A method is described for generating tunable far-infrared radiation. The apparatus includes a Schottky-barrier diode which has one side coupled through a conductor to a waveguide that carries a tunable microwave frequency, the diode having an opposite side which is coupled through a radiating whisker to a bias source. Infrared light is directed at the diode, and infrared light with tunable sidebands is radiated by the whisker through an open space to a reflector. The original infrared is separated from a tunable infrared sideband by a polarizing Michelson interferometer.

7 Claims, 2 Drawing Figures
METHOD AND MEANS FOR GENERATION OF TUNABLE LASER SIDEBANDS IN THE FAR-INFRARED REGION

ORIGIN OF INVENTION

The invention described herein was made under a contract with NASA, and is subject to the rights of the United States Government.

BACKGROUND OF THE INVENTION

Until recently, there has been an almost complete lack of sources for far-infrared light that was coherent and tunable. The sources that have heretofore been developed have produced extremely low power levels of such tunable coherent far-infrared light. A method for producing such light would have considerable uses.

SUMMARY OF THE INVENTION

In accordance with one embodiment of the present invention, a method and apparatus is provided for generating an appreciable amount of tunable electromagnetic radiation of a far-infrared wavelength. Coherent far-infrared radiation, such as from a laser, is combined with continuously tunable microwave radiation to produce far-infrared radiation of the original laser frequency and at least a first sideband frequency which equals the laser frequency plus or minus the tunable microwave frequency. The initial laser frequency is separated from the sideband frequency, so light which includes a high proportion of the sideband frequency is produced.

A means for separating the initial laser frequency from the sideband frequency includes a polarizing Michelson interferometer which includes a pair of rooftop reflectors and a polarizer. The rooftop reflectors are located at different distances from the polarizer, the difference being equal to an integer number of wavelengths of one of the components (the original infrared frequency or the sideband), and also equal to one-half wavelength plus an integer number of wavelengths of the other component. This results in different polarizations between the original laser frequency and the sideband, to permit reflection of one and passage of the other through a second polarizer.

The means for mixing the original far-infrared light as from a laser, with the tunable microwave includes a diode lying in an open area, with one side coupled to a waveguide carrying the tunable microwave frequency and another side coupled to a whisker that can radiate. A reflector that directs the original laser light at the diode, also receives the mixture of the laser frequency with the tunable sideband frequency.

The novel features of the invention are set forth with particularity in the appended claims. The invention will be best understood from the following description when read in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagram showing a system for generating tunable far-infrared radiation.

FIG. 2 is a partially sectional perspective view of the mixer device in the system of FIG. 1.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 illustrates a system 10 with an output 12 which delivers far-infrared electromagnetic radiation, or light, which can be continuously tuned within a limited range. The system includes a first input 14 which receives coherent infrared radiation from a source 16 such as a CO2 laser. The system has a second input 18 which receives microwave radiation from a tunable source 20, such as millimeter-wave phase-locked klystron, which can be tuned over a limited range. The system includes a mixer 22 which receives light of a first or original far-infrared frequency f0 produced by the source 16, and mixes it with the tunable microwave energy of frequency f. The result is the production of light of three frequencies, including light of the original frequency f0 light of a first sideband frequency f0+f, and light of another sideband frequency f0-f. The mixture, shown at 24, enters a polarizing Michelson interferometer 26. The interferometer 26 polarizes one of the components of the mixed frequencies, such as of the original frequency f0 by 90°, and polarizes another component such as a selected one of the sidebands such as f0+f, by 0°.

The two differently polarized components of frequencies f0 and f0+f encounter a polarizer 28, oriented at 45° to the direction of incoming light, which passes the 0° polarized component of frequency f0 and reflects the 90° polarized component f0+f. Light on an output 30 can then be used, although it will still contain an appreciable level of the original frequency f0. This original frequency f0 is further reduced by passing it through a scanning Fabry-Perot filter 32 and reflecting it by reflector 33 to an angle tunable mesh filter 34, to produce the output 12 which contains a high proportion of light of the sideband frequencies f0+f and f0-f. Since the frequency component f0 represents the frequency of the microwaves from the klystron 20 which is tunable, the far-infrared component in the output 12 can be tuned within the same limited frequency range as the output of the klystron 20 can be tuned.

The mixer 22 is shown in greater detail in FIG. 2. Microwaves of the frequency f are enter the mixer through a waveguide 40 which forms the input 18. For microwaves of a high frequency such as 93 GHz, the waveguide 40 must have a very small cross-section for efficient transmission, such as a rectangle which is about two millimeters by three millimeters on the sides. A miniature post 42 on a micrometer screw 43 passes through the waveguide, with the bottom of the post at 44 connected to the waveguide to ground that end of the post, and with the other end portion of the post 46 being free of direct connection to the upper end of the waveguide to isolate it therefrom. As a result, current of microwave frequency is induced in the post 42.

