

Feb. 20, 1962

R. L. COMSTOCK
MICROWAVE PULSE AMPLIFIER

3,022,463

Filed Dec. 17, 1959

2 Sheets-Sheet 1

FIG. 1

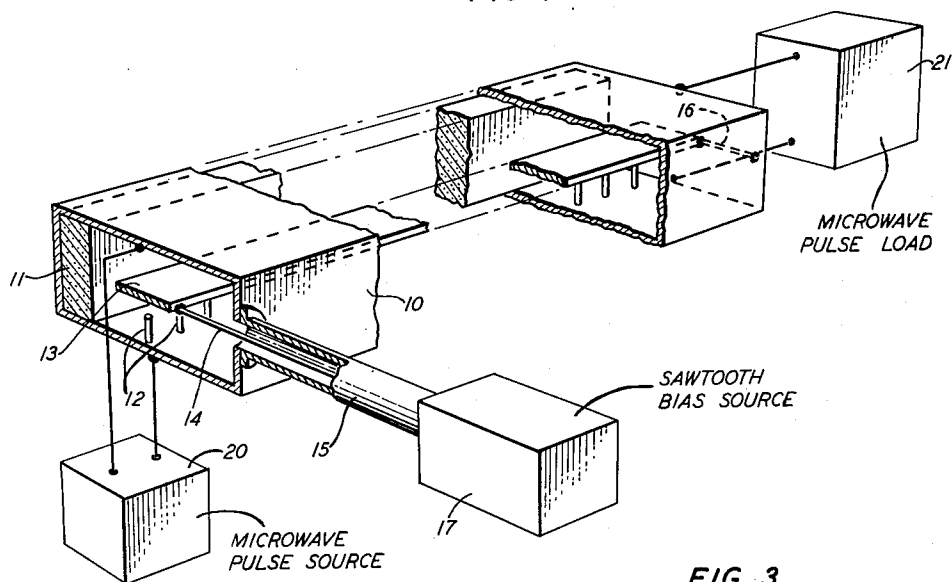


FIG. 3

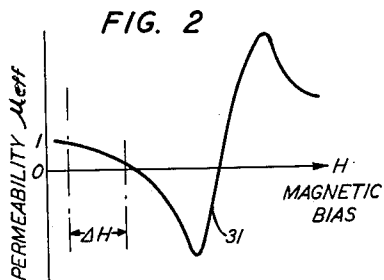
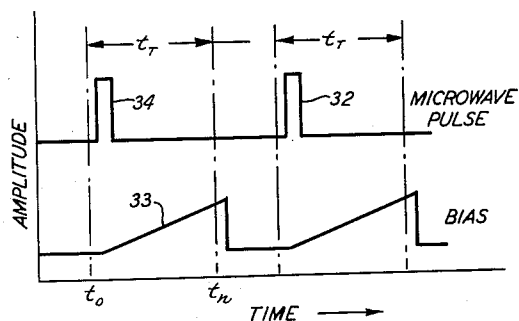
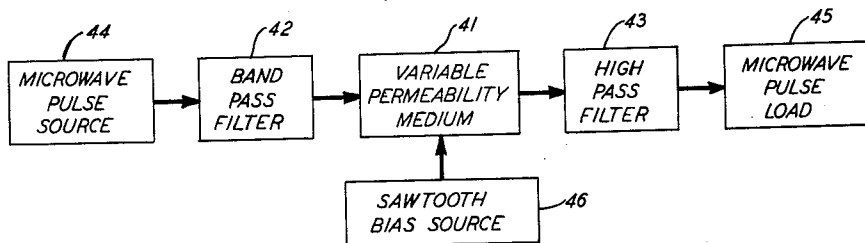


