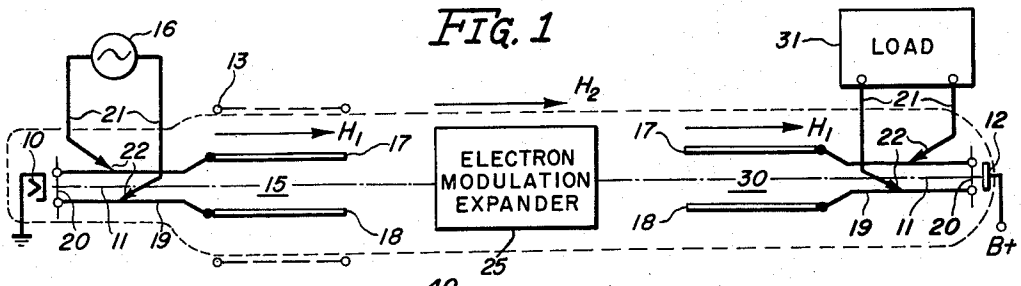
Nov. 8, 1960 R. ADLER 2,959,740

PARAMETRIC AMPLIFIER MODULATION EXPANDER

Filed May 1, 1959

FIG. 1



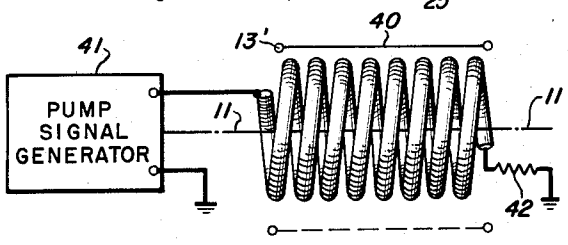


FIG. 2

FIG. 3a

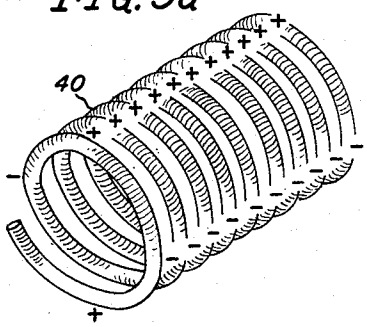


FIG. 3b

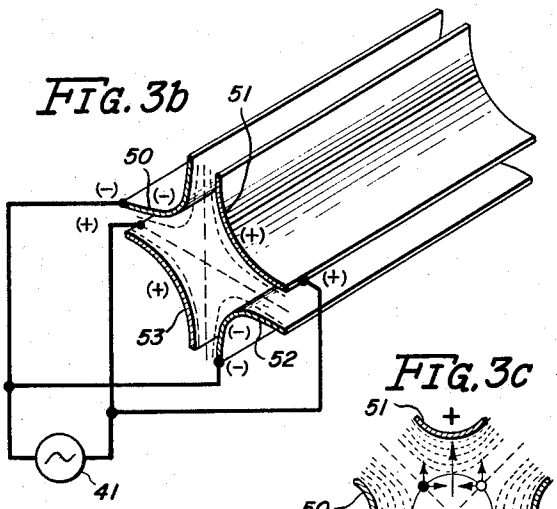
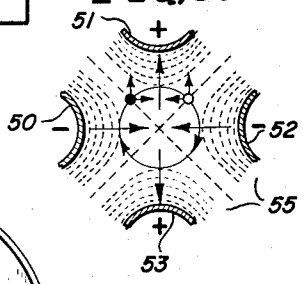


FIG. 3c



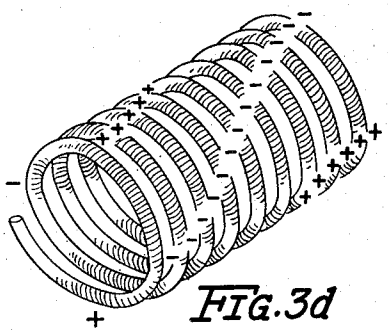
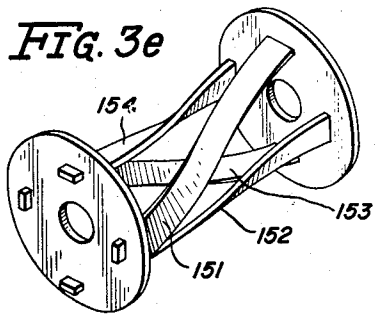


FIG. 3d

FIG. 3e



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PARAMETRIC AMPLIFIER MODULATION EXPANDER

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4 Claims. (Cl. 330—5)

The present invention is directed generally to parametric amplifiers of the fast wave transverse field type and concerns in particular the construction of a modulation expander for such an amplifier.

