

April 9, 1963

A. ASHKIN

3,085,207

PARAMETRIC AMPLIFIER

Filed July 26, 1961

3 Sheets-Sheet 1

FIG. 1

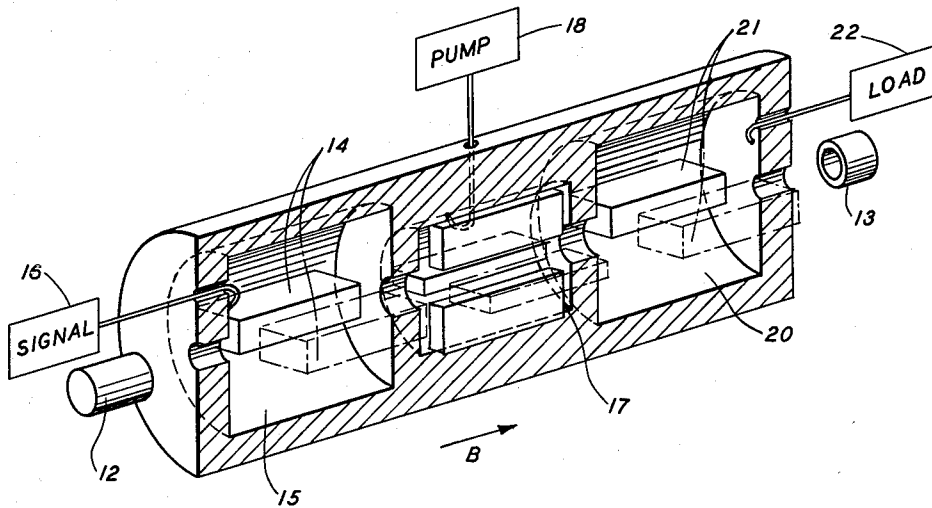


FIG. 2

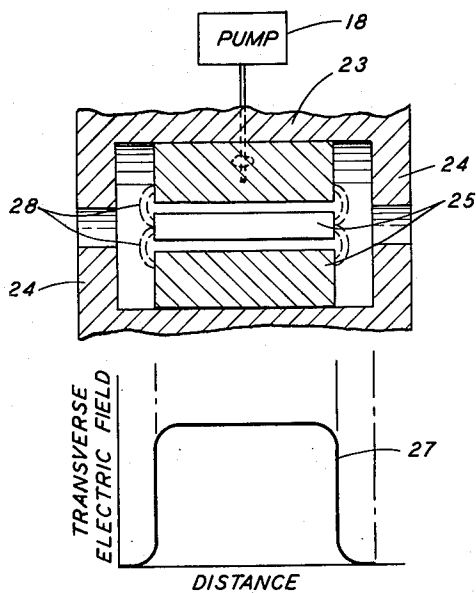
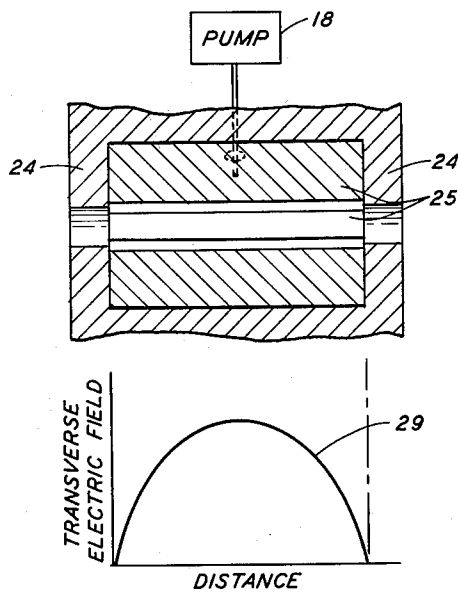


