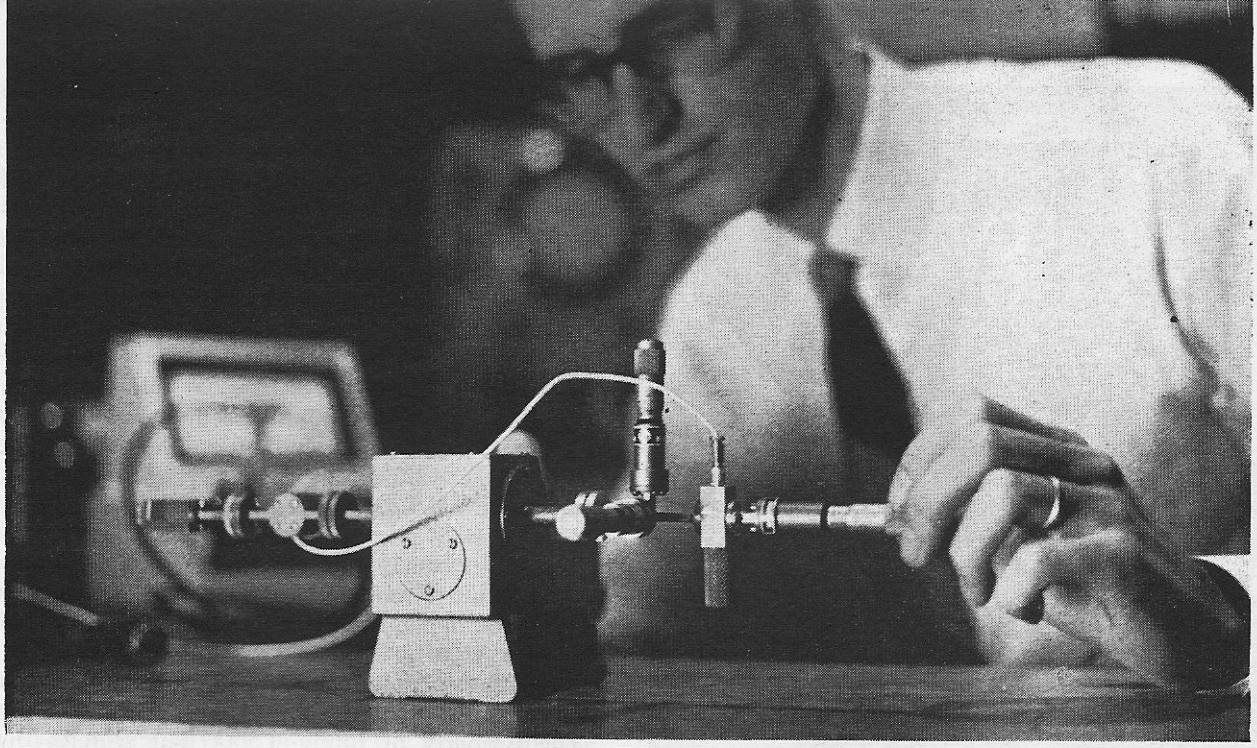


Oscillator mounted in a millimeter-wave system. The adjustable waveguide short-circuit being tuned by the author, and the E-H tuner to the left of the diode holder are used to optimize the load. The tuner is separated from the diode by a length of transmission line to provide a delay before the full load is applied to the diode.

Advanced technology

GaAs bulk oscillators stir millimeter waves

Watts of power in this unexploited frequency range are promised by diodes operating in the limited space charge accumulation mode

By John A. Copeland

Bell Telephone Laboratories, Murray Hill, N.J.

A new source of power may be the long-sought key to the exploitation of millimeter waves. Limited space charge accumulation (LSA) diodes promise to open the way to levels of power and frequency unattainable with any other active semiconductor device.

In the not-too-distant future, engineers should be able to use these diodes, energized by relatively low d-c voltages, to achieve:

- Watts of continuous millimeter-wave (30-300 Ghz) power with about 20% efficiency;
- Hundreds of kilowatts of pulsed microwave power.

