MODULATED BACKWARD WAVE OSCILLATOR

Filed Dec. 21, 1953 2 Sheets-Sheet 1

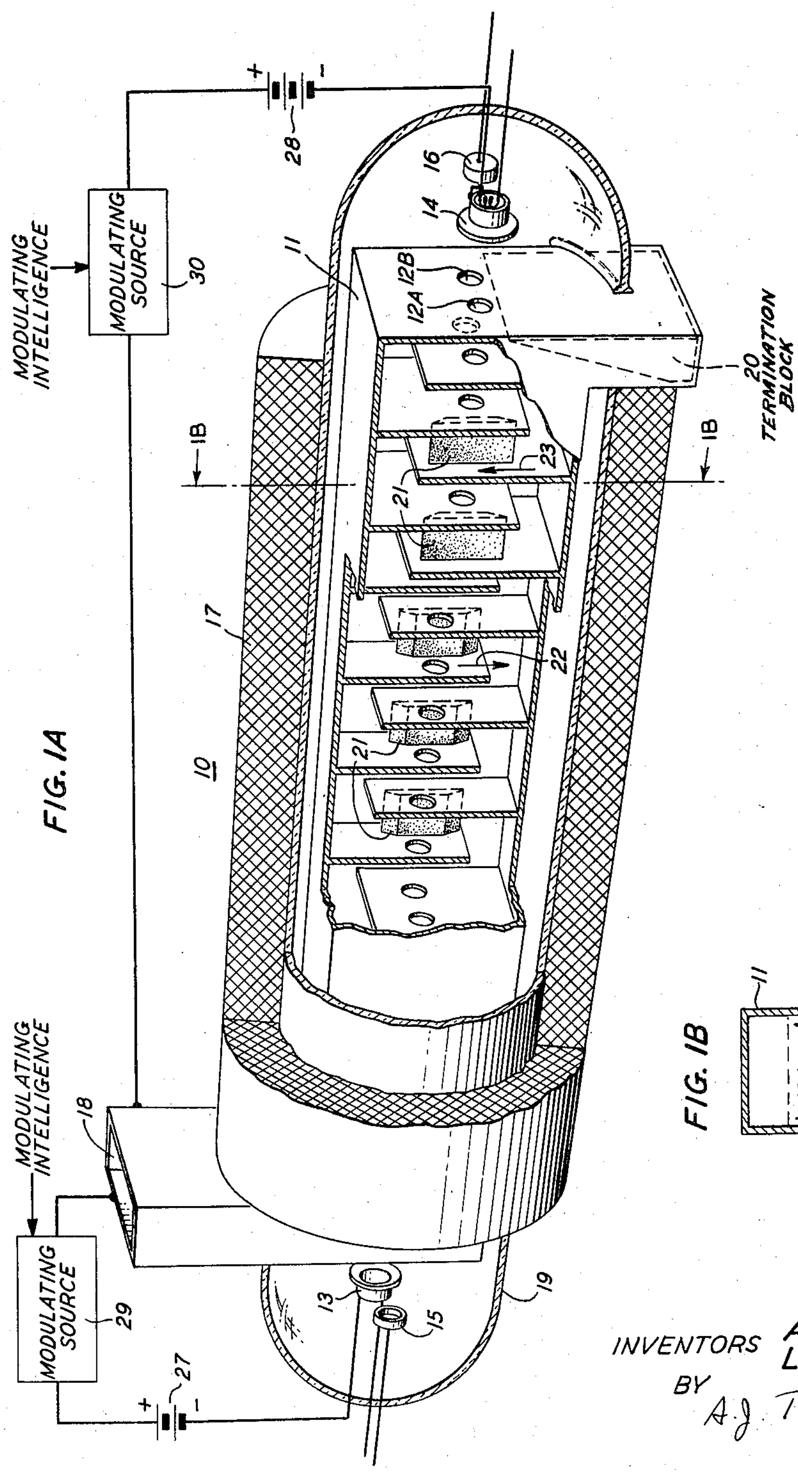


FIG. 1A

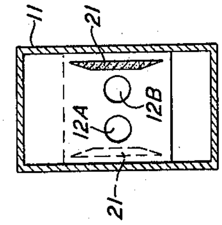


FIG. 1B

INVENTORS A. ASHKIN
L. R. WALKER
BY A. J. Torsiglieri
ATTORNEY

MODULATED BACKWARD WAVE OSCILLATOR

Filed Dec. 21, 1953 2 Sheets-Sheet 2

FIG. 2A

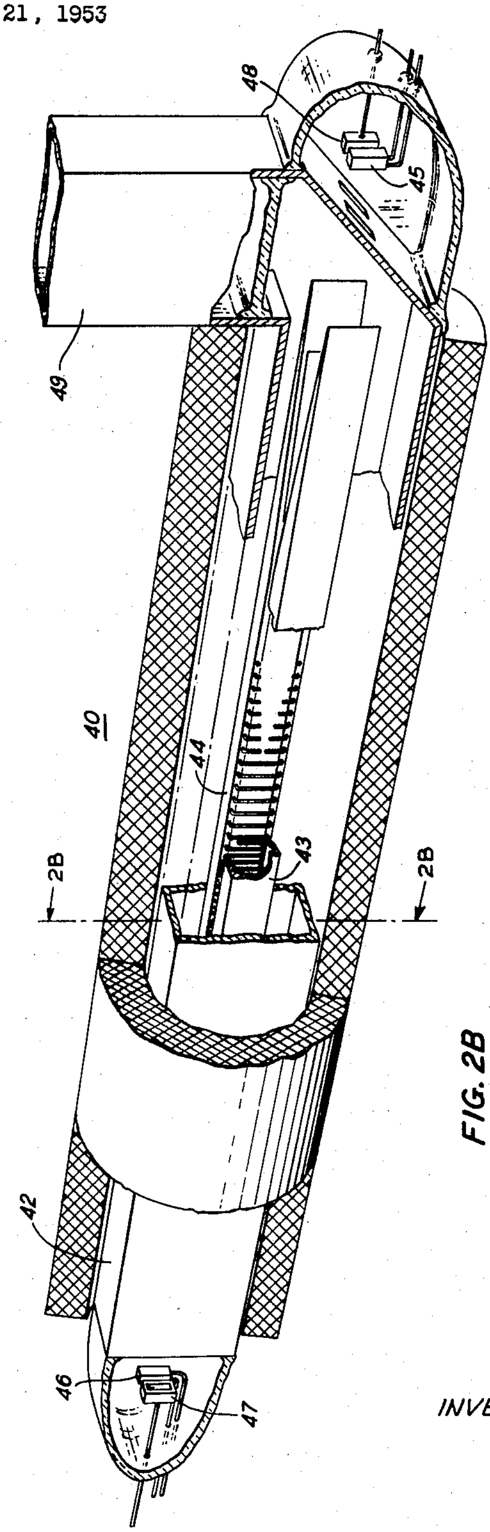
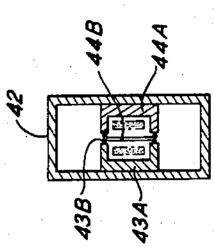


FIG. 2B



INVENTORS A. ASHKIN
L. R. WALKER
BY A. J. Torsiglieri
ATTORNEY

2,871,451

MODULATED BACKWARD WAVE OSCILLATOR

Arthur Ashkin, Irvington, and Laurence R. Walker, Bernardsville, N. J., assignors to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application December 21, 1953, Serial No. 399,284

4 Claims. (Cl. 332—25)

This invention relates to radio frequency oscillators and more particularly to oscillators which utilize the interaction between an electron beam and an oppositely or backward traveling electromagnetic wave to sustain oscillations.

