Progress in Solid-State Microwave Power Sources

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Abstract—Recent progress in the following areas is reviewed: high-power UHF and microwave transistors, high-power microwave transistor-oscillator multipliers and transistor-amplifier multipliers, high-power transistor-driven harmonic-generator chains, Gunn-type oscillators, and avalanche diode oscillators.

Introduction

THE AMOUNT of microwave power that can be generated with solid-state devices has been increasing at a remarkably fast rate. Three years ago the power output of transistors was limited to less than 1 watt for frequencies above about 300 Mc/s. Today, transistors having power outputs of 10 watts at 400 Mc/s and more than 1 watt at 1 Gc/s are available, and some of these newer high-power transistors can be used as oscillator multipliers or amplifier multipliers to produce several watts of power output in the 1 to 2-Gc/s range. Progress in transistor-driven varactor chains has been equally impressive: from about 3 watts at 1 Gc/s and 100 mW at 10 Gc/s in 1963, to about 10 watts at 1 Gc/s and 1 watt at 10 Gc/s today. In addition to the progress achieved with older types of power sources, new types of solid-state generators having high-power potential have also recently been developed, the most promising among them being Gunn-type oscillators and avalanche diode oscillators. With Gunn-type oscillators for example, peak powers of 190 watts at 1100 Mc/s have already been achieved in experimental devices.

This paper is divided into three parts. The first part deals with progress in high-power transistor amplifiers and oscillators, including oscillator multipliers and amplifier multipliers; the second with transistor-driven varactor harmonic-generator chains; and the third with Gunn-type oscillators and avalanche diode oscillators.

Transistor Amplifiers and Oscillators

Transistor amplifiers and oscillators can be operated in two distinct modes: fundamental mode (output frequency same as input frequency or as oscillation frequency) or harmonic mode (output frequency an integral multiple of input frequency or of oscillation frequency). Both modes of operation are important in microwave applications.

Fundamental Operation

Current Status: Progress in high-power transistors during the past seven years is summarized in Fig. 1,

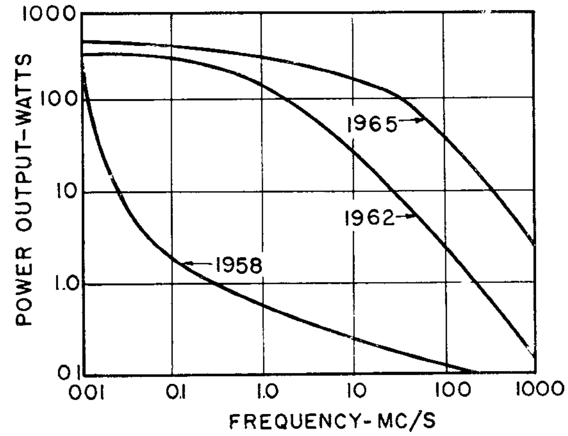

Fig. 1. Advances in transistor power output as a function of frequency. (After [1] and [2]).

TABLE I

UHF Performance of Several Overlay Transistors. Efficiencies Are in Excess of 40 Percent

Type	Amplifier			Oscillator	
	Frequency Mc/s	Gain dB	Power *W*	Frequency Mc/s	Power *W*
2N3866	400	10	1	1000*	1*
2N3553				500	1.5
2N3375	400	4	5	500	2.5
2N3733	400	4	10		

* This performance, unlike all others listed in the table, is not guaranteed by the manufacturer. It has been obtained with a few units in the author's laboratory.

which shows power output as a function of frequency for 'state-of-art' transistors for 1958, 1962, and 1965 [1], [2]. Most of the advances in power output have been achieved at the higher frequencies, and advances at these frequencies have in recent years averaged 3 to 4 dB per year.

Much of the recent progress in high-power high-frequency transistors can be attributed to advances in the accurate control of diffusion and photolithic processes in silicon technology. A good example of the application of these advances to high-power UHF transistors is the RCA 2N3375 overlay transistor [3]. The 2N3375 is an epitaxial, *n-p-n* silicon transistor. It achieves the high ratio of emitter periphery to emitter area required for efficient high-power operation at ultrahigh frequencies by means of 156 individual emitter sites interconnected by an overlay of metal. The dimensions of the silicon wafer or chip used in an overlay transistor are approximately 30 mils by 30 mils; the active region is 18 mils by 22 mils. Each emitter is a well-defined square having dimensions of 0.5 mil by 0.5 mil; the separation between emitters is 1.4 mils. (See

Manuscript received August 13, 1965.
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[1] or [4] for a photograph of a 2N3375 overlay chip.) The RF power densities that such a chip can generate are astonishingly high: over 5,000 watts per square inch.

