Multi-channel polarized thermal emitter

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M. U. Pralle et al.; Photonic crystal enhanced narrow-band infrared emitters; publication; Dec. 16, 2002; 4 pages, pp. 4685-4687 (copyright notice); vol. 81, No. 25; Applied Physics Letters; 2002 American Institute of Physics.

(Continued)

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ABSTRACT

A multi-channel polarized thermal emitter (PTE) is presented. The multi-channel PTE can emit polarized thermal radiation without using a polarizer at normal emergence. The multi-channel PTE consists of two layers of metallic gratings on a monolithic and homogeneous metallic plate. It can be fabricated by a low-cost soft lithography technique called two-polymer microtransfer molding. The spectral positions of the mid-infrared (MIR) radiation peaks can be tuned by changing the periodicity of the gratings and the spectral separation between peaks are tuned by changing the mutual angle between the orientations of the two gratings.

18 Claims, 6 Drawing Sheets

(5 of 6 Drawing Sheet(s) Filed in Color)
OTHER PUBLICATIONS


* cited by examiner
MULTI-CHANNEL POLARIZED THERMAL EMITTER

CROSS-REFERENCE TO RELATED PATENT APPLICATIONS

This patent application claims the benefit of U.S. Provisional Patent Application No. 60/999,949, filed Oct. 23, 2007, the teachings and disclosure of which are incorporated in their entirety herein by reference thereto.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT

This invention was made in part with Government support under Contract Number DE-AC02-06CH11358 awarded by the Department of Energy. The Government has certain rights in this invention.

BACKGROUND

Mid-infrared (MIR) radiation, in wavelengths from 2 to 10 micrometers is of particular interest for chemical and biological sensing because specific information based on the spectral absorption of MIR due to molecular rotational and vibrational transition is provided. To detect the absorption at a specific wavelength, two different wavelengths are used for reliable sensing where one wavelength is the same as the absorption wavelength and the other wavelength is used for reference. The sensing device requires a tunable MIR source and a spectrometer resulting in a bulky and expensive device.

For MIR radiation, a thermal source is widely used. The radiation spectrum of the thermal source is very broad as it follows Planck's radiation law and is therefore not easy to tune the spectrum without changing the temperature of the source. For detection of specific chemical information, a MIR source with narrow spectral distribution is advantageous to reduce power consumption and reduce background noise. There is a class of artificial micro-structures that can modify the thermal radiation spectrum by enhancing thermal radiation at a certain wavelength. Because the micro-structured thermal sources emit MIR radiation within a narrow range of wavelengths, adjustable by changing the structural parameters, it can be optimized as a MIR source for a specific absorption wavelength.

Thermal radiation can have two orthogonal polarizations and thermal radiation with one polarization that is independent of the thermal radiation of the other polarization. As a result, multiplexing is possible. Moreover, two thermal radiations with different polarizations reflect with different ratios when the incident angle is not normal to the reflecting surface, and this gives additional information for identifying chemical substances. Therefore, polarization engineering of MIR radiation brings additional advantages, in addition to the spectral narrowing of MIR radiation.

Generally, thermal radiation from a thermal source is considered unpolarized or weakly-polarized, which means the two polarizations of thermal radiation are equally distributed. The degree of polarization (DOP), defined by (P1−P2)/(P1+P2), is commonly used to show how much the thermal radiation is polarized, where P1 and P2 are the radiation powers of the two orthogonal polarizations, respectively. The DOP is 0% for unpolarized radiation and 100% for completely polarized radiation. Under special circumstances, DOP deviates far from 0%. For example, the thermal radiation emitted by flat metals starts with unpolarized radiation for normal emergence and increases in DOP with the angle of emergence, at first slowly, to about 90% percent at grazing emergence. Because the radiation power goes to zero at grazing emergence, it is not suitable for polarized MIR radiation in spite of high DOP. The conventional way to produce polarized thermal radiation with reasonable power is to pass the unpolarized thermal radiation through a polarizer, which filters the thermal radiation having unwanted polarization resulting in the wasting of more than half of the power used.

SUMMARY

A good MIR source for chemical sensing should simultaneously satisfy the requirements of high radiation power, narrow spectral distribution, and high DOP. Described herein are, among other things, MIR sources using layer-by-layer metallic photonic crystals, which emit MIR radiation at two different narrow wavelength ranges of MIR radiation with completely different linear polarizations and high emissivity. Additionally, the spectral separation between the emission ranges is adjustable.

