Feb. 11, 1964 W. HEYWANG 3,121,203

SEMICONDUCTOR MASER WITH MODULATING MEANS

Filed April 22, 1959 2 Sheets-Sheet 1

Fig.1

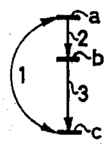


Fig.2a

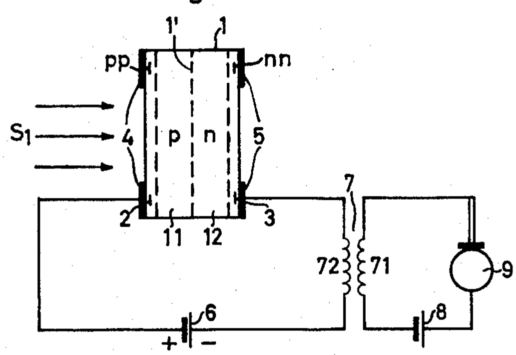


Fig.2b

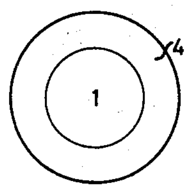


Fig.3

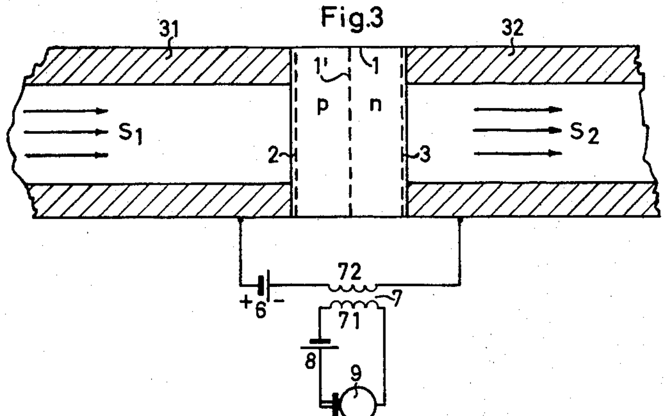
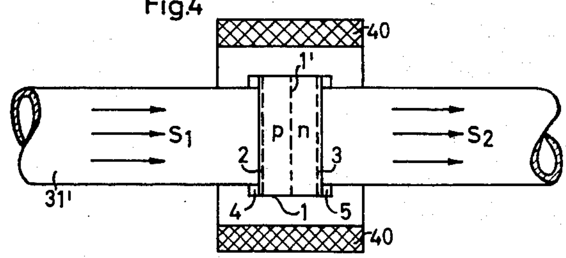


Fig.4



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SEMICONDUCTOR MASER WITH MODULATING MEANS

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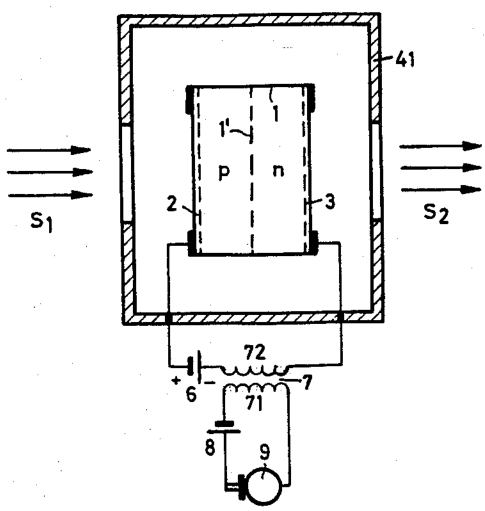
Fig.5



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SEMICONDUCTOR MASER WITH MODULATING MEANS

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16 Claims. (Cl. 332—52)

This invention relates to the control of very high frequency radiation and is particularly concerned with producing or amplifying very high frequency radiation according to the principle of microwave amplification by stimulated emission of radiation briefly referred to as "Maser" principle.