FIG. 3



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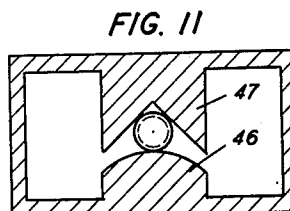
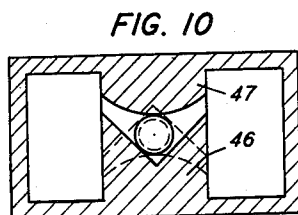
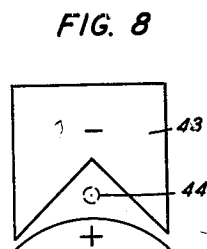
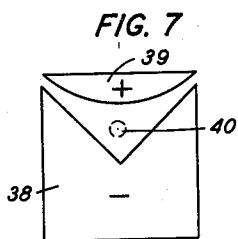
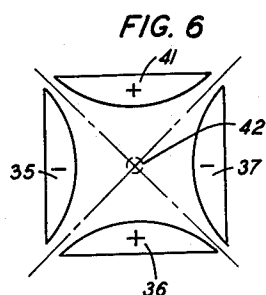
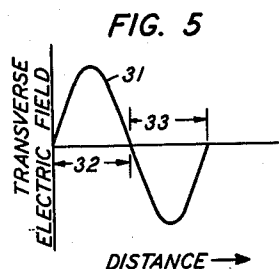
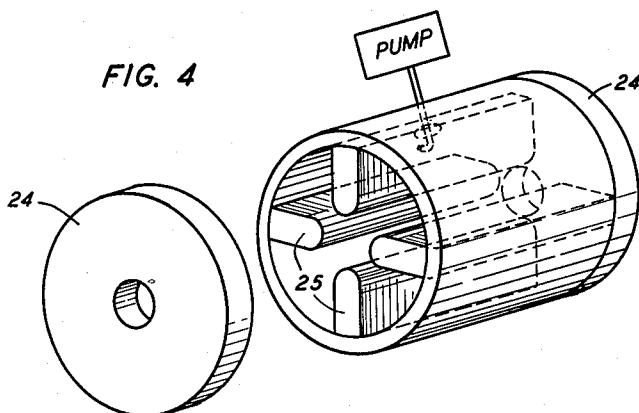
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FIG. 9

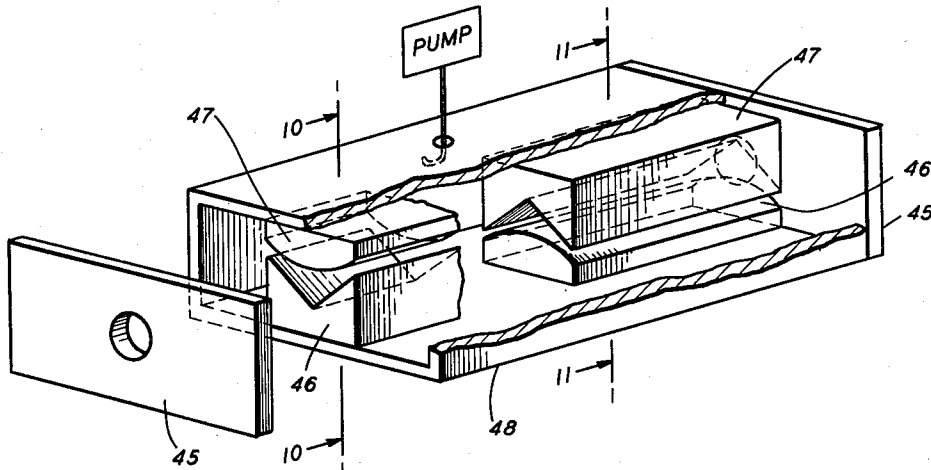
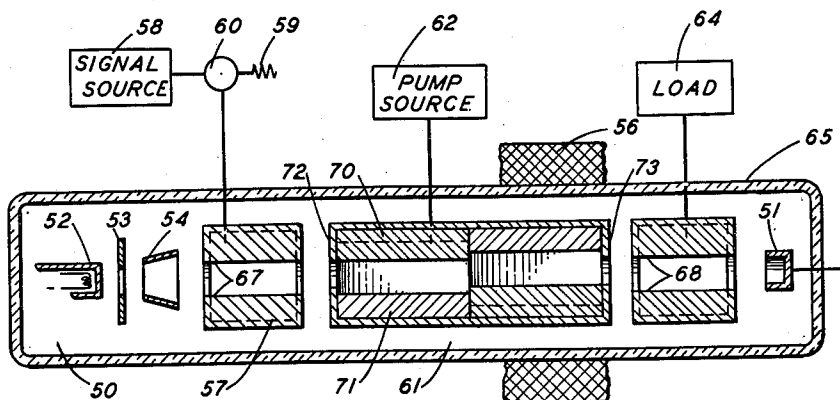