Parametric amplifiers may employ longitudinal fields in place of transverse fields as explained in a copending application of Robert Adler, Serial No. 738,546, filed May 28, 1958 and assigned to the assignee of the present invention. The material considered herein, however, has particular application to the transverse mode device and further consideration of the parametric amplifier will be restricted thereto.

As explained in the Adler application, a transverse-mode parametric amplifier comprises an electron gun for projecting a beam of electrons along a predetermined path to a collector or final anode. A focusing field which may be established by means of a solenoid encompassing a portion of that path may establish electron resonance in the beam and a signal may be transferred to the beam by means of a coupling device which is excited from the signal source and which is arranged along the beam path for interaction with the stream. This coupler may be a lumped or a distributed device and may be employed for imparting signal energy to the beam while at the same time extracting fast transverse noise components carried by the beam into the field of the coupler or input signal modulator as it is sometimes called. The interaction of the modulator and stream modifies the electron motion in accordance with the signal energy, causing the electrons to assume a helical or orbital path of travel under the influence of the signal.

Amplification of the signal carried by the stream is accomplished by means of a structure referred to as an electron modulation expander which expands the electron motion of the stream. One especially attractive form of modulation expander is the quadrupole structure described and claimed in a copending application of Glen Wade, Serial No. 747,764, filed July 10, 1958 and assigned to the assignee of the present invention.

The quadrupole structure is an arrangement of four electrodes excited in a particular relation by a pumping signal to establish an inhomogeneous electric field alternating at twice the electron resonance frequency. The field forces acting upon the electrons of the stream as it traverses the modulation expander occasion a net exponential growth of electron motion and thus gain of the signal carried by the stream.

Interposed between this modulation expander and the final collector is an output coupler or demodulator which, in the usual construction, is identical to the input modulator. It extracts the amplified signal energy from the beam for application to a load.

The described structure has been found to operate very satisfactorily in accomplishing parametric amplification of applied signals. It will be recognized that the quadrupole modulation expander is a lumped as distinguished from a distributed type of circuit structure having a high

Q. It functions optimally at a particular pumping frequency.

As an incident to the modulation expansion, a signal component referred to as an idler wave is established on the stream as a modulation product. This phenomenon is explained in both the Adler and Wade applications and is related to the pumping and signal frequencies in accordance with the following equation:

$$\omega_3 - \omega_1 = \omega_2 \quad (1)$$

where ω_1 is the signal frequency, ω_2 is the idler frequency and ω_3 is the pumping frequency.

It is apparent from Equation 1 that a modulation expander capable of efficient operation over a band of pumping frequencies permits flexibility in the selection of operating frequencies to effect amplifiction at a particular signal frequency. More particularly, it affords a choice of pumping frequency by means of which the idler component may be adjusted as to frequency and this may be highly desirable in particular installations. For example, if in a given installation it is found that an idler frequency of a particular value is undesirable because of the environment, the pumping frequency may be changed to displace the idler frequency-wise to avoid this objection. The arrangement to be described herein facilitates achieving this flexibility in the modulation expander of a parametric amplifier.

Accordingly, it is an object of the invention to provide a novel modulation expander for a fast wave transverse-mode parametric amplifier.

It is a particular object of the invention to provide a novel modulation expander for a parametric amplifier characterized by the fact that it may accommodate pumping frequencies within a selected frequency band.

A fast wave transverse-mode parametric amplifier employs an electron beam modulated with signal energy and projected along a predetermned path to a parametric modulation expander. Such an expander, in accordance with the instant invention, functions over a band of pumping frequencies centered about a given frequency. The expander comprises a transmission line wrapped about a portion of the beam path in accordance with a generally helical pattern so dimensioned that each turn of the helical pattern has an effective electrical length equal to twice the wave length at the aforesaid given or center frequency of the band of pumping frequencies.

