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MICROWAVE MODULATOR
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Fig. 1.

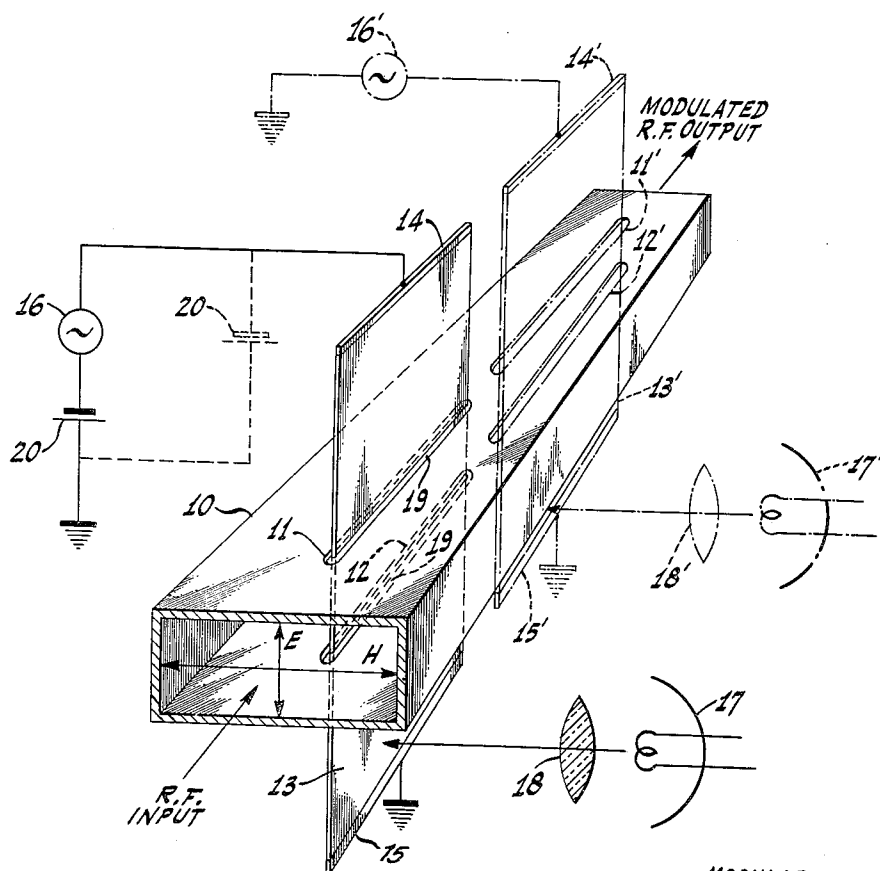
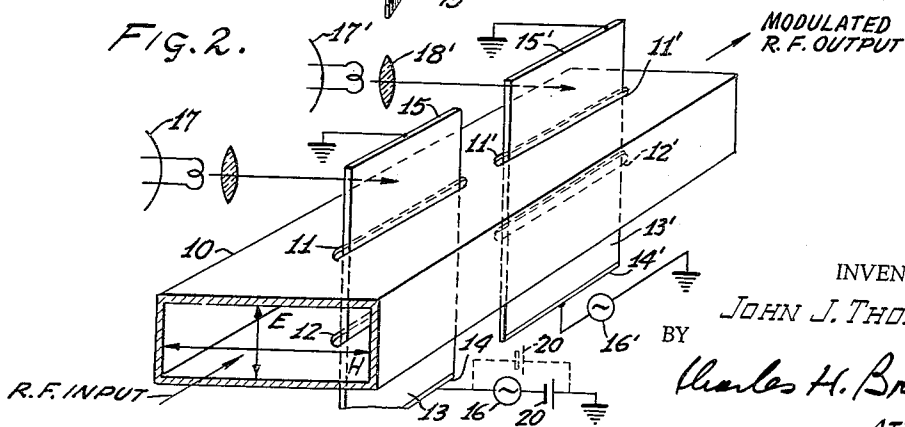


Fig. 2.



