United States Patent

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Original application Feb. 20, 1967, Ser. No. 617,231, now Patent No. 3,501,706, dated Mar. 17, 1970. Divided and this application Aug. 14, 1969, Ser. No. 870,903

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[54] **WAVEGUIDE STRUCTURE WITH PSEUDOCAVITY REGION FOR CONSTRAINING PUMP AND IDLER ENERGIES**
8 Claims, 5 Drawing Figs.

[52] **U.S. Cl.** .... **333/83 R,** 333/98 R
[51] **Int. Cl.** **H01p 7/06**
[50] **Field of Search** .... 333/73 W, 83, 95, 98

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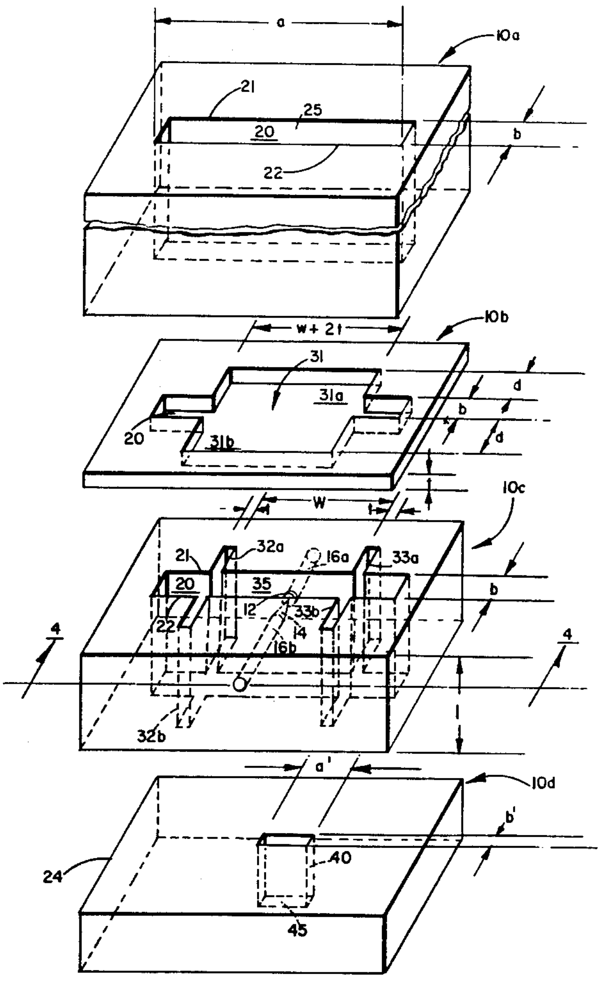
ABSTRACT: A noel waveguide structure usable in a broadband microwave parametric amplifier is described which comprises a rectangular waveguide with a pair of substantially U-shaped channels extending oppositely from the top and bottom of the waveguide to a depth of ¼ guide wavelength at the lower idler frequency. The channels define a pseudocavity region in the waveguide, within which region the idler and pump energy is constrained and parametric interaction occurs. The waveguide is of sufficient width to allow propagation of a signal in the lowest order transverse electric mode and contains a varactor diode as a nonlinear reactance to couple pump energy at a high frequency to a signal at a much lower frequency.



