April 12, 1960 D. V. GEPPERT 2,932,762

DISTRIBUTED MICROWAVE AMPLIFIER

Filed Sept. 11, 1957 2 Sheets-Sheet 1

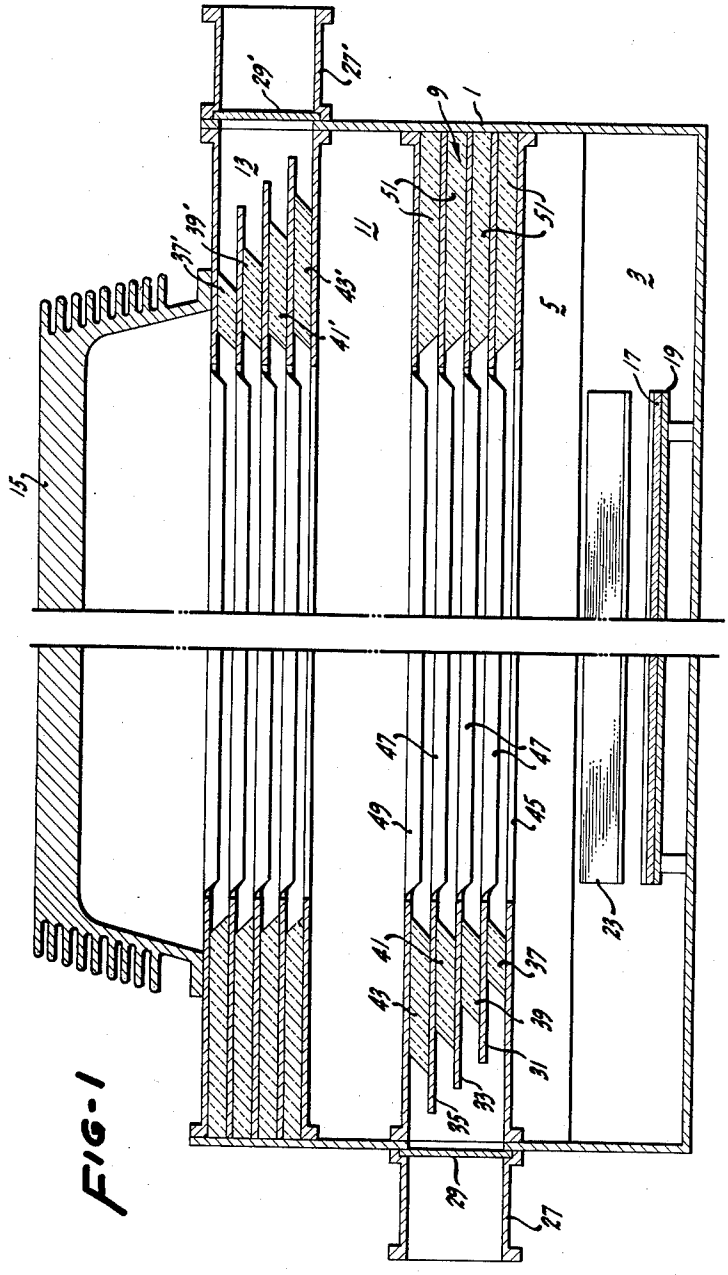


FIG. 1

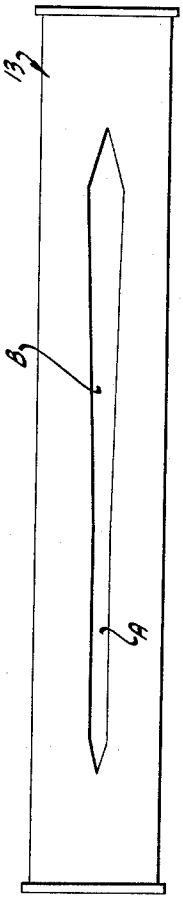


FIG. 3

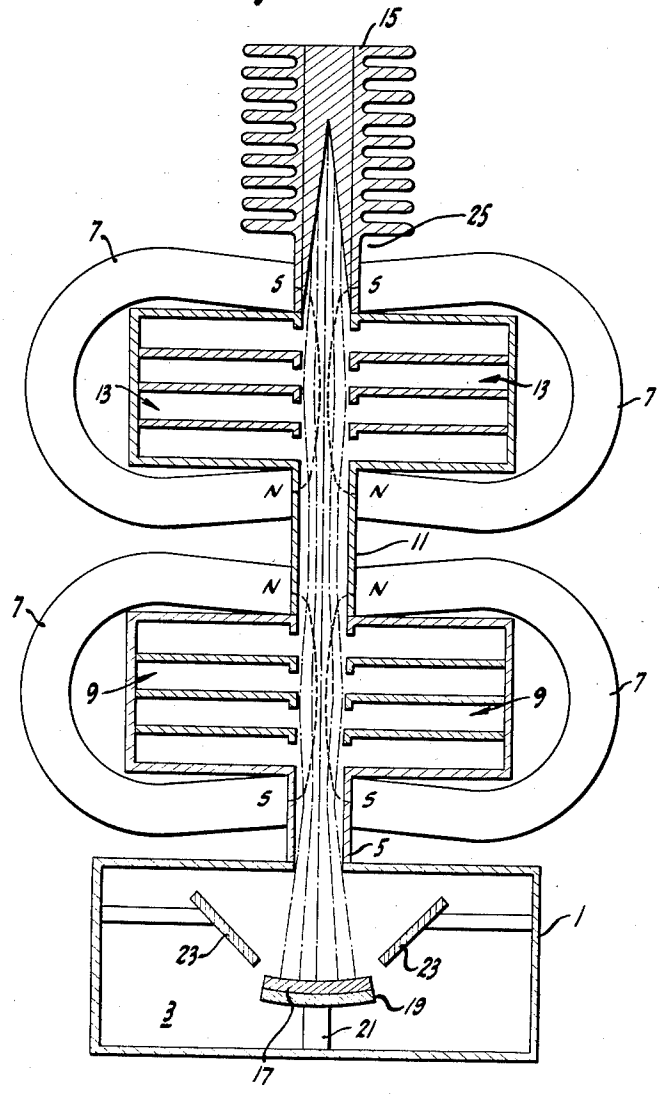
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DISTRIBUTED MICROWAVE AMPLIFIER

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FIG-2



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DISTRIBUTED MICROWAVE AMPLIFIER

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Application September 11, 1957, Serial No. 683,304

3 Claims. (Cl. 315—5.29)

This invention relates to microwave amplifying apparatus. Its primary objects are to provide a type of microwave amplifier having the following characteristics:

(*a*) Ability to handle very high power;
(*b*) Wide bandwidth, comparable to that of traveling-wave tubes;
(*c*) High gain;
(*d*) High stability;
(*e*) Efficiencies approaching the maximum possible efficiency of klystron amplifiers;
(*f*) Ready coupling to and matching against input and output circuits of conventional type;
(*g*) High cathode efficiencies;
(*h*) Compactness.

The characteristic feature of the present invention is a means for transferring energy between microwave circuits and an electron stream, in either direction; i.e., to velocity-modulate a stream of electrons through energy supplied by an input circuit and thereafter to demodulate the stream, transferring its energy to an output circuit. In present-day microwave practice there are several methods of doing this that differ widely as to their effective interaction ability or ability to velocity-modulate an electron stream by a given amount of radio frequency input power, the bandwidth they are capable of handling and the power that they can handle. The circuits that have been so used in the past may be tabulated and classified as follows:

No.	Type of circuit	Effective interaction ability	Bandwidth	Power handling ability
1	Resonant cavity	Very good	Very narrow	High.
2	Helix	Good	Very broad	Low.
3	Interdigital line	do	Narrow	Fairly high.
4	Disc loaded coax	do	Fairly broad	Do.
5	Disc loaded round guide (TM_{11})	Very good	Very narrow	High.
6	Nonresonant gap	Very poor	Very broad	Very high.