FIG. 12



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3,085,207

PARAMETRIC AMPLIFIER

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5 Claims. (Cl. 330-4.7)

This invention relates to electron beam devices and more particularly to cyclotron wave parametric amplifiers.

One of the serious drawbacks of electron beam amplifiers, such as the klystron and traveling wave tube, has been the spurious noise which necessarily accompanies the generation of an electron beam. A recent important advance in the art is the cyclotron wave parametric amplifier, known also as the quadrupole amplifier. By employing the principles of fast cyclotron wave parametric amplification, this device permits the direct removal of beam noise energy which would otherwise couple to the signal wave during the amplification process.

The electron gun of this device produces a beam that flows successively through an input coupler, a quadrupole amplifying resonator, and an output coupler. The beam is immersed in a uniform magnetic field which establishes a cyclotron frequency at which the electrons will rotate if acted upon by forces transverse to the field.

The input coupler is a resonant circuit that is tuned to the cyclotron frequency, and comprises a pair of parallel poles on opposite sides of the beam. When the input coupler is excited by a signal wave, electric fields are produced between the poles which are capable of exciting a signal cyclotron wave on the beam. Conversely, signal cyclotron wave noise energy, which is inherent in the beam, is transferred to the input coupler and can thereafter be dissipated. The pump resonator is excited by pump power which is usually twice the cyclotron frequency; this pump power interacts with the beam to amplify the signal cyclotron wave. A necessary condition for amplification is the production of quadrupole electric fields throughout the beam within the pump coupler; hence the term "quadrupole amplifier." The output coupler is identical with the input coupler and it extracts the amplified low noise signal wave from the beam.

Although the cyclotron wave parametric amplifier, as presently used, is capable of amplification with relatively low noise figures, even lower noise amplification is desirable. I have found that when the electron beam enters the quadrupole pump coupler of this device, it experiences a rather abrupt change of electric field. This abrupt transition may convert inherent synchronous wave noise into cyclotron wave noise, and thereby impair tube performance. The nature of synchronous waves is discussed in the patent of J. W. Kluver, No. 2,999,959 granted September 12, 1961.

Noise may also be introduced in the cyclotron mode of the beam by virtue of the electric fringing fields extending from the upstream and downstream ends of the pump resonator. These fringing fields have components that are parallel with the beam (longitudinal components) which may couple with the space-charge mode of the beam and thereby introduce space-charge wave noise to the signal wave. The nature of space-charge waves is also discussed in the aforementioned Kluver application.

Another drawback of the cyclotron wave parametric amplifier is the fact that the pump resonator can only be a half wavelength long. If the pump resonator is a full wavelength long, electric fields produced throughout the beam will reverse direction at the midpoint of the coupler. Hence, electrons that gain energy in the upstream half of the coupler, will lose energy in the downstream half and vice versa, and there will be no net amplification

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of the signal cyclotron wave. The length limitation of the pump resonator can be a very important consideration because the cyclotron wave gains energy as an exponential function of distance. Additional gain can theoretically be achieved by using two or more pump couplers between the input and output couplers. If this is done, however, each successive pump coupler must be very carefully positioned so that the successive pump fields are in spatial synchronism. This type of amplification is also relatively inefficient because the exponential gain with respect to distance is successively terminated.