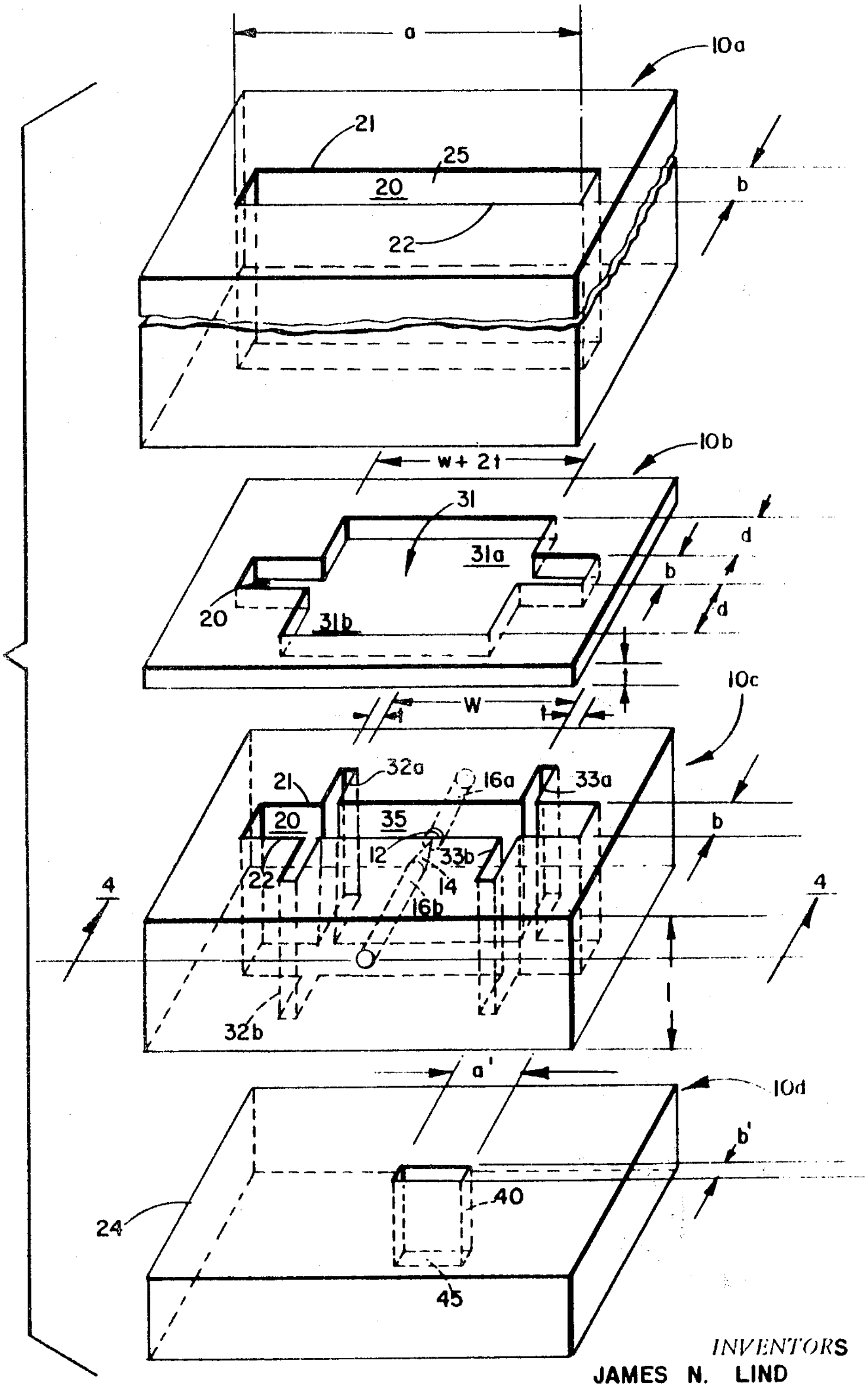


FIG. 1

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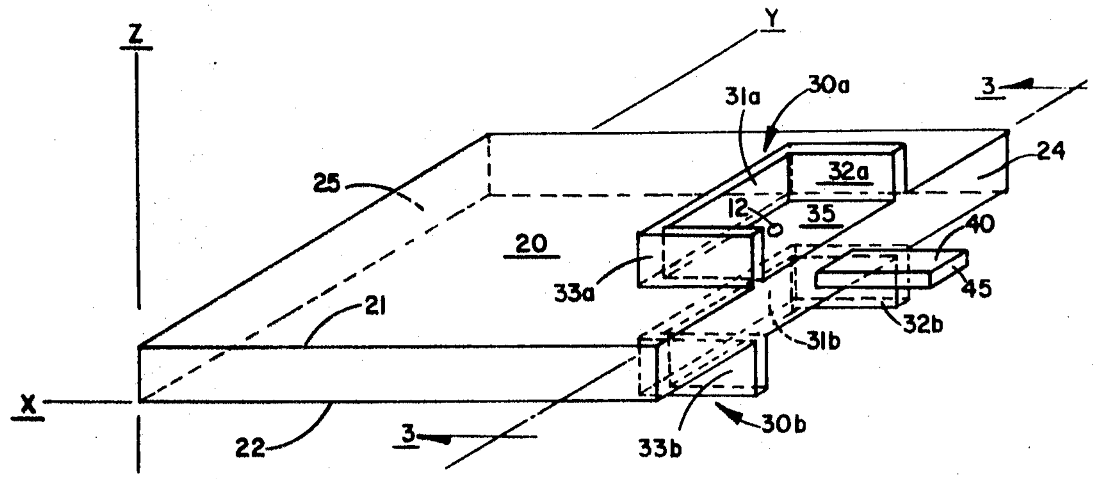