The features of the present invention, together with further advantages and benefits thereof, will be more clearly understood from the following description of particular embodiments thereof taken in conjunction with the annexed drawing in the several figures of which like components are designated by similar reference characters and in which:

Figure 1 is a schematic diagram of one form of fast wave transverse-mode parametric amplifier to which the modulation expander of this invention is especially adapted;

Figure 2 represents a modulation expander embodying the invention;

And Figures 3*a* to 3*e* are explanatory views used in describing the operation of the subject expander and its relation to the quadrupole type of modulation expander described and claimed in the above-identified Wade application.

Referring now more particularly to Figure 1, the parametric amplifier there represented comprises a source or electron gun **10** for developing and projecting a stream or electron beam along reference path **11**, **11**. The beam source may be entirely conventional and preferably includes the usual cathode together with suitable focusing and accelerating electrodes for developing a well-defined beam of electrons. For convenience of illus-

tration, this source has been represented merely by the usual symbol for an indirectly heated cathode. An electron beam collector **12** is disposed at the end of the path remote from source **10** and usually takes the form of an anode biased at a positive potential with respect to the cathode as indicated by potential source +B.

The amplifier has means for creating in the beam path a field for establishing electron resonance in the beam traversing that path. While electron resonance may be established through the agency of a magnetic or an electrostatic field, the arrangement in question is indicated as a solenoid **13** surrounding the beam path to establish lines of magnetic flux parallel thereto and of a strength establishing a selected cyclotron frequency for electron motion. The focusing field of the solenoid is indicated symbolically by arrow H_1.

Also spaced along beam path **11**, there are means for modulating the electron beam in response to an applied signal frequency. This modulating means is an electron coupler capable of imparting energy to the beam in response to signal energy received from a source **16**. Different forms of coupling structures may be employed in parametric amplifiers of the transverse-mode type. They may, by way of illustration, be resonant cavities, transmission lines, or deflection plates spaced alongside the beam for interaction therewith. As illustrated, modulator **15** includes a pair of deflector plates **17, 18** located on opposite sides of the beam path. For coupling signal source **16** to the modulator, a transmission line **19** having one end **20** short-circuited is coupled at its opposite end to deflectors **17, 18**. A transmission link **21** is tapped as indicated at **22** onto transmission line **19** in a position adjusted to match the impedance of source **16** to that presented by deflectors **17, 18**. Transmission line **19** has an effective electrical length of one quarter wave length at the frequency of the signal from source **16**.

Amplification is obtained in the parametric type of amplifier by means of a modulation expander for expanding the signal modulation of the beam. A modulation expander **25** is shown in block form in Figure 1 and its structure will be described in detail hereinafter. Suffice it for the moment to say that the modulation expander is a structure within which is established a restoring force or suspension for the electrons of the beam. This may conveniently be accomplished by the creation of a homogeneous magnetic focusing field represented symbolically by the arrow H_2 which establishes electron or cyclotron resonance of the same value as that of input coupler **15**. This focusing field may be developed by a separate solenoid included within the modulation expander but it is more convenient structurally to make use of a single elongated solenoid which encompasses not only the input modulator **15** but also modulation expander **25** and an output coupler **30** further along the beam path than the modulation expander and provided for a purpose to be considered presently.

Energy from which signal amplification is eventually derived is supplied by means of a driving or pumping signal generator included in expander **25** to produce an alternating inhomogeneous field having a frequency of approximately twice the cyclotron frequency. The time varying inhomogeneous field varies the stiffness of the electron suspension created by field H_2 periodically so as to impart energy to the electron motion.

As previously indicated, still further along beam path **11**, between modulation expander **25** and anode **12**, is an output coupler or demodulator **30** serving to extract the amplified signal from the beam for application to a load **31**. The output coupler is identical in structure to input coupler **15** and its component parts bear identical reference characters.

As thus far described the system of Figure 1 is a parametric amplifier of the general type described in both the Adler and Wade applications. If the modulation expander **25** is a quadrupole type of structure, the arrangement is then identical to that of the Wade application and further identical to that described in an article entitled Parametric Amplification of the Fast Electron Wave by Robert Adler, published in "Proceedings of the IRE," volume 46, No. 6, June, 1958 and a companion paper entitled A Low Noise Electron Beam Parametric Amplifier by Robert Adler, George Hrbek and Glen Wade published in the same publication, Volume 46, No. 10, under date of October, 1958.