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MICROWAVE MODULATOR

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This invention relates to microwave modulators. The invention particularly relates to a microwave modulator utilizing an illuminated semiconductor associated with a waveguide to which radio frequency energy is supplied, thereby permitting the radio frequency energy in the waveguide to be directly modulated in a manner independent of the radio frequency generating source.

Microwave modulation systems are known in which the modulation is accomplished by applying the modulating signal to the radio frequency generator so as to modulate the radio frequency energy at the generator. In generators including high power apparatus such as magnetrons and klystrons, the modulating stages must be isolated from the generator by circuits including capacitors, transformers, and so on. The need for isolation circuits increases the complexity and expense of such modulation systems.

It is an object of the invention to provide an improved microwave modulator which is simpler in construction and in operation than microwave modulators previously available.

A further object is to provide an improved microwave modulator utilizing an illuminated semiconductor such that the modulator functions independently of the radio frequency energy generating source.

Another object is to provide a novel microwave modulator in which the modulation is accomplished by controlling according to a modulating input signal the diffusion of charge carriers from an illuminated area of a semiconductor external to a waveguide to an area of the semiconductor located within the waveguide.

The object of the invention are accomplished by inserting a semiconductor wafer across a waveguide in the plane of the maximum electric field. One or both ends of the wafer extend outside of the waveguide. One of the ends of the wafer external to the waveguide is illuminated with a low intensity light of sufficient value to produce a predetermined density of minority charge carriers in the illuminated portion of the wafer. A modulating input signal voltage is supplied to the wafer. The diffusion of the minority charge carriers from the illuminated portion into the portion of the wafer inside the waveguide is controlled according to the input modulating signal, as a result of which there is obtained high level modulation of the radio frequency energy which is fed through the waveguide.

A more detailed description of the invention will be given in connection with the accompanying drawing wherein Figure 1 shows a microwave modulator constructed according to the invention; and Figure 2 shows a modification of the microwave modulator shown in Figure 1. A section of a rectangular waveguide 10 is shown. The dimensions of the waveguide 10 may be determined in a manner understood in the art so that the waveguide 10 is capable of operation at microwave powers in the frequency range, for example, of three thousand megacycles per second and higher. The waveguide 10 is constructed of a metallic material and may be

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constructed of copper or brass coated on its interior with silver to minimize losses. While a rectangularly shaped waveguide 10 is shown for purposes of description, the waveguide 10 may be of other shapes, such as square or circular, according to the requirements of a particular application.

Radio frequency energy supplied by a suitable source, not shown, is fed into one end of the waveguide 10, as indicated by the arrow. The electric field E and magnetic field H of the energy supplied are oriented in the waveguide 10 in the manner indicated by the bidirectional arrows. A pair of slots 11 and 12 are centrally positioned in opposite walls of the waveguide 10 so that a passage is provided across the waveguide 10 in the plane of the maximum electric field E. A thin wafer 13 of semiconductor material is inserted through the slots 11 and 12 with at least one end of the wafer 13 extending outside of the waveguide 10. The wafer 13 is positioned so that there is an appreciable coupling with the electric field E of the radio frequency wave existing in the waveguide 10. The wafer 13 is insulated from the walls of the waveguide 10 at the slots 11, 12. The insulating material 19 may comprise any suitable insulating material such as polystyrene or polytetrafluoroethylene (known in the art as "Teflon").

To avoid excessive insertion loss, the wafer 13 should be constructed from comparatively high resistivity material such as germanium, silicon or intermetallic compounds known in the art. The wafer 13 is constructed of a single conductivity type material having a conductivity in the intrinsic region. Material having n-type conductivity where electrons contribute to conductivity or material having p-type conductivity where holes (the absence of electrons) contribute to conductivity may be used. The term intrinsic is employed herein as definitive of a substantially pure semiconducting material wherein relatively few donor or acceptor atoms are present. The wafer 13 may be sliced from a single grown crystal of a given conductivity type or may be produced in any other manner understood in the art. The wafer 13 is to be distinguished from junction devices wherein both n-type and p-type conductivity regions are formed in a semiconductor body. In constructing the wafer 13, the thickness thereof should be considerably smaller than the skin depth of the radio frequency energy in the semiconductor. The penetration of the radio frequency energy in the semiconductor (or skin depth) is a direct function of the frequency of the radio frequency energy. By selecting the thickness of the wafer to be smaller than the skin depth, the radio frequency field will completely penetrate the wafer 13, and the absorption of radio frequency power by the semiconductor will be proportional to the semiconductor conductivity.

