

April 6, 1965

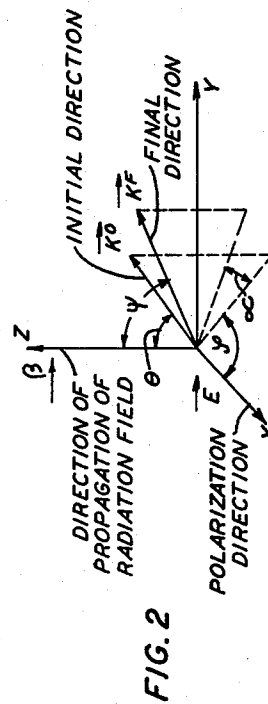
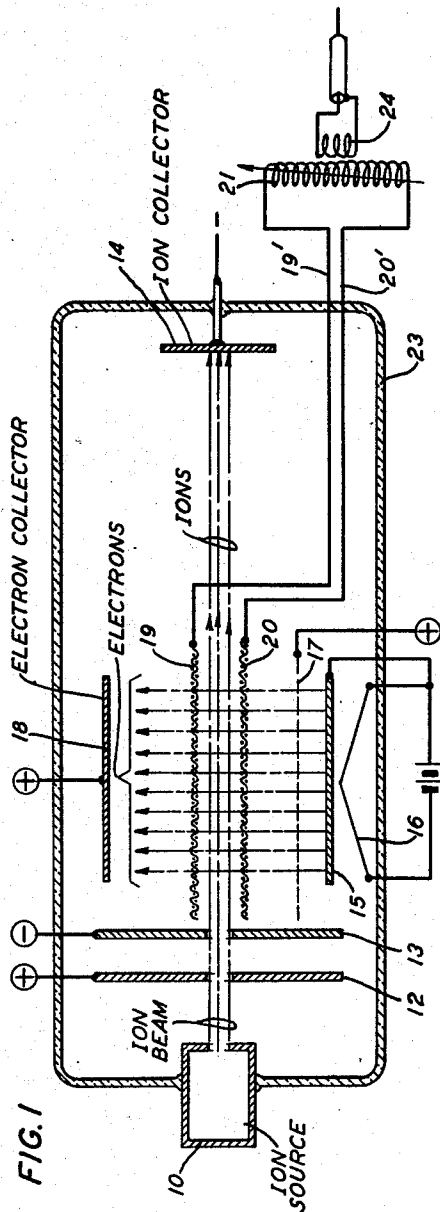
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3,177,435

AMPLIFICATION BY THE STIMULATED EMISSION OF BREMSSTRAHLUNG

Filed Sept. 21, 1962

3 Sheets-Sheet 1



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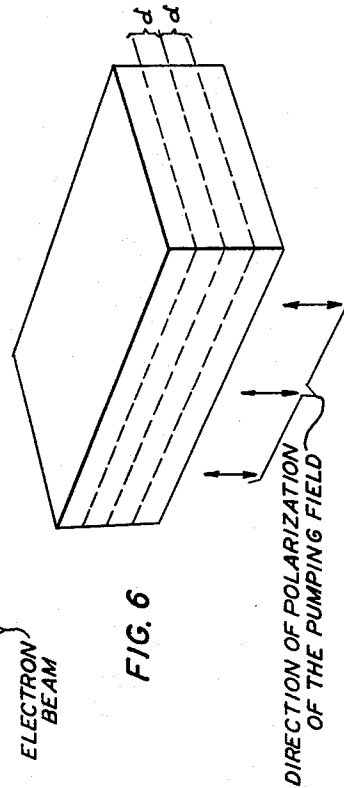
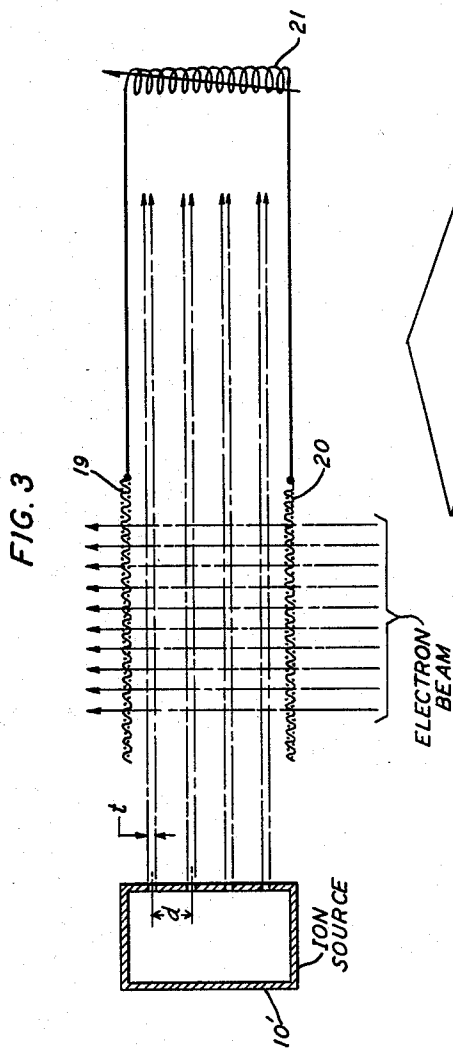
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AMPLIFICATION BY THE STIMULATED EMISSION OF BREMSSTRAHLUNG