The MIR source described herein is a polarized thermal emitter (PTE), and can emit polarized thermal radiation without using a polarizer at normal emergence. In contrast to using a polarizer, the PTEs preferentially emit thermal radiation of certain polarization through their structural anisotropy. For these structures, there is no loss of photons in producing polarized thermal radiation.

The PTE consists of two layers of metallic gratings on a monolithic and homogeneous metallic plate. The PTE in one embodiment is fabricated by a low-cost soft lithography technique called two-polymer microtransfer molding. The spectral positions of the MIR radiation peaks can be tuned by changing the periodicity of the gratings and the spectral separation between peaks are tuned by changing the mutual angle between the orientations of the two gratings.

Other aspects, objects, and advantages will become more apparent from the following detailed description when taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing(s) will be provided by the Office upon request and payment of the necessary fee.

The accompanying drawings incorporated in and forming a part of the specification illustrate several aspects of the present invention and, together with the description, serve to explain the principles of the invention. In the drawings:

FIG. 1 is a simplified isometric illustration of a two layer photonic crystal on an homogeneous backplane;

FIG. 2a-2e are isometric illustrations of a portion of the steps of an embodiment to create layer-by-layer metallic photonic structures;

FIG. 2f is an isometric illustration of a metallic photonic crystal on an homogeneous backplane creating a multi-channel polarized thermal emitter

FIG. 3a is a scanning electron micrograph of a multi-channel polarized thermal emitter with a mutual angle of ninety degrees between layers;

FIG. 3b is a scanning electron micrograph of a multi-channel polarized thermal emitter with a mutual angle of sixty degrees between layers;

FIG. 3c is a scanning electron micrograph of a multi-channel polarized thermal emitter with a mutual angle of thirty degrees between layers;
FIG. 3d is a schematic illustration of a radiometric setup used to make measurements of the multi-channel polarized thermal emitter;
FIG. 4a is a color map of the emissivity of the multi-channel polarized thermal emitter of FIG. 3a;
FIG. 4b is a color map of the emissivity of the multi-channel polarized thermal emitter of FIG. 3b;
FIG. 4c is a color map of the emissivity of the multi-channel polarized thermal emitter of FIG. 3c;
FIG. 4d is a set of polar plots of the three major emission peaks for the multi-channel polarized thermal emitter of FIG. 3a with the polar plots shown as circles with fitted curves;
FIG. 4e is a set of polar plots of the three major emission peaks for the multi-channel polarized thermal emitter of FIG. 3b with the polar plots shown as circles with fitted curves;
FIG. 4f is a set of polar plots of the three major emission peaks for the multi-channel polarized thermal emitter of FIG. 3c with the polar plots shown as circles with fitted curves;
FIG. 5a is a linear color map of the calculated polarization-dependent absorption spectra of the multi-channel polarized thermal emitter of FIG. 3a;
FIG. 5b is a linear color map of the calculated polarization-dependent absorption spectra of the multi-channel polarized thermal emitter of FIG. 3b;
FIG. 5c is a linear color map of the calculated polarization-dependent absorption spectra of the multi-channel polarized thermal emitter of FIG. 3c;
FIG. 5d is a color mapping of the electric field strength in a unit cell of the multi-channel polarized thermal emitter of FIG. 3a of the peak labeled P90a in FIG. 4a;
FIG. 5e is a color mapping of the electric field strength in a unit cell of the multi-channel polarized thermal emitter of FIG. 3a of the peak labeled P90b in FIG. 4a;
FIG. 5f is a graph of the calculated polarization angles for the peaks as a function of the mutual angle shown as curves with the measured values (e.g., P90a, P90b, P90c, etc.) as colored marks;
FIG. 6a is a color photograph of a polarized thermal radiation marker made from a multi-channel polarized thermal emitter with a mutual angle of ninety degrees between layers;
FIG. 6b is a graph illustrating the spectra of thermal radiation power of the multi-channel polarized thermal emitter of FIG. 6a;
FIG. 6c is a color graph of the thermal radiation distribution mappings of the multi-channel polarized thermal emitter of FIG. 6a taken at a polarization angle of zero degrees; and
FIG. 6d is a color graph of the thermal radiation distribution mappings of the multi-channel polarized thermal emitter of FIG. 6a taken at a polarization angle of ninety degrees.
While the invention will be described in connection with certain preferred embodiments, there is no intent to limit it to those embodiments. On the contrary, the intent is to cover all alternatives, modifications and equivalents as included within the spirit and scope of the invention as defined by the appended claims.