Arrangements operating in accordance with this principle make use of the fact that, when a particle, for example, an electron, is by radiation stimulated to pass from a term of higher energy content to a term of lower energy content, a radiation will be transmitted which corresponds to the energy difference of both terms, such radiation being often stronger than the stimulating radiation, the frequencies of the transmitted and of the stimulating radiation being the same.

Continuous transmission of radiation may be obtained by an auxiliary radiation which is in turn effective to cause particles to pass from the term of lower energy content to a term with an energy content exceeding that of the term from which the particles due to the stimulating radiation pass again into the lower energy content.

The various objects and features of the invention will appear in the course of the description which will be rendered below with reference to the accompanying drawing. In the drawing,

FIG. 1 shows an example of the manner in which a continuous transmission of radiation may be effected;

FIGS. 2*a* and 2*b* illustrate an embodiment of the invention; and

FIGS. 3, 4 and 5 show further embodiments of the invention.

Referring now to FIG. 1, showing in schematic representation the manner of effecting continuous transmission of radiation, terms *a*, *b*, *c* are indicated by short horizontal lines, the energy content of these terms decreasing from the top downwardly. The term *a* accordingly corresponds to an energy content greater than that of *b*, and *b* has an energy content exceeding that of *c*. In this arrangement, a particle (electron) is by auxiliary radiation lifted from the term *c* to the term *a* (see arrow 1), such electron thereupon dropping to the term *b* (see arrow 2), where it adheres. The stimulating radiation, which corresponds to the energy spacing between the terms *b* and *c*, thereupon causes this electron to pass from *b* to *c* (see arrow 3), thereby effecting transmission of amplified radiation the frequency of which as well as that of the stimulating radiation corresponds to the energy spacing E_{bc} between the term *b* and *c*, according to the known formula $E_{bc}=h \cdot \nu$, wherein h is Plank's constant and ν the frequency. Additional information with respect thereto may be found in the book entitled "Introduction to Solid State Physics," by Charles Kittel (University of California), published 1956 by Wiley, New York, page 122. The fact that the lifting of the electron on its path from *c* to *a* requires a greater energy than is liberated upon passage from *b* to *c*, shows that the auxiliary radiation for the lifting of the electron must have greater power than the radiation transmitted upon passage of the electron from *b* to *c*. However, the fact that the frequency of the auxiliary radiation by which the electron is lifted from *c* to *a* must be in accordance with the equation $\nu_{ca} \cdot h=E_{ca}$ higher than that of the transmitted radiation, is in such an arrangement more disturbing. The advantage of continuous transmission of a high frequency radiation is accordingly obtained at the expense of the serious drawback of having to provide for an auxiliary radiation which must not only have very high power but also a higher frequency.

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The invention avoids these disadvantages in most surprisingly simple manner by providing an arrangement for amplifying very high frequency radiation according to the Maser principle, comprising (*a*) an electron-conducting, particularly a mono-crystalline semi-conductor body having two mutually different regions in which the charge carriers have upon current flow through the semiconductor body different energy content, and in whose transition or junction area between these two regions the charge carriers of higher energy can be responsive to stimulation with high frequency radiation give off an amplified energy radiation of the same frequency; (*b*) a voltage source for effecting flow of charge carriers from the region of higher energy to the transition area; and (*c*) a radiation source the high frequency radiation of which permeates at least into the transition area of the semiconductor body.

The advantage resulting from the above noted features is that electrons of higher energy are by the voltage source continuously introduced into the transition zone between the two partial areas of the semiconductor body, these areas, under the influence of the stimulation radiation entering into the transition zone, passing to lower energy stages while giving off the amplified radiation, for example, recombining with positive charge carriers, and that maintenance of the radiation merely requires continuous current flow through the semiconductor body. The voltage placed on the semiconductor body is preferably a direct current voltage; however, for the modulation of the high frequency radiation transmitted from the semiconductor body, it may preferably fluctuate in the rhythm of the desired modulation frequency. Impulsewise transmission of radiation may be effected by placing on the semiconductor body which is continuously irradiated by a weak stimulation radiation, an alternating voltage or voltage impulses to provide in this manner for the transmission of high frequency radiation impulses.

