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(54) **RADIATIVE COOLING OF OPTOELECTRONIC DEVICES USING HYPERBOLIC METAMATERIALS**

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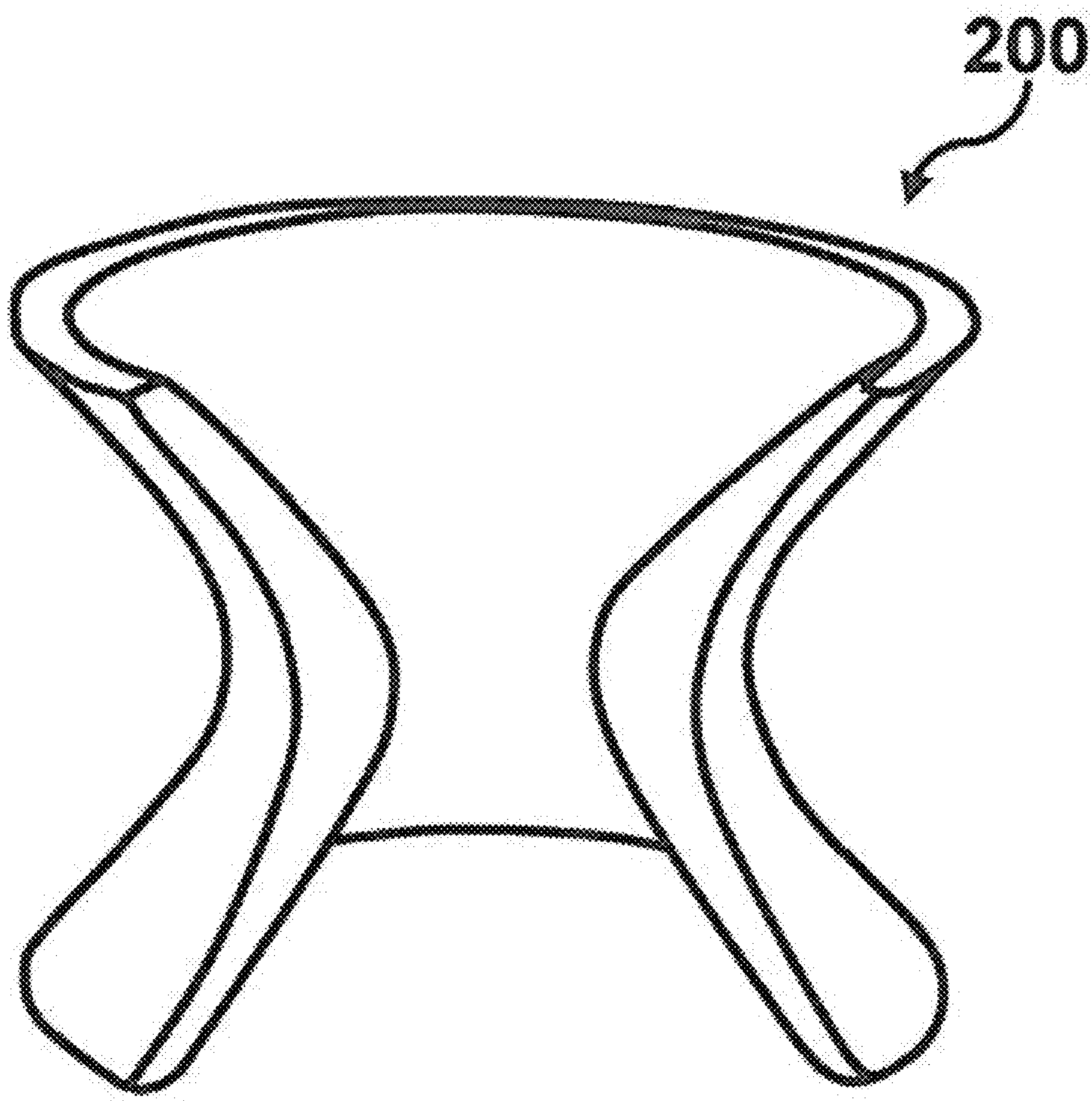
(57) **ABSTRACT**

A method of radiative cooling of optoelectronic devices using a hyperbolic metamaterial TIM layer below the heat generating optoelectronics is disclosed. Optoelectronic devices are optimized for high radiative heat conductance due to broad hyperbolic frequency band in the Long-Wavelength Infrared (LWIR) range with an efficient electromagnetic black hole thermal interface between the metamaterial TIM layer and a metallic heat sink. A modified Stefan-Boltzmann law in the hyperbolic metamaterial layer enables domination of the radiative heat transfer in the TIM layer. The broadband divergence of the photonic density of states in hyperbolic metamaterials leads to an increase in radiative heat transfer, beyond the limit set by the Stefan-Boltzmann law. The resulting radiative thermal hyper-conductivity approach or even exceed heat conductivity via electrons and phonons in regular solids.



