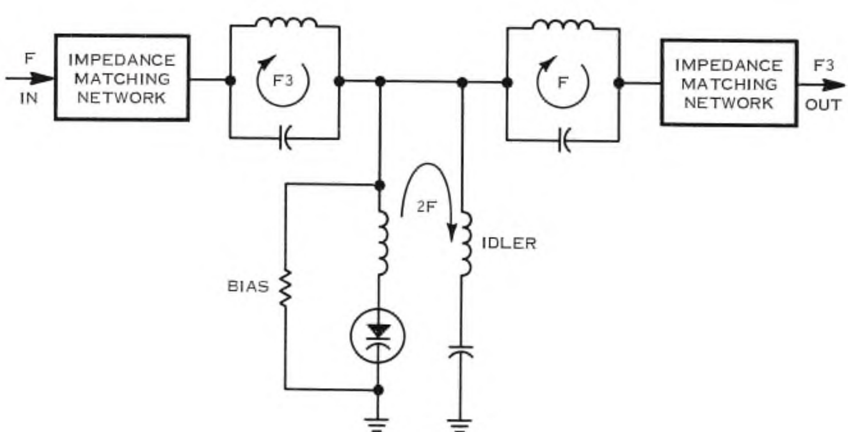

Figure 7. Frequency tripler is essentially the same as doubler, but requires a so-called "idler" circuit resonant at 2F harmonic.

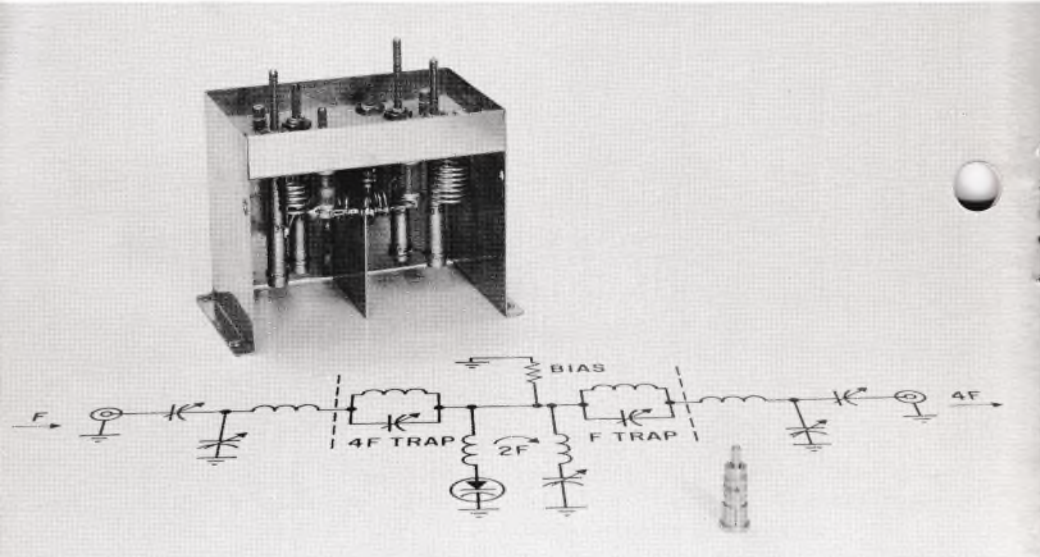

Figure 8. Actual frequency quadrupler and its schematic. This prototype device is of the same configuration as shown in Figure 7, also requires idler resonant at 2F.

Diode resistance is perhaps the most significant source of loss since it largely determines the amount of power that the diode will be able to handle.

Most of the diode series resistance occurs in the semiconductor material itself. For high frequency operation, it is necessary that the diode capacitance, and therefore the junction area, be quite small. For instance, for operation at 6000 mc, junction capacitance should be about 0.2 picofarad (micromicrofarad), thus dictating an almost microscopic junction area. The volume of semiconductor material involved is extremely small, yet it must dissipate whatever loss results. The power loss in the tiny semiconductor wafer will equal I^2R, where I is current and R is resistance. Even though series resistance may be low, typically only a few ohms, it provides most of the loss in the diode.