In operation, an electron beam issued from source **10** enters the field of the input coupler or modulator **15** wherein it is modulated with the applied signal from source **16**. It may be assumed that the signal frequency is essentially the same as the electron resonant frequency established by focusing field H_1 and interaction of the beam and input modulator results in transferring signal energy from deflection plates **17, 18** to the beam. At the same time, fast wave electron beam noise or other fast wave signal components carried by the beam are surrendered to the input coupler, purging the beam of undesired signal components. The beam, as it leaves modulator **15**, is characterized by electrons moving in an orbital or helical path such that the electron motion represents the applied signal. The time varying inhomogeneous field of the modulation expander **25** created under the influence of the pumping signal source expands the elcetron motion and effects amplification of the signal carried by the beam. The beam then enters output coupler **30** and the amplified signal is extracted from the beam and delivered to load **31**.

More detailed consideration will now be given to the structure of modulation expander **25** with particular reference to Figure 2. As there represented, the expander is a transmission line **40** which is wrapped about a portion of beam path **11** intermediate the input and output couplers. Preferably, the expander is in the form of a double helix in that the transmission line is itself a helix and the line is wrapped in accordance with a generally helical pattern of such dimension that the effective electrical length of each turn of the helical pattern is equal to twice the wave length of the center frequency of a desired band of pumping frequencies. The line is constructed to be substantially dispersionless over this band, that is to say, the line is constructed to exhibit a substantially constant velocity of wave propagation over the band. This may be achieved with a distributed transmission line structure over a band of useful width.

Of course, the structure including the electron beam source **10**, input and output modulators **15** and **30**, helix **40** of modulation expander **25** and collector or anode **12** is housed within a tube envelope as represented by the broken-line construction and as described in both the above-identified Adler and Wade applications. Consequently, any conventional supporting device may be adapted to the end that transmission line **40** is mechanically secured within the envelope in proper space relation to the beam path. For example, it is entirely appropriate to support the outside of helix **40** between three or four insulating supporting rods arranged parallel to the beam path **11**. The coil **13'** indicates the magnetic focusing structure for establishing the desired cyclotron frequency but, as pointed out earlier, in practical constructions of the tube a single elongated solenoid is employed to incorporate modulators **15** and **30** and the modulation expander.

One end of transmission line **40**, the end adjacent input modulator **15**, is coupled to a pump signal generator **41**. This may be a conventional oscillator tunable over a desired band of pumping signal frequencies. The opposite end of the transmission line is terminated in a resistor **42** selected to provide a matching termination for the line to avoid undesirable reflections.

In order to avoid undesirable electrostatic lens effects along the path of travel of the electron stream, suitable direct current potentials may be applied from a source

(not shown) to the deflection plates of modulators **15** and **30** and to helix **40** of the modulation expander.

The operation of the modulation expander of Figure 2 will be explained with reference to Figures 3*a*–3*c* and it will be assumed initially that pump signal generator **41** has been adjusted in frequency to the center of its operating frequency range. It will be further assumed that this frequency is twice the cyclotron frequency. For the assumed conditions, each turn of the helix defined by transmission line **40** has an effective electrical length that is twice the operating wave length of the pump generator. The potential distribution of Figure 3*a* is established at some instant on the turns of the helix **40**. The top and bottom portions of each turn are at a peak positive potential whereas the left and right hand portions of each turn, midway between the top and bottom, experience peak negative values. Since this potential distribution is true of every turn of the helix for the assumed conditions, the expander is fully analogous to the quadrupole structure described in the Wade application and in the Adler et al paper in the October, 1958 Proceedings of the IRE.

The quadrupole structure is represented in Figure 3*b* and comprises four electrodes **50**, **51**, **52** and **53** symmetrically disposed circumferentially around the beam path **11**. Each electrode has the shape of an equilateral hyperbola and the electrodes are disposed with their intermediate portions facing the beam path and their terminal portions projecting outwardly therefrom with each terminal portion spaced generally parallel from the adjacent terminal portions of the neighboring electrodes. Oppositely disposed electrodes **50**, **52** are coupled to one terminal of pump generator **41** and the other pair of oppositely disposed electrodes are coupled to the opposite terminal of the pump. At the instant in question, electrodes **51** and **53** are positive while electrodes **50**, **52** are negative. Accordingly, a symmetrical quadrupole field is developed within the space enclosed by the electrodes.