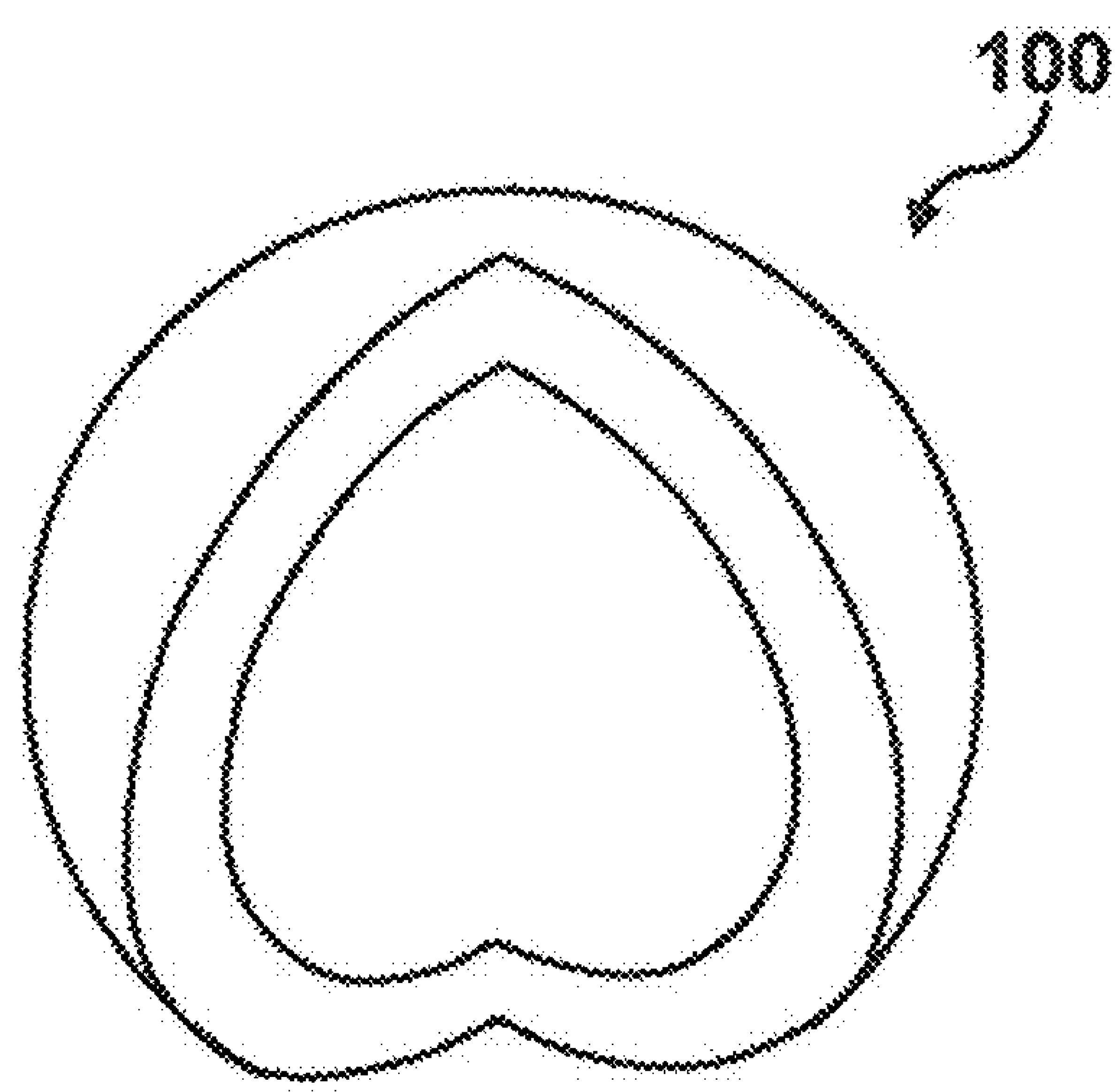


FIG. 1

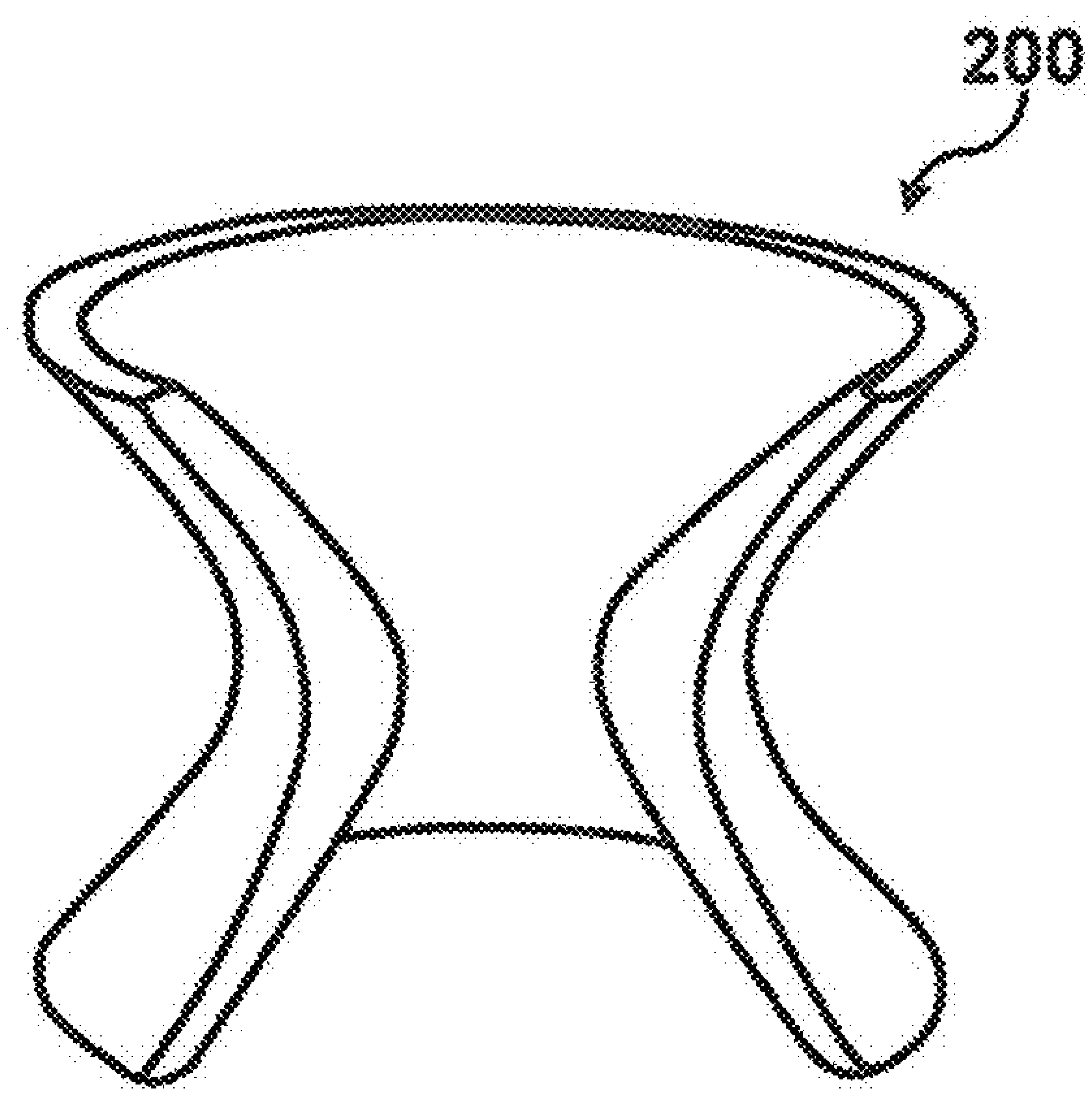