Filed Sept. 21, 1962

3 Sheets-Sheet 2



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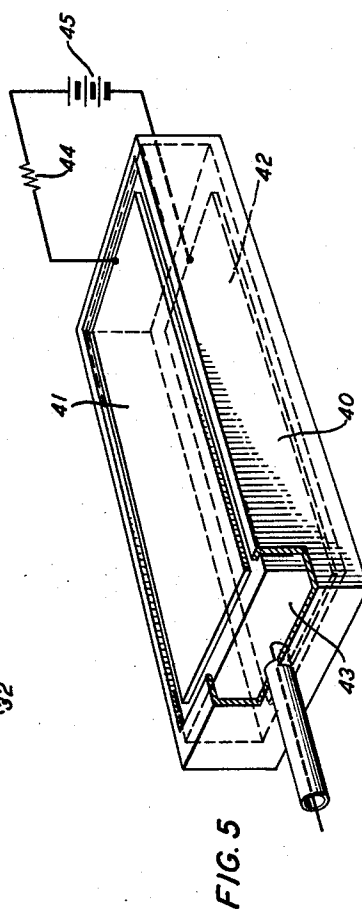
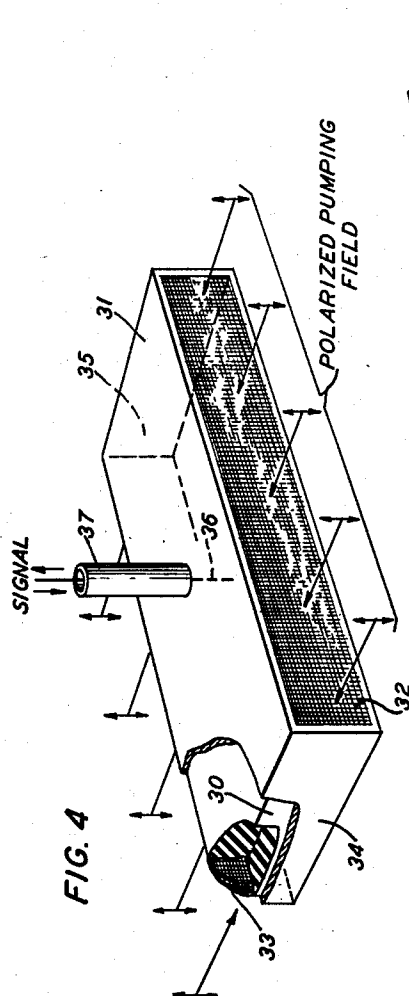
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AMPLIFICATION BY THE STIMULATED EMISSION OF BREMSSTRAHLUNG

Filed Sept. 21, 1962

3 Sheets-Sheet 3



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3,177,435

AMPLIFICATION BY THE STIMULATED
EMISSION OF BREMSSTRAHLUNG

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Filed Sept. 21, 1962, Ser. No. 225,318

14 Claims. (Cl. 330—4)

This invention relates to electromagnetic wave devices, and, more particularly, to amplifiers and oscillators whose mode of operation is based upon the stimulated emission of radiation from free electrons.

This application is a continuation-in-part of my co-pending application Serial No. 200,999, filed June 8, 1962, and now abandoned.

It is known that radiation can be emitted from a free electron in the presence of a static electric field. This process, known as bremsstrahlung, is described at page 364 in "The Theory of Protons and Electrons," by J. M. Jauch and F. Rohrlich, published by the Addison-Wesley Publishing Company, Inc., 1955.

It is a characteristic of bremsstrahlung, or deceleration radiation, that it is normally incoherent and that energy is radiated over a continuous spectrum in contrast to the radiative transitions between bound energy states utilized in the maser.

It is, accordingly, an object of this invention to induce coherent radiation from free electrons in the presence of a static field.

In accordance with the principles of the invention coherent emission of radiation from free electrons within a preferred range of frequencies is obtained by inducing bremsstrahlung in the presence of a signal radiation field having a frequency within the preferred range. This stimulated emission is obtained in one illustrative embodiment of the invention by the interaction of a stream of electrons and molecular nuclei (ions) in the presence of a signal field.

The stream of electrons is introduced into a region of a resonant structure tuned to a preferred, or signal frequency in a direction substantially parallel to the electric vector associated with the signal field as supported by the tuned structure. Simultaneously, a stream of ions are introduced into said region. Under the influence of the signal field, energy is radiated at the signal frequency due to the electron-nucleus interaction. The radiated energy, in turn, enhances the signal, producing amplification at the signal frequency.

By increasing the density of electrons and nuclei, the system can be caused to oscillate at the frequency of the tuned structure giving rise to an oscillator whose frequency can be varied simply by tuning the resonant structure. Such a device has a distinct advantage over amplifiers and oscillators which employ transitions between discrete energy levels since, in this latter arrangement, the frequency of operation is determined essentially by the particular active material utilized. For the same reason amplifiers and oscillators using stimulated bremsstrahlung can operate over broader bandwidths.

In addition, whereas prior art amplifiers, such as traveling wave tubes, require high electron velocities in order to match the phase velocity of a traveling wave or, as in a klystron, which requires the proper phase relationship between a bunched electron stream and the signal field, no such requirements are necessary in an amplifier utilizing the stimulated emission of bremsstrahlung. Stimulated emission of bremsstrahlung requires neither bunched electron beams nor the observation of any particular phase relationships. Moreover, it functions better with slow rather than fast electrons and no traveling wave structure

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is required since the fields for the stimulation process can be confined to a cavity or any other type of resonant structure.