It is an object of this invention to reduce the noise figure in a cyclotron wave parametric amplifier.

It is another object of this invention to increase the gain attainable in a cyclotron wave parametric amplifier without resorting to complicated fabrication techniques or multiple resonators.

It is still another object of this invention to increase the efficiency of a cyclotron wave parametric amplifier.

The pump resonator of a cyclotron wave parametric amplifier which is used at microwave frequencies is usually box-like or cylindrical, and has an apertured end plate at opposite ends to permit passage of the electron beam. It is a feature of this invention that the poles of the pump coupler extend the entire distance between the two end plates. Under this condition, the electric field distribution, with respect to distance, will be substantially the form of a half wavelength sinusoid. Accordingly, the electron beam gradually enters and leaves the pumping field, and the mixing of synchronous and cyclotron waves, that normally occurs upon an abrupt change of electric field, is substantially reduced. Further, there are no fringing fields around the input and output ends of the coupler because the electric field potential at those points is zero.

It is another feature of this invention that the pump resonator contain two poles each having a curved surface along half of its length and a V-shaped surface along the other half. In my co-pending application, Serial No. 23,526, filed April 20, 1960, it is shown that three of the poles of a quadrupole pump resonator can be replaced by a single V-shaped pole having an instantaneous polarity opposite that of the fourth pole. The direction of the pump fields with respect to the beam at a given instant in time depend upon which three poles have been replaced by the V-shaped pole. It is therefore possible, in accordance with my invention, to use a pump resonator that is a full wavelength long, by making each of the poles V-shaped along half of its length, and curved along the other half. The electron beam then experiences two positive half wavelength sinusoids of electric field, rather than a positive and a negative half wavelength sinusoid, as would normally be the case with a full wavelength pump coupler.

These and other objects and features of my invention will be more fully understood from a consideration of the following detailed description, taken in conjunction with the accompanying drawings, in which:

FIG. 1 is a schematic illustration of a conventional cyclotron wave parametric amplifier;

FIG. 2 is a sectional view of the microwave frequency pump resonator of the amplifier of FIG. 1;

FIG. 3 is a sectional view of the microwave frequency pump resonator in accordance with one aspect of this invention;

FIG. 4 is a perspective view of the resonator of FIG. 3;

FIG. 5 is a graph illustrating electric field intensity with respect to distance in a cavity resonator that is one wavelength long;

FIGS. 6, 7, and 8 illustrate the effect of substituting a V-shaped pole for a set of three poles in a quadrupole pump coupler;

FIG. 9 is a perspective view of a pump resonator in accordance with this invention;

FIG. 10 is a section taken along lines 10—10 of FIG. 9;

FIG. 11 is a section taken along lines 11—11 of FIG. 9; and

FIG. 12 is a schematic illustration of cyclotron wave parametric amplifier employing the principles of my invention.

Referring now to FIG. 1, there is shown a schematic illustration of a conventional microwave frequency cyclotron wave parametric amplifier. The device comprises an electron gun 12 for forming and projecting an electron beam toward a collector 13. A magnet (not shown) produces a longitudinal magnetic field B for focusing the beam and establishing cyclotron modes of propagation within the beam. An input coupler 15, comprising a resonant circuit that is tuned to the cyclotron frequency, modulates the beam with signal frequency energy from source 16, and removes fast cyclotron wave noise from the beam. The modulation results from transverse signal electric fields produced between parallel poles 14; inherent beam noise excites transverse electric field energy on poles 14, which can be conveniently removed. After modulation, the signal frequency energy propagates as a cyclotron wave. The beam then passes through a quadrupole pump resonator 17 which is normally tuned to twice the cyclotron frequency and is excited by pump power from a source 18. The pump resonator transfers energy from source 18 to the cyclotron mode on the beam, thereby amplifying the signal cyclotron wave. An output coupler 20, comprising parallel poles 21, extracts the amplified signal frequency energy from the beam and transmits it to an appropriate load 22.