The LSA diode performs well in the microwave range between 1 Ghz and 20 Ghz, but its prime contribution will probably come in the millimeter range, where it has a clear field; no currently available solid-state power source can do the job here,

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Size advantage of the LSA oscillator is evident in this comparison of it with an air-cooled, low-power klystron and its power supply.

and vacuum tubes have many shortcomings.

The millimeter region, still almost unexplored territory, is attractive for the large bandwidth capabilities it can give communications systems. The small antenna needed makes millimeter systems a natural for communications between space vehicles and for high-resolution radar.

Vacuum tubes for this frequency range are expensive, have lifetimes of only a few thousand hours, and need high voltages. The LSA diode promises lower cost, longer life, and the ability to operate on the low d-c voltages normally available in airborne vehicles.

Transistors, avalanche diodes, and Gunn diodes are transit-time devices, and their theoretical limitations hold maximum power levels to about 1,000 watts at 1 Ghz and 0.1 watt at 100 Ghz.

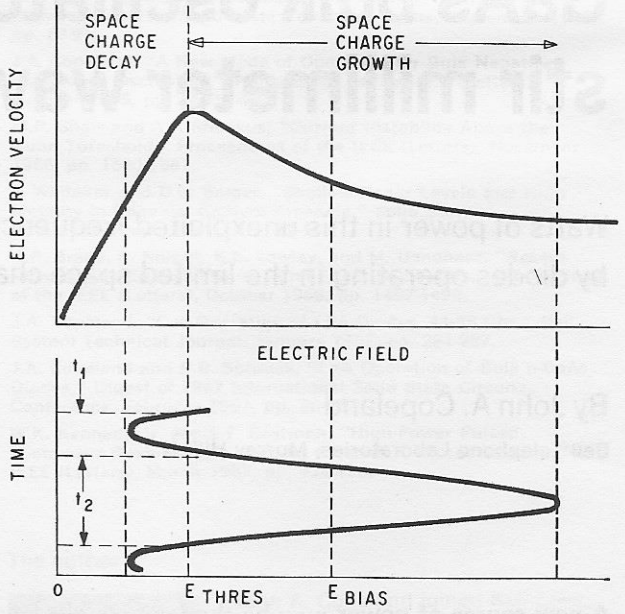
But the realization of high power in the LSA mode demands the production of either high-quality n-type gallium arsenide or such other compound semiconductors as cadmium telluride and indium phosphide. The best results so far in the LSA mode have been achieved with a GaAs device designed primarily as a Gunn oscillator. The device—the first to operate continuously in this mode—consists of an epitaxially grown active layer sandwiched between two highly conductive layers acting as low-resistance contacts to the active material. It produced 20 milliwatts between 44 and 88 Ghz with 2% efficiency. Operation of this diode was recently extended to 160 Ghz using a half-wave stub as part of the diode's package, a structure developed by Robert R. Spiwak at Bell Labs.

Other researchers, notably W.K. Kennedy Jr. and L.F. Eastman of Cornell University, have also reported LSA-mode high power at lower frequencies in the microwave region. The Cornell scientists measured a peak pulse power of 33 watts at X band with efficiencies as high as 3.4%.

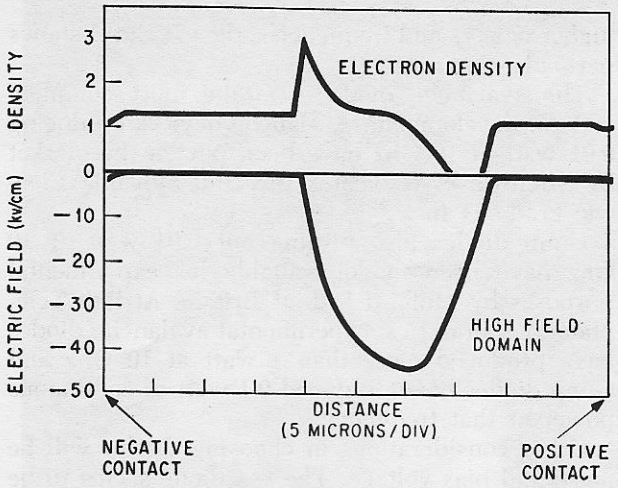
Two paths

A block of n-type gallium arsenide can be used to generate high-frequency power either as a Gunn diode or an LSA diode, but the latter mode of operation produces the higher frequency oscillations. The LSA mode isn't a transit-time phenomenon; it generates power because of a negative resistance effect in a resonant circuit. Operating frequency in the Gunn mode depends on the time needed for a space charge layer to drift across the device. In the LSA mode, it depends primarily on the associated resonant circuit.