FIG. 2

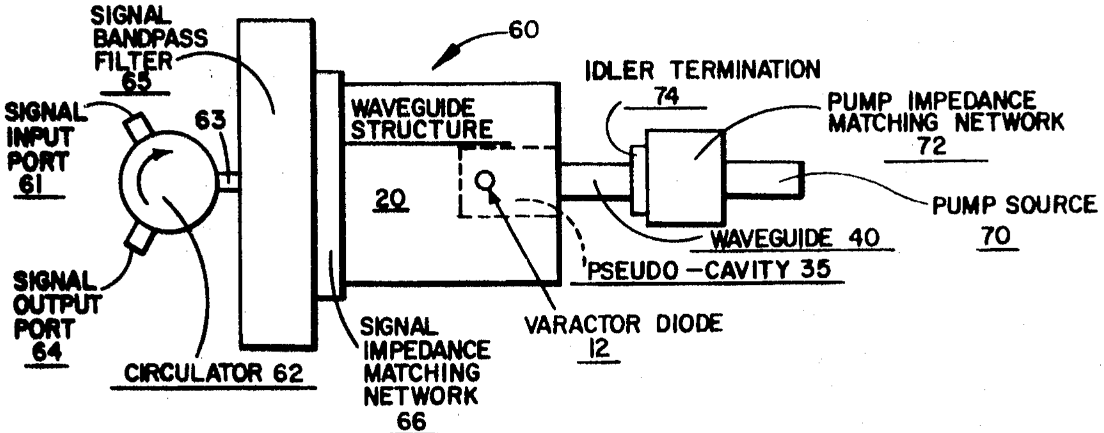

FIG. 6

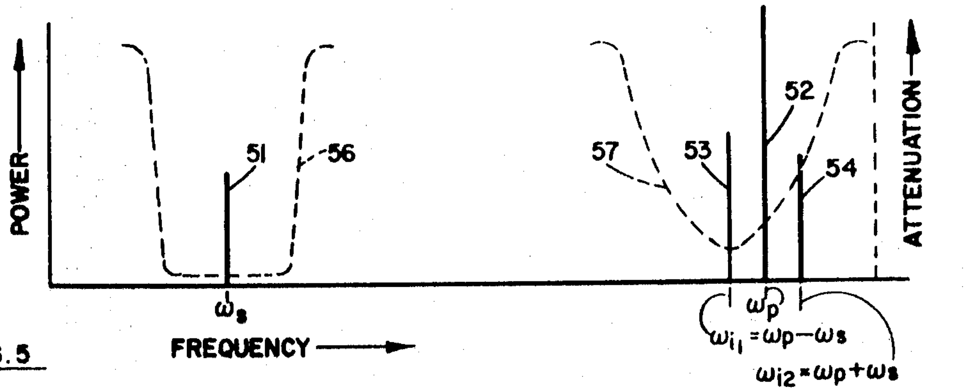

FIG. 5

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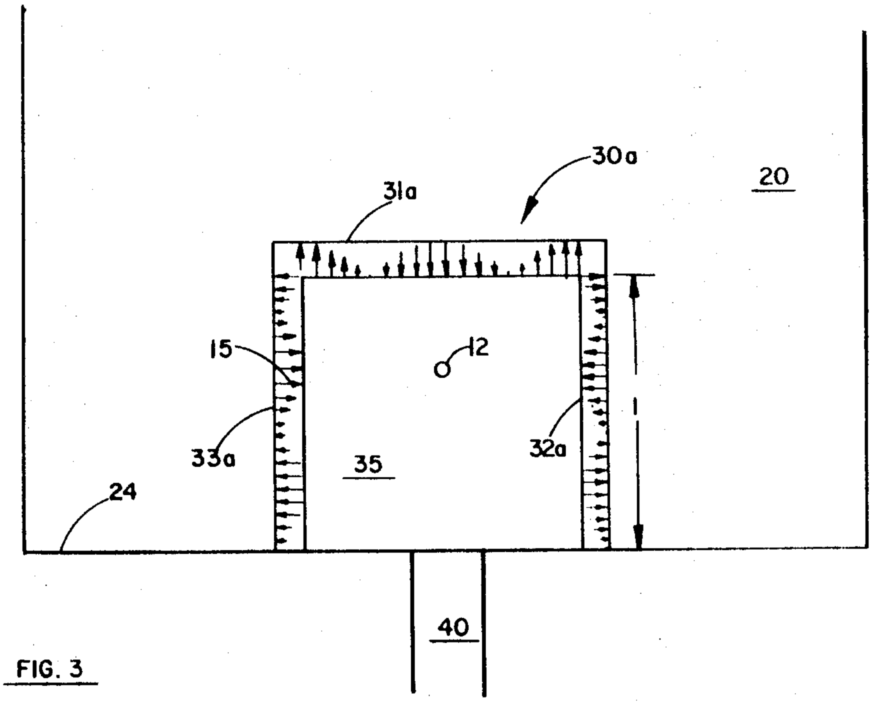

