Rayleigh and Mie Enhancement of Blackbody Radiation in Nanoscale Devices

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Abstract

A method for suppressing long wavelength radiation in blackbody emission is presented. In particular, Rayleigh and Mie theory are considered for the design nanoscale devices to shape the spectrum of blackbody radiation. The method combines the Planck blackbody emission spectrum with the Maxwell equation based suppression of long wavelength radiation from sub-wavelength apertures. In this, constituent nanoscale devices are used as blackbody radiators rather than scatterers of an incident field, a fundamentally different notion than classical scattering of an incident electromagnetic field. In essence, the nanoscale devices serve as an intermediary for converting energy into short-wavelength photons. Although the development focuses on using nanoscale devices to enhance visible wavelength while suppressing infrared, the approach is not limited to optical wavelengths. Results are presented showing potential for reducing the emitted wavelength by 25% to 50%. Finally, the method may prove useful in applications such as energy conversion systems, solar cells, and lighting.

1. Introduction

The theory of blackbody radiation is of fundamental importance in physics, as perhaps evidenced by the scientists, whose names are affixed to various blackbody relations and constants, including Kirchhoff, Planck, and Boltzmann [1]. Further underscoring the fundamental importance of this theory, blackbody radiation has long been considered to be a universal phenomenon [2]-[3].

It is therefore surprising that recent serious questions have been raised regarding such an important 150-year-old theory as blackbody radiation [2]-[3]. Of particular relevance to the present discussion are questions that have been raised regarding the inevitable universality of blackbody emission spectra. In addition, recent experiments provide empirical evidence that the universal blackbody radiation spectrum can be enhanced or suppressed by appropriately designed nanostructures and systems [4]-[8]. Of course, these new developments do not seem to threaten associated results in quantum physics, but rather open the door to new possibilities offered by the advent of nanotechnology.

The foregoing developments motivate the investigation of Rayleigh and Mie (Rayleigh/Mie) theory to design nanospheres and other nanodevices to enhance and/or suppress blackbody radiation spectra [9]-[10]. In this, nanostructures are designed to suppress blackbody radiation at undesired wavelengths and/or to enhance blackbody radiation at desired wavelengths. In particular, the present work considers systems to suppress infrared emission and enhance emission in the visible or near infrared region.

The present approach is based on using Rayleigh/Mie theory to design nanospheres that suppress blackbody radiation at long wavelength. It is important to note that these nanospheres are used as blackbody radiators rather than scatterers of an incident field. This is distinct from the more common scattering situation, where an incident electromagnetic field is scattered. Nevertheless, the fundamental Rayleigh/Mie behavior of electromagnetic radiation from sub-wavelength apertures is applicable to nanodevices.

In optics, Mie theory typically refers to Maxwell equation solutions for the interaction of electromagnetic radiation with particles having physical size of the order of the wavelength of the radiation. Rayleigh theory applies when the size of particle is much smaller that the wavelength of radiation. Although dielectric particles are commonly considered in Rayleigh/Mie theory, the procedure is readily extended to particles of more general composition such as carbon and metal [11]-[12]. Because Rayleigh/Mie behavior fundamentally results from the re-radiation of the constituent particles, the proposed thermal blackbody radiation will also follow Rayleigh/Mie theory by reciprocity. Similar relationships are encountered in results based on Maxwell equations for radar cross section of spherical targets, where the Mie region is often referred to as the resonance region [13]–[14].

The aforementioned suppression of long wavelengths will induce proportionally more power to be radiated at shorter wavelengths. Since energy must be conserved, a greater portion of the total radiated blackbody energy is then emitted in short wavelength photons than would be emitted in a larger blackbody. As a result, properly designed nanodevices may potentially serve as an intermediary for converting various energy sources into short-wavelength photons, or for converting photons from one wavelength to another. Such efficient conversion of thermal energy has recently been demonstrated in tungsten photonic crystals [6].

Finally, the present method may also be viewed as drawing upon an apparent contradiction between Maxwell

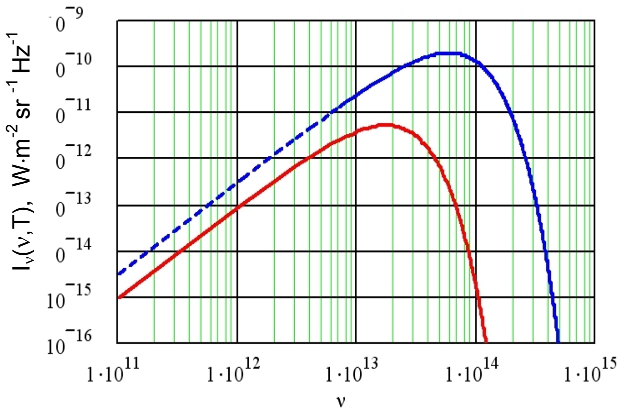

Fig. 1. Blackbody Spectral Radiance in $W \cdot m^{-2} \cdot sr^{-1} \cdot Hz^{-1}$ as a function of frequency in Hz. Upper-left blue dashed trace is 1000 K blackbody, lower solid red trace is 300 K temperature.