The ability of a circuit to interact with an electron beam to act as either a "buncher" or a "catcher" circuit depends, primarily, on two factors; first, the intensity of the fields which it can establish to velocity-modulate an electron beam passing through it, and, second, the time during which electrons are subjected to the fields corresponding to a given epoch of the cycle of the modulating wave. To produce a strong electric field requires that the circuit have a high impedance and this usually means that it is resonant and therefore narrow-band. Thus circuit No. 1, listed above, a resonant cavity such as is used in the usual type of klystron tubes, has a very high impedance at resonance and hence is a very effective buncher. Circuits 2 through 4 are non-resonant and have low impedance, but because the radio frequency field follows or tracks the beam as it passes through the device the interaction time is high, and such circuits are used in traveling-wave tubes. Circuit 5 is similarly used but since it depends upon resonance, its waveband, too,

is very narrow. Circuit No. 6, as used in the distributed klystron has low impedance and short time of interaction with any individual group of electrons in the beam, so that its effective interaction ability is very low.

The term "power handling ability" has two implications. It refers not only to the ability of the circuit to transmit large amounts of R.F. power without overheating or breakdown, but also in the possible magnitude of the D.C. beam current and hence to the power that can actually be developed.

The interacting circuit of the present invention is of relatively low impedance, deriving its effectiveness by increasing the time of interaction between the input radio frequency energy and the electrons of the beam, thus having properties in common with the traveling-wave tube. In contradistinction to such tubes of the conventional type, however, it is capable of handling electron beams of high density and large cross-section, being the equal in this respect to circuit No. 6, the nonresonant gap.

The present invention can best be understood by first considering the known functioning of the interaction units in a distributed traveling-wave klystron employing a nonresonant gap, this device having been described in an article entitled "The Duplex Traveling Wave Klystron," by T. G. Mihran, Proceedings of the IRE, volume 40, No. 3, March 1952. In this device, the buncher and catcher units are substantially identical, so that a single description will suffice for both. Input power is introduced into a rectangular waveguide, which is slotted longitudinally in the plane of its maximum electric field to form a passage through which a sheet beam of electrons is projected. In order to obtain maximum bunching effect, the waveguides are preferably of the ridged type, the slot being formed through the ridge. This concentrates the electric field in the gap formed between the ridge and the opposite side of the guide, into distance so short in comparison to the time required by any group of electrons to traverse it that little change of field intensity occurs during their transit.

Considering a given amount of input power, P_i, the voltage available across the gap to modulate the beam is, under these circumstances,

$$V_s=\sqrt{P_i Z_0}$$

where Z_0 is the impedance of the waveguide.

The lines used are nonresonant, and because Z_0 is therefore small the effective modulating voltage V_s is also small. As the wave travels down the guide, however, it modulates successive portions of the electron stream as it passes. The catcher guide is spaced from the buncher guide to form a drift-space between the two and permit some bunching of the electrons. The bunched electrons entering the catcher guide initiate a wave in it which travels along the catcher guide at the same rate as the waves and the consequent modulation of the stream travel along the buncher guide. Therefore, although both the bunching and the collection are relatively inefficient, the wave builds up linearly in the catcher

guide. It comes out that there is very small tendency to initiate waves traveling in the reverse direction.

Because of the low impedance of both guides and the consequent low effective velocity-modulating voltage in the device thus described it must be several feet in length in order to achieve even unity gain. This accounts for the designation of the interaction ability of gaps of this type as "very poor."

In accordance with the present invention the interaction units are each formed, not of a single waveguide, but of a plurality of superposed waveguides, longitudinally slotted, with the slots in alinement to form a transverse passage through the entire assembly parallel to the electric field and in the position of its maximum intensity along the guide. As in the case of the traveling-wave klystron each of the waveguides may be the ridged type. Considering first the buncher, all of these waveguides are fed from a common input transmission line and preferably the stacked waveguides are formed by separate septa subdividing a waveguide, of very much the same overall proportions as the input line, into a plurality of thin or flat subguides. The ridges may be formed by depending lips from each side of each of the longitudinal slots, similar lips being formed depending from one side of the main guide so that each subguide is substantially identical, electrically, to the others. The radio frequency input power divides equally between the subguides. Means are provided, however, for delaying the waves propagated through the subguides by different amounts and means are also provided for directing a sheet flow of electrons through the passage formed by the slots. The delays in the successive subguides traversed by the electrons are so proportioned as to make them substantially equal to the electron's transit time from gap to gap. Any group of electrons therefore is subjected to a field of the same phase and intensity in each subguide it traverses. Such successively increasing delays in the subguides can be achieved by loading successively longer sections of the subguides; preferably by filling these sections with dielectric material.