FIG. 3

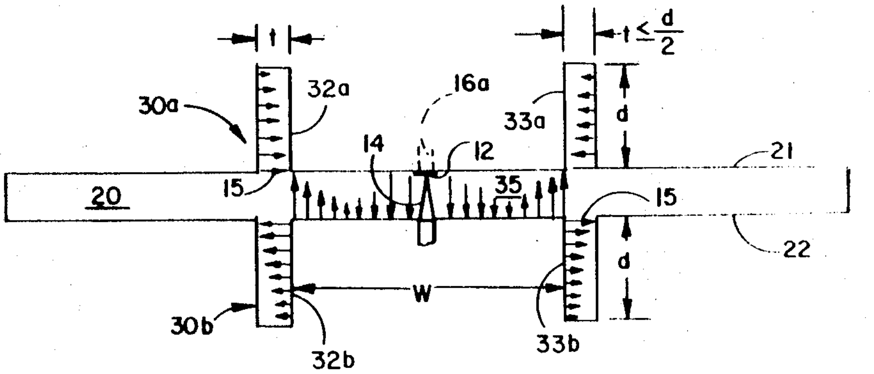

FIG. 4

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WAVEGUIDE STRUCTURE WITH PSEUDOCAVITY REGION FOR CONSTRAINING PUMP AND IDLER ENERGIES

CROSS REFERENCES TO RELATED APPLICATIONS

This application is a division of a prior application by the same applicants, Ser. No. 617,231 (now U.S. Pat. No. 3,501,706), filed in Group 252 on Feb. 20, 1967.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to a novel rectangular waveguide structure having substantially U-shaped channels, extending from its top and bottom, forming a pseudocavity region in which pump and idler energies may be constrained. The structure facilitates parametric amplification with extremely large percentage bandwidths of microwave signals introduced into the waveguide.

2. Description of the Prior Art

The principle factor limiting the sensitivity of microwave signal receivers is the noise inherent in the device used to amplify such signals prior to their detection. While low noise amplification may be achieved by the use of masers, these devices are restricted in their operation to natural frequencies of the maser material and usually must be operated in a cryogenic environment. A more acceptable approach is to use a parametric amplifier in which energy from an intense pump wave is coupled to the signal by a component exhibiting nonlinear reactance. Parametric amplification provides extremely low noise operation without the need for refrigeration.

Typical prior art microwave parametric amplifiers utilize structures having two adjacent waveguide cavities, one tuned to the signal frequency and a second tuned to the pump frequency. A back-biased diode having nonlinear capacitance, mounted in an aperture in a common wall between the two cavities, reactively couples energy between the pump and signal cavities.

Another typical parametric amplifier structure includes a rectangular waveguide to contain the pump energy. A varactor diode, mounted coaxially in a circular waveguide which intersects one wall of the rectangular guide, serves as the requisite nonlinear reactance. The signal may be introduced into the circular waveguide, and energy may be extracted either at the signal frequency via the circular waveguide or at the idler frequency via the rectangular waveguide.

While the parametric amplifiers described hereinabove may be tunable over a limited frequency range, they are essentially narrowband devices. Prior art broadband parametric amplification has required use of complex mechanical structures. Typical of such devices are the "Coupled-Cavity Travelling-Wave Parametric Amplifiers" described by K. P. Grabowski and R. D. Weglein in the Proceedings of the IRE, Volume 48, No. 12, beginning at page 1973. These devices utilize a series of inductively coupled microwave cavities each containing individual signal, idler, and pump resonant chambers and each containing a varactor diode. The cavities are cascaded and pump energy is applied to the diodes in an appropriate phase relationship to allow travelling wave parametric operation. While broadband performance may be achieved, the system is cumbersome mechanically, requires a plurality of cavities, and demands considerable care to maintain the proper pump phase at each varactor diode.

This application utilizes a novel waveguide structure having a pseudocavity region which permits pump and idler energy to be constrained to a small portion of a waveguide. This structure permits efficient parametric interaction between a signal present in the waveguide at a relatively low frequency and a pump having a considerably higher frequency. The structure is mechanically simple, and when used in a parametric amplifier requires only one reactive element and permits amplification with large percentage bandwidths.

SUMMARY OF THE INVENTION

The inventive waveguide structure has a pseudocavity region within which the pump and idler energy may be constrained. The structure comprises a rectangular waveguide having a width sufficiently large to support signal energy in the lowest order transverse electric mode. The rectangular waveguide includes substantially U-shaped channels extending from its top and bottom, and terminates in a second waveguide beyond cutoff. The channels, which preferably exhibit a depth of one-quarter guide wavelength of the lowest idler frequency, define the pseudocavity region. The length and width of the region are selected to ensure that both pump and idler energies are constrained and that a maximum electric field occurs at the location of a varactor diode disposed within the region. This varactor diode couples energy from the pump to the signal. The amplified signal may be extracted from the rectangular waveguide utilizing a microwave circulator. Nondegenerate broadband parametric amplification is achieved using a pump frequency much higher than that of the signal.