In a second embodiment of the invention, stimulated emission of bremsstrahlung is induced in a high resistivity crystal, doped with an appropriate impurity, by the application of a pumping field. The frequency of the pumping field is selected so as to pump electrons from the impurity levels to the conduction energy band of the crystal without pumping electrons from the valence band to the conduction band. To insure that the pumped electrons travel in the proper direction (i.e., parallel to the electric vector of the signal (stimulating) radiation), the pumping field is preferably polarized in a direction parallel to the signal electric field vectors. By providing a sufficiently high impurity density and pumping power, the system can be caused to oscillate. By reducing the impurity density or the pumping power, or both, the system can be used as a signal amplifier.

To reduce the tendency for impurity electrons to be spontaneously lifted from the forbidden band to the conduction band as a result of thermal agitation, the system is advantageously cooled below the ambient temperature.

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 is a first embodiment of the invention using gas ions;

FIG. 2, given for the purposes of explanation, shows the relative orientation of incident electrons and scattered electrons under the influence of ions;

FIG. 3 is a modification of the embodiment of FIG. 1 utilizing a periodically spaced multi-beam ion stream;

FIG. 4 is an alternative embodiment of the invention using a crystal;

FIG. 5 is a variation of the embodiment of FIG. 4 wherein a D.C. electric field is used instead of light to lift electrons into the conduction band of the crystal; and

FIG. 6 shows a crystal for use in connection with the embodiments of FIGS. 4 and 5 in which the impurities are periodically arranged in planes.

Referring to FIG. 1 there is shown a crossed-beam embodiment of the invention comprising a source 10 which emits a beam of ions. Under the influence of the charged electrodes 12 and 13, the ion beam is focused and caused to pass between a pair of parallel planar wire mesh condenser plates 19 and 20 to an ion collector 14. (For a discussion of ion beam sources see "Encyclopaedia Dictionary of Physics, vol. 4, Pergamon Press, 1961, pp. 29-30.)

A second beam, comprising a beam of electrons derived from a cathode 15 (suitably heated by a heating element 16), is caused to pass through the wire mesh condenser plates 19 and 20 substantially at right angles to the direction of flow of the ions under the influence of a positively charged accelerating grid 17 and an electron collector 18. The entire device is enclosed in an evacuated chamber 23.

Leads 19' and 20' which connect to the condenser plates 19 and 20, respectively, are brought out of the chamber 23 and connect to a tunable inductor coil 21. The coil and the condenser plates 19 and 20 form a tuned L-C circuit. Coupling means, such as a second coil 24 inductively coupled to coil 21, are used to couple electromagnetic wave energy into and out of the crossed-beam amplifier.

To derive the probability of stimulated emission or absorption from free electrons in the presence of a coulomb field, we consider two states of the physical system. The initial state consists of a free electron, represented by a plane wave, existing in the presence of a coulomb

field and a radiation (signal) field with a certain number, n , of photons in a particular mode while all other modes are empty. The final state consists of the same electron with different energy and momentum and with a number of $n+1$ photons, in the case of stimulated emission, or $n-1$ photons, in the case of absorption.

The transition probability between two states per unit time is given by W. Heitler in his book entitled "The Quantum Theory of Radiation," third edition, as

$$w = \frac{2\pi}{\hbar} |K_{F,0}|^2 \rho_F \quad (1)$$

where

$$\hbar = \frac{h}{2\pi} = 1.05 \cdot 10^{-27} \text{ erg. sec.}$$

$$K_{F,0} = \sum \left\{ \frac{V_{FI} H_{IO}}{E_0 - E'} + \frac{H_{FII} V_{II0}}{E_0 - E''} \right\} \quad (2)$$

V_{FI} and V_{II0} are the matrix elements of the coulomb potential (to be defined in greater detail below); H_{IO} and H_{FII} are the matrix elements of interaction of the radiation field (to be defined in greater detail below); and

$$\rho_F = \frac{m L^3 k^F}{\hbar^2 (2\pi)^3} d\Omega$$

is the number of final states in the unit energy range of the electron after interaction, with $\hbar k^F = mv_F$ being the momentum of the electron after scattering and with the element of solid angle $d\Omega = \sin \Psi (d\Psi)(d\alpha)$. Ψ and α specify the direction into which the electron is scattered (FIG. 2).

E_0 is the initial energy of the whole system including the electron and the radiation field while E' and E'' are the energies of the system in the intermediate virtual states. In the transitions to the intermediate states energy need not be conserved. However, energy conservation is required between the initial and final states of the whole system.

E_0 , E' and E'' are defined as follows:

$$E_0 = \frac{p_0^2}{2m} + n\hbar\omega \quad (3)$$

$$E' = \frac{p'^2}{2m} + (n \pm 1)\hbar\omega \quad (4)$$

and

$$E'' = \frac{p''^2}{2m} + n\hbar\omega \quad (5)$$

The (+) or (−) sign in (4) refers to emission or absorption respectively; $p = mv$ is the momentum of the electron.