In the typical backward wave oscillator of this kind, an electron beam is projected over a distance a plurality of operating wavelengths long past a wave interaction circuit of the kind which is characterized in that an electromagnetic wave propagating therealong in one direction has strong components thereof which have phase velocities in the direction opposite to that of wave energy propagation. It is characteristic that the noise components in the electron beam induce wave disturbances which propagate along the interaction circuit in a direction opposite to that of electron flow and which, accordingly, have components whose phase velocity is in the direction of electron flow. For oscillations at a given frequency the velocity of the electron beam is adjusted to provide interaction with a component traveling in the direction of flow of the backward-traveling noise-induced wave of the desired frequency whereby the wave is amplified and the electron beam is bunched correspondingly. Because the directions of wave energy propagation and electron flow are opposite, the electron beam provides positive feedback coupling, acting to return energy from points of higher level to points of lower level along the path of flow. When the beam current is sufficiently high, this action will sustain oscillations and oscillatory wave energy of the desired frequency becomes available for abstraction at the upstream end of the interaction circuit. Throughout the application, the terms "upstream" and "downstream" will be used to designate relative separation from the electron source, the term "upstream" denoting proximity along the path of flow to the electron source, and the term "downstream" denoting remoteness along the path of flow from the electron source.

It is characteristic of oscillators of this kind that the electrons are injected unbunched at the upstream end of the interaction circuit where the signal level is high and emerge strongly bunched at the downstream end of the interaction circuit where the signal level is low. This means that the interaction along the path of flow is always relatively low, which in turn results in operation which is relatively inefficient. Any attempt to increase the interaction between the beam and the signal wave which involves feeding back directly wave energy from the upstream to the downstream end of the circuit or bunching the electrons at the upstream end of the circuit suffers from the difficulty of phasing; that is, at certain frequencies this feedback will enhance interaction but at others reduce it. Such "moding" would deprive the backward wave oscillator of one of its most useful properties, i. e., the ability to be electronically tuned over a continuous wide range of frequencies.

The primary object of the present invention is to improve the efficiency of backward wave oscillators. Related objects are to make available in such oscillators high level output oscillatory waves with shorter interaction circuits and/or lower beam currents.

Another object is to make available an improved form of frequency modulator.

To these ends, a feature of the invention is the use in a backward wave oscillator of two distinct oppositely directed electron beams, the first beam to induce in the interaction circuit a growing electromagnetic wave of a desired frequency in the manner characteristic of backward wave oscillators known hitherto, and the second beam to interact with and amplify further this growing electromagnetic wave in the manner characteristic of forward wave amplifiers known hitherto. In conjunction with the two beams, there is utilized a wave interaction circuit of the kind which is characterized in that a wave propagating therealong gives rise to strong spatial harmonic components thereof which have phase velocities both in the direction of and opposite to that of wave propagation and which is suited for the projection therepast of two distinct electron beams for coupling to the propagating wave.

In operation, the primary beam interacts with a spatial harmonic component of a noise induced wave of a desired frequency which has a phase velocity in a direction opposite to that of wave propagation for setting up the oscillatory wave which grows with travel in the direction opposite to that of electron flow. The secondary beam is adjusted to interact with the spatial harmonic component of the oscillatory wave which has a phase velocity in the direction of wave propagation thereof. Thus, this secondary beam will serve to amplify the growing oscillatory wave, resulting in stronger interaction between this wave and the primary beam and thereby enhanced amplification of this oscillatory wave. This enhancement, in turn, will improve the interaction between the oscillatory wave and the secondary beam. It can be seen that the effect is cumulative, resulting in an improvement considerably greater than would have been obtained by utilizing as the current in the primary electron beam the sum of the currents in the two beams. Moreover, the increased efficiency of interaction makes possible a shortening of the length of the interaction circuit.

In an oscillator of this kind, it is important to insure that the secondary electron beam does not set up a second oppositely traveling oscillatory wave of its own. For this purpose, it is advantageous to make the interaction circuit nonreciprocal in its propagating characteristics, or alternatively, to operate the two beams at velocities sufficiently different that for the interaction circuit employed the velocity of the secondary beam will not be suited for inducing an oppositely traveling oscillatory wave of its own.