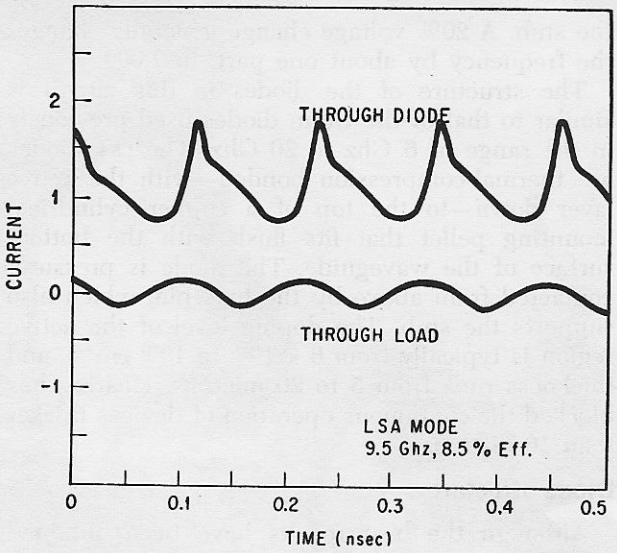
The property of n-type GaAs that is basic to both devices is a negative conductivity at electric fields exceeding about 3,000 volts per centimeter. Gallium arsenide is a "two-valley" semiconductor, having two electron-conduction band valleys at two different energy levels. The lower energy level band is the normal conduction band; electrons here have high mobility. The upper energy level band is normally not occupied, but when electrons are excited into this band, they have much less mobility. When the voltage across the diode is turned on, electrons generally remain in the lower band



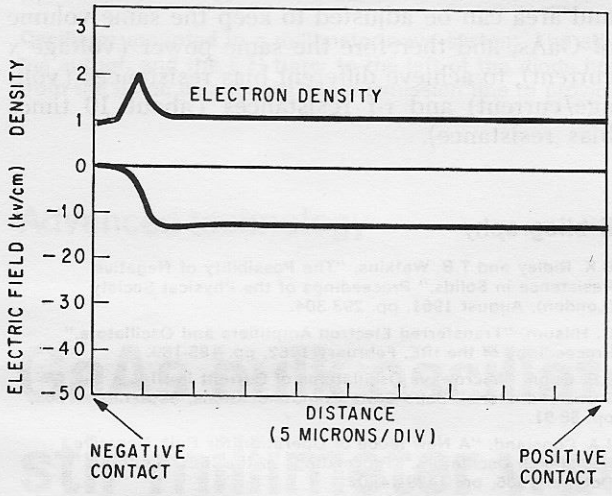
LSA diode must be biased on the negative resistance portion of its characteristic, but the r-f electric field must be high enough to swing below a critical voltage level for a fraction of each cycle to prevent space charge from building up. Interval t_1 should be greater than the domain relaxation time to allow the space charge to disappear, while interval t_2 should be less than the domain growth time.



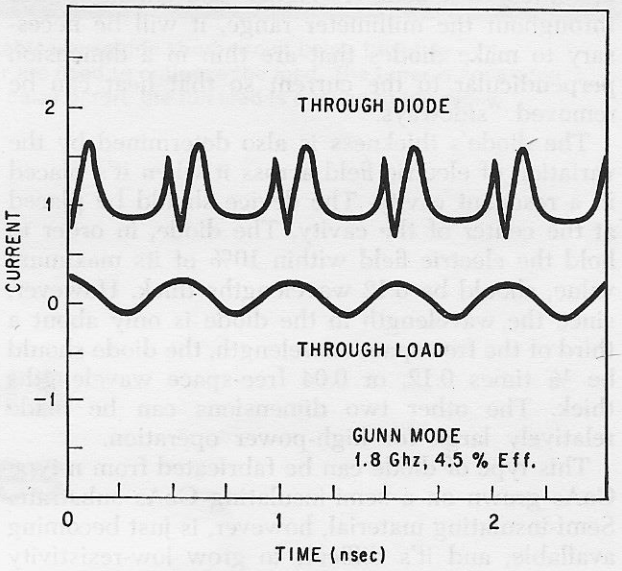
Movement of domains in the Gunn mode is shown in a frame from a computer-produced motion picture. The high-field domain moves completely across the diode. The narrow domain is the only region where the electric field is above the threshold for negative resistance.