The summation in (2) extends over all possible intermediate states. Using c.g.s. units, the matrix elements of the interaction Hamiltonian are given by

$$H_{IO} = -\frac{1}{\sqrt{L^3}} \frac{e}{m} \sqrt{\frac{2\pi\hbar}{\omega}} \left\{ \frac{\sqrt{n+1}}{\sqrt{n}} \right\} \frac{1}{L^3} \int e^{-i\vec{k}' \cdot \vec{r}} p_e e^{\mp i\vec{\beta} \cdot \vec{r}} e^{i\vec{k}^0 \cdot \vec{r}} d^3r$$

$$= -\frac{\hbar(k_x^0 \mp \beta_x)}{\sqrt{L^3}} \frac{e}{m} \sqrt{\frac{2\pi\hbar}{\omega}} \left\{ \frac{\sqrt{n+1}}{\sqrt{n}} \right\} \delta_{k'_x, k_x^0 \mp \beta_x} \cdot \delta_{k'_y, k_y^0 \mp \beta_y} \cdot \delta_{k'_z, k_z^0 \mp \beta_z}$$

$$H_{FII} = -\frac{1}{\sqrt{L^3}} \frac{e}{m} \sqrt{\frac{2\pi\hbar}{\omega}} \left\{ \frac{\sqrt{n+1}}{\sqrt{n}} \right\} \frac{1}{L^3} \int e^{-i\vec{k}^F \cdot \vec{r}} p_e e^{\mp i\vec{\beta} \cdot \vec{r}} e^{i\vec{k}'' \cdot \vec{r}} d^3r$$

$$= -\frac{\hbar(k_x'' \mp \beta_x)}{\sqrt{L^3}} \frac{e}{m} \sqrt{\frac{2\pi\hbar}{\omega}} \left\{ \frac{\sqrt{n+1}}{\sqrt{n}} \right\} \delta_{k_x'', k_x^F \pm \beta_x} \cdot \delta_{k_y'', k_y^F \pm \beta_y} \cdot \delta_{k_z'', k_z^F \pm \beta_z}$$

where

e and m are the charge and mass of the electron
 n is the number of photons in a box of volume L^3 (box normalization);

$\sqrt{n+1}$ and (−) sign relate to the emission case while $\sqrt{n}$ and (+) sign relate to the case of absorption;

$\omega = 2\pi f$ is the angular frequency of the radiation field;

$\vec{\beta}$ is the propagation vector of the radiation field for which

$$\beta = \left| \frac{\vec{\beta}}{\beta} \right| = \frac{\omega}{c}$$

$\vec{k}$ is the propagation vector of the plane electron wave and is equal to

$$\frac{2\pi}{L} (n_x, n_y, n_z)$$

n_x, n_y and n_z have to be integers because of box normalization;

$\hbar |\vec{k}| = mv$ the momentum of an electron;

p_e is the component of the momentum operator of the electron in the direction of the electric field vector of the radiation field; and the δ 's are the Kronecker δ -symbols.

We choose as the z -direction, the direction of propagation of the stimulating wave

$$\vec{\beta} = (0, 0, \beta) \quad (8)$$

The direction of polarization is taken to be the x -direction so that

$$p_e = -i\hbar \frac{\partial}{\partial x} \quad (9)$$

The matrix elements of the coulomb potential are given by

$$V_{II,0} = \frac{1}{L^3} Z e^2 \int \frac{e^{-i\vec{k}'' \cdot \vec{r}} e^{i\vec{k}^0 \cdot \vec{r}}}{|\vec{r} - \vec{r}_c|} d^3r = \frac{Z e^2}{L^3} \frac{4\pi}{|\vec{k}^0 - \vec{k}''|^2} \quad (10)$$

$$V_{F,1} = \frac{1}{L^3} Z e^2 \int \frac{e^{-i\vec{k}^F \cdot \vec{r}} e^{i\vec{k}'' \cdot \vec{r}}}{|\vec{r} - \vec{r}_c|} d^3r = \frac{Z e^2}{L^3} \frac{4\pi}{|\vec{k}^F - \vec{k}''|^2} \quad (11)$$

where

Z is the number of elementary charges of the nucleus;

$\vec{r} - \vec{r}_c$ is the distance between the point of integration and the nucleus.

The electron, after interaction, has an energy given by

$$\frac{1}{2} m v_F^2 = \frac{1}{2} m v_0^2 \mp \hbar\omega \quad (12)$$

and travels within the solid angle $d\Omega$ in the direction ψ , α . The probability function w , given by Equation 1, describes the probability per unit time that an electron, which is incident with angles θ and ϕ (as shown in FIG. 2) emits (or absorbs) a photon into the existing radiation wave carrying n photons. To obtain the total probability

W per unit time regardless of the direction of the scattered electron, we have to integrate w over all directions of scattering.

Before proceeding further we have to discuss the influence of the box normalization. The size of the box is arbitrary. The results become independent of the box if its sides L become infinitely long. It is apparent that

as $L \rightarrow \infty$ we get $w \rightarrow 0$. To avoid this difficulty we consider that for a box of finite size the number of emitted (or absorbed) photons per second is given by

$$\Delta N = W N_e''$$

if N_e'' electrons are present in the box. Introducing the number N_e' of electrons per unit volume we get

$$\Delta N = W L^3 N_e'$$

Calling N_e the number of incident electrons which, per second, fly through the unit area at speed v_0 we obtain

$$\Delta N = \frac{L^3}{W v_0} N_e \sigma N_e \quad (13)$$

The quantity σ defined by (13) is the scattering or interaction cross section. This name is justified by the observation that σ has the dimension of an area.