FIG. 2

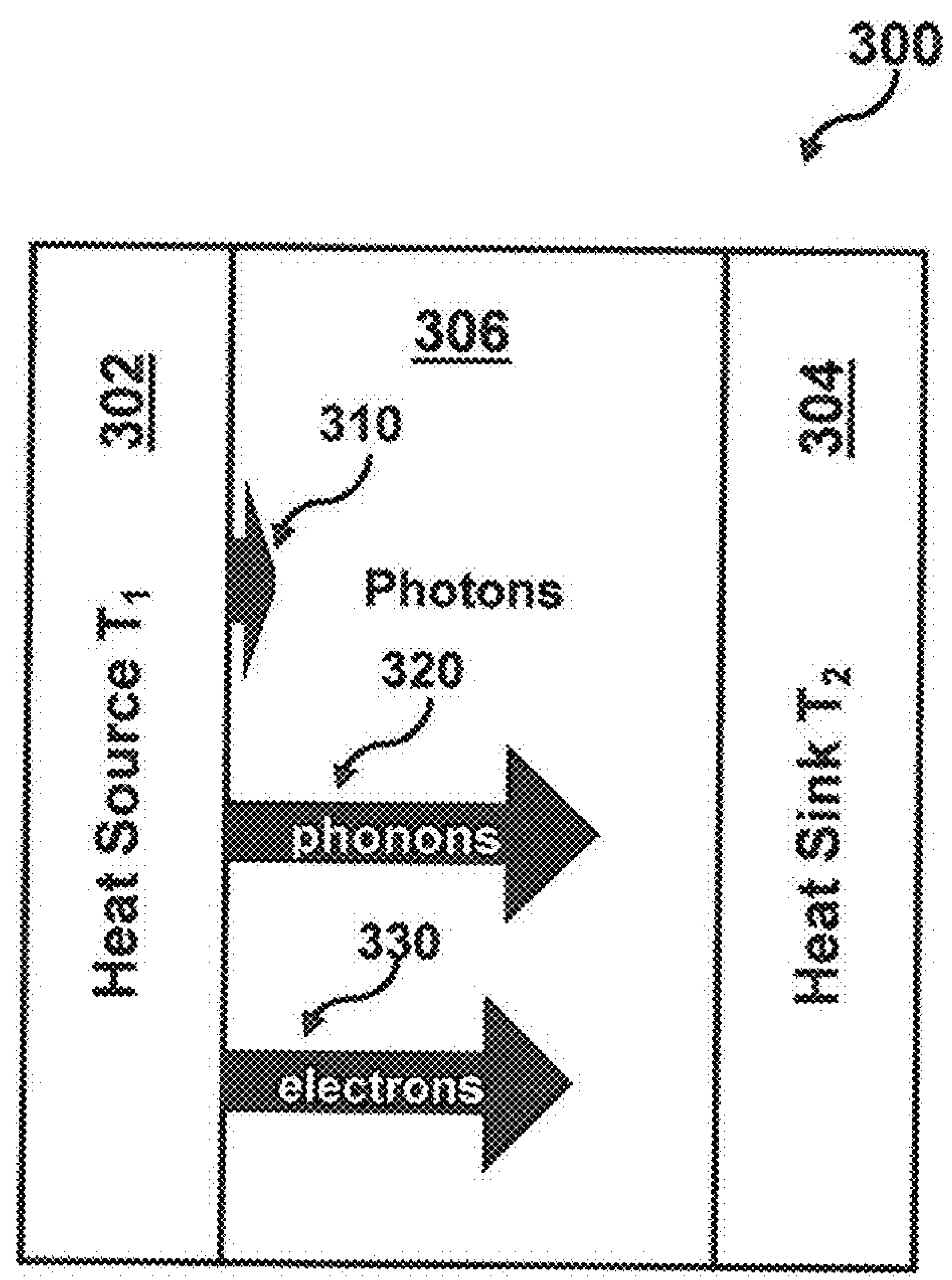

300
306
302
Heat Source T_1
310
Photons
320
phonons
330
electrons
304
Heat Sink T_2