It is thus an object of this invention to provide a waveguide structure having a pseudocavity region for constraining pump and idler energy to a portion only of a waveguide.

It is a further object of this invention to provide a microwave structure including a shorted waveguide containing substantially U-shaped channels extending from the top and bottom of the waveguide to form a pseudocavity region capable of containing therein signals substantially above the cutoff frequency of the waveguide.

Further objects and features of the invention will become apparent from the following description and drawings which are utilized for illustrative purposes only.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an exploded elevation view of the inventive microwave waveguide structure including channels defining a pseudocavity region in the waveguide.

FIG. 2 is an elevation view showing the interior surface of the waveguide structure illustrated in FIG. 1.

FIG. 3 is a diagram of a possible electric field distribution within the channels of the pseudocavity as viewed in a plane generally along the line 3—3 of FIG. 2.

FIG. 4 is a diagram of a possible electric field distribution within a portion of the pseudocavity as viewed in a plane generally along the line 4—4 of FIG. 1.

FIG. 5 is a graph showing the operational mode spectrum of the inventive broadband parametric amplifier.

FIG. 6 is a block diagram of a broadband parametric amplifier utilizing the inventive waveguide structure illustrated in FIGS. 1 and 2.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The novel waveguide structure which forms the subject matter of this application is illustrated in FIG. 1. The waveguide structure comprises four major sections **10***a*, **10***b*, **10***c*, and **10***d*, which may be assembled into a unitary structure. In a preferred embodiment each of the sections **10***a*, **10***b*, **10***c*, and **10***d* may be milled from a solid block of a metal such as copper having high conductivity. Dowel pins (not shown in the figures) may be used to ensure accurate alignment of the assembled sections. Alternately, the structure may be constructed as a single block for example, by casting. The interior surface of the assembled waveguide structure is illustrated in FIG. 2.

As illustrated by FIGS. 1 and 2, the waveguide structure comprises a waveguide section **20** which extends through section **10***a*, **10***b*, and **10***c*, and which terminates at shorting plane or wall **24** of section **10***d*. A second waveguide **40** having width a' and height b' also extends from wall **24** and terminates in port **45**. The end of waveguide section **20** opposite wall **24** is open and forms port **25**. Waveguide section **20** has a width a and height b, the latter measured between top **21** and bottom **22** of waveguide section **20**. As is well known to those skilled in the art, the lowest frequency signal which can be propagated in waveguide section **20** is one whose free space wavelength is equal to $2a$. Waveguide section **40**, whose width a' is considerably narrower than a, thus has a lowest propagation frequency considerably higher than that of waveguide section **20**. Thus wall **24** and waveguide **40** appear as a short circuit termination to a signal propagating in waveguide section **20** in the lowest mode.

Extending respectively from top **21** and bottom **22** of waveguide section **20** are substantially U-shaped channels **30**a and **30**b. These channels, which may terminate against wall **24**, define pseudocavity region **35** of waveguide section **20**. Channels **30**a and **30**b respectively comprise end sections **31**a and **31**b, first side grooves **32**a and **32**b, and second side grooves **33**a and **33**b. End sections **31**a and **31**b may be constructed by milling a rectangular opening **31** in section **10**b as illustrated in FIG. **1**. Grooves **32**(a and b) and **33**(a and b) may be constructed by milling appropriate slots through section **10**c. In a preferred embodiment, shown most clearly in FIG. **1**, the thickness of channels **30**a and **30**b is t; that is, end sections **31**a and **31**b, and side grooves **32** and **33**, each have the same thickness t. The length and width of pseudocavity region **35** are given by l and w respectively, as shown in FIG. **1**. Channels **30**a and **30**b each extend to a depth d above and below respective waveguide top **21** and bottom **22**. Criteria for the selection of the various dimensions t, l, w and d are described in detail hereinbelow in conjunction with the operational description of pseudocavity region **35**.

Varactor diode **12** is situated in pseudocavity region **35** and may be supplied with a DC bias via a wire introduced through hole **16**b in block **10**c (see FIG. **1**). A second contact to varactor diode **12** is provided by point contact **14** (not shown in FIG. **2**) which extends from bottom **22** of waveguide section **20**. Point contact **14** may be fashioned at the end of a metal rod and inserted into hole **16**a in section **10**c.

Operation of the pseudo cavity region **35** defined by substantially U-shaped channel members **30**a and **30**b best may be understood by reference to FIGS. **3** and **4**, which are viewed respectively along the lines **3**—**3** of FIG. **2** and **4**—**4** of FIG. **1**. In particular FIGS. **3** and **4** show typical electric field patterns which may be induced in channels **30**a and **30**b when these channels are of the preferred dimensions.