The UHF performance of the 2N3375 and of other overlay transistors is summarized in Table I. The present small quantity price of these transistors is less than five dollars per watt of 400 Mc/s output power.

Silicon transistors having a guaranteed oscillator power output of 1 watt at 1 Gc/s have recently become available from Fairchild Semiconductor. These transistors use an interdigital emitter geometry rather than many individual emitters as in the overlay transistors. The cost of this transistor is currently $250.

Outlook for the Near Future

Improved transistor chips: E. O. Johnson [5] has shown by very general arguments that for any transistor:

$$(P_m X)^{1/2} f_t \leq \frac{E_B V_s}{2\pi} \tag{1}$$

where P_m is the volt-ampere product, X is the reactive impedance of the collector-base capacitance, f_t is the cutoff frequency, E_B is the semiconductor dielectric breakdown strength, and V_s is the minority-carrier saturated drift velocity. For silicon,

$$\frac{E_B V_s}{2\pi} \approx 2 \times 10^{11} \text{ volts/second}, \tag{2}$$

so that for silicon transistors, assuming a conservatively high collector-base impedance of 20 ohms,[1]

$$\begin{aligned} (P_m)_{\max} &\leq 3350 \text{ watts} \quad \text{for } f_t = 700 \text{ Mc/s} \\ &\leq 837 \text{ watts} \quad \text{for } f_t = 1400 \text{ Mc/s}. \end{aligned} \tag{3}$$

The voltage-current product of today's best silicon UHF transistors is still orders of magnitude below the upper limit set by (3). For example, for the 2N3375, $f_t \sim 500$ Mc/s, X (at f_t) ~ 32 ohms, and $P_m \sim 100$ watts. This gap between ultimate limit and actual performance will undoubtedly be narrowed in the near future. Further improvements in silicon technology can be expected to yield transistor chips with significantly better UHF and microwave performance than the overlay or interdigital chips used in today's transistors. For example, improved chips mounted in special housings are expected to yield 20 watts of power output at 420 Mc/s by the end of this year. This represents an improvement by a factor of four over the power output capability of a 2N3375 chip.

[1] Equation (1) shows that one can trade impedance levels for power-handling capability; i.e., for a given material $(P_m X) \leq$ constant. In other words, one can always increase the power-handling capability of the device by simply increasing its active area. Increased device area, however, results in increased capacitance and, therefore, decreased impedance level. The lowest value of impedance that can be tolerated in an actual device depends both on the parasitic impedances of the housing, and on the skill of the circuit designer in devising low-loss low-impedance networks for matching to the device. These considerations apply not only to transistors, but also to the other semiconductor devices discussed in this paper.

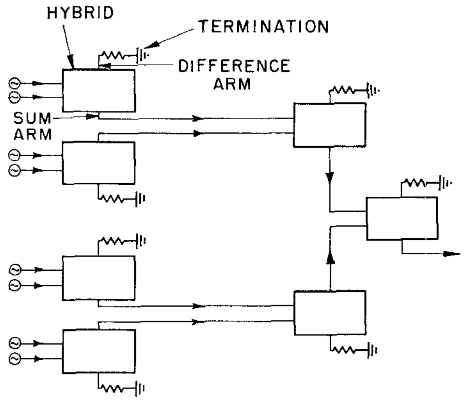

Fig. 2. Paralleling of transistor power sources by means of hybrids. The power output in the sum arm of each hybrid is the sum of the power in the two inputs, provided both inputs have the same power level and phase.

Transistors using multiple chips: A very promising approach to increasing power output is to parallel two or more similar transistor chips in a single housing. This approach is often quicker and less expensive than the development of larger chips. Paralleling of two overlay chips in a single housing has already been successfully demonstrated in RCA transistors. The power output of such two-chip transistors is twice that of a single-chip device.

The maximum number of chips that can be usefully paralleled depends to a large extent on the ability to efficiently match into and out of the multiple-chip transistor. As the number of paralleled chips is increased, the input and output impedances of the transistor decrease, and matching to the transistor becomes in general progressively more difficult. Conventional UHF circuits can comfortably handle the impedance levels required for matching the 2N3733 at 400 Mc/s (input about 5 ohms, output about 25 ohms). With more sophisticated circuits, it will probably soon be possible to match efficiently to impedance levels of a fraction of one ohm.