Computer-produced current waveform plot for a diode operating in the Gunn mode.



Excess electrons begin at the cathode in the LSA mode, but are squelched after going only a short distance. Most of the device is biased above the threshold for negative resistance and rf power is thus generated by essentially the entire volume of the diode.



Current waveform plot for the same diode operating in the LSA mode.

and the diode acts as a positive-resistivity component. As the electric field is increased, however, electrons begin to pick up energy and some are excited into the lower-mobility band. As the field is boosted still further, the current begins to decrease as the effect of a greater number of slower-moving electrons in the upper energy band becomes dominant. The voltage at which this negative resistivity effect sets in is about 3,000 volts per centimeter.

Cadmium telluride and indium phosphide have also exhibited this negative resistance effect, and there probably are many other group III-V and II-VI semiconductors that can act in the same way, but gallium arsenide is the only material now available with sufficient purity to make successful devices consistently.

The magnitude of the negative resistance effect in any of these materials depends on the intervalley energy gap and on temperature. At high temperatures, enough electrons are excited into the upper energy band to cause a material to act as a normal resistive device. Cooling, however, may permit materials with a small intervalley gap and a high-threshold electric field to generate power at frequencies in the far infrared range—above 1,000 Ghz.

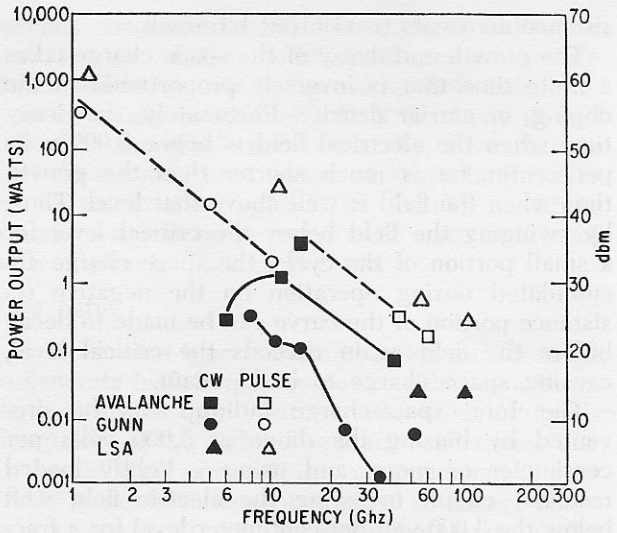
Although the critical electric field intensity is high, the actual voltage applied is only in the 6-to-28-volt range when the active region of the device is only about 10 to 50 microns thick. Because no transit-time requirement is involved, an LSA diode can be much longer than a Gunn device and thus deliver much higher power at a given

frequency; a Gunn diode has to be short to operate in the millimeter-wave range, and a larger voltage across it would cause avalanche breakdown. An analysis of the limitation on power imposed by the restriction that the length of the diode be inversely proportional to frequency, f, shows the Gunn-effect maximum power to be proportional to $f^{-2.5}$. The maximum power of other transit-time devices follows the same proportion.

Gunn effect

Gunn-effect oscillations stem from the behavior of space charge within the bulk semiconductor material. In normal ohmic material, space charge will decay exponentially with a time constant equal to the dielectric constant divided by the conductivity (the bulk counterpart to a resistance-capacitance time constant). When the conductivity is negative, however, space charge grows exponentially with time until, if unchecked, a narrow high-field domain forms. Inside the high-field domain, the critical field level of 3,000 volts per centimeter is exceeded and the region maintains its negative conductivity. The field outside the domain drops below the critical value, so this region—most of the diode—has a positive conductivity.