In one illustrative embodiment the interaction circuit comprises a rectangular wave guide which is folded back and forth on itself a plurality of times in serpentine fashion. By the insertion of suitably magnetized gyromagnetic septa in successive folds of the wave guide, the circuit is made to offer high attenuation to waves propagating therethrough in a first direction and low attenuation to waves propagating therethrough in the opposite direction. A primary electron beam is projected through successive folds of the wave guide in the direction corresponding to that of high wave attenuation for inducing in the circuit a backward traveling oscillatory wave. A secondary electron beam is projected through successive folds of the wave guide in a direction opposite to that of the primary beam for amplifying this oscillatory wave.

In applications as a frequency modulator, the modulating intelligence is used to vary the velocity of the primary electron beam past the interaction circuit, which action has the effect of varying the frequency of the oscillations. Where the oscillatory frequency is to be modulated over a wide frequency range, it may be advantageous to vary simultaneously the velocity of the secondary beam to insure maximum amplification of the growing oscillatory wave.

In another illustrative embodiment, the wave circuit comprises a wave guide which is loaded by a linear array of wires and the two electron beams are projected past on opposite sides of the linear array. With such a wave circuit, the phase velocities of the forward and backward traveling components of a wave of the desired frequency can conveniently be made so different that the velocity spread of the two beams will be sufficiently large that only a chosen one will set up a backward traveling growing oscillatory wave.

The invention will be better understood from the following more detailed description taken in conjunction with the accompanying drawings in which:

Fig. 1A shows in perspective cutaway view an illustrative embodiment of the invention which utilizes a folded wave guide circuit through which are projected two oppositely directed electron beams, and Fig. 1B is a transverse section taken along the lines 1B—1B of the embodiment shown in Fig. 1A;

Fig. 2A shows in perspective cutaway view another embodiment of the invention which utilizes as the wave circuit a wave guide loaded with a linear array of wires on opposite sides of which flow two oppositely directed electron beams, and Fig. 2B is a transverse section taken along the lines 2B—2B of the embodiment shown in Fig. 2A.

With particular reference now to the drawings, in the traveling wave tube oscillator **10** shown in Figs. 1A and 1B, a rectangular hollow wave guide **11** is folded back and forth on itself a plurality of times to form a serpentine wave path. The broad dimension of the wave guide is normal to the direction of folding while the narrow dimension of the wave guide is parallel to the direction of folding. Each fold of the wave guide is provided with two distinct apertures **12A** and **12B**, the various apertures forming two sets of aligned apertures on opposite sides of the tube axis for passage therethrough of separate electron beams. To this end, electron sources **13** and **14** at opposite ends of the evacuated glass envelope **15** which houses the tube elements are each aligned with a different set of apertures and provide electron beams for flow through successive folds. In target relationship with electron sources **13** and **14** at opposite ends of the envelope are the collector electrodes **15** and **16**, respectively. Flux producing means external to the envelope are employed to create a longitudinal magnetic field parallel to the paths of flow for focusing the two electron beams. In the embodiment illustrated, a solenoid **17** surrounds the tube envelope to provide the focusing magnetic flux. The wave guide **11** is of a non-magnetic material, such as copper, so as not to disturb this magnetic field. The output oscillatory wave energy is abstracted by way of an output coupling connection **18** to the wave guiding circuit at its end adjacent the electron source **13** which serves as the source of the primary beam. At the opposite end, the wave guiding circuit is terminated in a substantially reflectionless manner by the insertion of the tapered dielectric block **20** which is coated with a layer of lossy material such a aquadag. Various possible forms of coupling connections and terminations will be known to workers in the art.