Paralleling of packaged transistors: Perhaps the most obvious method of increasing the output of UHF transistor power sources is to parallel two or more packaged transistors. The usefulness of this approach has been demonstrated by H. C. Johnson of the author's laboratory, who obtained 34 watts at 370 Mc/s from a compact coaxial amplifier using three 2N3733 transistors in parallel.

If the paralleled transistors are mounted close to one another and made to act collectively in a single circuit as one large transistor, then, just as in the case of paralleled transistor chips, the impedance of the circuit must be decreased as the number of paralleled units is increased. On the other hand, if each transistor has its own circuit, then it is possible—in principle at least—to parallel arbitrarily large numbers of transistors without reducing impedance levels. Figure 2 shows, for example, how one can combine the outputs of eight similar transistor power sources in a constant-impedance network using seven hybrid rings. Similar networks can be used to parallel 2^N sources with 2^N-1 hybrids.

Work is proceeding on paralleling circuits that are simpler and more compact than the circuit of Fig. 2. With such circuits, power outputs well in excess of 100 watts at 400 Mc/s will undoubtedly be achieved in the near future.

Harmonic Generation in Transistors

Current Status: Transistors can be operated as amplifier multipliers and oscillator multipliers to produce power output at frequencies well above their cutoff frequency [6]–[8]. This mode of operation is particularly well suited for microwave applications because it makes it possible, for example, to generate microwave power with UHF transistors.

The nonlinear element primarily responsible for harmonic generation in transistors is the voltage and current-dependent capacitance of the depletion layer of the base-collector junction. Because this junction acts much as the junction in a varactor diode,[2] most of the well-known design considerations for varactor multipliers can also be applied to the design of transistor multipliers. The cutoff frequency of the base-collector diode of the newer UHF power overlay transistors is quite respectable; for example, for the 2N3735, $(f_c)_{B-C}$ $\sim$24 Gc/s at breakdown.

Caulton et al. [10] have built amplifier multipliers using a single 2N3375 overlay transistor. With an input of one watt at 500 Mc/s, they obtained the following results:

Frequency Gc/s	Power Output W	Collector Efficiency (RF Output/dc Input) Percent
1.0	2.6	41
1.0	3.6	30
1.5	1.8	20

A compact radiosonde transmitter using a transistor oscillator-quadrupler with a power output of $\frac{1}{4}$- to $\frac{1}{2}$-watt adjustable to any frequency in the 1660- to 1700-Mc/s range has been designed by Nelson and his coworkers [11] for the U. S. Army Electronics Laboratory. The frequency of this transmitter varies by less than 4 Mc/s for temperatures ranging from -55 to $+75$°C and for supply-voltage variations of ± 10 percent. The circuit schematic of the transistor oscillator-quadrupler is shown in Fig. 3.

Outlook for the Near Future: Significant improvements in the performance of high-power UHF and microwave transistor multipliers are likely to come from transistors specifically designed for use as multipliers. For example, development of an amplifier multiplier having a power output of 5 watts at 2.3 Gc/s has been started [12].

[2] The base-collector junction of a transistor, unlike the junction in a varactor, carries injected current. This current also contributes to the variation of the depletion-layer capacitance [9] although usually not significantly for overlay-type transistor structures.

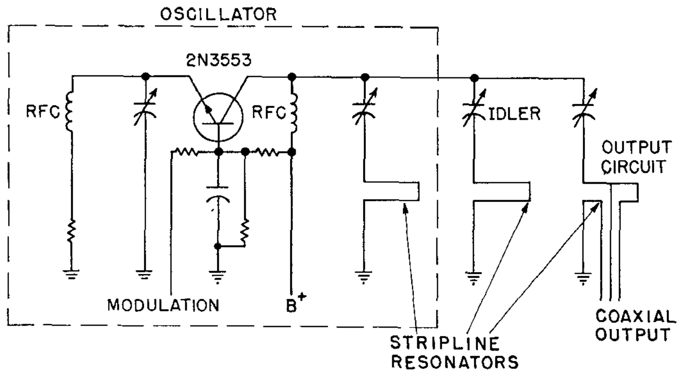

Fig. 3. Schematic diagram of transistor oscillator-quadrupler (Courtesy D. E. Nelson).