The high-field domain therefore destroys most of the negative conductance that might appear at the diode terminals. This domain isn't stationary, though; it drifts across the diode. As it disappears at the anode, another high-field domain forms at the cathode and begins its movement through the semiconductor. A cyclic current modulation is thus produced at microwave frequencies.



Maximum power available from three types of solid state oscillators. Because avalanche and Gunn diodes are transit-time devices, their maximum pulse power ultimately decreases with frequency in the proportion of $f^{-2.5}$. Much higher power is expected for the LSA diode.

The oscillation of the current caused by the modulation effect of the domains is the Gunn effect. The frequency is equal to the domain drift velocity —about 10^7 centimeters per second—divided by the diode's length. With an active region about 10 microns thick, for example, the Gunn frequency is 10 Ghz.

In the LSA diode, the buildup of space charge is suppressed and the diode exhibits a negative re-

Harnessing millimeter waves

When LSA diodes become commercially available, their principal job will be to give millimeter-wave systems the same high reliability now associated with solid state systems in use at lower frequencies. One can only speculate on the new communications systems and scientific instruments that will spring from the use of these diodes.

Millimeter-wave communications systems will have a larger bandwidth than present microwave setups, and, therefore, a much larger information capacity. A little-appreciated fact is that because of the limited capacity of today's base-band video circuitry, as much information as can currently be put on a laser beam can be put on a millimeter-wave carrier.

A 50-Ghz carrier wave with 1-Ghz bandwidth could carry about 100,000 voice communication channels or 100 television programs. Because of high attenuation in heavy rainstorms, however, long-range millimeter-wave surface communications signals will probably travel through buried waveguide rather than from tower to tower. An experimental guided-wave transmission system in this frequency range has been under study at Bell Telephone Laboratories for many years; LSA diodes recently made possible the first all-solid-state repeater for this system.

The use of millimeter waves can greatly increase the amount of communications carried by synchronous satellites. Since these satellites must be placed in a circle around the equator, and since those operating on the same frequency have to be far enough apart to prevent interference, there is a limit to the number that can use the same frequency (about 30). This means that the maximum number of satellite channels is roughly proportional to the available frequency range. The range of usable frequencies between 30 and 300 Ghz is more than 20 times as wide as the range below 30 Ghz. Also, frequencies above 30 Ghz are almost unused, whereas the lower frequencies are becoming saturated.

The rainfall attenuation problem in satellite communications can be solved by locating ground stations at distances from each other that make it improbable that they would all experience heavy rainfall at the same time.

Among the many other possible uses for the millimeter-wave region are:

- Spectrometers. Many solids, liquids, and gases exhibit high absorption at specific characteristic frequencies in the millimeter-wave region.
- Compact and inexpensive low-power radar systems for industrial applications and automotive traffic control.
- Point-to-point communications and high-resolution radar in the vacuum of interplanetary space.

sistance across its two output terminals.

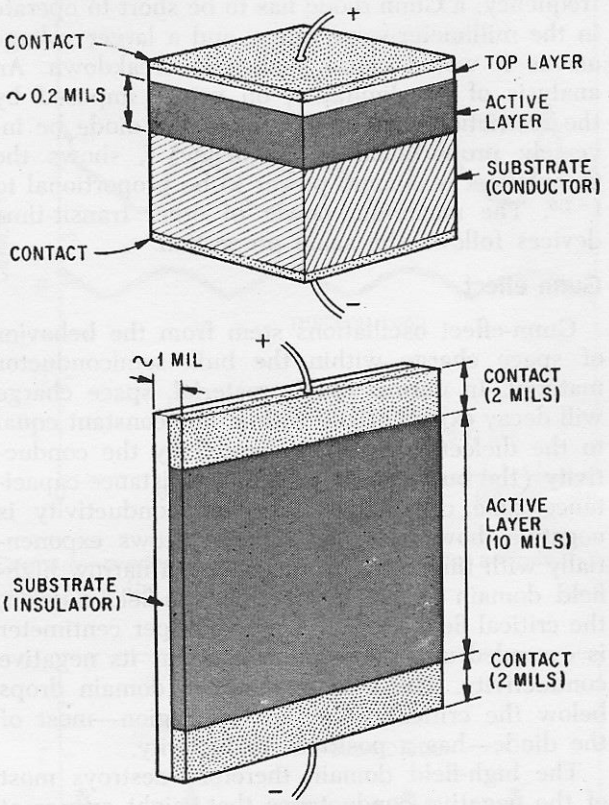
The growth and decay of the space charge takes a finite time that is inversely proportional to the doping, or carrier density. Fortunately, the decay time when the electrical field is below 3,000 volts per centimeter is much shorter than the growth time when the field is well above that level. Thus, by swinging the field below the critical level for a small portion of the cycle, the space charge accumulated during operation on the negative resistance portion of the curve can be made to decay before the field again exceeds the critical level, causing space charge to build again.