DETAILED DESCRIPTION

The multi-channel polarized thermal emitters described herein can provide linearly polarized thermal emission in multiple channels with high thermal radiation power, a high degree of linear polarization, and wide tunability in polarization status. The multi-channel polarized thermal emitter allows simultaneous control of spectral distribution and polarization of radiation, which has been believed not possible in spontaneous emission such as thermal radiation.
The resulting structure consists of two layers of metallic gratings on a monolithic and homogeneous metal plate. The spectral positions of the MIR radiation peaks can be tuned by changing the periodicity of the rods and the separation between peaks is tuned by changing the mutual angle between the orientations of the rod layers.

Turning now to FIGS. 3a-3d, a nickel metallic photonic crystal with only two layers (as in FIG. 3a) has two highly-enhanced thermal radiation peaks when the homogeneous backplane is added. Two more variations of metallic photonic crystals having mutual angles of 60° and 30° as seen in FIGS. 3b and 3c were fabricated to study polarized thermal radiation. The metallic photonic crystals (MPCs) are designated as 90°-, 60°- and 30°-MPCs, respectively. Measurements were made using the radiometric setup shown in FIG. 3d. The MPC 20 mounted on a heated copper block in a high vacuum chamber. Thermal radiation is collected at the surface normal angle and directed into a Fourier transform infrared (FT-IR) spectrometer (Magna 760, Nicolet) and then passed through a linear IR polarizer (Spectra-Tech Inc.). In the embodiments shown, the distance between rods is 2.6 μm and each rod is 1.1 μm wide and 1.2 μm high. The transmission axis of the polarizer is set as zero when it is parallel to the top layer of rods of the metallic photonic crystals as depicted to the far right of FIG. 3c. The collection angle is perpendicular to the surface with an acceptance angle of 11°. In the measurements, a sampling area was limited to approximately 1×1 mm².

Polarization-dependent thermal radiation power is measured at 800K as a function of the transmission angle of the polarizer from 0° to 180° in 10° steps. To obtain corresponding emissivities, thermal radiation power from a blackbody is also measured under the same conditions. An assumption was made that that thermal radiation from the blackbody source is completely unpolarized. Turning now to FIGS. 4a-4f, the emissivities of the MPCs with the mutual angles of 90° (FIG. 4a), 60° (FIG. 4b), and 30° (FIG. 4c) are colored-mapped at the same scale of 0 to 0.8. Polar plots of the three peaks for 90° (FIG. 4d), 60° (FIG. 4e), and 30° (FIG. 4f) are shown as colored circles with their fitted curves. The fitting parameters are shown under each label of the peaks. Since the emissivities are measured from 0° to 180°, the values out of the range are extended by the two-fold symmetry. Each radial division is 0.2.

In the emissivity map of the 90°-MPC in FIG. 4a, the two major emission peaks at 3377 cm⁻¹ and 2827 cm⁻¹, which are in the vicinity of the photonic band edge, are differently polarized parallel or perpendicular to the rods. The peaks are labeled with 90a and 90b, where 'a' and 'b' represent their family. The third peak, 90c, appears far from the photonic band edge, and its emissivity peak is significantly smaller and broader than 90a and 90b. When changing the mutual angle to 60° and 30° successively (as shown in FIGS. 4b and 4c), which means the bottom layer of each MPC rotates clockwise, the three peaks shift both in polarization angle and in wavelength. Spectroscopically, the peaks in the family ‘a’ show a relatively small shift less than 4% while the other peaks in the group ‘b’ and ‘c’ show larger red-shift up to 11% and 21%, respectively, in changing the mutual angle. In addition, notice that polarization angles of the two major peaks rotate counterclockwise in opposition to the rotation of the bottom layer in FIGS. 4e and 4f. For the three selected peaks of each MPC, polarization-dependent emissivities are polar plotted in FIGS. 4d, 4e, and 4f. By assuming a partial polarization, the measured emissivities are fit with a function of Malus’s law,