FIG. 4



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FIG. 5

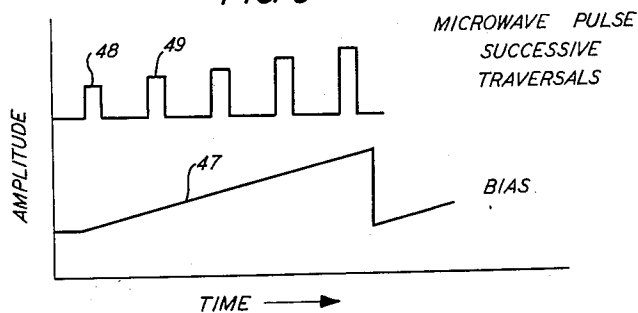


FIG. 6

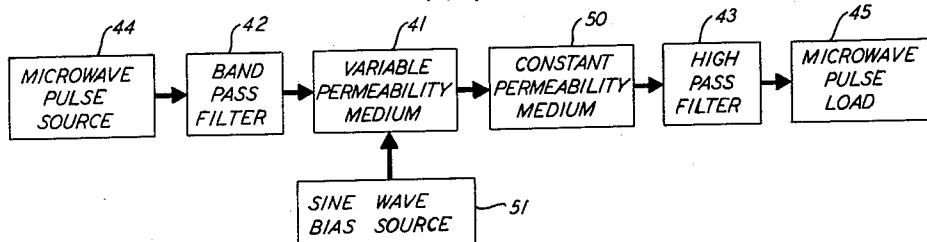
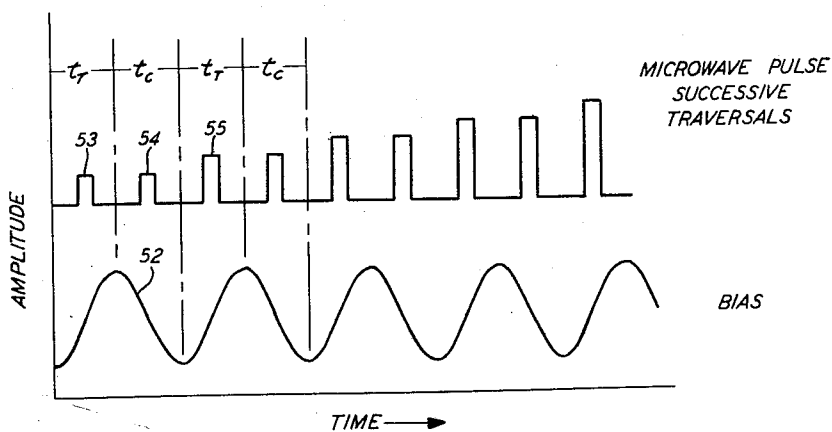


FIG. 7



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3,022,463

MICROWAVE PULSE AMPLIFIER

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Filed Dec. 17, 1959, Ser. No. 860,168

9 Claims. (Cl. 330—5)

This invention relates to solid-state amplifiers of the parametric type and more particularly to low noise microwave pulse amplifiers.

It is an object of the present invention to amplify microwave pulses by simplified, efficient and noise-free means.

The art of amplifying electromagnetic wave energy has recently been substantially advanced by the development of a whole new class of low-noise solid-state amplifiers. The amplifiers included in this class differ widely in design and operation and have been broadly subdivided into masers and parametric amplifiers. A summary and complete bibliography of the literature is to be found in an article "Solid-State Microwave Amplifiers" by Hubert Heffner in the IRE Transactions on Microwave Theory and Techniques, January, 1959.

The present invention represents a substantial departure from all of these devices. It is based in part upon the principle theoretically developed by F. R. Morgenthaler in an article "Velocity Modulation of Electromagnetic Waves" beginning on page 167 of the IRE Transactions on Microwave Theory and Techniques, April 1958. Morgenthaler has mathematically demonstrated that when an electromagnetic wave is propagated through a dielectric or permeable medium whose propagation constants vary as a function of time, the frequency of the wave energy within the medium is changed. Thus, if the dielectric or permeability constants of the medium are changed sinusoidally, frequency modulation results. Morgenthaler also considered the case of increasing these parameters in an infinitely extending medium according to a step transient and pointed out that the energy level was different before and after the step. No practical application of this phenomena was perceived.