If, now, n subguides are provided, the voltage in each of the lines is

$$V_n=\sqrt{\frac{P_1Z_0}{n}}=\frac{V_s}{\sqrt{n}}$$

The same electrons, however, are operated upon n times in traversing the gaps. Effectively, therefore, the voltage acting upon the electrons is

$$V_s=\frac{nV_s}{\sqrt{n}}=V_s\sqrt{n}$$

The circuit is therefore $\sqrt{n}$ times as effective as a buncher as is a single line.

The catcher line is substantially a duplicate of the buncher, except for the fact that phase-delaying sections are introduced into the subguides in reverse order; i.e., the subguide first traversed by the beam is loaded to introduce the greatest delay and the succeeding subguides introduce progressively smaller delays, so that the waves thus transmitted into an output line are brought back into phase.

The buncher and catcher interaction circuits are reciprocal, and the overall effectiveness of the device is proportional to the product of the buncher and catcher efficiencies. Since both are $\sqrt{n}$ times as efficient as a single distributed-gap line, the overall device has n times the gain of a single-gap line.

In a complete tube the buncher and catcher waveguides are spaced apart to provide a drift space between them and means are provided to focus the beam to confine it within the transverse passage formed by the slots. Preferably, also, the subguides are provided with energy-absorbing loads in the ends opposite to their connections to the input and output transmission lines respectively, to prevent any resonances owing to reflected waves.

All of the above, in addition to certain other theoretical considerations and features of advantage, will be developed more fully in the detailed description which follows of certain preferred embodiments of the invention, this description being illustrated by the accompanying drawings wherein:

Fig. 1 is a semi-schematic, longitudinal, sectional view of a high power amplifier tube embodying the present invention, complete except for focusing means;

Fig. 2 is a transverse sectional view of the tube of Fig. 1, showing also the arrangement of focusing magnets;

Fig. 3 is a plan view of one form of catcher guide, indicating a tapered slot arrangement for progressively varying the coupling of the subguides to the electron beam in order to obtain an additional current buildup within the tube after maximum theoretical voltage build-up has been attained.

The tube illustrated in Figs. 1 and 2 comprises an evacuated metal housing 1 comprising a number of vertically superposed elongated sections, each of generally rectangular form in cross-section. Of these sections, the lowest in the figure is a cathode section 3 wherein the sheet electron beam is developed. Immediately above the cathode section the envelope narrows to a neck 5 for accommodating the poles of a focusing magnet 7 (not shown in Fig. 1), immediately above which the envelope again widens to form the input or buncher waveguide 9. Above this, the envelope narrows to form a drift space 11 and then broadens again to form the shell of the output or catcher waveguide 13. A second set of focusing magnets 7 encloses the catcher waveguide 13. Surmounting the whole is a flanged collector-anode 15.

Within the section 3 there is mounted an elongated strip cathode 17 upon a similarly elongated heater element 19. As the tube illustrated is intended to operate with its anode and housing grounded, the cathode and heater are mounted on insulated struts 21. The electron emitting surface of the cathode is slightly concave to focus the electrons into the neck 5. Flanking the cathode are a pair of focusing electrodes 23 to assist in this function.

The sheet-like flow of electrons developed by this cathode structure, after passing through the body of the device, is collected upon the collector anode 15, which preferably is provided with a V-shaped groove 25 to increase the effective area upon which the beam strikes and thus decrease local heating.

It will be recognized that the beam-forming elements thus far described conform generally to klystron practice except for the sheet form of the beam developed. They can take other forms than those shown and while they are necessary elements of a complete device they are not considered to be novel, per se, the truly characteristic features of the invention being the construction of the buncher and catcher circuits enclosed within sections 9 and 13 of the tube.

The buncher circuit 9 conforms in dimension to a conventional rectangular waveguide adapted to propagate waves in accordance with the dominant TE_{10} mode. This section of waveguide couples to an input line 27, of the same general configuration, through a window 29, sealed to the envelope in order to maintain the vacuum within it, in accordance with accepted practice.