$$e_{\text{MAX}} \cos^2(\theta - \delta_{\text{MAX}}) + e_{\text{MIN}} \cos^2(\theta - \delta_{\text{MIN}} - 90°)$$

where $$e_{\text{MAX}}$$ and $$e_{\text{MIN}}$$ are the maximum and minimum emissivities at two orthogonal angles, $$\delta_{\text{MAX}}$$ and $$\delta_{\text{MIN}} - 90°$$, respectively. The fitting curves are co-plotted on the polar plots with their parameters shown below. All the polarization-dependent emissivities are fit by these calculations to an excellent degree, clearly demonstrating that the thermal emission is linearly polarized. From the parameters, DOP is calculated, defined by $$(e_{\text{MAX}} - e_{\text{MIN}}) / (e_{\text{MAX}} + e_{\text{MIN}})$$. The peaks in family ‘b’ show high DOP for all the mutual angles close to 0.5 with high emissivity.

Turning now to FIGS. 5a-5f, numerical simulations for the MPCs are shown. Polarization-dependent absorbance spectra of a 90° MPC (FIG. 5a), a 60° MPC (FIG. 5b), and a 30° MPC (FIG. 5c) are calculated and plotted as line color maps. Peak positions are marked with the same labels as in FIGS. 4a-4f. The profiles of the electric field strength in a unit cell of a 90° MPC are shown for 90a (FIG. 5d) and 90b (FIG. 5e). The strength is normalized to that of an incoming wave. In FIG. 5f, calculated polarization angles for the peaks as a function of the mutual angle are shown as curves with the measured values as colored marks. According to Kirchoff’s law, absorbance is directly related to emissivity at equilibrium. The excellent agreement with the experimental emissivity spectra in FIG. 4 is demonstrated. The small discrepancies may arise from the fact that the calculation considers only normal incidence while the experiment measures radiation within a finite acceptance angle. We also calculate polarization angles as a function of the mutual angle in FIG. 5f, which is also consistent with the experiment. The negative slope of the families ‘a’ and ‘b’ represents that the rotation directions of the structure and polarization angle are opposite.

From the results of the calculation, it was determined that 90a primarily originates from the enhancement of the intrinsic absorption of nickel in the top and bottom layer while 90b is resulted by the whole structure including the backplane. The calculated electric field profiles for 90a and 90b in FIGS. 5d and 5e show the 90°-MPC intensifies the internal electric field 7 to 10 times compared to that of the incoming wave, which suggests that significantly reduced group velocity increases the interaction of light with nickel and enhances the intrinsic absorption. In addition, the difference in the vertical positions of high electric field regions of 90a and 90b in FIGS. 5d and 5e explains why each peak is affected by different parts of the MPC.

A thermal marker was fabricated to demonstrate a potential application. As shown in FIG. 6a, this consists of two identical 90°-MPCs, one rotated 90° to the other. In the photograph of the thermal marker in FIG. 6a, the dark area surrounding the MPCs is a flat nickel surface. The left MPC was fabricated to have non-square shape for better discrimination in thermal imaging.

Spectra of thermal radiation power of the 90°-MPC for the two orthogonal polarizations at the same temperature of 800K is shown in FIG. 6b. The dashed lines show the range of wavelength used for the thermal imaging. The high emissivity and DOP of 90a and 90b in FIG. 6b allow the wavelength windows around the two major peaks to be utilized in polarized thermal radiation applications. At the same temperature, the two patterns are clearly distinguishable in the spatial distribution of thermal radiation of FIG. 6c (polarization angle of 0°) and 6d (polarization angle of 90°), which is not possible without a polarizing detector.

In the preceding description, the measurement system of FIG. 3d was calibrated using a blackbody source, which had an emissivity higher than 0.99, at two different temperatures. A home-built blackbody source was used to secure a radiation angle greater than 11°. The blackbody source is a copper block having a spherical cavity of 100 mm diameter and 10 mm exit opening. The entire inner surface is coated with
carbon black and exhibits the same thermal radiation power as that of a commercial blackbody source (M335, Mikron Infrared, Inc.). Because the measured thermal radiation spectrum, \( I'(T, \lambda) \) (\( T \)=temperature, \( \lambda \)=wavelength), included radiation from the surroundings reflected at the sample surface, \( I_0(\lambda) \), and the optical effect from the potassium bromide window 30 in FIG. 3a in the measurement of surface normal radiation, the spectral emissivity of the sample, \( e(T, \lambda) \), can be estimated from the following approximation:

\[
I'(T, \lambda) = I_{BB}(T, \lambda) + I_0(\lambda) - [1 - e(T, \lambda)]I'_0(\lambda)
\]

where \( I_{BB} \) and \( I_0 \) are the radiation powers from the blackbody at temperature \( T \) and from the surroundings, respectively, and \( I'_0 \) is the transmittance of the optical window. The approximation is valid because the transmittance of the sample is zero because of the homogeneous plane and the reflection from the sample is considered as specular for the near room-temperature background radiation in which nearly all spectral power lies above the diffraction limit of the MPC (2.6 \( \mu \)m). For the thermal images in FIGS. 6c and 6d, thermal radiation from a sample is collected at different 13x8 points with a spacing of 1 mm, same as the spatial resolution of the radiometry setup. Acquired thermal radiation powers within a given spectral window are averaged and normalized to reconstruct the spatial distribution of thermal radiation. With respect to numerical simulations, all calculations are based on a plane-wave-based transfer-matrix method. The absorbance maps in FIG. 5a, b, and c are calculated by subtracting calculated reflectance and transmittance from unity. For realistic calculations, experimentally-acquired optical constants of nickel are used for the absorbance maps while optical parameters for nickel in the handbook by Lynch, D. W., Hunter W. R. “Nickel (Ni)” in Handbook of Optical Constants of Solid, Palik, E. D. ed. (Academic, London, 1985) are used for the electric field profiles in FIGS. 6d and e.

Now that the multi-channel polarized thermal emitter has been described, a comparison of the performance of thermal emitters in three parameters: radiation power, spectral distribution and DOP can be made. Since the structure described herein is unique, direct comparison of performance in all aspects is not directly possible but general comparisons can be made. First, the radiation power can be compared by emissivity, the ratio of the radiation power of thermal emitter to that of a blackbody (perfect emitter). The width of a peak can be scaled by a quality factor, defined by a ratio of spectral position of the peak to the full-width-at-half-maximum of the peak. And DOP is used as index of degree-of-polarization. As summarized in the table, the multi-channel polarized thermal emitter demonstrates high performance in all three categories. Moreover, the unique two-channel radiation with different polarization makes the polarized thermal emitter useful for MIR source for chemical sensing.

<table>
<thead>
<tr>
<th>Number of tunable peaks</th>
<th>Emissivity (%)</th>
<th>Spectral width (( \lambda/\Delta\lambda ))</th>
<th>DOP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat metal</td>
<td>No tunable peak</td>
<td>&lt;5%</td>
<td>20% at 40°</td>
</tr>
<tr>
<td>Tungsten photonic crystal (described in C. H. Seager et al., Appl. Phys. Lett. 86, 244105 (2005))</td>
<td>Single tunable peak</td>
<td>&lt;80%</td>
<td>5.2/1.6 = 3.25 (T = 546K)</td>
</tr>
<tr>
<td>Nano-emitter (S. Ingvason et al., Opt. Exp. 15, 11249 (2007))</td>
<td>Peak 1</td>
<td>65-65%</td>
<td>3.75</td>
</tr>
<tr>
<td>Multi-Channel PTE</td>
<td>Peak 2</td>
<td>57-78%</td>
<td>4.72</td>
</tr>
</tbody>
</table>

From the foregoing, it can be seen that the MPC can enhance thermal radiation in the vicinity of its photonic band edge with a preferred polarization. As the polarized thermal radiation does not rely on angle sensitive phenomena such as refraction or diffraction, it can be used at a wide range of viewing angles and is scalable for different working wavelengths. The tailoring of polarization characteristics of thermal radiation makes possible advanced applications using polarized IR sources in sensing, security and energy science. It should be noted that unaligned three- or four-layer MPC structures can be useful for tuning the characteristics of thermal radiation because of the existence of universal peaks in the unaligned structures.

By introducing a homogeneous backbone to the woodpile structure, significant selective enhancement in thermal radiation is achieved from a two-layer structure requiring only coarse perpendicular alignment. This backbone also provides mechanical reinforcement to improve the durability of the structure.