Even where loss is small, it is still concentrated in a very small volume of matter. This results in a rather severe local temperature rise which will quickly ruin the device unless the heat is carried away very rapidly or the applied power is carefully limited. Because of this temperature problem, manufacturers almost exclusively use silicon as the semiconductor material because of its excellent thermal conductivity and low temperature sensitivity, compared to other semiconductors.

It follows that greater power can be accommodated if the loss is reduced. The power handling capability of the varactor is proportional to its breakdown voltage value, since the applied voltage must be limited to the range between the diode contact potential and the reverse voltage at which the diode breaks down.

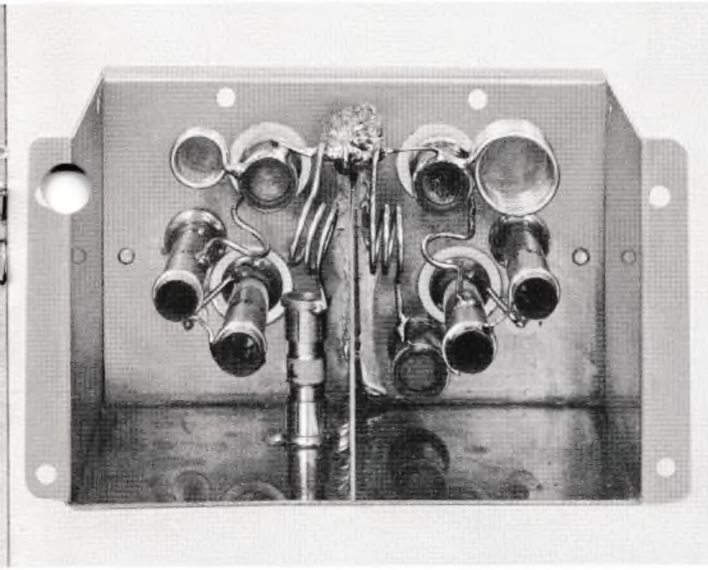

Figure 9. Detailed view of the quadrupler. Varactor is the cylinder attached to the wall in the left chamber. Sole source of power for such circuits is the input signal. Many such stages, plus special tuners may be required to reach microwave frequencies.

Practical Devices

Although these restrictions limit the amount of power that may be handled at high frequencies, it has been possible to generate as much as a watt at 6000 mc with laboratory units, and about half a watt with commercially available varactors. Power at these frequencies is achieved by cascading several multipliers in tandem. Although the efficiency of each stage may be high, depending on the degree of multiplication achieved, the total efficiency of the chain is much lower. For instance, if a chain of four frequency triplers were employed to convert a 95-mc signal to one of 6080 mc, and each tripler were 50% efficient, only 6% of the 95-mc input power would be converted to the 6080 microwave signal. If it were necessary to achieve a full watt of microwave output for transmission, at least 16 watts of input power would be required. Actually, even more input power is normally required, for at higher frequencies varactor efficiency becomes less.

Figure 10 shows a simplified block diagram of an actual multipler used to provide local oscillator energy in a microwave receiver. In this application, required power was 10 milliwatts or less. To achieve this, it was necessary to amplify the output of a crystal oscillator to provide $1\frac{1}{2}$ watts of driving power for the varactor multiplier chain. A tripler and two quadruplers yielded the desired 6400-mc signal at a power of 15 milliwatts — an efficiency of 1%.

This is directly comparable to the performance of reflex klystrons used as local oscillators, except that the multiplier chain is more complicated and far more difficult to adjust. Offsetting this difficulty is the fact that the power supply requirements for a multiplier chain are usually quite modest. Dc power is applied only to the crystal oscillator and the transistor power amplifiers which drive the multiplier chain. Unlike most solid-state local oscillators which have appeared in commercial microwave equipment, this one introduced slightly less noise than a typical local oscillator klystron.

The performance quality that can be obtained from multiplier chains is probably a function of the engineering refinement invested in the device. For all their efficiency in converting a frequency to its multiple, varactors have certain other characteristics which may cause only trouble.

For one, varactors are excellent mixers as well as efficient frequency multipliers. In fact, they appear to be slightly better mixers than multipliers. In addition to yielding a multiple of the input frequency, they also produce frequencies which are the sum and difference of the desired multiple and the frequencies which have appeared in preceding circuits.