Therefore, space-charge buildup can be prevented by biasing the diode at 5,000 volts per centimeter or more, and using a lightly loaded resonant circuit to swing the electric field well below the 3,000-volt-per-centimeter level for a fraction of each cycle.

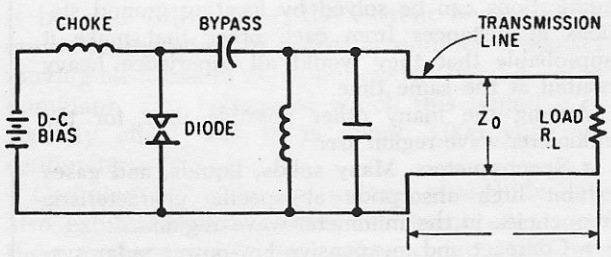
The criterion for LSA mode operation is that the ratio of diode carrier concentration to operating frequency, n/f, be in the range of 2×10^4 to 2×10^5, with an optimum value of about 6×10^4. To operate at 100 Ghz, for instance, diode doping should be about $6 \times 10^{15}/cm^3$. This narrow range of permissible doping levels and frequencies stems from the need to prevent the negative resistance effect from causing Gunn-mode oscillations.

Operation in the LSA mode requires that the resonant circuit be lightly loaded at first so oscillations can start. The starting push can come from the harmonic energy of the lower-frequency Gunn oscillations, or from the negative resistance of the diode when a Gunn domain is present. If the ratio of doping to frequency is in the proper range, Gunn domains can't form when the r-f amplitude is large enough to swing the voltage below the critical level during part of each cycle, and the carriers in the material can contribute directly to the conversion of d-c to r-f power.

Once LSA oscillation has started, the resonant circuit load and the output power and efficiency can be increased appreciably. A transmission line between the resonant circuit and the load can provide an automatic loading delay. Initially, the load across the diode is equal to the characteristic impedance of the transmission line. Only after the signal has traveled to the load and back to the resonant circuit does the diode see the steady-state load—the load resistance transformed by the length of mismatched transmission line.



Two types of bulk n-type gallium arsenide diodes. The upper device is constructed from an epitaxial layer on a high-conductivity substrate. Developed for use as a Gunn diode, it has also been used as a LSA oscillator above 44 Ghz. The thin structure of the lower diode, not yet built, offers a better method of heat dissipation.



Circuit for LSA operation uses a length of transmission line to introduce a delay before the load is applied to the diode. The basic oscillator is a negative resistance type, and the output frequency depends only on the tuning of the circuit.

Circuitry

In the actual waveguide circuit used for the LSA diode, the primary resonance is composed of the capacitance of the device and the inductance of a stub that is slightly less than a half-wavelength long at the LSA frequency, and half as wide as the waveguide. The coupling between the primary resonance and the waveguide can be varied by changing the angle between the stub and the bottom wall of the waveguide.

A waveguide short-circuit and an E-H tuner comprise the loading circuit, which is adjusted for maximum output; the short and E-H tuner are each about five wavelengths from the diode. The 9% efficiency obtained with 300-nanosecond pulses is quite good considering that the maximum theoretical efficiency for GaAs is 18.5%. A circuit in RG-99/U waveguide was used for operation to 94 Ghz.