Ohmic contacts 14 and 15 are provided at the ends of the wafer 13 to permit the application of a uniform electric field thereto. One end of the wafer 13, let us say at 15, is connected to ground or a point of reference potential and the other end, let us say at 14, is connected to the point of reference potential through a source of modulating input signal voltage 16. The connections to the ohmic contacts 14 and 15 may be completed by soldering or using other known techniques.

A source 17 of low intensity light in the order of one volt or less, such as a flash light bulb operated at low intensity, is positioned so as to illuminate an area at one end of the wafer 13 external to the waveguide 10 by means of a lens 18 or other focusing device. While a light source 17 suitable for emitting photons is shown, the source 17 may be any means for emitting radiation in the form of electrons or heavier particles. Many examples of suitable sources for radiating energy are known and a detailed description thereof is unnecessary. The source

17 is preferably set to radiate energy of a steady value sufficient in magnitude to exceed the forbidden band gap of the material used in the wafer 13. The band gap is defined as the energy required to produce electron-hole pair excitation and is a function of the material used. The energy radiated by source 17 whether photons, electrons or other charged particles is determined to be of sufficient magnitude to exceed the band gap and to produce electron-hole pairs in the illuminated area of the wafer 13. In the interaction of the radiated photons, electrons or other charged particles with the atoms of the atom lattice of the wafer 13, excess energy is produced in the interaction to cause the atoms to release valence electrons. As each electron is freed, an electron vacancy is created, producing an electron-hole pair. As the energy supplied by source 17 is increased over that required to exceed the band gap, a correspondingly larger number of electron-hole pairs are produced, and so on. A number of minority charge carriers in the form of holes and electrons are therefore created in the illuminated area of the wafer 13, the density of the charge carriers being determined according to the intensity of the radiation from the source 17.

Some of the charge carriers present in the illuminated area of the wafer 13 will diffuse into the portion of the wafer 13 within the waveguide 10 prior to recombination. The number of charge carriers undergoing such diffusion will depend on the density of the charge carriers produced in the illuminated area. The conductivity of the wafer 13 within the waveguide 10 depends directly on the number of charge carriers diffusing into the area of the wafer within the waveguide 10. As the number of charge carriers increases, the conductivity of the wafer 13 within the waveguide 10 increases, resulting in a corresponding increase in the absorption by the wafer 13 of the radio frequency energy present in the waveguide 10.

In the operation of the invention, an alternating current modulating input signal is supplied across the wafer 13 by the source 16. The intensity of the source 17 is determined so that sufficient charge carriers diffuse into the area of the wafer 13 within the waveguide 10 at the zero or average level of the alternating current signal to cause the rate of absorption of radio frequency energy to correspond to approximately fifty percent of the level of modulation desired. In this manner, the zero-signal radio frequency level is determined. As the modulating signal is applied across the wafer 13, the diffusion of charge carriers into the area of the wafer 13 within the waveguide 10 is modulated accordingly. As the signal supplied by source 16 increases in amplitude in one polarity, the diffusion of charge carriers will change in a direction determined according to the conductivity type of the wafer material. As the signal increases in amplitude in the opposite polarity, the diffusion of charge carriers will change in the opposite direction, and so on.