The goal is a collector efficiency of 50 percent with an RF input power of 3 watts.

Transistor-Driven Harmonic-Generator Chains

At present, transistor-driven varactor chains can produce by far the highest CW microwave power outputs of any known solid-state device. This pre-eminence of varactor chains is unlikely to be challenged in the foreseeable future by microwave transistors because transit-time limitations are inherently more serious in transistors than in varactor diodes, and because, for the same power and frequency, the impedance of varactors can usually be made considerably higher than the impedance of transistors.

Current Status

Recent progress in power output of transistor-driven driven varactor chains is summarized in Fig. 4, which shows curves of power output as a function of frequency for state-of-the-art chains for 1962 [13] and 1965. The figure shows improvements ranging from about a factor of three at 1 Gc/s to about a factor of ten at 10 Gc/s. This progress was made possible by improved high-power UHF transistors (see Fig. 1), and by improved varactor diodes combining high cutoff frequencies with high breakdown voltages [14], [15].

Today's chains can not only generate more power, but they are also significantly simpler and more efficient than the chains of three years ago. In the older chains, the high-power amplification usually took place at about 100 Mc/s; today, because of the advances in high-power UHF transistors, the high-power transistor stages usually operate in the neighborhood of 400 Mc/s. Thus, in the newer chains one or two high-power multiplier stages (and the losses associated with them) are eliminated. Significant improvements have also been made in the efficiency of the varactor multiplier stages [15]. The most dramatic improvement in this area has been achieved by Swan, who, using an experimental epitaxial GaAs varactor having a cutoff frequency of 800 Gc/s, obtained tripling efficiencies (from 4 to 12 Gc/s) of 80 percent at low power levels [16].

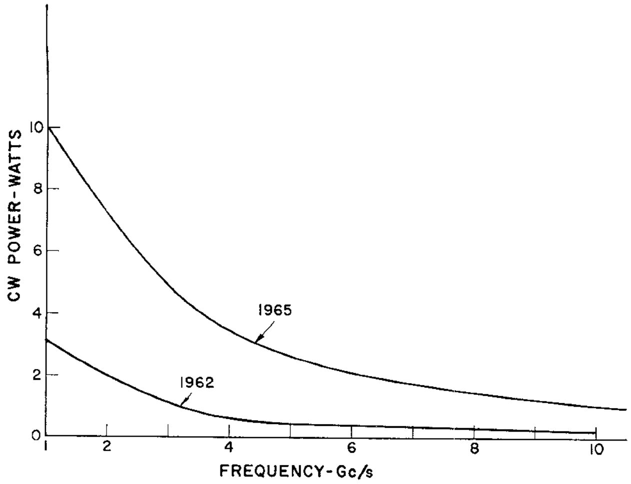

Fig. 4. Advances in cw power output as a function of frequency for transistor-driven harmonic-generator chains. The curve for 1962 is based on [13]. Overall efficiencies for the 1965 curve range from about 20 percent at 1 Gc/s to about 2 percent at 10 Gc/s.

Important advances have also been made in miniaturizing and ruggedizing transistor-driven chains, and several chains have been qualified for missile and space applications. An example of such a chain is a *C*-band transistor amplifier-varactor multiplier developed by J. J. Napoleon et al. [17]. This device, which has a volume of 26 cubic inches, accepts 104-Mc/s power in the 30- to 40-mW range and produces a power output of more than 400 mW at 5000 Mc/s. The environmental specifications for this multiplier are as follows:

Vibration—sinusoidal	5-g peak 15 to 2000 cs, sweep rate 2 minutes/octave
—random Gaussian	0.2 g^2/cs 20 to 1200 cs
Acceleration	Constant acceleration of 50 g applied along any axis
Shock	150 g in any direction for a duration of 1.5 milliseconds
Temperature—operating	0 to 75°C
—nonoperating	−60°C to 100°C

Advances have also been made in modulating the output of harmonic-generator chains. Several authors [18]–[20] have reported varactor upper-sideband upconverters with efficiencies of about 50 percent. Furthermore, it has recently been demonstrated that it is practical in many instances to apply wideband phase or frequency modulation to the input of chains, and then to multiply the modulated band to microwave frequencies [21], [22].

The individual stages of today's high-power varactor chains are usually either doublers or triplers. Multiplication by factors greater than three is generally avoided because high-order multipliers using conventional varactors are difficult to design (for efficient operation they require fairly complicated idler circuits), and because their efficiency is usually lower than that of cascades of well-designed doublers and triplers.