Basic semiconductor materials very well adapted for arrangements according to the invention include known substances adapted for diodes and transistors, for example, silicon, germanium, $A^{III}B^{V}$-compounds and, in addition other semiconductor substances, for example, bismuth-tellurid (Bi_2Te_3). The latter substance is particularly well adapted for purposes of the invention since it exhibits only a slight spacing between the valency band and the line band and having relative to the first mentioned substances only a slight heat conductivity, thereby further favoring the Maser effect.

In order to obtain in the semiconductor body regions of different energy content of the charge carriers, it will be advisable to use a semiconductor body having a p-zone and an n-zone. However, since the frequency of the stimulation radiation and the frequency of the transmitted radiation are, as noted before, in a fixed relationship to the energy loss suffered by the electron, stimulated by the permeating radiation, upon transition of the electron into the term of lower energy content, and since this frequency corresponds in the case of germanium or silicon to a wavelength of about 1 μm, it is for obtaining long wave radiation advisable to provide traps in the transition region between the two p- and n-zones. As explained in the book of Kittel, page 515, first paragraph, traps are impurity atoms or other imperfections in the crystal, the energy level of which may be at times occupied by electrons or holes. Traps are produced as impurities, for example, in silicon or germanium, by the building-in of nickel-, iron- and/or copper atoms. The energy spacing of one trap level from the other and from line band to trap and trap to valency band of the semiconductor is small in accordance with the desired wavelength of the transmitted radiation. Since upon using two traps, these traps must lie spatially similarly in the semiconductor, so that the electrons can pass under the influence of the stimulation radiation, it is suggested to form these two traps by building-in atoms or molecules of substances the term spacing of which is only very small and wholly within the prohibited band of the basic semiconductor material. Substances of this kind which are suitable in connection with germanium and silicon are, for example, nickel, iron, copper or grid defects with trap character. The traps may be "built" into the construction in the form of an impurity in the semiconductor, the amount of which will normally be small and controlled at least in part by the particular application. The spring structure of the trap levels may be utilized by the provision of an auxiliary magnetic field. In such a case, the term spacing and therewith the wavelength of the transmitted radiation may also be controlled by the magnetic field, for example, it may be modulated in the rhythm of impulses or an alternating voltage.

Further details of the invention will appear from the following explanations and from the embodiments shown in the drawing.

In the embodiment according to FIGS. 2*a* and 2*b*, the semiconductor body 1 consists of two partial regions 11 and 12 of which 11 is p-conducting and 12 n-conducting. The semiconductor body has moreover layers 2 and 3 for non-blocking contacting of the partial regions 11, 12, the over-doping of these layers being respectively indicated by *pp* and *nn*. These layers, serving for current electrodes or connections, are made as thin as possible so that they are well permeable for the entering and leaving radiation. The current connection is effected, for example, by means of annular metal electrodes 4 and 5 (see also end view FIG. 2*b*) to which is connected a voltage source 6. The polarization of the voltage source is such that the semiconductor 1 is operated in flow direction.

Accordingly, electrons will continuously flow from the partial region into the intermediate layer 1' of the semiconductor 1 between the two p- and n-regions 11 and 12, such electrons dropping in the intermediate layer 1' from their condition of higher energy which they have in the region 12, to a lower energy level, and particularly recombining with the defect electrons coming from the partial region 11. In order to obtain a particularly favorable radiation yield, the semiconductor is made disk-shaped with surfaces as plane as possible and above all, with the transition layer as plane as possible. The incident radiation, indicated in FIG. 2*a* by arrows S_1, due to the fact that its frequency ν, is smaller than the quotient from the energy spacing between the valency band and line band and Plank's effect quantum h, permeates into the intermediate layer 1' between the partial regions 11, 12 and releases there the amplified radiation which in turn radiates from the semiconductor.