A nonlinear photosensitive device 48 which has a fast response time, such as a Schottky-barrier diode, has one terminal connected directly to the top of the post 42 as by mounting the diode thereto. The other terminal of the diode contacts one end of a conductive whisker 50 whose other end passes through a small biasing voltage source 52 to ground. The biasing source 52 biases the diode 48 to an operating region. Light from the laser (which has passed through the interferometer) is reflected from a parabolic mirror 54 to the photosensitive diode 48. This light indicated at 56, which is of a frequency f0 is sensed by the diode, and modulates the microwave frequency current passing therethrough.
The resultant current, of the frequency $f_0$ mixed with the microwave frequency $f_m$ is radiated by the whisker $50$. The whisker $50$ is very thin to provide an efficient radiator for the high infrared frequencies. The region between the diode and reflector is an open structure, in that it is not confined by a waveguide of under ten millimeter (one centimeter) width. The radiated light indicated at $24$, includes the original frequency $f_0$ and the two sideband frequencies including one of frequency $f_0 + f_m$. This mixed frequency is here reflected back by the parabolic mirror $54$ in the same direction as it received the original laser frequency. However, it is possible to reflect the received mixed frequency in a different direction so only it, and not the original laser light, passes through the interferometer, although this decreases the efficiency.

In order to increase the amount of light directed to the parabolic reflector, a concentrating roof reflector, or mixer reflector $60$ is provided. The mixer reflector has a forward reflecting side facing $61$ on a side of the whisker $50$ which is opposite the parabolic reflector $54$. The mixer reflector includes two plane reflectors $62, 64$ that are angled at $90^\circ$ from one another, that is, imaginary lines such as $66$ which are normal to the surface of each reflector will intersect at $90^\circ$. The result of the mixer is the mixed light $24$ which includes the original and at least one sideband frequency (normally two sideband frequencies). A ground plane $67$ is also provided to isolate the region of the diode from the waveguide.

A selected sideband such as of frequency $f_0 + f_m$ is separated from the original frequency $f_0$ to a large extent, by a polarizing Michelson interferometer $26$ (FIG. 1). The interferometer includes two rooftop reflectors $70, 72$ and a polarizer $74$. The polarizer is oriented in a plane that extends between the rooftop reflectors $70, 72$. A moving means $76$ such as a piezoelectric transducer, attached to one of the reflectors $72$ can move it a small controlled distance towards and away from the polarizer $74$. The polarizer $74$ transmits half of the incoming beam at $24$ (which is at $0^\circ$ polarization), that the transmitted half $24a$ is reflected off the first reflector $70$ back to the polarizer. The polarizer reflects the other half of the beam at $24$ toward the second reflector $72$ which reflects the beam half $24b$ back to the polarizer. The beam halves $24a, 24b$ are at $90^\circ$ to each other and at $45^\circ$ to the plane of the polarizer, and the rooftop reflectors are spaced from the polarizer along the beam halves. The interferometer has two ports $73, 75$ along lines $24$ and $80$ in FIG. 1 that are at $90^\circ$ angles, and can receive light along either port and discharge it along the other.

The difference in the distances between each of the two reflectors $70, 72$ and the polarizer $74$, determines the polarization of each beam component which passes from the polarizer $74$ to another polarizer $28$. The difference in the distances between the polarizer $74$ and the two reflectors $70, 72$ is set so it equals a whole number of wavelengths of the first frequency $f_0$, but equals one-half wavelength plus a whole number of wavelengths of a particular sideband frequency such as $60 f_0 + f_m$. As a result, the light $80$ emerging from the interferometer includes one component of frequency $f_0$ which is not polarized, or in other words is polarized by $0^\circ$, and also includes another component equal to the frequency $f_0 + f_m$ which is polarized at $90^\circ$. The polarizer $28$ passes light of $0^\circ$ polarization and reflects light of $90^\circ$ polarization. The reflected light includes a large portion of light of the sideband frequency $f_0 + f_m$. In this way, light of the tunable sideband frequency $f_0 + f_m$ is largely separated from light of the original laser frequency $f_0$.

The polarizing Michelson interferometer $26$ has hitherto been used only as a spectroscopic tool, as to measure the wavelength of light, by noting how the level of light that passes through a polarizer varies, as one of the rooftop reflectors is moved slightly to change its distance from the polarizer $74$. However, applicant does not know of any use for the polarizing Michelson interferometer to separate light components of slightly different frequencies.