In accordance with the present invention, it has been recognized that if a microwave pulse is applied to a slow wave propagating medium the effective propagation constant as determined by the product of the permeability and dielectric constants of which can be decreased by decreasing either one or both of these parameters and if this pulse is so timed that it is entirely within the medium before the decrease starts, the pulse may then be taken out of the medium before the decrease stops in an amplified state. The medium may then be returned to its first condition of high dielectric, permeability constant or both to receive a subsequent pulse. These requirements mean that the parameters of the medium must be changed over a period that is equivalent to the transit time of the pulse through the medium. In accordance with the specific embodiments of the invention a capacitively loaded slow wave circuit is employed to increase the transit time through a ferromagnetic medium. The permeability of this medium is varied by the application of a sawtooth magnetic bias applied by a low impedance circuit so that this bias may be varied in the period of the transit time of the pulse through the medium.

In a more refined embodiment of the invention, the period over which the permeability may be changed is substantially increased, thus simplifying the design of both the medium and the means for obtaining the required permeability change, by making use of successive traversals through the amplifying medium during a single permeability decrease. The frequency change accom-

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panying the amplification is utilized by preceding the variable permeability medium by a band-pass filter through which the input pulse is admitted. The medium is followed by a high-pass filter which successively reflects the pulse until its frequency has been increased sufficiently by successive passes to exceed the cut-off frequency of the high-pass filter.

In a further embodiment the required variation of the permeability is further simplified by making use of an easily available sine wave variation. The transit time through the variable permeability medium is selected with respect to the transit time through a medium of constant permeability so that a successively reflected pulse is within the variable medium only during the amplifying portion of the sine wave.

These and other objects and advantages, the nature of the present invention and its various features will appear more fully upon consideration of the various illustrated embodiments now to be described in detail in connection with the accompanying drawings, in which:

FIG. 1 illustrates, partly in perspective and partly in schematic, a pulse amplifier combination in accordance with the invention;

FIG. 2 represents a typical characteristic of the permeability of the gyromagnetic element in FIG. 1 as a function of the magnetic field bias applied thereto;

FIG. 3 illustrates the time relationships between the pulses to be amplified and the bias in the pulse amplifier shown in FIG. 1;

FIG. 4 represents in block diagram schematic a second embodiment of a pulse amplifier, representing an improvement upon the embodiment of FIG. 1;

FIG. 5 represents the time relationships between the pulse to be amplified and the bias in the pulse amplifier of FIG. 4;

FIG. 6 represents in block diagram schematic an improved modification of the pulse amplifier of FIG. 4; and

FIG. 7 represents the time relationships between the pulse to be amplified and the bias in the pulse amplifier of FIG. 6.

Referring more particularly to FIG. 1, a pulse amplifying combination in accordance with the invention is shown comprising a section 10 of a microwave guiding structure of any suitable type and cross-section having disposed therein any suitable and conventional means for causing the velocity propagation of electromagnetic wave energy therein to be slowed and including therein also any suitable means for presenting to the wave energy propagating in guide 10 a permeability or dielectric constant dependent upon the degree of a relatively rapidly variable bias applied thereto. The source 20 of microwave pulses to be amplified is connected through suitable matching means to one end of guide 10 as shown schematically and a load 21 to which the amplified pulses are to be delivered is similarly connected to the other end of guide 10. Essentials of components for performing each of these functions are all well known in the art and need not be discussed in detail. By way of illustrating a specific embodiment, however, guide 10 takes the form of a conductively bounded wave guide of rectangular cross-section having disposed therein a comb type slow wave structure of the type described for traveling wave tubes by J. R. Pierce in Patent 2,708,238 granted May 10, 1955 or for traveling wave masers by R. W. DeGrasse et al. in an article "The Three Level Solid-State Traveling Wave Maser" in the Bell System Technical Journal, March, 1959. Specifically, this wave slowing mechanism comprises a plurality of conductive rods or fingers 12 extending a portion of the way across the interior of guide 10 from the center of one of its broad walls. When properly proportioned this array introduces