The shape of this field is indicated by the equipotential lines **55** of Figure 3*c*. The circular path within the field of the quadrupole represents the orbit of the electrons which is coursed at the cyclotron frequency and the four arrows along the axes show the forces exerted upon the electrons in the four regions or quadrants of the structure. The electron represented by the filled smaller circle at the top left of the electron orbital path encounters the forces indicated which accelerate it along its clockwise path. Another electron, shown as an empty circle at the top right of the electron path, is subjected to forces which decelerate its orbital motion. It is to be noted that there is no field at all at the center of the quadrupole and that the field intensity increases linearly with distance from the center. As a consequence, the forces exerted upon an orbiting electron are proportional to the radius of the circle in which it moves so that the radius must increase or decrease exponentially.

This amplification mechanism may be viewed by resolving the alternating quadrupole field pattern into two counter-rotating component patterns in the manner commonly employed in analyzing rotating electrical machines. Because the structure at hand has four poles, the component patterns complete one revolution for every two cycles of the pump frequency. Thus one of the patterns revolves synchronously with the orbiting electrons; the other one may be neglected. An electron which enters in the best phase condition with respect to the synchronous pattern remains in that phase throughout its passage through the quadrupole and it may also be shown that a phase-focusing process exists whereby an electron which enters with an intermediate phase is shifted toward the best phase position.

While the field pattern within the modulation expander of the present invention, featuring a helical transmission line disposed in a helical pattern about the beam path, is not identically the same as that of the quadrupole structure of Figure 3*c*, they are indeed very similar and accomplish amplification in the same way.

The field of a quadrupole having electrodes of hyperbolic configuration is described by the equation:

$$V=V_0\ (y^2-x^2) \tag{2}$$

where, V_0 is proportional to the instantaneous potential applied to quadrupole electrodes and, x and y are Cartesian coordinates. Equation 2 may be transferred to polar coordinates by substituting the usual conversion factors for x and y as follows:

$$x=r\ \cos\ \theta \tag{3}$$
$$y=r\ \sin\ \theta \tag{4}$$

Accordingly, Equation 2 may be rewritten as follows:

$$V=V_0r^2\ (\sin^2\ \theta-\cos^2\ \theta) \tag{5}$$

and by means of a trigonometric identity, Equation 5 converts into:

$$V=-V_0r^2\ \cos\ 2\ \theta \tag{6}$$

For a circle of constant radius r the potential is thus seen to be a cosine function of the azimuth θ, experiencing two complete cycles in one traverse around the circle. This is precisely the potential distribution along the circumference of the helical modulation expander of the present invention in a case where the pump frequency is twice the cyclotron frequency.

A significant difference does, however, exist between the quadrupole type of modulation expander and the helical modulation expander of Figure 2. As the pump wave travels around the circumference of the helical expander, the quadrupole field which it establishes within the expander rotates in a single direction, namely, the direction of wave travel around the helix. On the other hand, the application of an alternating voltage to the quadrupole structure of Figure 3*b* establishes a field which can be represented by two counter-rotating component patterns. As explained above, only one of these component patterns is utilized for amplification. With the present invention, the sense of pattern rotation is chosen to be consistent with the direction of the cyclotron magnetic field and no counter-rotating pattern is generated.

The condition of Figure 3*a* wherein the modulation expander of Figure 2 is the analogue of the quadrupole expander of Figure 3*b* results from the use of a pumping frequency which is twice the cyclotron frequency but there may be occasions when it is highly desirable to use a different pumping frequency. As explained earlier, this may be the case where one chooses to shift the frequency of the idler wave component which results as a modulation product in the process of expanding the modulation of the beam. If the selected pumping frequency is greater than twice the cyclotron frequency, the instantaneous potential distribution along helix **40** of the modulation expander at a given instant may be that represented in Figure 3*d* rather than that of Figure 3*a*. The result is an effective rotation of the quadrupole field within the expander as seen by electrons moving therethrough. This, of course, follows since at pump frequencies greater than twice the cyclotron frequency, the effective electrical length of each turn of the helix exceeds twice the wave length of the pump generator. This is analogous to a skewed quadrupole as represented in Figure 3*e* which is an expander structure described and claimed in the aforesaid Wade application. Its electrodes **150**—**153** are conductive strips skewed in a direction opposed to the direction of orbital movement of the electrons. Alternatively, the pumping signal frequency may be less than twice the cyclotron frequency which again results in effective rotation of the quadrupole field within the helix of the expander but this time in a direction opposite to that of Figure 3*e*, that is, skewed in the direction of orbital movement of the electrons. In either case the operation of the device in accomplishing expansion of the

beam motion is generally similar to that described in conjunction with Figures 3*a*–3*c*.