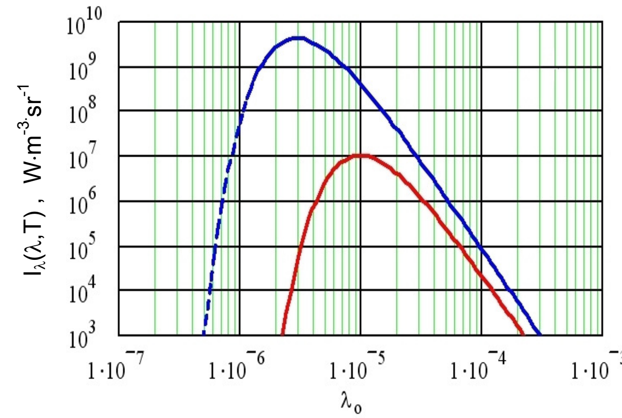

Fig. 2. Blackbody Spectral Radiance in $W \cdot m^{3} \cdot sr^{-1}$ as a function of wavelength in meters. Upper-left blue dashed trace is 1000 K blackbody, lower solid red trace is 300 K temperature.

equations and Planck's law of blackbody radiation for small blackbody emitters. On one hand, Rayleigh and Mie behavior of spherical radiators, antennas, and apertures are well known to severely attenuate the radiation of wavelengths that are much longer than the dimension of the radiator. On the other hand, universality of Planck's law of blackbody radiation might be thought to suggest that even nanoscale blackbodies would emit the Planck spectrum regardless of wavelength. The apparent contradiction therefore suggests that the Planck blackbody radiation of nanospheres should be modulated by Rayleigh/Mie behavior.

In the following sections, results are presented that suggest potential for more than 25% decrease in peak emitted wavelength. Such a 25% decrease in peak emitted wavelength would imply spectral emission equivalent to a blackbody at a corresponding increase in effective temperature and/or spectral emission with a corresponding improvement in power efficiency in emitting short wavelength photons.

2. Background and Theory

Blackbody radiation is one of the most fundamental physical properties of matter, and has been studied for nearly 150 years. Even the work of Planck rested upon the theory and experiments of Kirchhoff on blackbody radiation [2]. Despite this long history, controversy has recently arisen regarding aspects of the universality of blackbody emission spectra [3]. In particular, Kirchhoff and early experimenters used a carbon "catalyst" that essentially corrupted the blackbody experiments upon which Planck's work was based.

In particular, the issues raised suggest the possibility that blackbody emission spectra can be reshaped and reformed to create new devices or systems that may be capable of efficiently creating short-wavelength photons or efficiently converting energy to and from photons. Such potential applications are further supported by recent experiments that demonstrate the potential for reshaping the spectrum of blackbody emission [4]-[8]. Although some work has considered extinction coefficients of nanospheres, it does not seem that reshaped blackbody emission was an objective [15]. In the remainder of this section, Planck's theory of blackbody radiation and Rayleigh/Mie theory are reviewed. Then, these results are combined in the following section.

Planck's law for blackbody radiation can be expressed as a function of radiation frequency ν or as a function of radiation wavelength, λ. Most commonly, Planck's law is expressed as a function of frequency [1]:

$$I_{\nu}(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1} ,$$

where $I_{\nu}(\nu,T)$ is spectral radiance in $W \cdot m^{-2} \cdot sr^{-1} \cdot Hz^{-1}$ (watts per meter squared per steradian per hertz), λ is the radiation wavelength in meters, ν is frequency in Hz, $h=6.63\times10^{-34}$ is Planck's constant, $c = 3\times10^{8}$ m/s, $k=1.38\times10^{-23}$ is Boltzmann's constant, and T is temperature in kelvin. In the example of Fig. 1, $I_{\nu}(\nu,T)$ is plotted for temperatures of 300 K and 1000 K.

