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ELASTIC TRAVELING WAVE PARAMETRIC AMPLIFIER

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FIG. 1

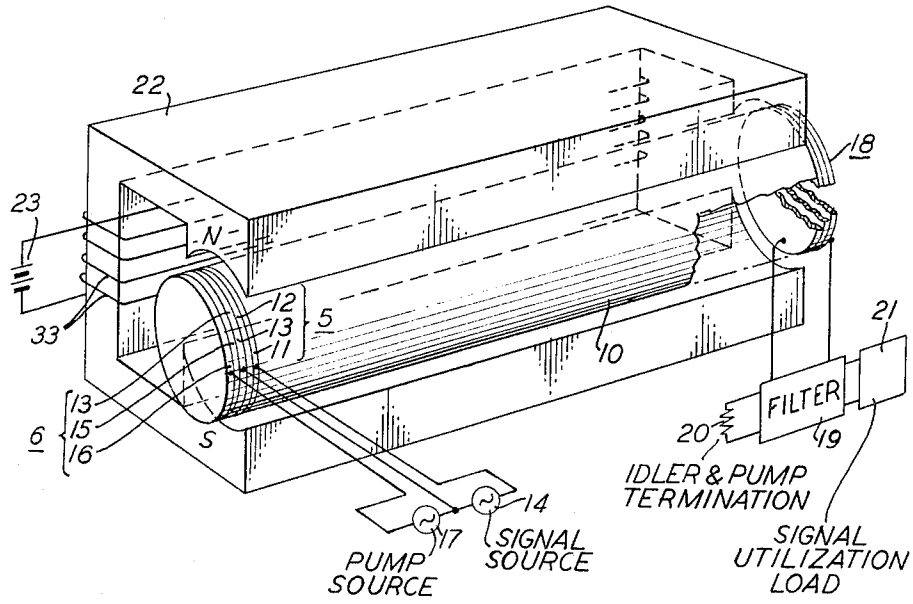
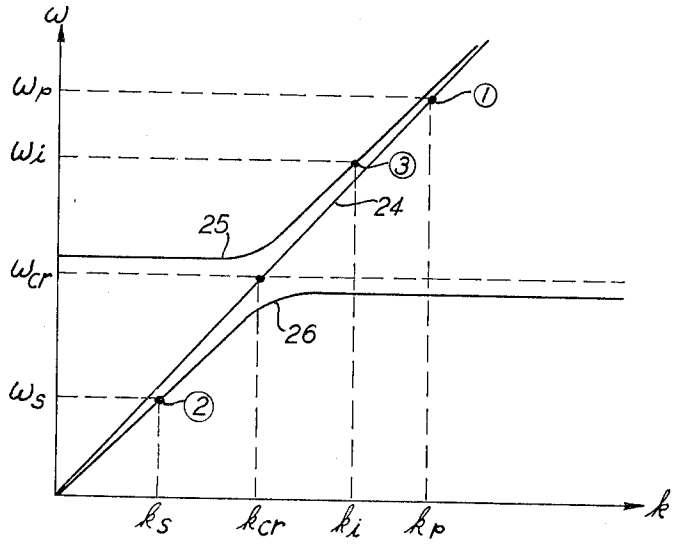



FIG. 2




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# ELASTIC TRAVELING WAVE PARAMETRIC AMPLIFIER

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4 Claims. (Cl. 330—4.6)

This invention relates to traveling elastic wave parametric amplifiers.

In an article entitled "Generation of Phonons in High-Power Ferromagnetic Resonance Experiments," by E. Schlömann, published in the September 1960 issue of the Journal of Applied Physics, pages 1647–1656, the nature of the interaction of spin waves and elastic vibrations in magnetic materials is investigated. This interaction has been applied by R. L. Comstock and B. A. Auld, and in their paper entitled "Parametric Coupling of the Magnetization and Strain in a Ferrimagnet. I. Parametric Excitation of Magnetostatic and Elastic Modes," published in the May 1963 issue of the Journal of Applied Physics, pages 1461–1464, a theoretical treatment is presented of the parametric coupling between the magnetization and elastic strain in a ferrimagnet produced by magnetic pumping. In particular, this paper discusses the parametric coupling between resonant magnetostatic and elastic modes.

In a companion paper by R. L. Comstock entitled "Parametric Coupling of the Magnetization and Strain in a Ferrimagnet. II. Parametric Excitation of Magnetic and Elastic Plane Waves," published in the same May 1963 issue of the Journal of Applied Physics at pages 1465–1468, the parametric coupling between traveling electromagnetic and elastic waves in a ferrimagnet produced by magnetic pumping is theoretically investigated.

The present invention, which is a further development in this art, relates to a new class of traveling wave amplifiers whose operation is based upon the parametric coupling between two traveling elastic waves in a magnetically saturated ferromagnetic medium. In particular, a signal, in the form of a first transverse (shear) wave, polarized in a first direction, is amplified by means of a pump transverse elastic wave, polarized at right angles to the signal wave. The two elastic waves are launched so as to propagate in a magnetic medium along a direction normal to the directions of polarization. The medium is magnetically saturated in a direction parallel to the signal polarization.