The axial propagation of the pump wave must be properly related to the velocity of electrons along the axial path **11, 11**. For the particular case in which the pump frequency is precisely that required to generate two cycles along the circumference of the helix, no specific relation between these two velocities is required. However, to accommodate operating conditions in which the pump frequency deviates from that nominal value, it is advantageous to design the helix, by appropriate selection of its parameters, to the end that the axial component of the propagation velocity corresponds with the velocity of the stream. If this is done and if the nominal pump frequency coincides with twice the cyclotron frequency, every electron keeps pace with a specific portion of the pump wave traveling about the circumference of the expander helix; this remains true regardless of the pump frequency, permitting the expander helix to be made as long as desired without limiting the range of usable pump frequencies.

Arrangements of the type represented in Figure 1 employing input and output couplers that use deflectors as a slow wave circuit for interacting with the beam are particularly suited to a condition of fast waves of infinite phase velocity on the beam; that is a condition in which the cyclotron frequency is the same as the signal frequency. In some installations it may be desirable to operate with a cyclotron frequency distinctly different from the signal frequency, being either higher or lower. This will result in fast waves of finite phase velocity developed on the beam in the input modulator but of the forwardly or backwardly directed type as explained in the Adler application, where forward is the direction from source **10** to anode **12** and backward is the opposite direction. For such finite phase conditions, more expeditious modulation of the beam with signal energy and stripping of undesired signal components carried by the beam into the input modulator is accomplished by the use of transmission line couplers. Modulation expansion and signal gain may be achieved with the arrangement of Figure 2 for either condition. In other words, the arrangement described is useful in different combinations of finite and infinite phase velocity phenomenon in the three sections constituted by the couplers and the modulation expander. Where different conditions of phase velocity are desired, it may be more appropriate to employ separate solenoids at these portions of the beam path in order to separately develop the focusing fields.

The described arrangement introduces a very desirable flexibility into the operation of the parametric amplifier and does so by means of a simplified structure. In particular it accommodates operation with a pumping frequency selected within a band of frequencies so that the relative frequencies of the signal and idler wave components may be adjusted in accordance with the requirements of individual installations.

While a particular embodiment of the invention has been shown and described, it will be obvious to those skilled in the art that changes and modifications may be made without departing from the invention in its broader aspects, and, therefore, the aim in the appended claims is to cover all such changes and modifications as fall within the true spirit and scope of the invention.

I claim:

1. In an amplifying system in which an electron beam modulated with signal energy is projected along a predetermined path, a parametric modulation expander for operation over a band of pumping frequencies centered about a given frequency comprising: a transmission line wrapped about a portion of said path in accordance with a generally helical pattern and having an electrical length per turn which is equal to twice the wave length at said given frequency.

2. In an amplifying system in which an electron beam modulated with signal energy is projected along a predetermined path, a parametric modulation expander for operation over a band of pumping frequencies centered about a given frequency comprising: a transmission line wrapped about a portion of said path in accordance with a generally helical pattern, having a substantially constant velocity of propagation over said band, and having an electrical length per turn which is equal to twice the wave length at said given frequency.

3. In an amplifying system in which an electron beam modulated with signal energy is projected along a predetermined path, a parametric modulation expander for operation over a band of pumping frequencies centered about a given frequency comprising: a helical transmission line wrapped about a portion of said path in accordance with a generally helical pattern, having a substantially constant velocity of propagation over said band, and having an electrical length per turn of said pattern which is equal to twice the wave length at said given frequency.

4. In a parametric type of amplifying system having a predetermined electron resonance frequency and in which an electron beam modulated with signal energy is projected along a predetermined path with a particular velocity, a parametric modulation expander for operation over a band of pumping frequencies comprising: a transmission line wrapped about a portion of said path in accordance with a generally helical pattern, having an electrical length per turn which is equal to twice the wave length at a pumping frequency corresponding to twice said resonance frequency and having an axial component of propagation velocity substantially equal to the velocity of said beam.

No references cited.