In operation, the noise on the primary electron beam serves to induce in the wave circuit electromagnetic waves which proceed therethrough in the direction from the terminated end toward the output end and so opposite to the direction of flow of the primary beam. The velocity of this electron beam is chosen to favor interaction between the primary electron beam and an oppositely traveling noise induced wave of the desired frequency whereby this favored wave grows with travel towards the output coupling connection **18**. For such interaction, the velocity of the electron beam is made substantially equal to the phase velocity in the direction of flow of a component of the wave of desired frequency which is advancing through the wave guide **11** in the direction opposite to that of electron flow. Such interaction may be described as interaction with a forward traveling spatial harmonic of the backward traveling wave. Henceforth, for the sake of convenience the direction of flow of the primary electron beam will be termed the forward direction, and the opposite direction the backward direction. Alternatively, this may be viewed as adjusting the velocity of flow of the primary beam so that each group of electrons thereof sees substantially the same phase of the electric field of the oppositely propagating wave in successive wave guide folds. Because the direction of electron flow is opposite to the direction of wave propagation, the primary electron beam serves to provide positive feedback, returning energy from regions of high level to regions of low level. When the current in this electron beam is sufficient, oscillations are set up at the desired frequency. These are the operating principles of backward wave oscillators of the kind known hitherto.

The presence of the secondary electron beam which is provided by electron source **14** serves to reduce the value of the starting current needed to initiate and sustain these backward wave type oscillations and to increase the output level of the oscillations. The velocity of the secondary electron beam is adjusted to interact cumulatively with the noise induced oscillatory wave. For interaction, the velocity of this electron beam is made substantially equal to the phase velocity in the direction of flow of a component of the oscillatory wave. Such interaction is of the kind normally used in the usual spatial harmonic amplifier and for present purposes will be described as interaction with a backward component of the backward traveling oscillatory wave. Because the primary and secondary beams are interacting with forward and backward traveling components, respectively, of the same backward traveling wave, their two velocities will not only be in opposite directions but also generally of different magnitudes.

Alternatively the operation may be described as follows. The primary electron beam is provided with a velocity which results in interaction with the negative space harmonic of the oscillatory wave while the secondary beam is provided with a velocity which results in interaction with a positive space harmonic of the oscillatory wave, where the positive and negative space harmonics have phase velocities, respectively, in the direction of and the direction opposite of, that of the group velocity of the oscillatory wave.

The secondary electron beam often will have a tendency to induce growing noise waves of its own for traveling upstream therealong if the wave circuit is broad band. For this reason, it is advantageous to make the wave circuit **11** nonreciprocal in its attenuation characteristics whereby the attenuation to a wave propagating in the direction from the terminated end of the wave circuit **11** to the output coupling connection **18** is low, while the attenuation to waves propagating in the direction from the output coupling connection to the terminated end is much higher. In a copending application Serial No. 399,252, filed December 21, 1953, by R. Kompfner, it is taught that a folded wave guide circuit of the kind employed in tube **10** can be made nonreciprocal by the insertion therein of gyromagnetic septa, for example of ferrite, suitably magnetized. In particular, the desired nonreciprocal properties can be achieved by positioning ferrite septa **21** in regions intermediate between one narrow side wall of the wave guide and the wave guide axis extending longitudinally parallel to the wave guide axis. In the presence of the longitudinal magnetic field used for focusing the electron beam, septa so positioned will be magnetized in a transverse direction parallel to the electric vector in the wave guide. Since the direction of low attenuation is related both to the direction of the biasing magnetic field and on which side of the wave guide axis the various septa are positioned, it becomes necessary to dispose the septa in adjacent folds on opposite sides of the wave guide axis since the direction of wave propagation relative to the direction of the longitudinal magnetic field reverses with successive folds. To illustrate the shift in position of the septa relative to the tube axis with successive folds, one portion of the tube is shown cut open along the tube axis while another portion is shown cut open along a side wall.

It is characteristic of an oscillator of this kind that the frequency of oscillations will be controlled by the velocity of the primary electron beam through the wave circuit, which velocity is controlled by the potential difference between the electron source **13** and the wave circuit **11**. This voltage is controlled by the voltage supply source **27** connected therebetween. The voltage source **28** connected between the electron source **14** and the wave circuit controls the velocity of the secondary beam past the wave circuit and this is adjusted for maximum gain of the oscillatory wave.