Extending through the waveguide formed by the section 9 are a plurality of septa; thin metal sheets extending horizontally across and longitudinally of the main guide. Since these septa are normal to the electric field established within the guide by the TE_{10} mode and are very thin they have only a very small effect upon the effective impedance looking into the guide, and hence cause negligible reflection. In order to minimize even the small effect that they introduce their ends are stepped, as shown. The lowest septum, 31, starts some distance inward from the window 29, the next higher septum, 33, starts some-

what nearer the window while the uppermost, 35, begins only a short distance back from the window.

There is a close analogy between the septa and the taps on a voltage divider; one-fourth of the total electric field across the guide is intercepted by each and since the impedance looking into the guide as a whole is substantially unchanged by the presence of the septa it follows that the input power divides equally between the four subguides formed within the main guide by the septa.

A short distance beyond the end of the septa forming the subguides, the latter are loaded by blocks of dielectric, forming a delay-line section within each subguide. The length of the loading sections depends upon the potential difference between the anode and cathode of the tube. By the time the beam electrons have entered the neck portion 5 of the tube they have obtained substantially their ultimate velocity and, in the absence of radio frequency energy in the buncher and catcher waveguides, are traveling in a substantially equipotential space at constant velocity which is proportional to the square root of the cathode-anode voltage. The length of the dielectric loading-block 37 is not too important, since it is introduced primarily for structural reasons and electrically could be omitted. Block 39 is sufficiently longer than block 37 to delay waves propogated through it by an additional interval equal to that required for electrons, traveling at the designed velocity, to traverse a distance equal to the separation between the lower wall of the guide 9 and septum 31, while blocks 41 and 43 are increased in length by equal increments. Preferably both ends of each of the blocks are tapered, to form gradual transitions between the loaded and unloaded sections of the subguide.

A slotted section of the subguides starts a short distance beyond the end of the loading-blocks. A simple slot 45 is formed in the surface of the main guide 9. Each of the septa, however, is provided with a lip 47 depending from side of the slot, which nearly closes the space between it and the next lower surface, and a similar lip 49 depends from the slot in the upper wall of the main guide 9. Jointly these lips form an open ridge down the center of each guide, and the electric field of waves propagating through the guides in concentrated in the gap between this ridge and the next lower surface. The impedance of the ridged guide differs materially from the unridged portions of the subguide of which it forms a part, and the lips 49 and 47 are therefore tapered, as shown, to form a matching transitional section through which the waves enter the ridged portion. The ends of all of the slots are also tapered for the same reason.

At the output end of the device the lips are similarly tapered to provide a smooth termination to a final section, wherein there are disposed loading-blocks 51 of resistive material, matched to the impedance of the guide, to absorb the energy transmitted through it and prevent reflections that would upset the traveling-wave characteristics within the guide and create standing wave patterns that would upset its intended operation.

The catcher guide of section 13, beyond the drift space 11 substantially duplicates the elements in the buncher, but is turned end-for-end with corresponding elements located at opposite ends of the tube. Accordingly, the elements in the catcher guide are designated by the same reference characters as those in the buncher but distinguished by accents. As viewed in Fig. 1, the primary difference lies in the disposition of the loading elements 37′ to 43′, these being in inverted order, the element 37′, giving the least delay, being located in the upper subguide instead of the lower one. Except for this inversion of location the loading blocks in the catcher guide are preferably identical to those in the buncher guide. Because of the symmetry of construction the phase velocity of waves propagated through

the guides is substantially identical. The successive subguides through which the electron flow passes receive their energy from the beam in succession, the waves in each successive subguide being delayed by an interval equal to the transit time of the electrons from one guide to the next. By postulate, therefore, any "bunch" of electrons entering the catcher "sees" the same phase of the waves propagated through each successive guide. In the catcher section the waves of the lowest subguide are advanced in space ahead of those in the one next above it and so on successively. The loading sections delay the emergent waves by equal increments, bringing them back into phase as they emerge into the section that couples them to the outgoing line 27′.

As has been shown in the article in the "Proceedings of the IRE" cited above, the voltage wave in the catcher guide builds up lineraly to a maximum value equal to the D.C. voltage of the beam.