FIG. 3

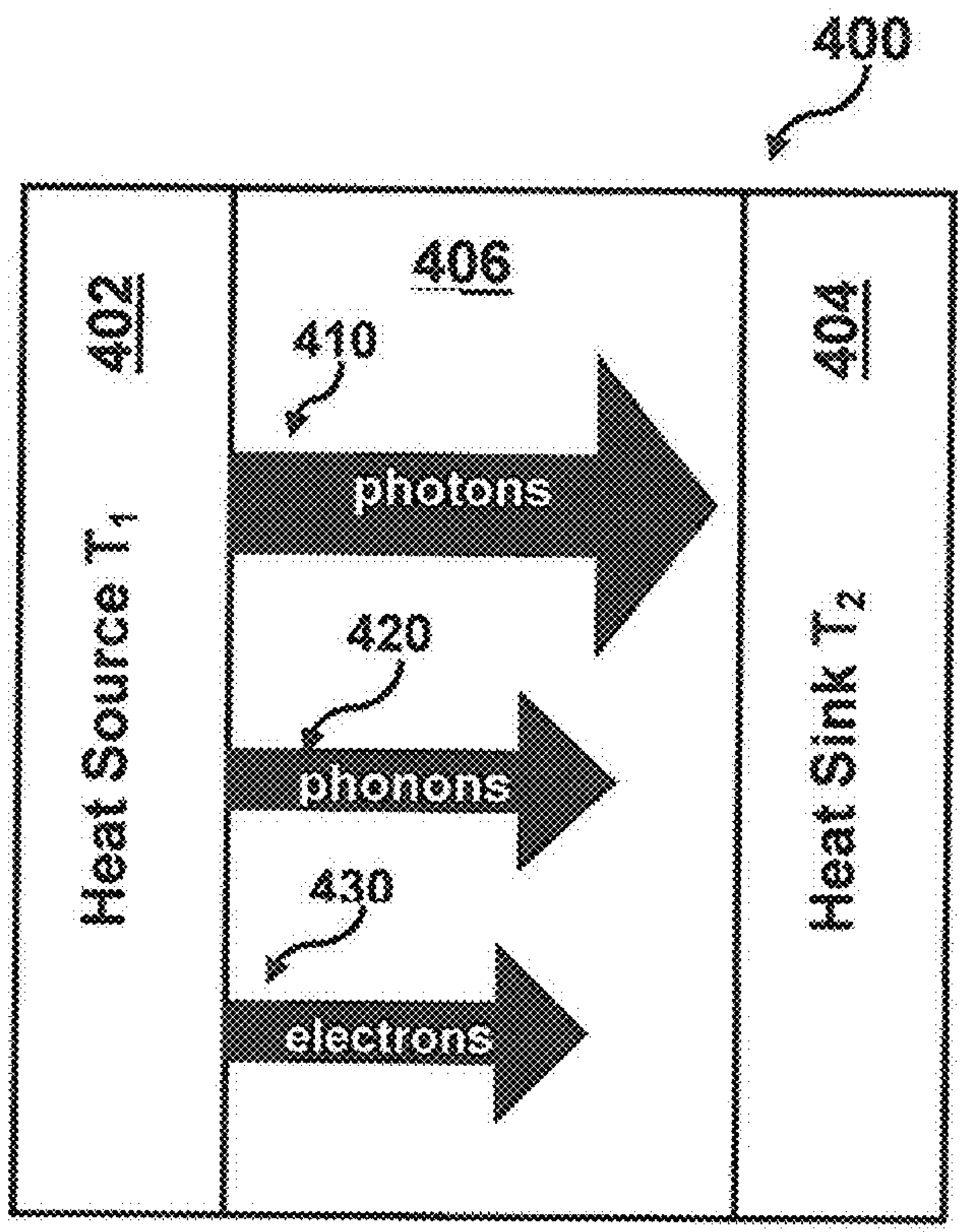

400
406
402
Heat Source T_1
410
photons
420
phonons
430
electrons
404
Heat Sink T_2

FIG. 4

RADIATIVE COOLING OF OPTOELECTRONIC DEVICES USING HYPERBOLIC METAMATERIALS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This Application claims rights under 35 USC §119 (e) from U.S. Application Ser. No. 61/661,588 filed 19 Jun. 2012 the contents of which are incorporated herein by reference.

TECHNICAL FIELD

[0002] Embodiments are generally related to thermal management techniques. Embodiments also relate to a thermal interface management (TIM) metamaterial having very high heat conductance dominated by thermal radiation. Embodiments additionally relate to a system and method of dissipating heat generated by electronic and optical signal processing devices.

BACKGROUND OF THE INVENTION

[0003] Dissipation of heat generated by electronic and optical signal processing devices is a major problem which limits device performance in harsh military and civilian applications. The problem is severe when large amount of heat has to be dissipated over a small period of time. Significant enhancements in fundamental device materials, technologies, and system integration have led to rapid increase in the total power consumption of CMOS, tele-communication, active sensing and imaging devices. However, relatively little progress has occurred in thermal management techniques mainly in the high heat conductance materials and TIMs.

[0004] Metamaterial technologies have matured over the past decade for a variety of applications such as super resolution imaging, cloaking, and perfect absorption. Various classes of metamaterials have emerged that show exotic electromagnetic properties like negative index, optical magnetism, giant chirality, epsilon-near-zero, bianisotropy, and spatial dispersion among many others. The central guiding principle in all the meter materials consists of fabricating a medium composed of unit cells far below the size of the wavelength. The unique resonances of the unit cell based on its structure and material composition as well as coupling between the cells lead to a designed macroscopic electromagnetic response.