Although the signal, pump, and output resonators are shown as portions of a single block, each could constitute a separate and distinct element. FIG. 2 illustrates in cross-section a conventional quadrupole pump resonator that could be either a separate element or a portion of a block as shown in FIG. 1. The resonator comprises an outer wall 23, two end plates 24, and four poles 25, only three of which are shown. Central apertures in the end plates 24 permit passage of the electron beam. This type of structure produces a well-defined transverse quadrupole electric field throughout the beam. Curve 27 is a graph showing the variation of the electric field intensity produced by the cavity versus distance along the cavity axis.

I have found that this type of quadrupole electric field increases the noise figure of the device by converting synchronous wave noise to cyclotron wave noise. As is known, the signal cyclotron wave is defined by the relative phase positions and radii of gyration of successive rotating electrons. Spurious synchronous waves are defined by the relative displacement of successive electrons from the central axis of the device. The quadrupole electric field of FIG. 2 constitutes an abrupt discontinuity which will cause displaced electrons to rotate and will cause rotating electrons to be displaced from their normal positions. This process amounts to a mixing of the cyclotron and synchronous waves of the beam, with an accompanying transfer of energy between them. Since synchronous wave noise has not been extracted from the beam, the conversion process introduces noise to the signal cyclotron wave.

Noise may also be introduced by virtue of the fringing electric fields 28 of FIG. 2. These fields invariably have longitudinal components which may couple with spurious space-charge waves on the beam. As is known, space-charge waves are defined by successive compressions and rarefactions of electron density, and can be modulated or demodulated by electric fields that are parallel with the path of flow of the beam. Like synchronous wave noise, the space-charge wave noise is not extracted from the beam. If it couples with the quad-

ruple electric fields, it may be introduced to the signal cyclotron wave, and undesirably increase the noise content at the output.

These disadvantages may be overcome by constructing the resonant pump coupler as shown in FIGS. 3 and 4. The resonators of FIGS. 3 and 4 are designed to be one-half wavelength long at the pump frequency. The four poles 25 extend the entire distance between end plates 24. Under these conditions, the electric field distribution along the beam will be in the form of a half wavelength sinusoid as shown by curve 29. This being the case, the beam will enter the quadrupole field relatively gradually, rather than experiencing an abrupt discontinuity. As a consequence, spurious displacements of electrons will be relatively unaffected and the conversion of synchronous waves to cyclotron waves will be greatly reduced or eliminated.

Further, because of its sinusoidal distribution, the electric field at the input and output ends of the pump coupler is zero. There are therefore no fringing fields, as in the coupler of FIG. 2 and no danger of space-charge wave noise being coupled to the signal cyclotron wave.

A common drawback of both of the devices of FIGS. 2 and 3 is their length limitation. If the resonator of FIG. 3 is a full wavelength long, the electric field will reverse direction at the resonator midpoint, as shown by curve 31 of FIG. 5. As is known, roughly half of the electrons of a cyclotron wave parametric amplifier enter the pump resonator in a proper phase position to gain energy, while the other half lose energy. If the electric field reverses direction as shown in FIG. 5, the electrons that gain energy along the upstream portion 32 will lose energy along the downstream portion 33 because of the reversed direction of the quadrupole field. Hence, there will be no net signal wave amplification.

It is possible, in accordance with my invention, to construct a full wavelength coupler, as will be appreciated from a consideration of FIGS. 6 through 9. In my aforementioned co-pending application, it is disclosed that three of the poles of a quadrupole pump coupler can be replaced by a single V-shaped pole that has an instantaneous polarization opposite that of the fourth pole. This replacement is illustrated in FIGS. 6 and 7 wherein poles 35, 36, and 37 of FIG. 6 are replaced by a V-shaped pole 38 of FIG. 7. The polarity shown on the poles 38 and 39 of FIG. 7 has the same effect on an electron beam 40 as the polarity shown on poles 35, 36, 37, and 41 of FIG. 6 has on electron beam 42. In other words electrons that would be in a phase position to gain energy in the arrangement of FIG. 7, would likewise be in a phase position to gain energy in the device of FIG. 6.