The use of the terms “a” and “an” and “the” and similar referents in the context of describing the invention (especially in the context of the following claims) is to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. The terms “comprising,” “having,” “including,” and “containing” are to be construed as open-ended terms (i.e., meaning “including, but not limited to,”) unless otherwise noted. Recitation of ranges of values herein are merely intended to serve as a shorthand method of referring individually to each separate value falling within the range, unless otherwise indicated herein, and each separate value is incorporated into the specification as if it were individually recited herein. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., “such as”) provided herein, is intended merely to better illuminate the invention and does not pose a limitation on the scope of the invention unless otherwise claimed. No language in the specification should be construed as indicating any non-claimed element as essential to the practice of the invention.

Preferred embodiments of this invention are described herein, including the best mode known to the inventors for carrying out the invention. The description of various embodiments of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise embodiments disclosed. Variations of those preferred embodiments may become apparent to those of ordinary skill in the art upon reading the foregoing description. For example, one can envision a multi-color IR emitter and polarization-selective IR absorbers as the two emission or absorption wavelengths are selectable using an additional polarizer with the multi-channel polarized thermal emitter described herein. The inventors
What is claimed is:

1. A polarized thermal emitter (PTE), comprising:
   a homogeneous backplane;
   a metallic photonic crystal positioned on the backplane, the
   metallic photonic crystal having a first grating layer
   oriented along a first axis and a second grating layer
   positioned on the first grating layer oriented along a
   second axis; and
   wherein the metallic photonic crystal emits mid-infrared
   (MIR) radiation at two different linear polarizations
   when supplied with un-polarized thermal radiation; and
   wherein a mutual angle exists between the first axis and the
   second axis, and wherein the mutual angle is selected to
   vary spectral separation between peaks of the MIR
   radiation emitted therethrough.

2. The PTE of claim 1, wherein each of the grating layers
   includes a plurality of parallel rods having a periodicity, and
   wherein the periodicity is selected to vary spectral positions
   of peaks of the MIR radiation emitted therethrough.

3. The PTE of claim 1, wherein each of the grating layers
   includes a plurality of parallel rods having a periodicity, and
   wherein the periodicity is selected to vary spectral positions
   of the peaks of the MIR radiation emitted therethrough.

4. The PTE of claim 1, wherein the first axis and the second
   axis are angularly displaced from one another by 60°.

5. The PTE of claim 1, wherein the MIR radiation is emitted
   at two different narrow wavelength ranges.

6. The PTE of claim 1, wherein the metallic photonic
   crystal emits MIR radiation at two different linear
   polarizations and high emissivity when supplied with
   un-polarized thermal radiation.

7. The PTE of claim 1, further comprising a third grating
   layer positioned on the second grating layer oriented along
   the first axis and a fourth grating layer positioned on the third
   grating layer oriented along the second axis.

8. The PTE of claim 7, wherein each of the grating layers
   comprise a plurality of parallel rods having a periodicity,
   wherein the rods of the first grating layer and the third
   grating layer are offset from one another, and wherein the rods of
   the second grating layer and the fourth grating layer are offset
   from one another, such that the metallic photonic crystal has
   a four-layer periodicity.

9. The PTE of claim 8, wherein the rods of each grating
   layer are spaced a distance from one another, and wherein the
   offset is half of the distance.

10. The PTE of claim 1, wherein the homogeneous backplane
    is a monolithic and homogeneous metallic plate.

11. The PTE of claim 1, wherein the metallic photonic
    crystal is a nickel metallic photonic crystal.

12. A polarized thermal emitter (PTE), comprising:
    a homogeneous backplane;
    a metallic photonic crystal positioned on the backplane, the
    metallic photonic crystal having a first grating layer
    oriented along a first axis and a second grating layer
    positioned on the first grating layer oriented along a
    second axis;
    wherein the metallic photonic crystal emits mid-infrared
    (MIR) radiation at two different linear polarizations
    when supplied with un-polarized thermal radiation; and
    wherein the first axis and the second axis are angularly
    displaced from one another; and
    wherein the first axis and the second axis are angularly
    displaced from one another by 30°.