For frequency modulation operation, a source **29** of modulating voltage under the control of modulating intelligence is connected serially with the voltage source **27** for varying the accelerating potential acting on the primary beam. In instances where the wave circuit **11** is highly dispersive, variations in the frequency of the oscillatory wave result in variations of the phase velocity of the components interacting with the secondary electron beam. To maintain the condition for maximum interaction between the secondary beam and the growing oscillatory wave over a wide range of frequencies, it becomes necessary to vary the velocity of this secondary electron beam as the frequency of oscillation is changed. In general, the magnitude of the two beam velocities should advantageously be varied in the same direction simultaneously. Accordingly, a source **30** of modulating voltage similarly under the control of the modulating intelligence is connected serially with the voltage source **28** for varying the accelerating potential on the secondary beam in synchronism with changes in the accelerating potential on the primary beam.

Figs. 2A and 2B show a backward wave oscillator **40** utilizing a wave circuit which is of narrower band than that used in the tube shown in Figs. 1A and 1B so that it becomes less important to make the wave circuit substantially unidirectional in its transmission characteristics.

The various tube elements are house in an evacuated envelope **41**. The wave circuit comprises a hollow wave guide **42** of rectangular cross section within which, centrally located, extend two rectangular sections **43** and **44**, each having one wall 43A, 44A flush with a broad wall of the wave guide **42** and the wall 43B, 44B opposite thereto formed of a linear array of spaced wires. Of course, portions of the walls of wave guide **42** may serve as walls 43A, 44A. The two sections **43** and **44** each extend approximately half way across the wave guide **42** and the wires forming their walls 43B and 44B are interleaved to form one substantially linear array of wires, successive wires of the array being integral alternately with sections 43 and 44. As a result, waves traveling through the wave guide **42** induce currents in adjacent wires of the linear array formed by walls 43B, 44B which are in opposite directions so long as the uniform spacing between the wires in the linear array is appreciably less than one half the wavelength of the wave in the wave guide 42. Accordingly, there will be an electric field set up between adjacent wires whose direction reverses with succeeding gaps between adjacent wires and which, accordingly, is well suited for interaction with an electron beam. The characteristics of such an array of wires as a wave circuit are described more fully in L. R. Walker Patent 2,746,036 issued May 15, 1956.

Electron sources **45** and **46** at opposite ends of the envelope provide the two distinct electron beams and collectors **47** and **48** serve as their respective targets. The electron source **45** serves to provide the primary beam which is employed to set up the growing oscillatory wave while the electron source **46** provides the secondary beam used for amplification of the growing oscillatory wave. The spread in phase velocities of the backward and forward traveling components of the oscillatory wave will generally be wide and so the spread in velocities of the two beams needs similarly to be wide. As a result, the velocity of the secondary beam will not be in the range suited for establishing a growing wave of its own on the wave circuit.

In the manner characteristic of backward wave oscillators, the wave circuit is provided with an output coupling connection **49** at its upstream end relative to the primary electron beam while its opposite end is terminated by the insertion of suitable resistive absorbing means. To avoid reflections, each of the two sections **43** and **44** gradually disappears at its two ends into the wave guide **42**. To illustrate the manner of the merger a portion of the envelope at the output end of the tube is cut away. As can be seen, first the wire walls 43B, 44B gradually disappear, then the walls connected thereto are tapered till they vanish also.

For operation as a frequency modulator, provision can be made for modulating the beam accelerating voltages in the manner described in connection with the oscillator shown in Fig. 1A.

It should be evident from the embodiments illustrated that the principles of the invention can be applied to backward wave oscillators using diverse forms of wave circuits.