For instance, if a varactor chain is driven by a 6-mc signal as the first stage in reaching a higher frequency, the 6-mc component will be sharply attenuated in the first multiplier by the presence of frequency "traps" and other filtering. However, with each successive multiplication, 6-mc sidebands will be present above and below the desired multiple. As multiplication increases, these sidebands gain strength relative to the desired frequency. In the worst case, this enhancement of the spurious frequencies is equal to 20 log R, where R is the degree of multiplication. Assume, for instance, that the 6-mc signal is doubled, and that the filtering in the doubler reduces the 6-mc signal 50 db in the doubler output. If the 12-mc output is multiplied an additional 64 times to yield 768 mc, the 6-mc sidebands will appear on either side of the carrier at each stage. Assuming that the filters in these multipliers are too broad to attenuate these sidebands further, they will grow in strength relative to the desired frequency. After a multiplication of 64 times, the sidebands will be only 13 db lower in amplitude than the desired 768-mc signal. Further multiplication would enhance these spurious sidebands even more. In addition to the 6-mc sidebands, other frequencies which occur in the chain would also be pres-

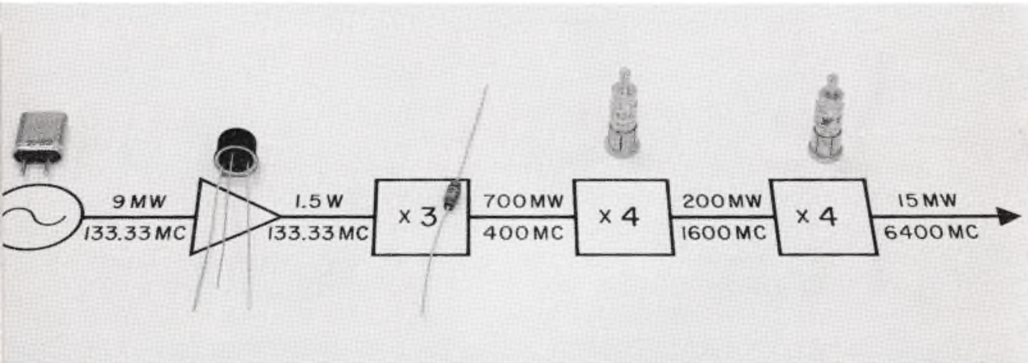

Figure 10. Simplified block diagram of an experimental microwave local oscillator. Actual circuit is much more complex than indicated here. At microwave frequencies, coaxial or stripline circuits are required. Greater multiplying factors may be achieved in each stage, but these tend to be less efficient than low-order multipliers. Principal advantage is to reduce the number of expensive diodes and other components required.