13. A polarized thermal emitter (PTE), comprising:
    a metallic photonic crystal positioned on the backplane, the
    metallic photonic crystal having a first grating layer
    oriented along a first axis and a second grating layer
    positioned on the first grating layer oriented along a
    second axis;
    wherein the metallic photonic crystal emits mid-infrared
    (MIR) radiation at two different linear polarizations
    when supplied with un-polarized thermal radiation; and
    wherein the first axis and the second axis are angularly
    displaced from one another; and
    wherein the first axis and the second axis are angularly
    displaced from one another by 60°.

14. A method of tuning characteristics of mid-infrared
    (MIR) radiation emitted by a polarized thermal emitter (PTE)
    having a homogeneous backplane and a metallic photonic
    crystal positioned on the backplane, the metallic photonic
    crystal having a first grating layer oriented along a first
    axis and a second grating layer positioned on the first
    grating layer oriented along a second axis, constructed
    such that the metallic photonic crystal emits MIR radiation
    at two different linear polarizations when supplied with
    un-polarized thermal radiation, the method comprising the
    step of:
    - defining a mutual angle between the first axis and second
    - varying the mutual angle to vary a spectral separation
    - peaks of the MIR radiation.

15. The method of claim 14 wherein each of the grating
    layers includes a plurality of parallel rods having a periodicity,
    further comprising the step of varying the periodicity of
    the rods of the grating layers to vary spectral positions
    of peaks of the MIR radiation.

16. The method of claim 14, wherein the step of varying
    the mutual angle comprises the step of setting the mutual angle
    to 90°.

17. A method of tuning characteristics of mid-infrared
    (MIR) radiation emitted by a polarized thermal emitter (PTE)
    having a homogeneous backplane and a metallic photonic
    crystal positioned on the backplane, the metallic photonic
    crystal having a first grating layer oriented along a first
    axis and a second grating layer positioned on the first
    grating layer oriented along a second axis, the first axis and the second
    axis defining a mutual angle therebetween, constructed such that
    the metallic photonic crystal emits MIR radiation at two
    different linear polarizations when supplied with un-polarized
    thermal radiation, the method comprising the step of:
    - defining a mutual angle between the first axis and second
    - varying the mutual angle to vary a spectral separation
    - peaks of the MIR radiation.

18. A method of tuning characteristics of mid-infrared
    (MIR) radiation emitted by a polarized thermal emitter (PTE)
    having a homogeneous backplane and a metallic photonic
    crystal positioned on the backplane, the metallic photonic
    crystal having a first grating layer oriented along a first
    axis and a second grating layer positioned on the first
    grating layer oriented along a second axis, the first axis and the second
    axis defining a mutual angle therebetween, constructed such that
    the metallic photonic crystal emits MIR radiation at two
different linear polarizations when supplied with un-polarized thermal radiation, the method comprising the step of:

11 varying the mutual angle to vary a spectral separation
between peaks of the MIR radiation, wherein the step of
varying the mutual angle comprises the step of setting
the mutual angle to 60°.

* * * * *
It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Delete the title page and substitute therefore with the attached title page showing the corrected number of claims in patent.

In the Claims

Column 9, lines 31-34
Please cancel claim 3.

Claim 4
Column 9, Line 36, after the word “another by” delete “60°” and insert --90°--.
MULTI-CHANNEL POLARIZED THERMAL EMITTER

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Assignee: Iowa State University Research Foundation, Inc., Ames, IA (US)

Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 1285 days.

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Filed: Oct. 23, 2008

Related U.S. Application Data

Provisional application No. 60/999,949, filed on Oct. 23, 2007.

Int. Cl.
H01L 35/02 (2006.01)
G01J 3/10 (2006.01)

U.S. Cl.
USPC 250/504 R

Field of Classification Search
USPC 250/493.1, 504 R, 503.1

See application file for complete search history.

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(Continued)

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ABSTRACT

A multi-channel polarized thermal emitter (PTE) is presented. The multi-channel PTE can emit polarized thermal radiation without using a polarizer at normal emergence. The multi-channel PTE consists of two layers of metallic gratings on a non-planar and homogeneous metallic plate. It can be fabricated by a low-cost soft lithography technique called two-polymer microtransfer molding. The spectral positions of the mid-infrared (MIR) radiation peaks can be tuned by changing the periodicity of the gratings and the spectral separation between peaks is tuned by changing the mutual angle between the orientations of the two gratings.

17 Claims, 6 Drawing Sheets
(5 of 6 Drawing Sheet(s) Filed in Color)