By way of example, the wafer 13 may be constructed of germanium having p-type conductivity. As the modulating signal goes more positive, the diffusion of charge carriers into the area of the wafer 13 within the waveguide 10 decreases since fewer charge carriers in the form of holes are present in the area of the wafer 13 within the waveguide 10. The conductivity of the wafer 13 decreases, causing the radio frequency absorption rate to decrease with a corresponding increase in the level of the modulated radio frequency signal. As the modulating signal goes more negative, the diffusion of charge carriers increases, since more holes are drawn into the area of the wafer 13 within the waveguide 10. The conductivity of the wafer 13 increases, the radio frequency absorption rate increases and a corresponding decrease in the level of the modulated radio frequency signal occurs.

By the above action, the radio frequency energy fed through the waveguide 10 is modulated about the zero-signal radio frequency level. The speed of response of

the invention is limited only by the minority charge carrier drift velocity (or diffusion rate) in the presence of the applied field. The higher the minority carrier drift mobility in the material used, the greater the speed of response. The modulated radio frequency energy may be taken from the output end of the waveguide 10 as indicated by the arrow and applied to any suitable utilization circuit.

In certain applications, the diffusion of the minority charge carriers from the illuminated area of wafer 13 into the area of the wafer 13 within the waveguide 10 can be further controlled by applying a small, external direct current bias voltage in the order of $\frac{1}{2}$ to 1 volt across the two ohmic contacts 14 and 15. The source of bias voltage 20 may be connected in series with the source 16, as shown, or may be connected across the wafer 13 as indicated by the dotted lines. Depending upon the polarity of this applied voltage, the resulting field either aids or opposes the diffusion of the minority charge carriers, thus increasing or decreasing the radio frequency adsorption. The absorption can not be reduced below the value which exists in the absence of illumination by the source 17. The increase in absorption is limited by the decreasing skin depth with increasing conductivity.

The invention is not to be confused with devices in which some form of signal control is accomplished by varying the density of charge carriers within a semiconductor body. As pointed out above, the source 17 is set so as to provide a fixed intensity of radiation. The density of the charge carriers produced in the wafer 13 remains constant. According to the invention, the diffusion of the charge carriers is modulated and not the density thereof.

By way of example, an embodiment of the invention has been constructed in which a germanium wafer of p-type conductivity and having a resistivity of 25 ohm-centimeters was inserted into a section of Ku band waveguide (frequency=13.5 kilomegacycles per second) in the manner shown in the drawing. The wafer was 1 centimeter long, 0.6 centimeter wide and .033 centimeter thick. The source consisted of a standard microscope lamp operated at reduced voltage. The level of illumination was adjusted for maximum linearity in the modulated radio frequency output. A sinusoidal audio modulating voltage of the order of one volt was applied to the wafer. No direct current bias voltage was employed. A depth of 80% amplitude modulation was readily obtained in the radio frequency output, and the response of the system extended from direct current to several kilocycles.

While a particular embodiment of the invention is shown in the drawing, various modifications may be made thereto without departing from the spirit of the invention. Instead of only a single wafer 13 inserted across the waveguide 10, a number of similar wafers may be inserted across the waveguide 10 spaced along the length thereof. As shown in Figure 2, a second wafer 13' is inserted across the waveguide 10. In practice, any number of the wafers may be inserted in a similar manner across the waveguide. The second modulator including the wafer 13' is similar in operation and construction to that described, and similar components are given similar reference numbers primed. In one application, the first and second modulators can be operated on a time division basis. The intensity of each of the radiation sources 17, 17' associated with the respective wafers 13, 13' could be set to produce a different zero-signal radio frequency level in the waveguide 10 for the corresponding wafer. Each wafer modulator therefore produces, in turn, a level of modulation different from that produced by the remaining wafer modulators. As a result, a pulse multiplex time division microwave modulation system of simple construction is provided.

An arrangement such as described above can also be

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adapted for use in a code signalling system. Each wafer may correspond to an element or character of a code signal. By selectively operating the radiation sources 17 according to the code combination to provide illumination or no illumination to the corresponding wafers, a code transmission system is provided. A signal is produced having amplitude variations corresponding to the make up of the code combination.

A microwave modulator of simple construction and operation is provided. A feature of the modulator is the fact that it functions entirely independently of the radio frequency generating source. Isolation circuits and similar circuits required in prior art microwave modulators are eliminated, greatly reducing the complexity and expense of the modulator as compared to that of the previously known devices.