What is claimed is:

1. In an oscillator, a wave interaction circuit a plurality of operating wavelengths long of the kind which is characterized in that a wave propagating therealong in a given direction gives rise to components thereof with phase velocities both in the direction of and direction opposite to that of wave propagation, a first electron source at a first potential for forming a primary electron beam for flow past said interaction circuit for interaction with a predetermined component of a wave of desired frequency having a phase velocity in the direction opposite to that of wave propagation, a second electron source at a second different potential for forming a secondary electron beam spaced apart from said primary electron beam for flow past said interaction circuit in a direction opposite to that of the primary electron beam for interacting with a component of the wave of desired frequency and having phase velocity in the direction of the wave propagation, dissipative termination means at the downstream end of said interaction circuit relative to said first electron beam, and means coupled to the end of the interaction circuit upstream along the primary electron beam for abstracting for utilization oscillatory wave energy.

2. In an oscillator, a wave interaction circuit of the kind which is characterized in that a wave propagating therealong in a given direction gives rise to components thereof with phase velocities both in the direction of and direction opposite to that of wave propagation, means inserted along said interaction circuit for offering low attenuation to waves traveling therealong in the given direction and high attenuation to waves traveling therealong in the direction opposite to the given direction, means for forming a first electron beam for flow past said interaction circuit in the direction opposite to the given direction for interacting with a component of a wave of desired frequency having a phase velocity in the direction opposite to the given direction, means for forming a second electron beam spaced apart from said

first electron beam for flow past said interaction circuit in the given direction for interacting with a component of the wave of desired frequency and having a phase velocity in the given direction, dissipative termination means at the downstream end of said interaction circuit relative to said first electron beam, and means for abstracting wave energy coupled to the end of the interaction circuit upstream along the first beam.

3. In a frequency modulator a wave interaction circuit of the kind which is characterized in that a wave propagating therealong in a given direction gives rise to spatial harmonic components thereof with phase velocities both in the direction of and direction opposite to that of wave propagation, means for forming a first electron beam of a first velocity for flow past said interaction circuit in the given direction for interacting with a predetermined spatial harmonic component of a wave of desired frequency and having a phase velocity in the direction opposite to that of wave propagation, means for forming a second electron beam spaced apart from said first electron beam and of a different second velocity for flow past said interaction circuit in a direction opposite to that of the first electron beam for interacting with a predetermined spatial harmonic component of the wave of desired frequency having phase velocity in the given direction, dissipative termination means at the downstream end of said interaction circuit relative to said first electron beam, means under the control of modulating intelligence for varying the velocity of both electron beams in their flow past said interaction circuit, and means coupled to the end of the interaction circuit upstream along the first electron beam for abstracting for utilization wave energy.

4. In an oscillator, a wave interaction circuit having a given pass band of frequencies of the kind which is characterized in that a wave propagating therealong in

a given direction gives rise to negative and positive space harmonics, means for forming a first electron beam for flow past said interaction circuit over a distance a plurality of operating wavelengths long for interacting with a negative space harmonic of a wave of desired frequency in the pass band, means for forming a second electron beam spaced apart from said first electron beam for flow past said interaction circuit over a distance a plurality of operating wavelengths long in a direction opposite to that of the first electron beam for interacting with a positive space harmonic of the wave of desired frequency, dissipative termination means at the downstream end of said interaction circuit relative to said first electron beam, and means coupled to the end of the interaction circuit upstream along the first electron beam for abstracting for utilization wave energy.

References Cited in the file of this patent

UNITED STATES PATENTS

2,586,816	Hansen et al.	Feb. 25, 1952
2,603,773	Field	July 15, 1952
2,630,544	Tiley	Mar. 3, 1953
2,654,047	Clavier	Sept. 29, 1953
2,730,647	Pierce	Jan. 10, 1956
2,757,311	Huber et al.	July 31, 1956

FOREIGN PATENTS

993,102	France	July 18, 1951

OTHER REFERENCES

Journal of App. Phys., vol. 24, No. 6 pages 816–817, June 1953.

Article by E. C. Dench, Tele-Tech, November 1953, pages 64–66 and 157–162.

Proceedings of the IRE, pp. 478–482, April 1952.