The operating frequency is primarily determined by the length of the stub, and it can be varied over a 15% range by bending the stub up and down, about 0.2% by tuning the E-H tuner, or about 0.5% by inserting a dielectric near the free tip of

the stub. A 20% voltage change generally changes the frequency by about one part, in 1,000.

The structure of the diodes in this circuit is similar to that of the Gunn diodes used previously in the range of 6 Ghz to 20 Ghz. The LSA diodes are thermal-compression bonded—with the active layer down—to the top of a copper cylindrical mounting pellet that fits flush with the bottom surface of the waveguide. The diode is pressure-contacted from above by the bias pin, which also supports the stub. The doping level of the active region is typically from 6 x 10^{15} to 10^{16} cm^{-3}, and thickness runs from 5 to 20 microns. Heating has blocked the continuous operation of devices thicker than 10 microns.

Diode structure

Although the best results have been obtained with a diode in which the proper conductivity active layer is sandwiched between two highly conductive layers, this design isn't the optimum one for LSA operation. To achieve higher continuous power throughout the millimeter range, it will be necessary to make diodes that are thin in a dimension perpendicular to the current so that heat can be removed "sideways."

The diode's thickness is also determined by the variation of electric field across it when it's placed in a resonant cavity. The device should be placed at the center of the cavity. The diode, in order to hold the electric field within 10% of its maximum value, should be 0.12 wavelengths thick. However, since the wavelength in the diode is only about a third of the free-space wavelength, the diode should be ⅓ times 0.12, or 0.04 free-space wavelengths thick. The other two dimensions can be made relatively large for high-power operation.

This type of diode can be fabricated from n-type GaAs grown on a semi-insulating GaAs substrate. Semi-insulating material, however, is just becoming available, and it's difficult to grow low-resistivity n-type GaAs on such a substrate because of problems with the diffusion of p-type impurities from the substrate into the n-type epitaxial layer. The first growing of high-quality material on semi-insulating substrates was done in England in 1966 at Standard Telecommunication Laboratories and at Plessey Co.

The generation of high-power pulses requires pieces of uniform GaAs much larger than have yet been produced. For example, a 150-kilowatt, 10-Ghz diode (10,000 volts, 80 amp d-c input) should be about 1 by 1 by 0.1 centimeter. Diodes of this size will probably be made from bulk-grown material where the crystals are grown from molten GaAs, or from solution-grown material formed from gallium and arsenide ions in solution. Until now, the largest bulk-grown diodes operated in the LSA mode have been about 0.1 by 0.1 by 0.02 centimeter.

For the next few years, system designers will have to choose between LSA, Gunn, and avalanche diodes if they want a solid-state source of 0.1 to 10 watts at frequencies between 5 and 30 Ghz. For higher powers and frequencies, the LSA diode shows particular promise.

The avalanche diode is in the most complete state of development. Avalanche devices producing 0.01 watt at 10 Ghz have been put on the market by Microwave Associates Inc. and Sylvania Electric Products Inc.

Gunn diodes also turning out 0.01 watt at 10 Ghz have been made available for experimental purposes by Mullard Ltd. of Britain. At Bell Telephone Laboratories, experimental avalanche diodes have produced more than 1 watt at 10 Ghz and Gunn diodes have produced 0.1 watt of continuous power at that frequency.

Other considerations in choosing diodes will be noise and bias voltage. The LSA diode seems to be the quietest and the avalanche diode the noisiest.

At 10 Ghz, an avalanche diode requires from 50 to 100 volts, and a Gunn diode about 100 volts —100 volts divided by the frequency in gigahertz. An LSA diode can be designed to operate at any voltage from 25 volts to above 500 volts. The length and area can be adjusted to keep the same volume of GaAs, and therefore the same power (voltage x current), to achieve different bias resistances (voltage/current) and r-f resistances (about 10 times bias resistance).

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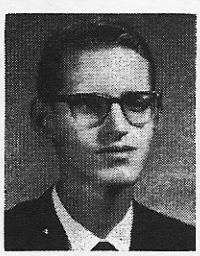
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John A. Copeland joined Bell Labs two years ago after receiving his doctoral degree in physics from Georgia Institute of Technology. He has since been engaged in research on bulk-effect devices, and was the first to predict the possibility of LSA oscillations.