Parametric coupling takes place between the signal and pump waves because of magnetoelastic interaction. Since maximum parametric interaction occurs when the frequency and phase relationships set forth by P. K. Tien are realized, the wave frequencies and the magnetic biasing are advantageously adjusted to satisfy these criteria. (See "Parametric Amplification and Frequency Mixing in Propagating Circuits," by P. K. Tien, published in the Journal of Applied Physics, vol. 29, No. 9, pages 1347–1357.) Since the dispersion characteristic of selected magnetoelastic waves is such that these preferred conditions can be approximately satisfied over a broad frequency range, it is a feature of the present invention that broadband operation is inherently possible.

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

FIG. 1 shows a traveling elastic wave parametric amplifier in accordance with the invention; and



FIG. 2, included for purposes of explanation, shows the magnetoelastic dispersion curves for the modes selected for use in the amplifier shown in FIG. 1.

Referring to the drawings, FIG. 1 shows an illustrative embodiment of the invention comprising a cylindrical rod **10**, advantageously formed from a single crystal of non-conductive magnetic material, together with associated input and output transducers. A preferred material would be characterized by a significant level of gyromagnetic activity over the frequency range of interest, low elastic loss, and a high magnetoelastic coupling coefficient. One material particularly suitable for this purpose at microwave frequencies is yttrium iron garnet. While the orientation of the crystal axis in cylinder **10** does not appear to be critical insofar as the present invention is concerned, it is preferred that the cylinder axis coincide with one of the crystal axes, and in a material having cubic symmetry, that the other axes coincide with the directions of polarization of the elastic waves if only to facilitate mode purity and design calculations.

Wave energy, in the form of transverse (shear) waves, is coupled into one end of cylinder **10** by means of an electromechanical transducer. Since two different transverse waves at different frequencies are to be simultaneously launched in the same direction, the transducer must either be sufficiently broadband to excite elastic waves at both frequencies, or two separate transducers must be used. By way of illustration, the transducer can be of the type described by N. F. Foster in his copending application Ser. No. 387,837, filed on Aug. 6, 1964, and assigned to applicants' assignee. As indicated by Foster, a predominant shear mode vibration is produced by means of a relatively rapid evaporation of piezoelectric material, such as cadmium sulfide, at an acute angle to the surface of a relatively cooler silver substrate. Accordingly, a transducer **5** for coupling the signal wave to rod **10** comprises a first layer of silver **11**, a layer of piezoelectric material **12** deposited upon the silver layer in a direction and manner to produce transverse elastic waves polarized in a first direction, and a second layer of silver **13**. The signal wave, derived from a signal source **14**, is applied across the two silver layers **11** and **13**.

The pump transducer **6** is similarly constructed and comprises a second layer of piezoelectric material **15** deposited between silver layer **13** and a third layer of silver **16**. In particular, layer **15** is deposited on silver layer **13** in a direction to produce transverse electric waves polarized in a direction perpendicular to the direction of polarization of the signal wave. The pump source **17** is applied across silver layer **13** and silver layer **16**.

At the opposite, or output end of rod **10**, there is located an output transducer (or two transducers) **18** for extracting from rod **10** an amplified output signal wave, the pump wave, and, in the nondegenerate mode of parametric operation, an idler wave. Transducer **18** generates an electrical signal in response to the elastic waves within rod **10** and couples it to a tuned filter **19** which separates the idler and pump energy from the signal wave energy. The idler and pump waves are resistively terminated in a dissipative termination **20**. The signal wave is, in turn, coupled to a signal utilization load **21**.

A steady magnetic bias field is impressed transversely across rod **10** in a direction parallel to the direction of polarization of the elastic signal wave. As illustrated in FIG. 1, this biasing field is supplied by means of an electromagnet **22**, energized by means of a coil **33** and a direct-current source **23**.

In operation an electromagnetic signal, derived from signal source **14**, is applied to the signal transducer **5**. The latter causes a transverse elastic wave to be launched along rod **10**. At the same time, electromagnetic pump

energy, derived from pump source **17**, is applied to the pump transducer **6** which launches a second transverse elastic wave along rod **10**. As noted previously, the two elastic waves are polarized at right angles to each other and to the direction of propagation.

As the signal elastic wave propagates along rod **10**, spin waves are induced, such that the total signal wave energy propagates in the magnetoelastic mode. The degree of magnetoelastic coupling is a function of the operating point.