In a preferred embodiment, the depth d of channels **30**a and **30**b essentially is equal to one-quarter guide wavelength of the energy desired to be constrained within pseudocavity region **35**. For energy introduced in the appropriate mode, this ensures that the electric field (represented by arrows **15** in FIGS. **3** and **4**) is a maximum in the planes of top and bottom surfaces **21** and **22** of waveguide section **20**. Thus, a wave introduced into pseudocavity region **35** (e.g., via waveguide section **40**) will see a very high impedance at the periphery of pseudocavity region **35** defined by channels **30**.

Note that the energy will be constrained to pseudocavity region **35** and will not extend out into waveguide section **20** beyond the region defined by substantially U-shaped channels **30**a and **30**b. In a preferred embodiment width w of pseudocavity region **35** essentially is equal to an integral number of one-half guide wavelengths of the signal being constrained. Similarly the preferred length l of pseudocavity region **35** is equal to an integral number of one-half guide wavelengths plus one-quarter guide wavelength. These preferred values are illustrated in FIGS. **3** and **4**, which show the electric field distribution for energy introduced into pseudocavity region **35** in the TE_{303} mode.

Using the configuration of FIGS. **3** and **4**, varactor diode **12** may be placed three-quarters of a guide wavelength from wall **24** and midway between grooves **32**a and **33**a. As illustrated, this will ensure an electric field maxima at the location of varactor diode **12** for energy introduced into pseudocavity region in the TE_{303} mode.

In a preferred embodiment, the groove thickness t of channels **30**a and **30**b should be less than one-half the depth d of grooves **32** and **33**. An optimum value for thickness t is in the order of one-tenth guide wavelength. A greater thickness t may result in the excitation of spurious modes within channels **30**a and **30**b, resulting in a significant decrease in the ability to constrain energy to within pseudocavity region **35**.

Since the thickness t is considerably less than the width a of waveguide section **20**, a relatively low-frequency signal introduced into waveguide section **20** will see only a very small inductive perturbation in its field due to the existence of channels **30**a and **30**b. Thus a signal of a first relatively low frequency (introduced via port **25**) may be present throughout waveguide section **20** at the same time that a wave at a second much higher frequency (introduced by way of port **45** and waveguide **40**) may be present only in the pseudocavity region **35** of waveguide section **20**.

Signals having a one-quarter guide wavelength ($\lambda g/4$) slightly greater or less than d also will be constrained somewhat by channels **30**a and **30**b to pseudocavity region **35**. However, the degree of containment will be slightly reduced from the optimum value obtained when the channels depth d is exactly $\lambda g/4$. Thus it is possible to use pseudocavity region **35** to constrain energy at several closely related frequencies.

In another embodiment of the inventive waveguide structure (not illustrated), a second pair of channels may extend from the top and bottom of waveguide **20** to form a second pseudocavity region surrounding the first pseudocavity region. This second region then may function to constrain any residual energy not completely contained by the first, smaller pseudocavity. In yet another embodiment, two adjacent pseudocavity regions may be formed in the same waveguide. If appropriate care is taken to prevent excitation of spurious modes, the side grooves of one pseudocavity simultaneously may be used as the side grooves of the adjacent channel, even though the two adjacent regions are of different size.

Further, it will be understood that various other modifications may be made to waveguide structure **20** within the spirit and scope of this invention. For example, although FIGS. **1** and **2** illustrate channels **30**a and **30**b as terminating against wall **24**, this is not required. Rather channel sections **30**a and **30**b may be separated some distance from wall **24** and include yet another groove to form substantially rectangular shaped channels. These channels then will define a rectangular pseudocavity region within the main waveguide **20**, into which region energy may be introduced, e.g., by way of a coaxial waveguide introduced through top **21** and bottom **22**. Alternately, it may be possible to form pseudocavity region **35** using only one channel, extending either from top **21** or bottom **22**. Such a configuration would provide somewhat less energy containment than the opposing channel embodiments illustrated, but may be advantageous in certain applications where it is impractical to prepare grooves in one waveguide wall.

The characteristics described hereinabove indicate that the waveguide structure illustrated by FIGS. **1** and **2** is well suited for application in a microwave parametric amplifier capable of broadband operation in the nondegenerate operational mode.

The theory of parametric amplification has been described widely in the literature, as for example, in the textbook entitled "Coupled Mode and Parametric Electronics" by William H. Louisell, published in 1960 by John Wiley and Sons, New York. Basically, parametric amplification involves the mixing of a signal at frequency $\omega_s=2\pi f_s$ with an intense energy source called a pump having a frequency ω_p. (In the following discussion, the term "frequency" will be used to denote the circular frequency $\omega=2\pi f$, where f is the frequency of interest). When combined in the presence of a nonlinear reactance (e.g., a varactor diode) energy is coupled between the pump and the signal. The interaction also gives rise to energy at two additional frequencies $\omega_{i1}=\omega_p-\omega_s$ and $\omega_{i2}=\omega_p+\omega_s$; these are called idlers. Nondegenerate parametric operation occurs when ω_p is not equal to $2\omega_s$.