[0005] One class of artificial media which received a lot of attention is hyperbolic metamaterials. They derive their name from the unique form of the iso-frequency curve which is hyperbolic instead of circular as in conventional dielectrics. With today's nanofabrication techniques, it is possible to manufacture artificial materials such as photonic band gap materials and metamaterials which exhibit very unusual material properties like negative refraction. Because of such properties they are considered as good candidates for perfect lensing, for repulsive Casmir forces and enhanced or tunable radiative heat flux at the nano scale to mention a few. There exists a class of uni-axial metamaterials for which the permittivity and permeability tensor elements are riot all of the same sign.

[0006] In particular, for such materials the dispersion relation for the solutions of Helmholtz's equation inside the material is not an ellipsoid as for normal uniaxial materials but a hyperboloid. For this reason such materials are also called hyperbolic materials. These materials have already been considered for super-resolution imaging and enhanced thermal conductivity inside the material itself. The heat flux between two bodies consisting of hyperbolic materials showing that these materials can have large thermal conductivity for a broad frequency range resulting in large heat fluxes and that they can be used to realize a blackbody at the nano scale.

[0007] A need therefore exists for an improved method of dissipating heat generated by electronic and optical signal processing devices.

BRIEF SUMMARY

[0008] The following summary is provided to facilitate an understanding of some of the innovative features unique to the disclosed embodiment and is not intended to be a full description. A full appreciation of the various aspects of the embodiments disclosed herein can be gained by taking the entire specification, claims, drawings, and abstract as a whole.

[0009] It is, therefore, one aspect of the disclosed embodiments to provide for thermal management techniques.

[0010] It is another aspect of the disclosed embodiments to provide for a Thermal Interface Management (TIM) metamaterial having very high heat conductance dominated by thermal radiation.

[0011] It is a further aspect of the present invention to provide for a system and method of dissipating heat generated by electronic and optical signal processing devices.

[0012] The aforementioned aspects and other objectives and advantages can now be achieved as described herein. Radiative cooling of optoelectronic devices using hyperbolic metamaterials is disclosed. The broadband divergence of the photonic density of states in hyperbolic metamaterials leads to an increase in radiative heat transfer, beyond the limit set by the Stefan-Boltzmann law. The resulting radiative thermal "hyper-conductivity" approach or even exceed heat conductivity via electrons and phonons in regular solids.

[0013] Microelectronic device using hyperbolic metamaterials solves thermal management issues in optoelectronic device& Hyperbolic metamaterials have divergent photonic density of states; therefore its radiative heat conductance also diverges. The method of radiative cooling of optoelectronic devices uses a hyperbolic metamaterial TIM layer below the heat generating optoelectronics. Optoelectronic device is optimized for high radiative heat conductance due to broad hyperbolic frequency band in the Long-Wavelength Infrared (LWIR) range with an efficient "electromagnetic black hole" thermal interface between the metamaterial TIM layer and a metallic heat sink. A modified Stefan-Boltzmann law in the hyperbolic metamaterial layer enables domination of the radiative heat transfer in the TIM layer.

[0014] Those skilled in the art will appreciate that the present invention allows for radiative heat dissipation into a hyperbolic metamaterial which is many orders of magnitude larger compared to heat dissipation into regular materials.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] The accompanying figures, in which like reference numerals refer to identical or functionally-similar elements throughout the separate views and which are incorporated in and form a part of the specification, further illustrate the disclosed embodiments and, together with the detailed description of the invention, serve to explain the principles of the disclosed embodiments.

[0016] FIG. **1** illustrates a perspective view of phase space volume between two constant frequency surfaces for an elliptical dielectric material, in accordance with the disclosed embodiments;

[0017] FIG. **2** illustrates a perspective view of phase space volume between two constant frequency surfaces for a hyperbolic material with $\epsilon_\perp<0$, $\epsilon_\parallel>0$, in accordance with the disclosed embodiments;

[0018] FIG. **3** illustrates a schematic diagram of different thermal conductivity mechanisms in metals and dielectric, in accordance with the disclosed embodiments; and

[0019] FIG. **4** illustrates a schematic diagram of different thermal conductivity mechanisms in hyperbolic media, in accordance with the disclosed embodiments.

DETAILED DESCRIPTION

[0020] The particular values and configurations discussed these non-limiting examples can be varied and are cited merely to illustrate at least one embodiment and are not intended to limit the scope thereof.

[0021] A hyperbolic metamaterial thermal interface layer is positioned below the heat generating optoelectronic layer, which is optimized for high radiative heat conductance into a heat sink. Due to a broad hyperbolic frequency band in the LWIR range, radiative heat dissipation into a hyperbolic metamaterial is many orders of magnitude larger compared to heat dissipation into regular materials.