The scattering cross section is, according to (13), defined by

$$\sigma = W \frac{L^3}{v_0}$$

If we use the probability w of Equation 1 instead of W we obtain the differential scattering cross section

$$d\sigma = w \frac{L^3}{v_0} \quad (14)$$

Using all the equations from (1) to (14), we obtain as the differential cross section

$$d\sigma = \frac{8\pi e^6 Z^2 N k^F d\Omega}{m\omega v_0} \left\{ \frac{k_x^0}{\left(\frac{p_0^2 - p'^2}{2m} \mp \hbar\omega \right) \left(\vec{k}' - \vec{k}^F \right)^2} + \frac{k_x''}{\left(\frac{p_0^2 - p'^2}{2m} \right) \left(\vec{k}^0 - \vec{k}' \right)^2} \right\}^2 \quad (15)$$

where we have taken

$$N = \frac{n}{L^3} \quad (16)$$

with N being the number of photons per unit volume. Since the normalization factor L has been eliminated from (15), we can now safely let $L \rightarrow \infty$.

The Kronecker δ -symbols in (6) and (7) require that

$$\vec{k}' = \vec{k}^0 \pm \vec{\beta} \text{ or } \vec{p}' = \vec{p}^0 \mp \hbar \vec{\beta} \quad (17)$$

and

$$\vec{k}' = \vec{k}^F \pm \vec{\beta} \text{ or } \vec{p}' = \vec{p}^F \pm \hbar \vec{\beta} \quad (18)$$

Then from Equations 17 and 18, we have

$$\vec{k}' - \vec{k}^F = \vec{k}^0 - \vec{k}' = \vec{k}^0 - \vec{k}^F \mp \vec{\beta} \quad (19)$$

Referring to FIG. 2, the following relation can be derived

$$\left(\vec{k}^0 - \vec{k}^F \mp \vec{\beta} \right)^2 = k^0^2 + k^F^2 + \beta^2 \mp 2k^0\beta \cos \theta \pm 2k^F\beta \cos \psi - 2k^0k^F (\cos \theta \cos \psi \mp \sin \theta \sin \psi \cos \alpha) \quad (20)$$

Integrating Equation 15 over all directions of the scattered electron yields the total interaction cross section σ . If the cross section σ_e and σ_a for the cases of emission and absorption of radiation respectively were equal, no net effect would be observed. If their difference

$$\sigma_T = \sigma_e - \sigma_a$$

is positive, stimulated emission of radiation occurs, while a negative value of σ_T indicates absorption.

With the help of Equations 12, 15, 17, 18, 19 and 20 the following equation is obtained

$$\sigma_T = \frac{4e^6 Z^2 N}{m^3 v^4 f^2} \left\{ (3 \cos^2 \varphi \sin^2 \theta - 1) \ln \frac{2mv^2}{\hbar f} - 2 \cos^2 \varphi \sin^2 \theta \right\} \quad (21)$$

where

$e = 4.803 \times 10^{-10}$ e.s.u. electron charge

$m = 9.11 \times 10^{-28}$ gr. electron mass

f = signal frequency

N = photon density

Z = number of elementary charges of the ion

v = velocity of the incident electron

Equation 26 holds if

$$2\pi \frac{Ze^2}{\hbar v} \ll 1, \frac{mv^2}{\hbar f} \gg 1 \text{ and } \frac{c}{v} \gg 1 \quad (22)$$

It will be noted from Equation 21 that $\sigma_T > 0$ for cases where the electron beam is incident in a direction more or less parallel to the direction of the electric vector of the signal field. However, substantial deviations from a parallel direction can be tolerated. If

$$\ln \frac{2mv^2}{\hbar f} \gg 1$$

we find that σ_T will be positive, indicating emission of radiant energy, as long as the incident electron beam remains within 50 degrees from the direction of the signal field. The three decibel point (output power reduced to one-half) is reached when the electron beam deviates by approximately 35 degrees. Thus, whereas most efficient operation is realized when the direction of electron flow is parallel to the electric vector of the signal field, this is not a critical limitation. Operation at reduced efficiency can be realized over a considerable angle of incidence for the electron beam.

The number ΔN of emitted photons per second is obtained if we multiply σ_T by the number of electrons N_e which penetrate per second the unit area containing the nucleus with a charge Ze . If there is more than one nucleus interacting with the electron stream we obtain the total number of emitted photons per second by multiplying the total number of nuclei N_n with the electron flux density N_e which per second interacts with them provided the density of nuclei is low. For electrons incident parallel to the electric vector of the signal field, we obtain

$$\frac{\Delta N}{N} = \frac{8e^6 Z^2 N_e N_n}{m^3 v^4 f^2} \left[\ln \frac{2mv^2}{\hbar f} - 1 \right] \quad (23)$$

Equation 23 shows that the ratio of emitted photons per second to the stimulating photon density decreases rapidly as the electron velocity v increases. Within the limits set by (22), we obtain more emission with slower electrons. The number of emitted photons also increases with decreasing frequency.

The coherence of the stimulated emission with the signal field for the process described hereinabove follows from exactly the same arguments used to prove the coherence of stimulated emission in masers. One important difference, however, is that the spontaneous emission in the case of bremsstrahlung covers a continuous spectrum of frequencies.

We conclude this discussion by stating the condition for achieving self-sustained oscillation when the radiation is confined in a cavity. Defining the cavity Q as

$$Q_L = \omega \frac{NV \hbar f}{u' \hbar f} = \frac{\omega NV}{u'} \quad (24)$$

where

V is the cavity volume,

N the photon density, and

n' the number of dissipated photons per second, the cavity oscillates if $n' = \Delta N$.

This leads to the following expression for the minimum product necessary to achieve oscillation if, again, electron incidence parallel to the electric vector of the signal field is assumed;

$$N_e N_n = \frac{\pi m^3 v^4 f^2 V}{4e^6 Z^2 Q_L \left[\left(\ln \frac{2mv^2}{\hbar f} \right) - 1 \right]} \quad (25)$$

The oscillating frequency is only determined by the cavity. If many cavity modes can exist, oscillation will start in the mode with the smallest factor

$$\frac{f^3}{Q_L}$$

For use as an amplifier the bandwidth can be much larger than the bandwidth of conventional masers because there is no build-in resonance in this process to limit the frequency.