capacitive loading to wave energy propagating along guide 10 and decreases its propagation velocity. It should be understood, however, that this particular form of slowing means is shown only by way of illustration and any other slow wave structure may be used including types used in traveling wave tubes, masers and other microwave devices. For example, guide 10 could be substantially filled with a very high dielectric constant, low loss, material or use could be made of the interior conductive corrugations disclosed in Patent 2,659,817 granted November 17, 1953 to C. C. Cutler. The need for and the degree of slowing required for the purposes of the present invention will be discussed further hereinafter.

The particular means selected to illustrate the means for varying the permeability presented to wave energy in guide 10 is of the ferromagnetic type. A very simple form is illustrated comprising a slab like element 11 of low conductivity material capable of exhibiting gyromagnetic effects at the frequency of said wave energy, such as ferrite, disposed along a narrow wall of guide 10. The particular biasing means illustrated comprises a flattened conductive member 13 which forms the center conductor of a strip line running substantially axially along guide 10. The top and bottom walls of guide 10 comprise the ground planes of the strip line. One end of strip 13 is connected to the center conductor 14 of a coaxial line 15 having the outer conductor thereof connected to the conductive boundary of guide 10. The other end of strip 13 is connected by short 16 to guide 10. Coaxial 15 is connected to a source 17 of sawtooth biasing current having the period, duration and form to be described hereinafter. Note that strip 13 and its associated connections comprise essentially a direct current path, the strip line form being utilized only to minimize inductance so that the current through strip 13 may be rapidly changed. Therefore when an increasing sawtooth current is applied from source 17 to strip 13, an increasing current conducted by strip 13 develops loops of magnetic field of increasing intensity around the strip which pass through the material of element 11 in the regions which contain the high frequency field of the propagating wave energy in guide 10.

This method of biasing is preferred over one comprising a solenoid disposed upon the outside of guide 10 because the inductance of such a coil and eddy currents in the conductive guide walls would limit the frequency at which the bias could be varied. However, any other biasing scheme which has been proposed for use where rapidly changing biases are contemplated may be used, such as those known to be suitable for ferromagnetic modulators, for example.

FIG. 2 shows the now familiar characteristic of the effective permeability versus magnetic biasing field strength for an element such as 11 biased as described by the field produced by the current on strip 13. It is immaterial for the purposes of the present invention whether this characteristic is reciprocal or non-reciprocal, whether it is a characteristic presented to circularly polarized components or to linearly polarized components or whether, as will be shown, the exact form of its functional variation with field is known. All that is necessary is that curve 31 decrease from unity as the bias is increased. Such a characteristic may be obtained by means of a number of combinations of ferrite material configuration, biasing field, and high frequency magnetic field relationships. Those treated by the art involving circularly polarized high frequency magnetic fields are only a part. If a substantial circularly polarized component is present in the region containing the gyromagnetic material, as will be the case in the specific structure illustrated for moderate loading by rods 12, then curve 31 represents that permeability presented to a magnetic field which is positively circularly polarized when viewed in the positive direction of the biasing field. Further descriptions of these characteristics and the physical phenomena

underlying them may be found in an article "Behavior and Application of Ferrite in the Microwave Region" by A. G. Fox et al. in the Bell System Technical Journal, January, 1955.

In accordance with the present invention the polarization of the current produced by bias source 17 and excited upon strip 13 is selected so that the magnetic field of a wave propagating in the direction from source 20 to load 21 within element 11 is presented by the permeability represented by curve 31. The amplitude of this current is selected so that variation between the base value and the peaks of the sawtooth wave carries the bias over a region of curve 31 represented approximately by ΔH of FIG. 2.