In practice it has proved very difficult to achieve more than unity voltage gain in a single-gap tube. In a four-gap tube the voltage gain can be made practically the theoretical four times as great as the single gap device, which is equivalent to a power gain of 12 db. The gain of power goes up substantially as the square of the number of subguides in the collector and catcher. The limitation of the number of subguides used is structural and mechanical and not theoretical; although four subguide lines are here shown this number has been chosen only as one convenient for illustration.

There are various secondary effects in the operation of a tube of this character (such, for example, as the effect of beam loading of the waveguide) that complicate the operation in comparison with the simple mathematical and theoretical picture here given. These effects are of the same nature as those effective in any amplifier using the klystron principle and do not materially affect the overall comparison of the present invention with its predecessor devices.

Although the tube described has in common with the traveling-wave tube the fact that its effectiveness depends upon increasing the time wherein the interaction between an electron beam and a modulating voltage are effective, by means of a distribution in space, it does not suffer from the difficulties inherent in the traveling-wave tube due to the possibility of backward-wave action. Coupling between the input and output is wholly by means of the electron beam and in the direction of its flow. Hence the device is inherently stable, although it can, of course, be made to develop oscillations by feeding back energy from the output to the input externally of the tube.

The voltage build-up in a tube of this character yields only one-half of the maximum possible cavity-type klystron efficiency and to obtain higher efficiency other means must be employed, i.e., a build-up of current after maximum voltage has been attained. One method of obtaining additional efficiency and power, up to an approach to the maximum achievable value, is by progressively decreasing the impedance of the subguides in the direction in which the waves therein are propagated. This can be done by a progressive flattening of the guide beyond the build-up section, or, what is substantially equivalent, the progressive narrowing of the gaps between the depending lips at the edges of the slots; i.e., effectively increasing the height of the ridge in the ridged guide. Another way of accomplishing an equivalent result is by progressively decreasing the coupling between the waveguides and the electron stream. This can be done by tapering the slots (in the collector guide only) as shown in Fig. 3. This figure shows a top view of the catcher guide. The linear build-up section A is provided at the input end, at the left of the figure. Beyond this linear section the slot widens gradually for a distance considerably greater in length than the build-up section, following which, beyond the end of the cathode stream, the slot is reverse-tapered to form a transition section into the main waveguide.

Various other means of obtaining a current build-up, following the voltage build-up, are possible but that shown is at present considered to be the simplest to construct.

As was shown in the equation given above for the voltage effective in modulating the beam, this voltage is proportional to the square root of the impedance of the individual waveguides across which the electric fields are developed. The impedance is, of course, reduced by ridging the guides, correspondingly reducing the available modulating voltage. The length of the gaps is chosen in accordance with standard klystron practice to yield gap transit angles in the neighborhood of 90°. If a single gap were to be used, as in the traveling-wave klystron, the same gap angle would be used. In a ridged waveguide the impedance for small gaps between the ridge and the opposite face is substantially independent of the height of the guide. Therefore, with equal gaps the impedance of the individual guides may be made very nearly equal to that of an undivided guide and the full advantage of the divided guide obtained.

What may not be very apparent is that the subguide construction may make the use of ridged guides unnecessary. For example, if the transit time of the electrons across the entire buncher (or catcher) is equal to one full period of the operating frequency, the transit time across each of the subguides will be one-fourth cycle. Accordingly, the beam in traversing the entire stack of guides is effectively subjected to substantially the full voltage available across the main input guide, instead of a lower voltage due to the reduced impedance in a ridged guide. Whether or not the guides are to be ridged is therefore a question that depends to a large degree upon the beam velocity and operating frequency.

It should be apparent that the reciprocity theorem holds as between the buncher and the collector and that therefore the same factors that control the efficacy of the guide in modulating the beam are also effective in the catcher in demodulating it. There is no theoretical reason for limiting the number of subguides in either buncher or catcher to four, the limit being established by constructional factors rather than theoretical ones.

While the use of subguides in a single casing is the most convenient arrangement, it should be evident that the same principles can be embodied by the use of separate individual guides, spaced apart in the same general manner as the gaps are spaced in the embodiment shown. Such an arrangement would have little advantage, since it would lead to both more bulky apparatus and more difficult focusing. Hence in general it would not be employed unless there were some reason, not immediately evident, for using it, but in theory it would not differ from that specifically illustrated.