Curves **25** and **26** in FIG. 2 show the dispersion characteristic of the spin waves and elastic waves in a ferromagnetic material which, when the effect of magnetoelastic interaction is included, characterizes the modes selected for use in the present amplifier. A full development of the dispersion characteristics of coupled spin and elastic waves, along with the equations which underlie them, can be found in the above-cited article by Schlömann. (Also see the October 1965 special issue of the Proceedings of the Institute of Electrical and Electronics Engineers on Ultrasonics.) In particular curves **25** and **26** of FIG. 2 show the relation between angular frequency $\omega$ and the wave number $k$, where $k$ is equal to $2\pi$ divided by the wavelength $\lambda$. Waves with low values of $k$, are either elastic waves or spin waves with relatively little coupling between the elastic and spin waves. The coupling, however, increases with increasing $k$ and reaches a maximum for a particular value of $k=k_{cr}$, corresponding to a particular value of frequency $\omega=\omega_{cr}$. These two values together define a point in the $\omega-k$ diagram which is designated the "crossover" point. The so-called crossover frequency $\omega_{cr}$ is a function of the internal biasing field $H_i$, and is given for the present case, in which the direction of propagation is normal to the biasing field, as

$$\omega_{cr}=\gamma[H_i(H_i+4\pi M_s)]^{1/2}$$

where $\gamma$ is the gyromagnetic ratio for the particular material, and $M_s$ its saturation magnetization.

As $k$ increases beyond the crossover point, the magnetoelastic interaction decreases, becoming negligibly smaller for relatively large value wave numbers.

In addition to the above-described dispersion characteristic of the magnetoelastic modes, FIG. 2 includes a curve **24** which describes the relation between $\omega$ and $k$ for the pump wave. Since the polarization of the pump is normal to the direction of the magnetic biasing field, the pump wave propagates with its energy in the elastic mode. As such, curve **24** is essentially linear.

To achieve a high level of parametric interaction between the pump wave and the signal wave, the operating point for the signal wave is advantageously selected in the region near the crossover point and, for the non-degenerate mode of operation, the pump frequency is usually selected to be approximately twice the critical frequency. That is

$$\omega_p\approx 2\omega_{cr} \qquad (1)$$

Referring again to FIG. 2, the pump is designated as point **1** on curve **24**. The signal is identified as point **2** on the lower branch of the magnetoelastic dispersion curve **26**.

When the theory of elastic and spin wave modes in ferromagnetic materials is considered in its entirety so as to take account of second order as well as first order interactions, it can be shown that mixing takes place between the pump wave and the magnetic portion of the signal wave, to produce an idler wave. This idler wave is generated at a frequency $\omega_i$ such that

$$\omega_i+\omega_s=\omega_p \qquad (2)$$

The idler wave is identified as point **3** on curve **25** in FIG. 2.

Associated with each of these waves is a wave number $k_i$, $k_s$ and $k_p$. As is well known in the art, parametric interaction is maximum when

$$k_i+k_s=k_p \qquad (3)$$

Because of the symmetrical nature of the two branches of the dispersion curve, the preferred condition given by Equation 3 is inherently obtained to a high degree of approximation, and significant signal amplification is realized. It is for this reason that an amplifier in accordance with the invention is basically broadband.

The amplified signal and the resulting idler wave energy are coupled out of rod **10** by the output transducer **18** and into filter **19** where the idler and signal frequencies are separated. The idler wave energy is typically dissipated in the resistive load **20**, whereas the signal wave energy is coupled to the signal load **21** for further processing or ultimate utilization.

In the description given above, a separate idler frequency was assumed for purposes of generality. It is understood, however, that the amplifier can also be operated in the degenerative mode simply by making the pump frequency equal to twice the signal frequency. In either event, the design procedure is basically the same. Recognizing that the magnetoelastic coupling is maximum at the crossover point, the rod is biased so that the crossover frequency is close to the signal frequency. This, however, is a matter of compromise, for while the magnetoelastic coupling increases as the crossover frequency is made to approach the signal frequency, the signal losses also increase since the crossover frequency represents a condition of gyroacoustic resonance. There is, however, a region over which the amplifier gain increases faster than the losses. The optimum biasing condition can be readily found emperically by varying the magnetic biasing field and measuring the gain.

Advantageously, the pump frequency is made as low as possible for several reasons which include more efficient operation of the pump transducer, higher gain due to the closer location of the idler frequency to the crossover frequency, and broader band operation.

In all cases it is to be understood that the above-described arrangement is merely illustrative of but one of the many possible applications of the principles of the invention. For examples, the shape of the magnetic medium can be ellipsoidal or spherical, and the transducers can be placed side-by-side rather than one upon the other. Thus, numerous and varied other arrangements in accordance with these principles may readily be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

**1.** An elastic wave amplifier comprising:
an element of nonconductive magnetic material;
means for launching two transverse elastic waves within said element for propagation therein in a given direction;
said elastic waves having different frequencies and being polarized at right angles to each other and to said direction of propagation;
means for applying a steady magnetic field to said magnetic material in a direction parallel to the direction of polarization of the lower frequency wave;
and means for extracting amplified wave energy at said lower frequency from said element.

**2.** The amplifier according to claim **1** wherein the frequency of one of said elastic waves is equal to twice the frequency of the other of said elastic waves.

**3.** The amplifier according to claim **1** wherein said two waves induce a third wave in said material such that the sum of the frequencies of said third wave and one of said two waves is equal to the frequency of the other of said two waves.

4. The amplifier according to claim 1 wherein said steady magnetic field produces a condition of gyro-acoustic resonance in said element at a critical frequency, and wherein the frequency of one of said two waves is approximately equal to twice said critical frequency.

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