The timing of the sawtooth wave with respect to the pulse to be amplified is very important and is illustrated in detail in FIG. 3. Referring therefore to FIG. 3 characteristic 34 represents a first pulse in a train of pulses to be amplified and 32 represents a subsequent pulse. The time t_0 represents the instant that the entire pulse (the trailing edge thereof) has entered the medium of element 11 and the time t_n represents the instant the entire pulse (the trailing edge thereof) leaves the medium. The difference between these two times is the transit time t_T through the medium. Characteristic 33 represents the sawtooth bias current which commences to increase at a time no sooner than t_0 and preferably at an instant thereafter. During the transit time t_T of the pulse through the medium, the bias increases. At an instant later than t_n , the bias returns to its base value to repeat the process upon the entry of another microwave pulse 32. The decrease in the bias must not occur while the pulse is still within the medium.

This process results in gain to the pulse and an increase in its frequency. During the time the pulse is passing through the medium, the permeability of the medium is decreased. Energy must be expended in changing this parameter which energy must go into the pulse on the medium. If the pulse is already in the medium before the change starts, no change in the spatial properties of the pulse is possible. (If the change starts before the pulse is completely in the medium, the impedance change would cause reflections as the pulse enters the medium.) Therefore since the spatial properties cannot change and yet the phase velocity must change, the signal frequency and its energy level must increase.

These statements will now be supported by the analysis which follows in which a wave equation is derived relative to the problem of time varying parameters. The assumptions are:

(1) One dimensional wave with

$$\frac{\partial}{\partial X} = \frac{\partial}{\partial Y} = 0$$

in rectangular coordinates.

(2) The dielectric coefficient is a constant in both space and time.

(3) The medium is free of either charges or currents, with zero conductivity.

(4) The scalar permeability μ is time variable but does not vary in space.

(5) The analysis begins with the wave inside the medium described above.

Maxwell's equations in this case are:

$$\nabla \times \vec{E} = -\frac{\partial}{\partial t} \mu_0 \mu H$$

$$\Delta \times \vec{H} = \epsilon \frac{\partial \vec{E}}{\partial t}$$

$$\nabla \times \nabla \times \vec{E} = \nabla (\nabla \cdot \vec{E}) - \nabla^2 \vec{E}$$

and

$$\nabla \cdot \vec{E} = 0 (\epsilon \text{ is a scalar})$$

Then:

$$\nabla^2 \bar{E} = -\frac{\partial}{\partial t} \mu_0 \epsilon \frac{\partial \bar{E}}{\partial t}$$

assume further:

$$\bar{E} = \bar{a}_y E_y (\bar{a}_y: \text{unit vector})$$

then

$$\frac{\partial^2 E_x}{\partial y^2} = \mu_0 \epsilon \frac{\partial}{\partial t} \mu \frac{\partial E_x}{\partial t}$$

and with

$$\dot{E}_x = \frac{\partial}{\partial t} E_x(y, t)$$

$$(1) \quad \frac{\partial^2 E_x}{\partial y^2} = \mu_0 \epsilon \left[\mu \ddot{E}_x + \dot{\mu} \dot{E}_x \right]$$

Solutions of (1) with enough generality to allow the fitting of the as yet unspecified boundary conditions are now derived. Assume a product solution:

$$E_x(y, t) = Y(y) T(t)$$

with:

$Y''(y)$ representing space differentiation

$T(t)$ representing time differentiation

Substitute in (1):

$$(2) \quad \frac{Y''(y)}{Y(y)} = \mu_0 \epsilon \left[\mu \frac{\ddot{T}(t)}{T(t)} + \dot{\mu} \frac{\dot{T}(t)}{T(t)} \right] = -k^2$$

where k^2 is the separation parameter. Here

$$Y'''(y) + k^2 Y(y) = 0$$

with the solution:

$$(3) \quad Y = A \sin ky + B \cos ky$$

and k must be found from boundary conditions. The space variations are seen to remain independent of changes in the permeability. The time variations must now be found from (2).

$$(4) \quad \ddot{T}(t) + \dot{T}(t) \frac{\dot{\mu}(t)}{\mu(t)} + \frac{k^2 T(t)}{\mu_0 \epsilon \mu(t)} = 0$$

The exact form of Equation 4 is as yet unspecified since the form of $\mu(t)$ is unstated.