Fig. **5** is a graph illustrating a parametric operational mode spectrum; the wideband parametric amplifier may be operated in the corresponding mode. As indicated in FIG. **5**, solid vertical line **51** represents the power present at signal frequency ω_s, the center frequency of the amplifier passband. Similarly, line **52** represents the power present in the pump wave at frequency ω_p. Lines **53** and **54** respectively represent the power which will be present at the idler frequencies ω_{i1} and ω_{i2} when parametric interaction occurs.

For optimum wideband parametric amplification with nearly constant gain across the band of interest, it is desirable to use an input band-pass filter to define the bandwidth of the signal to be amplified. Further, it is desirable to have extreme separation between frequencies ω_s and ω_p. The theoretical considerations on which these factors are based are described in the article by George Matthaei, entitled "A Study of the Optimum Design of Wideband Parametric Amplifiers and Upconverters," published in the IRE Transactions on Microwave Theory and Techniques, Volume MIT-9, No. 1, Jan. 1961, pages 23–38.

As shown superimposed on the operational mode spectrum of FIG. **5**, dashed curve **56** illustrates the preferred attenuation characteristics of an input band-pass filter which may be used as a component of the wideband parametric amplifier. Note that the passband region is centered around frequency ω_s and that the width of the passband defines the bandwidth of the amplifier. Note also in FIG. **5** that frequency ω_p is widely separated from ω_s. For example, if ω_s is selected to be 9 GHz. and the passband of attenuation curve **56** is selected to extend from 8 GHz. to 10 GHz., then ω_p may be selected to be a frequency of 94 GHz. In this example, the idler frequencies will be ω_{i1}=85 GHz. ±1 GHz. and ω_{i2}=103 GHz. ±1 GHz. (Of course, it is to be understood that these frequencies are cited by way of example only, and that the parametric amplifier described herein may be operated at other frequencies as well.)

A block diagram of the broadband parametric amplifier **60** utilizing the inventive waveguide structure is shown in FIG. **6**; parametric interaction occurs in pseudocavity region **35**, in which region varactor diode **12** is located. The characteristics of the waveguide structure have been described hereinabove in conjunction with FIGS. **1** and **2**. In a preferred embodiment, the depth *d* of channels **30***a* and **30***b* is selected to equal one-quarter guide wavelength at the lower idler frequency ω_{i1}. Since the pump and upper idler frequencies (ω_p and ω_{i2} respectively) are not far removed from lower idler frequency ω_{i1}, energy at these frequencies also will be constrained to within pseudocavity region **35**, but to a slightly lesser degree. This characteristic is illustrated by curve **57** in FIG. **5** which represents the "passband" of pseudocavity region **35**. Note that at frequencies ω_p and ω_{i2}, pseudocavity region **35** will present a slightly reactive load as viewed from waveguide **40**.

The signal to be amplified is introduced into parametric amplifier **60** by way of signal input port **61** in microwave circulator **60**. Microwave circulator **62** is of a type well known to those skilled in the art, and functions to allow a signal introduced through input port **61** to exit via common port **63** while insuring that a signal which enters via port **63** will leave circulator **62** via output port **64**.

The signal to be amplified enters signal band-pass filter **65** from circulator common port **63**. Signal band-pass filter **65**, well known to those skilled in the art, may be of the type described, e.g., in chapter 9 of the book entitled "Microwave Filters, Impedance Matching Networks, and Coupling Structures" by George Matthaei, et al., McGraw-Hill Book Company, 1964. In a preferred embodiment, signal band-pass filter **65** will exhibit the attenuation characteristics described generally by curve **56** in FIG. **5**. That is, filter **65** will have minimum attenuation within the desired passband, and high attenuation at all other frequencies.

The signal from band-pass filter **65** next passes through signal impedance matching network **66**, which to match the input signal to the small inductive perturbation which it will see in waveguide **20** as a result of the presence of pseudocavity region **35**. Impedance matching network **66** also serves to introduce the signal into waveguide **20** in a particular mode, e.g., in the TE_{10} mode, the lowest mode which can be supported by waveguide structure **20**. The design of impedance matching network **66** is well known to those skilled in the art, and is described for example in Chapter 6 of the book "Microwave Filters, Impedance-Matching Networks, and Coupling Structures," referenced above. In a preferred embodiment, waveguide structure **20** will have a width *a* (see FIG. **1**) which is one-half free space wavelength at the lowest frequency of the signal passband. This will allow the signal to be introduced into waveguide structure **20** in the TE_{10} mode.