What is claimed is:

1. A microwave modulator comprising, in combination, a waveguide adapted to carry radio frequency energy, a wafer constructed of a single conductivity-type semiconductor material having minority carriers inserted across said waveguide in a plane providing interaction between said wafer and the electric field in said waveguide, said wafer having at least one end extending outside of said waveguide through an opening in the surface area of said waveguide, means for insulating said wafer and said waveguide from one another at said opening, a radiation source positioned to illuminate an area of said wafer on an end thereof external to said waveguide, and means to apply a modulating input signal to said wafer.

2. A microwave modulator comprising, in combination, a waveguide for propagating microwave energy, a wafer constructed of a single conductivity type semiconductor material having a conductivity in the intrinsic region and having minority carriers inserted across said waveguide in the plane of the maximum electric field in said waveguide, at least one end of said wafer extending outside of said waveguide through a slot in the surface area of said waveguide, means for insulating said wafer and said waveguide from one another at said slot, a radiation source of steady intensity positioned to illuminate an area of said wafer on an end thereof external to said waveguide, and means to apply a modulating input signal to said wafer.

3. A microwave modulator as claimed in claim 2 and wherein said waveguide is a rectangularly shaped hollow-pipe waveguide having broad and narrow walls, said slot being centrally located in a broad wall of said waveguide and extending along the length of said waveguide a distance to accommodate said wafer.

4. A microwave modulator comprising, in combination, a waveguide for propagating microwave energy, a wafer constructed of a single conductivity type semiconductor material having minority carriers inserted across said waveguide in the plane of the maximum electric field in said waveguide, said wafer being of a thickness to permit said energy to completely penetrate said wafer, one end of said wafer extending outside of said waveguide through a first opening in the surface area of said waveguide, the opposite end of said wafer extending outside of said waveguide through an opening opposite to said first opening in the surface area of said waveguide, a radiation source of steady intensity, means for focusing the radiation from said source to illuminate an area of said wafer on an end thereof external to said waveguide, means to insulate said waveguide and said wafer from one another at said openings, and means to apply a modulating signal voltage to said wafer.

5. A microwave modulator comprising, in combination, a waveguide adapted to carry radio frequency energy, a wafer constructed of a single conductivity type semiconductor material having minority carriers inserted across said waveguide in the plane of the maximum electric field in said waveguide, at least one end of said wafer extending outside of said waveguide through a slot

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in the surface area of said waveguide, means for insulating said wafer and said waveguide from one another at said slot, a radiation source positioned to illuminate an area of said wafer on an end thereof external to said waveguide, the intensity of the radiations from said source being set to produce a given density of said minority carriers in said illuminated area, whereby a number of said carriers diffuse into the portion of said wafer within said waveguide, and means to apply a modulating signal to said wafer to modulate said diffusion of said carriers.

6. A microwave modulator comprising, in combination, a waveguide adapted to carry radio frequency energy, a wafer constructed of a single conductivity type semiconductor material having a conductivity in the intrinsic region and having minority carriers inserted across said waveguide in the plane of the maximum electric field in said waveguide, one end of said wafer extending outside of said waveguide through a first slot in the surface area of said waveguide, the opposite end of said wafer extending outside of said waveguide through a slot opposite to said first slot in the surface area of said waveguide, means for insulating said wafer and said waveguide from one another at said slots, said wafer being of a thickness to permit said energy to completely penetrate said wafer, a radiation source of steady low intensity, means for focusing the radiation from said source to illuminate an area of said wafer on an end thereof external to said waveguide, the intensity of the radiations from said source being set to produce a given density of said minority carriers in said illuminated area, whereby a number of said carriers diffuse into the portion of said wafer within said waveguide, a source of modulating signal voltage, and means to apply said modulating signal voltage from said last-mentioned source to said wafer to modulate said diffusion of said carriers.