It can also be shown that Equation 25 applies to the first embodiment of the invention if Q_L is taken as the loaded Q of the L-C resonant circuit and V as the condenser volume.

In the embodiment of FIG. 1 the ions, which constitute the scattering elements, are randomly distributed over the interaction region between the plates 19 and 20. The resulting photon emission, from Equation 23, is seen to be proportional to the number of ions N_n . It can be shown, however, that by a periodic arrangement of the ions within the interaction region, there is a substantial enhancement in the amount of emission obtainable over the amount obtainable from a random distribution of ions. In particular, it can be shown that if the scattering centers are spaced a distance

$$d = \frac{v}{f} \quad (26)$$

where

v is the electron velocity, and
 f is the signal frequency,

the number of stimulated photons emitted per second is proportional to the square of the number of ions (i.e., $\propto N_n^2$).

In FIG. 3 there is shown an arrangement for making use of this phenomenon. The structure is essentially the same as that of FIG. 1 except that in the FIG. 3 embodiment a plurality of discrete ion beams are used, spaced in accordance with the requirements set forth in Equation 26. For purposes of illustration the only elements shown in FIG. 3 are the wire mesh condenser plates 19 and 20, inductor 21 and a modified ion source 10'. The latter comprises a multi-beam source for projecting a plurality of ion beams of thickness t through the region between plates 19 and 20. The beams are separated from each other by an amount

$$d = \frac{v}{f}$$

Preferably the ion beams are projected through the interaction region in a direction at right angles to the direction of the electron stream. So projected, the velocity v used to compute the beam spacing is the total electron velocity. If the ion beams and the electron stream are not perpendicular to each other, the velocity v is taken as the component of the electron velocity perpendicular to the ion beams.

Each of the ion beams has a thickness t within the interaction region which is smaller than the beam spacing. Preferably the beam thickness is less than one-tenth the beam spacing

$$\left(t \leq \frac{d}{10} \right)$$

In a typical embodiment operating at a signal frequency of $f = 1 \times 10^9$ cycles per second, and assuming an electron velocity $v = 10^8$ centimeters per second, the spacing between beams is one millimeter.

The rest of the structure of FIG. 3 (not shown) and its operation are as disclosed in connection with FIG. 1.

In a third embodiment of the invention, bremsstrahlung is stimulated in a solid by inducing a flow of free electrons through a high resistivity material. In accordance with the invention, a high resistivity material is doped with an appropriate impurity. The presence

of the impurity introduces electrons having energy levels in the forbidden band. Preferably, the energy levels of the impurity should be located as far from the conduction band as possible. The material is located in a signal radiation field and simultaneously "pumped" with a second radiation field whose frequency is high enough to pump impurity electrons from the impurity levels in the forbidden band to the conduction band but not high enough to pump electrons from the valence band to the conduction band. Thus, if we represent the forbidden band as ΔE and the difference between the impurity levels and the conduction band as ΔE_i , the pumping frequency f_p is given by

$$\frac{\Delta E_i}{h} \leq f_p < \frac{\Delta E}{h}$$

where h is Planck's constant.

The pumping ionizes the impurity and, as explained hereinabove, electrons passing in the vicinity of a nucleus (i.e., the ionized impurity) in the lattice structure emit radiation. To insure that the electrons move in the desired direction (i.e., in a direction substantially parallel to the electric vector of the signal radiation field), the pumping field is preferably polarized in a direction parallel to the signal field.

In FIG. 4, there is illustrated an embodiment of the invention using a solid material. In this embodiment, a block of high resistivity material 30, doped with a suitable impurity is placed within a conductively bounded cavity 31.

Material 30 is essentially an insulator at the temperature at which it is intended to be used. More specifically, the energy required to lift electrons from the impurity levels and the valence band into the conduction band of the material is sufficiently large that essentially no electron can be spontaneously lifted into the conduction band by thermal agitation. In addition, the updoped material is transparent to the pumping radiation.

The impurity concentration has to be adjusted so that a sufficient number of scattering centers are available as required by the theory.

Cavity 31 is, typically, a section of rectangular waveguide whose narrow walls 32 and 33 are made of screen mesh and whose ends are terminated by means of conductive members 34 and 35 which extend transversely across the guide. The cavity is preferably proportioned to support wave energy at the signal frequency in the TE_{101} cavity mode.

Means for introducing and extracting signal wave energy from cavity 31 are provided in any convenient manner known in the art. In FIG. 4, a probe 36 is inserted into the cavity through the center of one of the broad walls of the waveguide section. The probe can be an extension of the center conductor of a coaxial transmission line 37 or it, alternatively, can be a post extending between cavity 31 and a second section of waveguide.

In the embodiment of FIG. 4, the pumping energy is introduced into the cavity 31 through the screen mesh walls 32 and 33. This is possible since, as will be explained hereinbelow, the pumping field is derived from a light source. Since the direction of the electric field associated with the signal frequency is perpendicular to the wide walls of cavity 31 for the TE_{101} cavity mode, the pumping field is also preferably polarized in a direction perpendicular to the wide walls of cavity 31.