In order to avoid the wavelength of the amplified radiation leaving the semiconductor or the wavelength of the stimulating radiation S_1, respectively, becoming too small, that is, to obtain, for example, a radiation in the millimeter range, there are provided traps, as mentioned before, at least in the intermediate region 1', for the electrons coming from the region 12 and for the defect electrons, respectively, coming from the region 11, the energy spacing of which is small in accordance with the desired wavelength. The electrons passing in these traps from the line band are by the incident radiations S_1 stimulated to pass respectively in the valency band or into a trap of lower energy content lying at the same place, recombining there with the defect electrons and transmitting incident to the corresponding transition the amplified radiation having the desired wavelength corresponding to the small energy spacing.

The energy of the transmitted radiation depends also upon the amount of electrons simultaneously stimulated for transition and therefore is proportional to the strength of the current flowing through the semiconductor 1. This is utilized in the arrangement according to FIGS. 2*a*, 2*b*, a transformer being for this purpose provided the primary winding 71 of which is, for example, supplied with alternating current from a source 8 by way of a microphone 9, producing in the secondary winding 72 an alternating voltage superposed upon the voltage from the source 6. This alternating voltage results in a correspondingly fluctuating current flow through the semiconductor 1, thus producing a transmitted radiation with energy fluctuating in the rhythm of the speech frequency.

Further details of the invention will appear from the following description with reference to the embodiments illustrated in FIGS. 3 and 4.

In FIG. 3, the disk-shaped semiconductor 1 is arranged between two wave guides 31, 32 which serve as current connections for the over-doped *pp* and *nn* layers of the semiconductor 1. The wave guide 31 is connected with the positive (+) pole of the battery 6 the negative (−) pole of which is connected with the wave guide 32 by way of the secondary winding of transformer 7. The semiconductor is accordingly on a voltage source polarized in flow direction so that the electrons are continuously supplied from the n-conductive part of the semiconductor into the intermediate layer 1' disposed between the p-zone and the n-zone. The primary winding of the transformer 7, as already noted in connection with FIG. 2*a*, is connected to battery 8 in series with microphone 9, so that an alternating voltage in rhythm of the speech frequency impressed on the microphone, is superposed on the direct current voltage from the source 6.

The semiconductor is arranged between the wave guides so that the transition layer 1' between the two p-n-zones extends approximately perpendicular to the axes of the two wave guides 31, 32. The incident radiation indicated at S_1 therefore impacts the intermediate layer 1' approximately perpendicularly. The amplified radiation S_2 is in the described manner stimulated in this intermediate layer by the stimulation radiation S_1, the amplified radiation S_2 leaving the semiconductor substantially in the direction corresponding to the direction of the incident radiation S_1 and entering the wave guide 32.

As shown in FIG. 4, dielectric hollow radiators may be used in place of the metallic wave guides 31, 32, the incident radiation S_1 being in such case in known manner guided within a rod-shaped non-conductor. The incident radiation S_1 will again impact the transition layer 1' between the two p-n-zones of the semiconductor approximately perpendicularly. A dielectric radiation conductor may also serve for the transmitted radiation S_2, the radiation leaving the semiconductor entering in such case into the end of a rod-shaped radiator and being in known manner propagated therealong. Contact rings 4 and 5 are provided in FIG. 4 in a similar manner as in FIG. 2*a*, for contacting the hollow conductors to which may be connected in suitable manner (not shown) a voltage source polarized in the flow direction of the p-n-transition, for example, the circuit shown in FIG. 2*a*.