Two cases are now given for the time variation of $\mu(t)$, both of which are monotonically increasing functions of time. This process could not continue indefinitely of course but under duty cycle operation employed by the invention no physically unrealizable situation arises.

Case I: The variation of the permeability with time takes the form:

$$\mu = \mu_1 e^{-2t}$$

which is an exponential variation of μ with decrement 2δ .

Equation 4 under this assumption for μ results in the approximate solution:

$$(5) \quad T(t) = V_0 e^{\delta t} \left[\sqrt{\tau} Z_{1/3} \left(\frac{2\tau^{3/2}}{3\sqrt{3}} \right) \right]$$

where

$$\tau = \frac{P}{r} (1 + qt)$$

r, P, q are constants satisfying:

$$\frac{r^3}{p^2 q^2} = \frac{1}{3}$$

$Z_{1/3}$ is any Bessel Function of order $1/3$.

Case II: The variation of permeability with time takes the form

$$y = B t^{1-\alpha}$$

From Jahnke and Emde, "Tables and Functions," 1945, the equation:

$$(6) \quad y'' + \frac{1-2\alpha}{x} y' + \left[(\beta \gamma x^{\gamma-1})^2 + \frac{\alpha^2 - p^2 \gamma^2}{x^2} \right] y = 0$$

is satisfied by:

$$(7) \quad y = x^\alpha Z_p(\beta x^\gamma)$$

Repeating Equation 4

$$5 \quad \ddot{T} + \frac{\dot{\mu}}{\mu} \dot{T} + \frac{k^2}{\mu_0 \epsilon \mu} T = 0$$

By suitable manipulation Equation 4 can be identified with (6). In (6) replace the independent variable x by t . Then let:

$$\mu = \frac{1-2\alpha}{t}$$

which has as its solution:

$$15 \quad (8) \quad \mu = B t^{1-2\alpha}$$

let

$$\frac{k^2}{\mu_0 \epsilon \mu} = (\beta \gamma t^{\gamma-1})^2 + \frac{\alpha^2 - p^2 \gamma^2}{t^2}$$

20 with

$$\alpha^2 - p^2 \gamma^2 = 0$$

$$\frac{k^2}{\mu_0 \epsilon \mu} = (\beta \gamma t^{\gamma-1})^2$$

25

$$\mu = \frac{k^2 / \epsilon \mu_0 \gamma^2 (1-\gamma)}{\beta^2 \gamma^2}$$

For (8) and (9) to be satisfied:

$$30 \quad (10) \quad \begin{aligned} 2(1-\gamma) &= 1-2\alpha \\ p^2 \gamma^2 &= \alpha^2 \end{aligned}$$

$$\frac{k^2}{\epsilon \mu_0 \beta^2 \gamma^2} = B$$

35 Thus, depending on a choice of one parameter the three unknowns p, γ, α can be determined. Stated differently, it is possible to obtain solutions of the form (7):

$$T(t) = t^\alpha Z_p(B t^\gamma)$$

40 with a variation in μ as:

$$\mu = B t^{1-2\alpha}$$

Thus, given α above, γ and p will be uniquely determined. β must then be found from:

$$\frac{k^2}{2\mu_0 \beta^2 \gamma^2} = B$$

where B is evaluated from a boundary value on μ .