For purposes of illustration, consider the high resistivity material 30 to be a cadmium sulfide (CdS) crystal doped with an excess of either cadmium or sulphur. For cadmium sulfide the forbidden energy gap is

$$\Delta E = 2.4 \text{ ev.} = 3.84 \times 10^{-12} \text{ ergs.} \quad (27)$$

This corresponds to a frequency

$$f = \frac{\Delta E}{h} = 5.8 \times 10^{14} \text{ cycles per second} \quad (28)$$

which establishes the maximum permissible frequency of the pumping field since, as indicated above, a higher frequency pump would pump electrons from the valence band to the conduction band.

Doping with excess cadmium or excess sulphur introduces electrons within the forbidden band whose energy levels are 0.02 ev. below the conduction band. To suppress any tendency for the impurity electrons to enter the conduction band as a result of thermal excitation, the cadmium sulfide is advantageously cooled to liquid helium temperature (4° K.).

In operation, the impurity electrons are preferably made to move in a direction parallel to the electric vectors of the signal radiation field by exposing the cadmium sulfide to a pumping radiation field polarized in a direction parallel to the signal field electric vector. As indicated above, however, this is not a critical limitation in that the direction of the electron flow and, hence, the direction of polarization of the pumping field can deviate from the direction of the signal field. The pumping field has a frequency high enough to ionize the impurity atoms by pumping impurity electrons from the forbidden band to the conduction band but not high enough to pump electrons from the valence band to the conduction band. From Equation 28, this places the maximum frequency of the pumping field below 5.8×10^{14} cycles per second. (Pump light containing higher frequencies could be used. However, the energy contained in the higher frequencies would be absorbed before it could penetrate appreciably into the crystal.) Since visible light is readily available, red light at a frequency, f_p , of approximately 4.5×10^{14} cycles per second is used. The light does not have to be coherent nor monochromatic, but can cover a wide band.

To achieve oscillations with a cavity Q of approximately 300 and a crystal volume, V, of 77 cm.³ (2 cm. x 5.5 cm. x 7 cm.) at a signal frequency, f_s , of 1×10^9 cycles per second, 200 watts of polarized pumping light is used. At the pumping frequency, f_p , this corresponds to an emission of 6.7×10^{20} photons per second. Assuming all the pumping energy is absorbed in the crystal and noting that the process of light absorption consists of ionization of the impurities, a total of

$$nV = 6.7 \times 10^{20} \quad (29)$$

free electrons are created throughout the volume of the cadmium sulfide crystal. The current density, N_e (the number of electrons per unit area per second), is

$$N_e = nI = \frac{6.7 \times 10^{20}}{77} \times 10^{-3} = 8.7 \times 10^{16} \frac{\text{electrons}}{\text{cm.}^2 \text{ sec}} \quad (30)$$

wherein the mean free path, l , for electrons scattered in cadmium sulfide at 4° K. is taken as approximately 10^{-3} cm.

The electron velocity, v , is obtained from

$$\frac{1}{2} m_{\text{eff}} v^2 = hf - A \quad (31)$$

where

hf is the photon energy,

$A = 0.02$ ev., the energy gap between the impurity level and the conduction band, and

$m_{\text{eff}} = 0.3$ $m_0 = 0.3 \times 9.11 \times 10^{-28} = 2.7 \times 10^{-28}$, the effective electron mass.

From Equation 31, we obtain an electron velocity of $v = 1.15 \times 10^8$ cm. per second.

Using Equation 25 and including a dielectric constant $\epsilon = 10$ to take into account the coulomb potential within the solid crystal ((25) being multiplied by ϵ^3 to include the effect of the dielectric) we obtain a product

$$N_i N_e = 4 \times 10^{34} \text{ cm.}^{-2} \text{ sec.}^{-1} \quad (32)$$

Thus, the required impurity density n_i would be

$$n_i = \frac{N_i N_e}{N_e V} = 6 \times 10^{16} \text{ impurities/cm.}^3. \quad (33)$$

To take into account the influence of scattered electrons which might give rise to absorption if they are incident upon an ion in a direction perpendicular to the electric vector of the signal radiation field, a safety factor of 100 is introduced making the impurity density approximately 6×10^{18} impurities per cm.³.

To operate as an amplifier, rather than an oscillator, either the impurity concentration or the pumping power can be reduced or the loaded Q can be lowered by increasing the coupling to the output cable or waveguide.

In the illustrative embodiment described above, a pumping light was used to cause electrons to move in the desired direction. Other means can be used, however, such as a strong D.C. electric field. In this alternate arrangement, the D.C. field is sufficiently large to exceed the breakdown voltage for the insulator or high impedance material.

It is well known that any insulator will start to conduct if a D.C. electric field of sufficient intensity is applied across it. The high D.C. voltage lifts electrons from the valence band and from impurity levels into the conduction band. The impurities are partially ionized by electron impact.

The requirements for the high resistivity material are similar to the embodiment using optical pumping. However, the forbidden energy region does not have to be as large. In the optical pumping embodiment, the energy gap had to be wide enough so that

$$\Delta E > hf$$

with f = frequency of the pump wave.

For the case of D.C. breakdown excitation, the energy gap need only be wide enough that thermal excitation of electrons does not occur. Impurities are still needed, however, to provide scattering centers. The D.C. voltage is preferably applied parallel to the electric vector of the signal field in order to force the electrons to move in the right direction.