In this embodiment, there is also provided a coil 40 for producing responsive to current flowing therethrough (effected by suitable means) a magnetic field permeating the transition region 1', such field being effective to compel in a trap disposed in the transition region, which has only one effective energy term, a splitting of this term into two closely neighboring terms and thereby producing an energy surge depending upon the strength of the magnetic field, which results in a relatively large wavelength of the transmitted radiation.

FIG. 5 shows a semiconductor body 1 disposed within a tuned hollow space resonator 41, such semiconductor body being circuited according to the invention with respect to the entering and leaving radiation S_1, S_2. The remaining reference numerals correspond to those applied to corresponding parts shown in FIGS. 2 to 4.

Changes may be made within the scope and spirit of the appended claims which define what is believed to be new and desired to have protected by Letters Patent.

I claim:

1. An arrangement for respectively amplifying and producing very high frequency radiation according to the principle of microwave amplification by stimulated emission of radiation, comprising an electron-conducting semiconductor body having two regions which are different one from the other and in which the charge carriers have upon current flow through said body different energy content and in which the charge carriers of higher energy can in the transition area between said two regions give off an amplified energy radiation of identical frequency, responsive to stimulation by means of high frequency radiation, a direct current voltage source for conducting to the transition area charge carriers from the region of higher energy, and a radiation source the high frequency radiation of which permeates at least into the intermediate area of said semiconductor body.

2. An arrangement according to claim 1, comprising traps for the charge carriers of higher energy embedded in said transition area, said charge carriers stimulated by the radiation permeating into the semiconductor body passing into a lower energy stage and giving off radiation thereby.

3. An arrangement according to claim 1, comprising traps embedded in said transition area for charge carriers of lower energy, the charge carriers of higher energy stimulated by the radiation permeating into the semiconductor body passing into said traps and thereby giving off radiation.

4. An arrangement according to claim 1, wherein the region of higher energy content of charge carriers is n-doped in the semiconductor body.

5. An arrangement according to claim 1, wherein the region of lower energy content is p-doped.

6. An arrangement according to claim 1, wherein the voltage source connected to both regions of said semiconductor body is polarized in flow direction.

7. An arrangement according to claim 1, comprising a resonator tuned to the transmitted radiation frequency for enclosing said semiconductor body.

8. An arrangement according to claim 1, comprising a radiation propagating member, said semiconductor body being disk-shaped and being disposed with respect to said radiation-propagating member so as to be impacted only on one side thereof by the radiation which stimulates the amplified radiation.

9. An arrangement according to claim 8, wherein said radiation-propagating member is a hollow wave guide in which is disposed said disk-shaped semiconductor body.

10. An arrangement according to claim 8, wherein said radiation-propagating member is a rod-shaped dielectric radiation conductor, said disk-shaped semiconductor body being disposed at the end of said rod-shaped radiation-propagating member.

11. An arrangement according to claim 1, comprising means for varying the voltage placed on the semiconductor for modulating the radiation transmitted therefrom in the rhythm of the desired modulation while maintaining constant the energy radiation entering into the semiconductor.

12. An arrangement according to claim 1, wherein said semiconductor body is disk-shaped with said transition area disposed approximately in parallel to the surfaces thereof and extending approximately perpendicularly to the direction of the incident radiation.

13. An arrangement according to claim 12, comprising electrode means disposed upon the semiconductor body which are permeable to the radiation.

14. An arrangement according to claim 12, comprising electrode means disposed upon the semiconductor body so as to leave the surfaces of the semiconductor body which extend approximately in parallel to the transition layer at least partially free for the passage of incident and transmitted radiation, respectively.

15. An arrangement according to claim 14, wherein the dimensions of said transition layer perpendicularly to the direction of incident radiation are a multiple of the wave length of the transmitted radiation.

16. An arrangement according to claim 12, in combination with means generating a magnetic field permeating the transition area for producing relatively long wave radiation with wavelengths up to a few centimeters at traps embedded in the transition area having only one operatively effective energy term, said magnetic field causing splitting of said term into a plurality of closely neighboring terms.

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