FIG. 8 illustrates the replacement of poles 35, 41, and 37 of FIG. 6 by a single V-shaped pole 43. Again the polarity shown in FIG. 8 has the same effect on an electron beam 44 as the polarities of poles 35, 36, 37, and 41 of FIG. 6 has on beam 42. Notice, however, that the uppermost pole 43 of FIG. 8 has a polarity opposite that of the uppermost pole 39 of FIG. 7. In spite of this polarity difference, the electrons that gain energy in beam 44 of FIG. 8 are of the same instantaneous phase as the electrons that gain energy in beam 40 of FIG. 7. This phenomenon is employed in a manner shown in FIG. 9 to permit the use of a full wavelength pump coupler.

FIG. 9 illustrates two poles 46 and 47 that are mounted within a full wavelength cavity resonator 48 having a pair of end plates 45. Because poles 46 and 47 extend the entire distance between end plates 45, the electric field distribution along the length of resonator 48 is a full wavelength sinusoid as shown by curve 31 of FIG. 5. At the upstream end of the resonator, pole 47 has a curved surface while pole 46 has a V-shaped surface as shown in FIG. 10. At the downstream end, these configurations are reversed as shown in FIG. 11.

This configuration reversal compensates for the electric field reversal that occurs at the midpoint of the resonant pump coupler. Although the instantaneous polarity of both poles 46 and 47 reverse direction at their midpoint, electrons that are in proper phase position to gain energy continue to gain along the entire length of the coupler.

The employment of my inventive concepts in a cyclotron wave parametric amplifier is illustrated in FIG. 12. An electron beam is formed by an electron gun 50 and projected toward a collector 51. Electron gun 50 is shown as comprising a cathode 52, a focusing electrode 53 and an accelerating electrode 54. The operation of the device is substantially the same as that of the device of FIG. 1. A magnet 56 surrounds the device and produces a longitudinal magnetic field that focuses the beam and establishes a cyclotron mode of wave propagation. An input coupler 57 transfers signal wave energy from a source 58 to the cyclotron mode of the beam and extracts noise wave energy at the signal frequency from the beam which is transmitted to, and dissipated by, an impedance 59. A circulator 60 directs signal energy from source 58 to input coupler 57, and directs noise energy from coupler 57 to impedance 59. A pump coupler 61 provides amplification of the signal cyclotron wave on the beam by transferring pump wave energy from a source 62 to the beam. An output coupler 63 extracts the amplified signal wave from the beam which is then transmitted to an appropriate load 64. The entire device is maintained in a substantial vacuum by an envelope 65.

Input coupler 57 and output coupler 63 are resonant circuits that are tuned to the mean signal frequency, which is substantially equal to the cyclotron frequency. Parallel poles 67 and 68 of the input and output couplers correspond, respectively, to parallel poles 14 and 21 of FIG. 1. Poles 67 may advantageously extend the entire distance between the walls of input coupler 57, as shown, so that the electric field distribution produced within the electron beam is in the form of a half wavelength sinusoid. With this type of structure, the beam will enter the signal frequency electric field gradually, and there will be no danger of synchronous wave-cyclotron wave mixing. In most applications, however, the signal frequency electric field is very weak and the effects of such mixing may be negligible, in which case the input coupler may take a more conventional form. The parallel plates of the input and output couplers therefore need not necessarily extend the entire length of the coupler.

The power delivered to the beam by the pump resonator 61, however, is usually many times that of the input coupler. In accordance with my invention, the poles 70 and 71 of the pump coupler extend the entire distance between end plates 72 and 73 so that a sinusoidal distribution of the pump field is produced along the beam. Since the electric field intensity at end plates 72 and 73 is zero, no fringing fields are produced, and there is no danger of space-charge wave noise being coupled to the signal cyclotron wave. Further, there can be substantially no mixing of the synchronous and cyclotron waves because the beam enters and leaves the pump field gradually.