FIG. 5 shows an arrangement for D.C. pumping in which the top and bottom walls 41 and 42 of a waveguide cavity 40 are in ohmic contact with the crystal 43 but are insulated from the sides of the cavity. Proper choke arrangements, as used for waveguide flanges, may be provided to prevent the signal field from leaking out of the cavity. The resistor 44 in series with the source of high D.C. potential 45 is used to limit the breakdown current and to protect the crystal from damage.

It may be advantageous to provide several D.C. contacts along walls 41 and 42 rather than only one in order to achieve higher field intensities locally and thus reduce the required voltage.

Periodic spacing of the scattering centers to enhance the photon emission can also be resorted to in the solid state embodiments of FIGS. 4 and 5. When this technique is used, the impurities, instead of being randomly distributed throughout the crystal, are arranged in parallel planes separated by the distance d measured in a direction parallel to the direction of polarization of the pumping field, as shown in FIG. 6. Crystals of this type can be obtained by depositing the impurities periodically as the crystal is grown. The thickness t of each impurity layer is preferably small compared to the spacing, d , between layers, being of the order of one-tenth or less

$$\left(t \leq \frac{d}{10} \right)$$

As an example, and assuming an electron velocity of the order of 10^7 cm./sec. and a frequency f of one kilomegacycle per second, d is equal to 0.1 millimeter.

In all cases it is understood that the above-described arrangements are illustrative of a small number of the many possible specific embodiments which can represent applications of the principles of the invention. Numerous and varied other arrangements can readily be devised in accordance with these principles by those skilled in the

art without departing from the spirit and scope of the invention.

What is claimed is:

1. Apparatus supportive of electromagnetic wave energy comprising:

a resonant structure tuned to a given frequency,
means for introducing into a region of said structure a beam of electrons, said beam making an angle of less than 50 degrees with respect to the direction of the electric field associated with said energy within said region,
means for introducing a beam of ions into said region, and coupling means for extracting electromagnetic wave energy from said apparatus at said given frequency.

2. Apparatus according to claim 1 wherein said electron and ion beam densities are sufficient to induce oscillations at said frequency.

3. Apparatus according to claim 1 wherein means are provided for applying wave energy to said resonant structure at said given frequency,

and wherein amplified wave energy is extracted through said coupling means at said given frequency.

4. Apparatus in accordance with claim 1 wherein said beam of electrons is introduced into said region in a direction substantially parallel to the direction of the electric field associated with said energy within said region, and wherein said beam of ions is introduced into said region in a direction substantially perpendicular to said electron beam.

5. Apparatus according to claim 1 wherein said resonant structure comprises:

a pair of planar, parallel wire mesh condenser plates and an inductor,
wherein said ion beam passes between said plates in a direction substantially parallel thereto,
and wherein said electron beam passes through said wire mesh plates in a direction substantially perpendicular thereto.

6. Apparatus supportive of electromagnetic wave energy comprising:

a resonant structure tuned to a given frequency f ,
means for introducing an electron beam into a region of said structure in a direction substantially parallel to the direction of the electric field associated with said energy within said region,
said electrons having a velocity v ,
means for introducing into said region of said structure a plurality of spaced ion beams in a direction perpendicular to said electron beam,
said ion beams being spaced from each other a distance given approximately by

$$d = \frac{v}{f}$$

and having a beam width that is less than d ,
and coupling means for extracting electromagnetic wave energy from said apparatus at said frequency.

7. An electromagnetic device comprising:

a source of electromagnetic radiation consisting of a dielectric material having a forbidden energy band ΔE and a given impurity density,
means for cooling said material,
means for increasing the energy level of electrons within said material from an energy level within said forbidden band to an energy level within the conduction band of said material,

said electrons being caused to move within said material with a velocity v and thereby caused to radiate electromagnetic wave energy over a band of frequencies,

means for inducing stimulated emission at a selected frequency within said band of frequencies comprising a resonant structure tuned to said selected frequency and electromagnetically coupled to said radiant wave energy,

and means for extracting wave energy from said structure at said selected frequency.

8. The device according to claim 7 wherein said impurities are arranged in discrete parallel planes spaced apart at a distance d equal to v/f .

9. The device according to claim 7 wherein said means for increasing the energy level of said electrons comprises an electric field of constant amplitude greater than the breakdown voltage of said material.

10. In combination;

a source of electromagnetic radiation consisting of a dielectric material having a forbidden energy band ΔE and a given impurity density,

means for cooling said material,

means for inducing spontaneous radiation from said material over a band of frequencies comprising a pumping wave of frequency f_p less than $\Delta E/h$, but greater than $\Delta E_i/h$, where h is Planck's constant and ΔE_i is the energy difference between the impurity levels in the forbidden band and the conduction band of said material,

means for inducing stimulated emission at a selected frequency within said band of frequencies comprising a resonant cavity tuned to said selected frequency, said material being located within a region of said cavity,

said pumping wave being polarized in a direction having a substantial electric field component parallel to the direction of polarization of wave energy as supported by said cavity within said region, and means for extracting wave energy from said cavity at said frequency.

11. Apparatus according to claim 10 wherein: the intensity of said pumping field and the impurity density cause oscillations at said frequency.

12. Apparatus according to claim 10 including means for introducing signal wave energy into said cavity at said given frequency,

and wherein said coupling means extracts amplified signal energy from said cavity at said given frequency.

13. Apparatus according to claim 10 wherein said enclosure is a section of rectangular waveguide, and wherein said material comprises:

a crystal of cadmium sulfide doped with an excess of either cadmium or sulphur.

14. Apparatus according to claim 10 wherein said pumping field is polarized in a direction substantially parallel to the direction of the electric field supported by said cavity within said region.

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