One of the factors entering into the operation of the present invention, as it does into all tubes employing the klystron principle, is beam-transmission efficiency. Any electrons striking the elements within the tube prior to traversal of the catcher gaps are wasted and serve to generate heat without contributing to the output power. A sheet beam, although it could be focused in various ways, presents a number of special problems. The most economical method of accomplishing the focusing is that referred to briefly in the first part of the present detailed description, i.e., magnets encompassing the buncher and catcher respectively. The magnets 7 are of horse-shoe cross-section and of a length at least equal to and preferably slightly greater than the length of the slots forming the transverse passage through the respective waveguides. The disposition of these magnets will be at once apparent from the drawing of Fig. 2; it should be pointed out however, that where the poles of the two sets of magnets are adjacent to each other in the recess formed by the drift space between the buncher and catcher guides, like poles must be side-by-side in order to establish magnetic fields of the desired shape. This is indicated by the letters "N" and "S" on the poles shown.

A very great advantage of the present structure over the distributed klystron lies in its compactness and consequent ease of construction and overall practicability. It is known that even to attain unity gain in a single-gap device requires that it be many feet in length (at S band). Discussion of tube "efficiencies" ordinarily neglect the power expended in heating the cathode but this power is not in fact negligible. The reduction in length of a tube by a factor of n reduces the power expended in such heating to $1/n$. The savings in material, floor space and weight resulting from the invention should be obvious.

The various features and modifications that have been discussed above can be combined in numerous permutations and combinations and for certain parts of the device numerous equivalents are available. The form of tubes specifically illustrated and described in detail are therefore not intended to limit the scope of the present invention, all intended limitations being specifically set forth in the following claims.

I claim:

1. In a microwave amplifier tube, means for coupling a spatially distributed electron beam to a transmission line comprising a plurality of parallel rectangular ridged wave guides mounted in superposed position with respect to the direction of the electric fields of waves propagated therethrough, the centers of the ridges of said waveguides having corresponding longitudinal slots therein providing a transverse passage substantially parallel to the direction of said electric fields through said waveguides, means for directing a flow of electrons through said passages distributed substantially throughout the length of said slots, a transmission line connected with all of said waveguides, and means interposed between said transmission line and the slotted portions of said waveguides for delaying the phases of waves propagated through said means for intervals substantially equal to the transit-times of electrons of said flow between the electric fields in successive ones of said waveguides.

2. A microwave amplifier tube comprising a first plurality of superposed rectangular waveguides and a second plurality of superposed waveguides spaced therefrom and parallel thereto, all of said waveguides having longitudinal ridges and longitudinal central slots formed in said ridges alined to form a continuous transverse passage therethrough parallel with the electric fields within said waveguides, an input line coupled with said first plurality of waveguides, an output line coupled with said second plurality of waveguides, means for directing an electron flow transversely through said passage and distributed along the slots forming it, said electron flow traversing said first and second pluralities of waveguides successively, means for delaying waves entering said first plurality of waveguides from said input line by increments increasing progressively in the order in which said waveguides are traversed by said electron flow, and means for delaying waves entering said output line from said second plurality of waveguides by increments increasing progressively in inverse order to that in which the waveguides of said second plurality are traversed by said electron flow.

3. A microwave amplifier tube comprising input and output rectangular waveguides mounted in spaced parallel relationship with the wider surfaces thereof opposed, each of said waveguides being provided with longitudinally extending septa subdividing it into a plurality of subguides, each of said guides and septa having corresponding longitudinal slots therein to form a transverse passage therethrough, one wall of each of said waveguides and each of said septa being provided with depending lips on each side to the slots formed therein, the lips on said one wall of each waveguide extending into the interior of that waveguide, means for directing a flow of electrons ex-

tending throughout substantially the entire length of said slots through said passage to traverse said input waveguide and said output waveguide successively, an input transmission line connected to one end of said input waveguide, an output transmission line connected to the opposite end of said output waveguide, loading means interposed in the subguides of said input waveguide to delay waves propagated through said subguides toward said slots by different amounts increasing progressively toward said output waveguide, and loading means interposed in the subguides of said output waveguide for delaying waves propagated therethrough by different amounts decreasing progressively away from said input waveguide

to bring waves received by said output transmission line back into phase.

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