7. A microwave modulator comprising, in combination, a waveguide for propagating microwave energy, a wafer constructed of a single conductivity type semiconductor material having a conductivity in the intrinsic region and having minority carriers inserted across said waveguide in the plane of the maximum electric field in said waveguide, said wafer being of a thickness to permit said energy to completely penetrate said wafer, one end of said wafer extending outside of said waveguide through a first slot in the surface area of said waveguide, the opposite end of said wafer extending outside of said waveguide through a slot opposite to said first slot in the surface area of said waveguide, means for insulating said wafer and said waveguide from one another at said slots, a light source of steady low intensity, means for focusing the light radiated by said source to illuminate an area of said wafer on an end thereof external to said waveguide, the intensity of the light from said source being set to cause a given density of minority carriers to be produced in said illuminated area by the interaction of the photons radiated from said source and the atoms in the atom lattice of said wafer material, whereby a number of said carriers diffuse into the portion of said wafer within said waveguide, a source of modulating signal voltage, means to apply said modulated signal voltage from last-mentioned source to said wafer to modulate said diffusion of said carriers.

8. A microwave modulator as claimed in claim 7 and wherein said waveguide is a rectangularly shaped hollow-pipe waveguide having broad and narrow walls, said slots being located centrally in said broad walls and extending along the length of said waveguide a distance to accommodate said wafer.

9. A microwave modulator as claimed in claim 7 and wherein said wafer is constructed of semiconductor material having only p-type conductivity.

10. A microwave modulator as claimed in claim 7 and wherein said wafer is constructed of semiconductor material having only n-type conductivity.

11. A microwave modulator as claimed in claim 7 and wherein a bias voltage source is connected across said wafer.

12. A multiplex microwave modulation system comprising, in combination, a waveguide adapted to carry radio frequency energy, a plurality of wafers each constructed of a single conductivity type semiconductor material having minority carriers inserted across said waveguide, said wafers being spaced from one another along said waveguide in the plane of the maximum electric field in said waveguide, at least one end of each of said wafers extending outside of said waveguide through a separate slot in the surface area of said waveguide, means for insulating said wafers and said waveguide from one another at said slots, said wafers being of a thickness to permit said energy to completely penetrate said wafers, a separate source of radiations positioned with respect to each of said wafers so that each radiation source illuminates an area at an end of the wafer with which it is associated external to said waveguide, the intensity of the radiations from said sources being set to produce given densities of said minority carriers in said illuminated areas, whereby numbers of said carriers diffuse from the respective illuminated areas into the portion of the wafers within said waveguide, and means to individually apply modulating signal voltages to said wafers to modulate said diffusion of said carriers, the modulation of the diffusion of said carriers in each of said wafers being determined by the modulating signal voltage applied to that wafer.

13. A microwave modulator comprising, in combination, a rectangular hollowpipe waveguide adapted to carry radio frequency energy, a wafer constructed of a single

conductivity type semiconductor material inserted in the plane of the maximum electric field in said waveguide through slots centrally located in opposite walls of said waveguide, one end of said wafer extending outside of said waveguide through one of said slots and the opposite end of said wafer extending outside of said waveguide through the other of said slots, said wafer being of a thickness to permit said energy to completely penetrate said wafer, means to insulate said wafer and said waveguide from one another at said slots, a light source of steady low intensity, means for focusing the light radiated by said source to illuminate an area of said wafer on an end outside of said waveguide, the intensity of said light being set to cause a given density of minority charge carriers to be produced in said illuminated area, whereby a number of said carriers diffuse into the portion of said wafer within said waveguide, a separate ohmic contact at each of the ends of said wafer outside of said waveguide, a source of modulating signal energy, means to connect said last-mentioned source to the ohmic contact at said one end, means to connect the ohmic contact at said opposite end to a point of reference potential, the diffusion of said carriers being modulated according to said modulating signal energy.

14. A microwave modulator as claimed in claim 13 and including a bias voltage source connected between the ohmic contact at said one end and said point of reference potential.

References Cited in the file of this patent

UNITED STATES PATENTS

2,856,589 Kazan Oct. 14, 1958