In order that maximum gain and efficiency is attained, pump resonator 61 is a full wavelength long at the pump frequency. This necessarily implies that the electric field reverses direction at the midpoint of the coupler. To compensate for this reversal, the configuration of poles 70 and 71 is reversed at the coupler midpoint as it best seen in FIGS. 9 through 11. Hence, electrons that are in a proper phase position to gain energy, continue to gain energy along the entire length of the coupler.

It is to be understood that the above-described arrangements are merely illustrative of the application of the principles of this invention. Numerous other arrange-

ments may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. An electron beam device comprising: means for forming and projecting an electron beam along a path; means adjacent said path for moulding said beam in a cyclotron mode; a cavity resonator adjacent said path having a pair of end plates; means within said resonator defining an interaction region; said last-mentioned means comprising two poles extending the entire length between said end plates, one of said poles having a V-shaped surface adjacent a first portion of said interaction region and a curved surface adjacent a second portion of said interaction region, the other pole having a curved surface adjacent said first portion of the interaction region and a V-shaped surface adjacent said second portion of the interaction region.
2. Electron beam pumping apparatus comprising: a source of pump frequency energy; a resonator connected to said source which is substantially one wavelength long at said pump frequency; two poles within said resonator each having a curved surface along half of its length and a V-shaped surface along the other half of its length; the curved surface of each of the poles being adjacent and opposite the V-shaped surface of the other pole.
3. An electron discharge device comprising: means for forming and projecting an electron beam along a path; a source of signal frequency energy; means for modulating said beam with signal frequency energy; means for amplifying said signal frequency energy comprising a pump resonator that is connected to a source of pump frequency energy; said pump resonator comprising two poles extending axially on opposite sides of said path, one of the poles having a V-shaped surface adjacent a first portion of the path and a curved surface along a second portion of the path, the other pole having a curved surface along said first portion of the path and a V-shaped surface along said second portion of the path; and means for extracting said signal frequency energy from said beam.
4. A cyclotron wave parametric amplifier comprising: means for forming and projecting an electron beam along a path; means for producing a magnetic field along said path thereby establishing a cyclotron mode of wave propagation within the beam; a source of signal frequency wave energy; means for causing said signal frequency energy to propagate within said beam as a cyclotron wave; said last-mentioned means comprising a first cavity resonator surrounding a portion of said path and having a pair of parallel poles on opposite sides of the path which extend the entire length of said first resonator, whereby the signal energy is applied to the beam as a sinusoidal function of distance and the beam experiences a gradual change of electric field; a source of pump frequency energy; means for applying said pump frequency energy along part of said path as a sinusoidal function of distance, whereby said beam experiences a gradual change of electric field; said last-mentioned means comprising a second cavity resonator having a pair of end plates and two poles extending parallel with said path the entire distance between the end plates; one of said poles having a V-shaped surface adjacent a first portion of said path and a curved surface adjacent a second portion of said path, the other pole having a curved surface adjacent said first portion of the path and a V-shaped surface adjacent said second portion of the path; and means comprising a third cavity resonator for extracting said signal frequency energy from said beam.
5. A cyclotron wave electron beam device comprising: means for forming and projecting a beam of electrons along a path; means for producing a magnetic field along said path; means for imparting rotational kinetic energy to said electrons; means for amplifying said rotational energy comprising a pump frequency source; a resonator coupled to said source for applying pump frequency elec-

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tric field energy to said beam; said resonator being a full wavelength long at said pump frequency, whereby the direction of the instantaneous electric fields produced in the beam reverse direction at the midpoint of the resonator; means for maintaining a consistent phase relationship between said electric fields and said rotating electrons comprising two poles within the resonator disposed on opposite sides of said beam; each of said poles having a curved surface along half of its length and a V-shaped

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surface along the other half of its length; the curved surface of each of the poles being adjacent and opposite the V-shaped surface of the other pole; and means for extracting rotational kinetic energy from said beam.

References Cited in the file of this patent**FOREIGN PATENTS**

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