Applicant has generated tunable far-infrared light of various frequencies. In one test, the laser $16$ was operated at $693$ GHz and the klystron was operated at $93$ GHz and was tunable over a range of about $50$ MHz around its center frequency. The diode $48$ was biased by about $50$ mV of constant voltage to optimize the sideband signal. The original laser beam from the source $16$ was about a millowatts level, while the laser sideband radiation at $600$ and $786$ GHz was measured to be about $3.0$ microwatts. In another test, far-infrared light of a frequency of $1627$ GHz produced about $2.5$ microwatts of sideband power at $1532$ GHz which was tunable by about $50$ MHz. The diode antenna was formed by the whisker $50$ which had a width of about $13$ microns and a length of about $1.7$ millimeters. The whisker diameter should be less than one hundred microns for efficient radiation. The two polarizers such as $28$ and $74$ are polyester sheets with closely spaced conductive lines (spaced about $10$ microns apart), such as Model $1GP224$ infrared polarizers sold by Cambridge Physical Science. Each rooftop reflector such as $70, 72$ comprises two plane reflecting surfaces at $90^\circ$ angles to one another.

Thus, the invention provides a means for generating far-infrared radiation which is tunable. This is accomplished by mixing a far-infrared coherent light beam with a tunable microwave frequency. The mixing can be accomplished by coupling microwaves from a waveguide to a diode lying in an open structure on which the infrared laser light is directed, with the mixed frequencies radiated by a whisker contacting an end of the diode. A selected infrared sideband which is tunable, is separated from the original laser frequency by passing the light through a polarizing Michelson interferometer.

Although particular embodiments of the invention have been described and illustrated herein, it is recognized that modifications and variations may readily occur to those skilled in the art, and consequently, it is intended that the claims be interpreted to cover such modifications and equivalents.

What is claimed is:

1. Apparatus for generating tunable electromagnetic radiation of a far-infrared wavelength comprising:
   means for generating infrared radiation of a predetermined frequency;
   means for generating microwave radiation of a microwave frequency, said generating means being capable of continuously varying the frequency of the microwave radiation, at least within a predetermined range;
   means for mixing said infrared and microwave radiation to generate mixed radiation containing first infrared radiation of said first infrared frequency and second infrared radiation of a second infrared frequency representing a first sideband frequency.
which differs from said first frequency by said microwave frequency;
means for separating radiation of said second infrared frequency from said mixed radiation;
said separating means comprising a polarizing Michelson interferometer which includes first and second rooftop reflectors and a first polarizer, all arranged so said mixed radiation encounters said first polarizer, with one part of the mixed radiation passing through said first polarizer to said first reflector and back to the first polarizer, and another part of the mixed radiation reflecting off said first polarizer to said second reflector and back to the first polarizer, said separating means also including a second polarizer positioned to receive at least a portion of the first radiation part from the first polarizer after the first radiation part reflects from the first reflector to the first polarizer, and to also receive at least a portion of the second radiation part from the first polarizer after the second radiation part has reflected from the second reflector;
said first and second reflectors located at different distances from the first polarizer, the difference in distance equal to an integral number of wavelengths of one of said radiation components, said separating means comprising:
a mixer reflector having a forward reflecting side;
a waveguide which carries said microwave radiation; a diode;
first and second conductors which contact opposite sides of said diode and are coupled to said waveguide to pass current of said microwave frequency through said diode;
means for directing light of said first frequency at said diode;
one of said conductors being a whisker and extending in front of said mixer reflector to radiate said mixed radiation.
3. Apparatus for generating tunable electromagnetic radiation comprising:
mixing coherent first infrared radiation with microwave radiation of a microwave frequency which is tunable over at least a limited frequency range, to obtain a mixed radiation which includes a first component of said first frequency and an second component of said second frequency.
4. The apparatus described in claim 3 wherein:
the difference in distance of said rooftop reflectors from said first polarizer equals a whole number of wavelengths of one of said radiation components and a whole number plus one-half wavelength of the other of said components.
5. A method for generating tunable far-infrared radiation comprising:
mixing coherent infrared radiation with microwave radiation of a microwave frequency which is tunable over at least a limited frequency range, to obtain a mixed radiation which includes a first component of said first frequency and an second component of said second frequency.
6. Step of separating including directing said mixed radiation into one port of a polarizing Michelson interferometer which also has a second port, and directing light which exits the second port against a rooftop reflector and an interferometer polarizer; establishing the rooftop reflectors at distances from the interferometer polarizer so the difference in the distance between said interferometer polarizer and each rooftop reflector equals a whole number of wavelengths of one component and also equals one-half wavelength plus a whole number of wavelengths of the other component.

A method for generating tunable far-infrared radiation comprising:
mixing coherent infrared radiation of a first frequency with tunable microwave radiation, to obtain mixed radiation which includes at least a first
sideband frequency which differs from said first frequency by the frequency of said microwave radiation, and separating the first sideband frequency from said mixed radiation; said step of mixing includes contacting a first side of a light sensitive diode with a first conductor which is coupled to a waveguide which contains said tunable microwave radiation, and coupling a second side of said conductor through a whisker to said waveguide, said whisker lying in front of a concentrating reflector; directing said coherent radiation of said first frequency at said diode, and receiving said mixed radiation from said whisker.

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