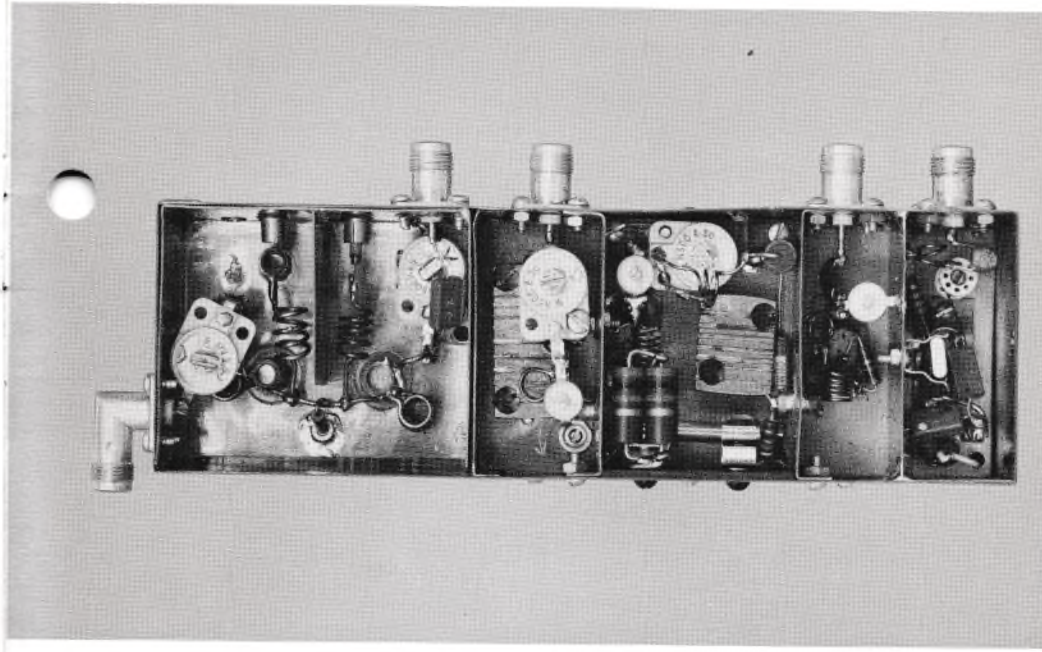

Figure 11. Typical solid-state multiplier circuit. This "breadboard" device employs crystal oscillator to drive varactor multipliers. Output is 450-mc signal which is used to drive more multipliers.

ent. However, since these have undergone less multiplication and lie farther from the desired frequency they will probably be attenuated much more. In order to obtain reasonably pure frequencies, therefore, it is vital that filtering be extremely effective, particularly in the earliest multiplier stages. This, however, tends to increase the cost and complexity of the equipment and reduces bandwidth. This is one of the reasons why varactor multipliers are generally used for generating single frequencies rather than for broadband modulated signals.

Other Difficulties

Varactors show a variety of effects which complicate the design of frequency multipliers. These include hysteresis, tuning difficulties, parametric amplification and oscillation, and others. Hysteresis may be present when the input signal to a multiplier is smoothly increased and the output signal is observed to make a large, sudden jump. As input power is reduced gradually, the output signal will drop sharply, but not at the same point at which it previously jumped. In some cases, a circuit may have two possible operating conditions at certain signal levels. When the circuit is first energized it will operate in one or the other of the two modes, but may switch spontaneously to the other under the influence of strong driving signals. When this occurs, it is usually the result of extreme detuning

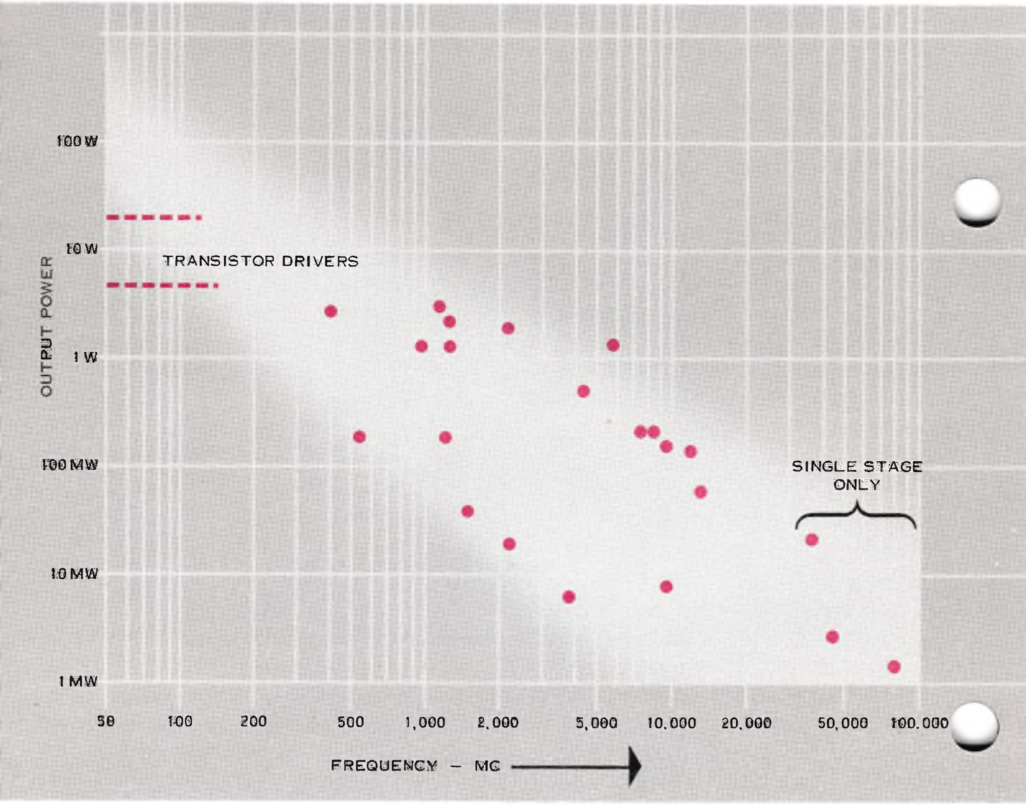

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Figure 12. Typical performance capabilities of present-day production varactors. In general, the greater the power-handling ability, the lower the maximum operating frequency. These limits are imposed by materials and techniques used in manufacturing the devices.