These analytical results may be summarized:

50	$\mu(t)$	$T(t)$
Case I.....	$\mu_1 e^{-2\delta t}$	$V_0 e^{\delta t} \sqrt{\tau} Z_{1/3} \left(\frac{2}{3} \sqrt{3} \tau^{3/2} \right)$
55		$\tau = \frac{P}{r} (1 + qt)$
Case II.....	$B t^{1-2\alpha}$	$t^\alpha Z_p(B t^\gamma)$

In Case I the term $V_0 e^{\delta t}$ predicts gain for $\delta > 0$. $Z_{1/3}(\nu)$ is periodic with varying period and shows a decrease in a period of the time variation.

In Case II the essential properties of the last case are shown with the added property that the order of the Bessel function solution is left unspecified. Both cases have one property in common that should be noted—the permeability must be decreased to obtain gain. This is consistent with the physical picture given above. Both solutions also share the necessity for spectral representation in the frequency domain which means that during the period the pulse is in the medium it will undergo some spread in frequency as well as the desired net increase in frequency. The anisotropic character of a magnetized ferrite medium does not violate the assumptions under which the analysis was made since for a uniform trans-

mission line the effective permeability is a scalar and hence the conclusions drawn are valid.

A quantitative picture of a typical embodiment in accordance with the invention may now be given. Consider a structure of the type described a foot long with a built-in slowing of 1,000, i.e., the phase velocity is

$$\frac{1}{1000}$$

the velocity of light.

here:

$$t_a = 10^{-6} \text{ sec.}$$

For 20 db of gain in this foot, using Case I:

$$|E| \cong |E_0| e^{\delta t}$$

$$20 \log E/E_0 = 20 = 20\delta t \log_{10} e$$

for

$$t = 10^{-6}$$

$$\delta = \frac{1}{.434t} \cong 2 \times 10^6$$

Since μ_{eff} can be changed at most from 1 to 0 (for $\mu_{\text{eff}} \leq 0$ the wave will not penetrate the ferrite and interaction ceases) the variation in μ is:

$$\mu = 1e^{-2\delta t}$$

Or, μ must change from 1 to

$$\frac{1}{e}$$

in a time of $\frac{1}{4} \times 10^{-6}$ sec. This fast a drop in μ is not impractical since it is greater than any of the relaxation times of the medium. As the foregoing indicates the main limiting factors of the invention are the maximum of pulse transit time through the medium that can be obtained by a practical degree of slowing (without undue loss) in a medium of practical length and the maximum rapidity with which the magnetic bias may be varied. In FIGS. 4 and 5 an embodiment is shown in which these limiting factors are greatly reduced by enabling a plurality of successive traversals through the medium during a single bias increase period. Thus, 41 represents components for producing a variable permeability medium which may be identical to that shown in FIG. 1. Medium 41 is biased by a sawtooth wave from source 46 having the amplitude versus time variation represented by characteristic 47 on FIG. 5. Medium 41 is preceded by a filter 42 having a band-pass characteristic corresponding to whatever happens to be the frequency band of the input pulse applied thereto from source 44. Medium 41 is followed by a high-pass filter 43 having a lower frequency cut-off that is higher than the pass-band of filter 42 by an amount equal to the frequency increase in the pulse for each traversal through the medium 41 times the number of round-trip traversals that can be made during one period of sawtooth 47. Filter 43 is followed by load 45 for receiving and utilizing the amplified pulse of increased frequency.

Thus a pulse of microwave energy enters the pass-band filter 42 and passes through medium 41 where it is presented with a decreasing permeability as described with reference to FIGS. 1, 2, and 3 hereinbefore. Such a pulse is represented on FIG. 5 by 48. The wave amplitude as well as its frequency is increased. This pulse is then reflected by filter 43 so that it traverses medium 41 in the reverse direction. The pulse is now reflected by filter 42 since the pulse frequency has been shifted out of the pass-band of the filter. The reflected pulse then undergoes a subsequent traversal through medium 41 as represented by 49 on FIG. 5. The process continues until the pulse spectrum is shifted above the cut-off of filter 43 through which the pulse passes in its amplified state to load 45.