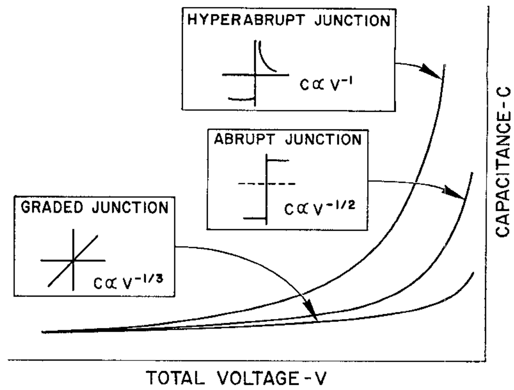

Fig. 5. Capacitance as a function of total voltage (applied back-bias voltage plus built-in potential) of graded, abrupt, and hyperabrupt *p-n* junctions. Also shown are the impurity profiles for each type of junction. Conventional varactors usually have capacitance-voltage variations between those of graded and abrupt junctions.

Efficient high-order multiplication with relatively simple circuits can be achieved in multipliers using either step-recovery (charge-storage) diodes [23] or hyperabrupt varactor diodes [24]. Both of these diodes are considerably more nonlinear than conventional varactors (see Fig. 5 for a comparison of the capacitance-vs.-voltage characteristics of conventional varactors and hyperabrupt varactors), and they can produce efficient high-order multiplication without the use of idler circuits. For example, for output frequencies up to L band, efficiencies approaching 30 percent have been obtained with high-order (10 to 20), step-recovery multipliers using only an input and an output resonator [23]. Similar efficiencies have been obtained with idlerless times eight multipliers using hyperabrupt varactors ($f_{out} \sim 4$ Gc/s, $P_{out} \sim 250$ mW) [25]. Step-recovery diodes having large power-handling capabilities are difficult to fabricate, and the power output of step-recovery multipliers is, therefore, presently limited to about 20 mW at *X*-band frequencies and to 200 mW at *L*-band frequencies. The power-handling capability of hyperabrupt varactors is many times larger than that of presently available step-recovery diodes.

Outlook for the Near Future

Progress in high-power transistor-driven varactor harmonic-generator chains promises to continue at a high rate. As discussed before, the power output and upper frequency limit of transistor drivers is constantly being raised. Significant improvements are also likely to occur in the performance of varactor multipliers, primarily because of improvements in varactor diodes. One can expect, for example, that within two years it will be possible to construct chains having cw power outputs of 10 watts at *X*-band frequencies.

New Types of Solid-State Oscillators

Two new solid-state power sources with great promise have recently been developed: Gunn-type oscillators and avalanche diode oscillators. Neither of these new devices can at present compete in cw power output, frequency stability, or spectral purity with transistor-driven varactor chains. On the other hand, both devices are basically simpler and more compact than chains, and the peak-pulse power outputs already obtained with Gunn-type oscillators at L-band frequencies are considerably larger than those now obtainable from chains.

The active element of a Gunn-type oscillator [26] is usually a slab of suitably doped GaAs. The dc supply voltage is applied across the slab by means of ohmic contacts, and, in microwave applications, the slab is usually mounted in a resonant cavity. Results obtained so far with Gunn-type oscillators are summarized in Table II. Particularly impressive is the peak power output of 190 watts at 1100 Mc/s obtained by Dow and Mosher [29]. This power output is considerably higher than has been reported so far for any other all-solid-state device, although a pulsed varactor doubler having a power output of about 200 watts peak at 1 Gc/s has been constructed [30].

TABLE II
PERFORMANCE OF GUNN-TYPE OSCILLATORS

Mode of Operation	Frequency (Gc/s)	Power Output	Efficiency (Percent)	Reference
cw	4.35	15.5 mW	—	27
Pulsed	4.96	1.83 w	—	27
Pulsed	~3.0	2.5 w	7	28
Pulsed	1.1	190 w	9	29

Peak power outputs of 80 mW at 12 Gc/s [31] and cw power outputs of 13 mW at 10 Gc/s [32] have recently been obtained from avalanching silicon diodes. The principle of operation of these diodes appears to be similar to that of a negative-resistance diode originally proposed by W. T. Read in 1958 [33], where the required 180 degree phase shift between diode current and applied voltage is produced partly in an avalanche region and partly in a drift region.

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