[0022] Hyperbolic metamaterials exhibit unique electromagnetic properties resulting from the broadband singular behavior of their density of photonic states. This singular behavior is best understood through a visual representation of the density of states in terms of the phase space volume enclosed by two surfaces corresponding to different values of the light frequency. For extraordinary waves in a uniaxial dielectric metamaterial, the dispersion law describes an ellipsoid in the wave momentum (k–) space (which reduces to a sphere in isotropic media where $\epsilon_\parallel=\epsilon_\perp$). The phase space volume enclosed between two such surfaces is then finite, corresponding to a finite density of photonic states. However, when one of the components of the dielectric permittivity tensor is negative, the following equation,

$$\frac{k_\parallel^2}{\epsilon_\perp}+\frac{k_\perp^2}{\epsilon_\parallel}=\frac{\omega^2}{c^2} \tag{1}$$

describes a hyperboloid in the phase space. FIG. **1** illustrates a perspective view of phase space volume between two constant frequency surfaces for an elliptical dielectric material **100** and FIG. **2** illustrates a perspective view of phase space volume between two constant frequency surfaces for a hyperbolic material **200** with $\epsilon_\perp<0$, $\epsilon_\parallel>0$.

[0023] As a result, the phase space volume between two such hyperboloids (corresponding to different values of frequency) is infinite, leading to an infinite density of photonic states. While there are many mechanisms leading to a singularity in the density of photonic states, this one is unique as (in the effective medium limit) it leads to the infinite value of the density of states for every frequency where different components of the dielectric permittivity have opposite signs. This behavior explains the robust performance of hyperbolic metamaterials: while disorder can change the magnitude of the dielectric permittivity components, leading to a "deformation" of the corresponding hyperboloid in the phase (momentum) space, it will remain a hyperboloid and will therefore still support an infinite density of states. Such effective medium description will eventually fail at the point when the wavelength of the propagating mode becomes comparable to the size of the hyperbolic metamaterial unit cell a, introducing a natural wave number cut-off given by:

$$k_{max}\sim 1/a \tag{2}$$

[0024] Depending on the metamaterial design and the fabrication method used, the unit cell size in optical metamaterials runs from a ~10 nm (semiconductor and metal-dielectric layered structures) to a ~100 nm (nano wire composites). As the "hyperbolic" enhancement factor in the density of states scales as

$$\rho(\omega)\propto\rho_0(\omega)\left(\frac{k_{max}}{\omega/c}\right)^3 \tag{3}$$

where $\rho_0\sim\omega^2$ is the free-space result, even with the cut-off taken into account, the "hyper-singularity" leads to the optical density of states enhancement by a factor of 10^3-10^5. Physically, the enhanced photonic density of states in the hyperbolic metamaterials originates from the waves with high wave numbers that are supported by the system. Such propagating modes do not have an equivalent in "regular" dielectrics where $k\leq\sqrt{\epsilon}\omega/c$. As each of these waves can be thermally excited, a hyperbolic metamaterial will therefore show a dramatic enhancement in the radiative transfer rates.

[0025] Furthermore, it is the density of the photonic states $\rho(\omega)$ that limits the blackbody radiation energy density u_T and the energy radiated per unit area of a black body $S_T\,\alpha\,u_T$

$$u_T=\int_0^\infty d\omega\frac{\hbar\omega}{\exp\left(\frac{\hbar\omega}{kT}\right)-1}\rho(\omega), \tag{4}$$

leading to the Stefan-Boltzmann upper bound to the radiative energy flux given by

$$S_T^{(0)}=n^2\sigma T^4 \tag{5}$$

and the corresponding value of the electromagnetic energy density is given by

$$u_T^{(0)}=(4n^3/c)\sigma T^4 \tag{6}$$

for a dielectric with the refractive index n. As a result, the singular behavior of the photonic density of states in hyperbolic metamaterial takes these media beyond the realm of the Stefan-Boltzmann law, with no ultimate limit on the radiative heat transfer.

[0026] For the energy flux along the symmetry axis of a uniaxial hyperbolic metamaterial is given by,

$$S_T \simeq \frac{\hbar c^2 k_{max}^4}{32\pi^2} \int_{\epsilon_{\|}\cdot\epsilon_{\perp}<0} d\omega \frac{1}{\exp\left(\frac{\hbar\omega}{k_B T}\right)-1} \left| \frac{\epsilon_{\perp}\frac{d\epsilon_{\|}}{d\omega} - \epsilon_{\|}\frac{d\epsilon_{\perp}}{d\omega}}{\det\|\epsilon\|} \right| \quad (7)$$

where the frequency integration is taken over the frequency bandwidth corresponding to the hyperbolic dispersion. Note that the heat flux is very sensitive to the dispersion in the hyperbolic metamaterial, $d\epsilon/d\omega$. The derivative of the dielectric permittivity determines the difference in the asymptotic behavior at of the two hyperbolic surfaces that determine the phase space volume between the frequencies ω and $\omega+d\omega$, and thus defines the actual value of the density of states.