While the sawtooth bias employed in FIGS. 4 and 5 is readily obtainable, a sine wave bias is often easier to

generate. Thus by means of the modification of the invention shown in FIG. 6, a conventional sine wave bias may be used. In other respects the embodiment of FIG. 6 is the same as that of FIG. 4 and corresponding reference numerals have been used to designate corresponding components. Modification will be seen to reside in the addition of a time delay introducing medium 50 of constant permeability following variable permeability medium 41. Medium 50 has a delay or transit time t_C approximately equal to the transit time t_T of medium 41 and may consist simply of a suitably loaded length of wave guide. Bias source 51 now comprises a source of sine wave current having, as represented by characteristic 52 on FIG. 7, a period equal to the sum of transit times t_T and t_C . Bias wave 52 is so timed with respect to the periodic receipt of pulses that during the half-cycle of increasing bias and decreasing permeability in medium 41, an initial pulse, as represented by 53 on FIG. 7, is within medium 41. During the following half-cycle of decreasing bias and increasing permeability the pulse is within medium 50. On the second traversal, the pulse will be within medium 41 during the following increase in bias as represented by 55. The process continues until the frequency of the pulse has been increased to a value above the cut-off frequency of filter 43. The pulse then may pass to load 45. Any number of pulses may be amplified simultaneously so long as the frequency of the bias wave 52 has been synchronized with the repetition rate of the pulses so that all pulses are within medium 41 during its amplifying period and within medium 50 during other portions of the cycle.

While the principles of the present invention have been illustrated in terms of a medium of variable permeability, the principles of amplification illustrated depend upon the product of the dielectric and permeability constants and may be practiced as well with a medium of variable dielectric constant. An example of such a medium would be a wave guide loaded with material such as barium titanate, biased by a suitably produced, variable electric field.

In all cases it is understood that the above-described arrangements are illustrative of a small number of the many possible specific embodiments which can represent applications of the principles of the invention. Numerous and varied other arrangements can readily be devised in accordance with these principles by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A microwave pulse amplifier comprising a medium having an effective propagation constant that is decreased with respect to time over a period and then increased, means for applying said pulse to said medium before said decrease starts for transit through said medium during said decrease, and means for substantially completely removing said pulse from said medium before said decrease stops.

2. An amplifier for a microwave pulse comprising a medium having a microwave permeability that decreases in response to the intensity of a magnetic bias applied thereto, means for applying said pulse to said medium for transit through said medium, means for applying a magnetic bias to said medium, and means for gradually increasing the intensity of said bias over the period that said pulse is in transit through said medium and then for decreasing said intensity after said pulse leaves said medium.

3. The pulse amplifier according to claim 2 wherein said medium includes an asymmetrically positioned element of ferrite therein.

4. The pulse amplifier according to claim 2 including means for slowing the propagation of said pulse through said medium for increasing the period during which said pulse is in transit through said medium.

5. The pulse amplifier according to claim 4 wherein

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said means for applying said bias comprises a source of sawtooth current having a period of sawtooth increase that is greater than the transit time of said pulse through said medium and a repetition rate equal to the repetition rate of the pulses to be amplified.

6. The pulse amplifier according to claim 4 including a filter of narrower band than said medium preceding said medium and a high-pass filter having a pass band substantially above the frequency band of said pulse following said medium.

7. The pulse amplifier according to claim 6 wherein said means for applying said bias comprises a source of sawtooth current having a period of sawtooth increase

that is several times greater than the transit time of said pulse through said medium.

8. The pulse amplifier according to claim 6 including means interposed between said medium and said high-pass filter for introducing a constant delay substantially equal to the transit time of said pulse through said medium.

9. The pulse amplifier according to claim 8 wherein said means for applying said bias comprises a source of sine wave current having a period equal to substantially twice said transit time of said pulse through said medium.

No references cited.