Pump energy may be supplied from pump source **70** which may comprise a reflex klystron oscillator and a microwave isolator, both operating at the pump frequency ω_p. These components are well known to those skilled in the art. Energy from pump source **70** passes through pump impedance matching network **72**, upper idler termination **74**, and waveguide **40** into pseudocavity region **35**. The function of impedance matching network **72** is to match the pump wave to the reactance exhibited by pseudocavity region **35** at the pump frequency. Network **72** performs the further function of ensuring that the pump energy is introduced into pseudocavity region **35** in an appropriate mode e.g., the TE_{303} mode illustrated in FIGS. **3** and **4**) to ensure that the pump electric field will be a maxima at the location of varactor diode **12**.

In a preferred embodiment, the width *a'* of waveguide **40** is selected to provide a cutoff frequency between lower idler frequency ω_{i1} and pump frequency ω_p. Further, waveguide **40** should be sufficiently long so that pump impedance matching network **72** does not interact with energy at lower idler frequency ω_{i1}. In a typical embodiment, a waveguide **40** length which will ensure 20 db. attenuation at idler frequency ω_{i1} is sufficient for satisfactory operation. These considerations will allow pump energy from pump source **70** to be introduced into pseudocavity region **35** via waveguide **40**, but will prevent energy at the lower idler frequency ω_{i1} from exiting pseudocavity region **35** via waveguide **40**. In effect, this will completely constrain energy at the lower idler frequency ω_{i1} to within pseudocavity region **35**. Upper idler termination **74** is a reactive trap which functions to reflect energy at the upper idler frequency ω_{i2} (which energy will propagate through waveguide **40**) back into pseudocavity region **35**.

With the parametric amplifier illustrated in FIG. **6**, when a signal and a pump are introduced into waveguide structure **10**, parametric amplification will occur and the amplified signal may be extracted via impedance matching networks **66**, signal band-pass filter **65**, circulator common port **63**, circulator **62**, and signal output port **64**. The bandwidth of the amplifier will be defined by the passband of signal band-pass filter **65** (see curve **56** of FIG. **5**).

It will be apparent that the inventive waveguide structure described in conjunction with FIGS. **1** and **2** is not limited to use in a broadband parametric amplifier, and may be employed in various other microwave devices. Moreover, while the invention has been described and illustrated in detail, it is to be clearly understood that the same is by way of illustration and example only, and is not to be taken by way of limitation, the spirit and scope of the invention being limited only by the terms of the appended claims.

We claim:

1. A rectangular waveguide having means for constraining energy at a given frequency to within a region of said waveguide,
   - said means comprising at least one channel extending orthogonally from a wider wall of said waveguide to a depth of essentially one-quarter guide wavelength of said frequency,
   - said channel being substantially U-shaped and comprising an end section and first and second side grooves, said channel forming a pseudocavity capable of supporting a mode of electrical signals at a frequency different from that of at least another mode supportable in said waveguide.

2. The structure as defined in claim 1 wherein a second end section is included at the open end of said grooves of said channel to form a substantially rectangular-shaped channel which defines a rectangular pseudocavity region.

3. In a waveguide having a lowest propagation frequency, means for constraining energy having a second frequency higher than said lowest propagation frequency to within a pseudocavity region of said waveguide, said means comprising,

two channels extending oppositely one from the other from the top and bottom of said waveguide to a depth of essentially one-quarter guide wavelength of said second frequency,

said channels being substantially U-shaped and comprising an end section and first and second side grooves wherein the thickness of said end section and said side grooves measured in the plane of attachment to said waveguide is no greater than one-half the depth of said channels.

4. A structure as defined in claim 3 wherein the width of said pseudocavity region is an integral number of one-half guide wavelengths at said second frequency, and the length of said pseudocavity region is an integral number of one-half guide wavelengths plus one-quarter guide wavelengths at said second frequency, said width being the distance between said side grooves of said U-shaped channels and said length being the distance from the open end of a side groove to the remote side of the end section.

5. A structure as defined in claim 3 wherein one end of said waveguide is short circuit terminated, wherein said channels are substantially U-shaped, and wherein said terminated end of said waveguide provides one boundary of said pseudocavity region.

6. A structure as defined in claim 5 further comprising means for introducing energy into said pseudocavity region, said means comprising a second waveguide extending from said terminated end of said waveguide and having a cutoff frequency higher than said lowest propagation frequency.

7. A structure as defined in claim 5 wherein the thickness of said channels is approximately one-tenth guide wavelength at said second frequency.

8. A structure as defined in claim 7 wherein said pseudocavity region has a width of one guide wavelength at said second frequency, and a length of one and one-quarter guide wavelength at said second frequency.