[0027] The most practical and widely used systems leading to hyperbolic dispersion rely on either the metal-dielectric semiconductor layer approach or incorporate aligned metal nanowire composites. For the planar layers design, the hyperbolic behavior is observed for the wavelengths above ~10 μm if the system is fabricated using semiconductors, or for the wavelength above ~1 μm if the metamaterial is composed of metal-dielectric layers. For the nanowire based approach, the hyperbolic dispersion is present at $\lambda \geq 1$ μm. As a result, with either of these conventional metamaterial designs, the desired hyperbolic behavior covers the full range of wavelength relevant for the radiative heat transfer.

[0028] The following thermal energy flux equations are obtained, for the layered metamaterial design,

$$S_T \simeq \frac{\epsilon^{(0)}}{4} S_T^{(0)} \left(\frac{k_{max}}{k_p}\right)^4 \quad (8)$$

[0029] For the nanowire-based composite,

$$S_T \simeq S_T^{(0)} \frac{5}{16\pi^2} \left(\frac{k_{max}^2}{k_T k_p}\right)^2 \quad (9)$$

[0030] where $S_T^{(0)}$ is the blackbody thermal energy flux for emission into the free space,

$$\epsilon^{(0)} \simeq \frac{\epsilon_d}{1-p} \quad (10)$$

[0031] ρ is the volume fraction of the conducting component of the metamaterial

[0032] ϵ_d is the permittivity of the dielectric component of the composite

$$k_p = \sqrt{\frac{4\pi N}{m^*}} \frac{e}{c} \quad (11)$$

[0033] N and m* are respectively the free charge carrier density in the metamaterial and their effective mass

[0034] the thermal momentum $k_T = k_B \hbar c$

[0035] FIG. **3** illustrates a schematic diagram **300** of different thermal conductivity mechanisms in regular media **306** comprising metals and dielectrics and FIG. **4** illustrates a schematic diagram **400** of different thermal conductivity mechanisms in hyperbolic media **406**. In FIG. **3**, different thermal conductivity mechanisms includes transfer of photons **310**, phonons **320** and electrons **330** from heat source **302** to heat sink **304**. In FIG. **4**, different thermal conductivity mechanisms includes transfer of photons **410**, phonons **420** and electrons **430** from heat source **402** to heat sink **404**.

[0036] Parametrically, the nanowire-based approach shows a higher enhancement, as

$$k_T << k_p (\lambda_T \simeq 10 \ \mu m, \lambda_p \simeq 1 \ \mu m) \quad (12)$$

[0037] However, with existing technology metamaterial layers can be fabricated with much smaller thickness (down to 10 nm) than the practical values for the nanowire periodicity (≥100 nm). As a result, in both cases,

$$S_T \simeq (10^4 \ldots 10^5) S_T^{(0)} \quad (13)$$

thus firmly placing hyperbolic metamaterials in the realm of practical applications for radiative heat transfer and thermal management.

[0038] While the present invention has been described in connection with the preferred embodiments of the various figures, it is to be understood that other similar embodiments may be used or modifications and additions may be made to the described embodiment for performing the same function of the present invention without deviating there from. Therefore, the present invention should not be limited to any single embodiment, but rather construed in breadth and scope in accordance with the recitation of the, appended claims.

What is claimed is:

1. A method of radiative cooling of optoelectronic devices comprising:

positioning a hyperbolic metamaterial thermal interface layer below a heat generating optoelectronic layer.

2. The method of claim wherein said hyperbolic metamaterial has a metal-dielectric layered design.

3. The method of claim **1**, wherein said hyperbolic metamaterial incorporates aligned metal nanowire composites.

4. The method of claim wherein said hyperbolic metamaterial comprises divergent photonic density of states.

5. The method of claim **1** wherein said hyperbolic metamaterial comprises divergent radiative heat conductance.

6. The method of claim **1** wherein said optoelectronic devices are optimized for high radiative heat conductance into a heat sink.

7. The method of claim **1** wherein radiative heat dissipation into said hyperbolic metamaterial is of greater orders of magnitude.

8. The method of claim **1** wherein said hyperbolic metamaterial exhibit electromagnetic properties resulting from broadband singular behavior of their said photonic density of states.

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