of the circuit or of changes in impedance caused by the variable capacitance of the varactor. With suitable care in circuit design and adjustment these effects may be avoided.

Parametric amplification within the varactor may be another source of trouble. Parametric amplifiers are those which use a varying "parameter" such as reactance to take power from one source of energy and use it to build up or amplify another. Parametric amplifiers are sometimes used as the first stage of microwave receivers where receiver thermal noise must be low, as in satellite communications. In general, parametric amplifiers require a "pump" frequency, usually at twice the frequency of the signal to be amplified, which provides the energy necessary to amplify the input signal.

Varactors often show a tendency to behave as parametric amplifiers. Energy from the input signal may be used to nourish parametric amplification of noise, subharmonics, low-level fundamental frequencies, or other signals which may be present. Spurious, chance resonances in the circuitry may increase these effects, leading to unstable operation.

A characteristic difficulty in varactor multiplier chains is the tuning and adjustment of the circuit. Varactor characteristics change with signal amplitude, and this, in turn, varies with circuit tuning. Because of the mutual interaction between the signal, the varactor, and the rest of the circuit, most multipliers must be tuned in "one direction" only. If some element is changed too far, tuning cannot be corrected by merely returning the adjustment to a previous setting. The varactor reactance will have altered in response to the improper setting and will not be the same as it was at the previous setting. When many tuning elements are involved, tuning may become a most delicate and precarious undertaking.

Conclusions

Although varactors introduce a number of design problems, these can be overcome with suitable insight and care. The varactor diode permits many applications which have not heretofore been practicable. Better and simpler ways of using varactors will be developed. Progress in semiconductor techniques will undoubtedly yield varactors with lower series resistance and higher breakdown voltage, thus extending the cut-off frequency and power handling capability. This can be expected to permit completely solid-state microwave systems at frequencies where they are not now practicable.

One aspect of the current interest in varactors as a source of microwave energy is the hope that they will have greater reliability. Although semi-conductor devices are, in general, forging well ahead of electron tubes in reliability, this varies from device to device, and is also a function of how they are used. After the superior reliability of varactors has been thoroughly established, they will still have to be used with other varactors in complex circuits. Reliability, like efficiency, is the product of all the individual "reliabilities" of the components in a given piece of equipment. If a multiplier uses six varactors which are each 90% reliable, the entire multiplier will have a reliability of only 59%, assuming that all the other components in the circuit—power transistors, crystals, resistors, and the like — have perfect reliability. Thus, for a time, at least, the increased complexity of varactor devices may tend to offset their still-unproven reliability advantage. Better circuits and better components are bound to come with time and experience, however, and microwave users can look forward to substantial benefits. •

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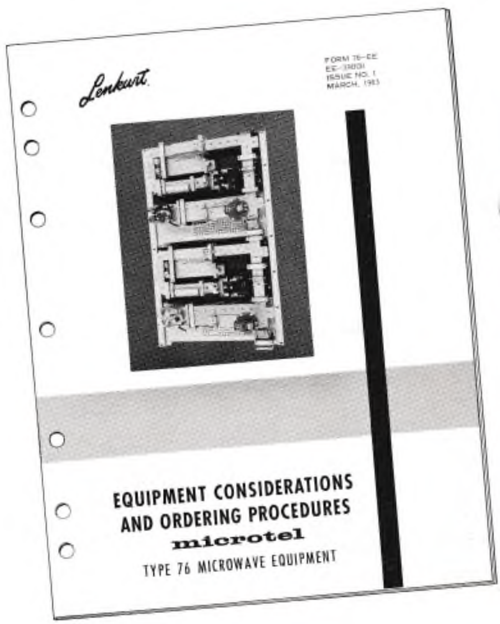

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