For the following discussion, however, it is more convenient to express Planck's law as a function of wavelength:

$$I_{\lambda}(\lambda,T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kT}-1} ,$$

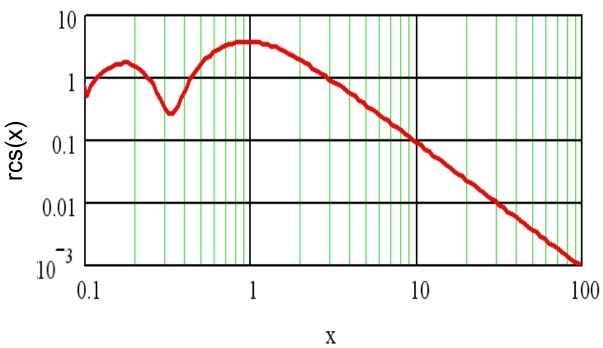

Fig. 3. Normalized radar cross section rcs(x) of a conducting sphere as a function of size parameter x, where x=λ/2πr, r is the sphere radius, and λ is wavelength. Cross section value of x=1 corresponds to effective cross section area of πr^2. Linear region on right side of plot corresponds to Rayleigh region, ripples on left side correspond to Mie region.

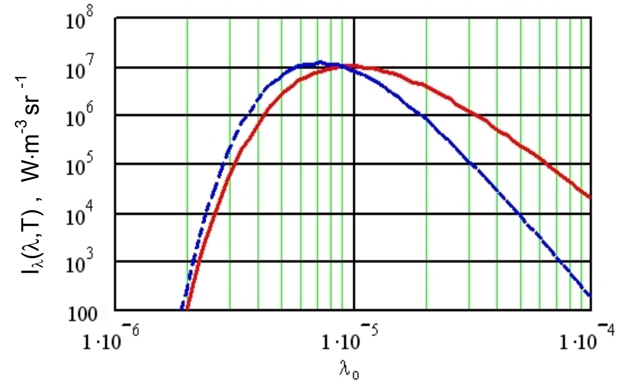

Fig. 4. Blackbody Spectral Radiance $I_\lambda(\lambda,T)$ in $W{\cdot}m^{-3}{\cdot}sr^{-1}$ as a function of wavelength in meters. Lower-left red solid trace is 300 K blackbody, upper-left dashed blue trace is 300 K blackbody of radius 500 nm adjusted for Rayleigh/Mie effect. Rayleigh/Mie effect causes attenuation of long wavelengths and also shifts the peak wavelength to approximately 27% shorter wavelength.

where $I_\lambda(\lambda,T)$ is spectral radiance in $W{\cdot}m^{-3}{\cdot}sr^{-1}$. Plots of $I_\lambda(\lambda,T)$ are given in Fig. 2 for for temperatures of 300 K and 1000 K.

As previously noted, the present method combines the Planck blackbody emission spectrum with Rayleigh/Mie theory. For the purposes of the following discussion, Rayleigh/Mie theory is applied to the blackbody nanosphere as a radiator, rather than as a scatterer. As usual, Mie theory refers to Maxwell equation solutions for electromagnetic radiation when particles have physical size of the order of the wavelength of the radiation. As particle size becomes smaller relative to wavelength, the behavior transitions to Rayleigh. Perhaps the most familiar example of the Rayleigh behavior in scattering is the blue color of the sky, underscoring the effect of particle size on wavelength.

As also mentioned earlier, dielectric particles are most commonly considered in Rayleigh/Mie theory, but the analysis is readily extended to particles of different composition [11]-[12]. Therefore, the following analysis will not dwell on any specific material. In addition, an aerosol or suspension of nanospheres is considered as a blackbody radiation source. To simplify the present discussion, the aerosol or suspension is assumed to be sufficiently diffuse that the nanospheres can be considered as an independent blackbody radiators.

As a consequence of the spherical geometry of the radiator, the Rayleigh/Mie radiation characteristics of a sphere are combined with the blackbody radiation spectrum of each sphere. In addition, the Rayleigh/Mie analysis below draws upon the previously noted radar cross section of spherical targets [13]-[14]. Thus, the radar cross section of a sphere is used to model the effective electromagnetic radiation area or aperture of the nanosphere. In essence, each nanosphere is modeled as a spherical antenna.

Unfortunately, the Rayleigh/Mie behavior of a spherical object is not simple and is beyond the scope and constrained space of the present discussion. Nevertheless, Fig. 3 shows the normalized radar cross section rcs(x) as a function of parameter x = λ/2πr, where r is the radius of the sphere and λ is the wavelength of radiation. The right side of the plot in Fig. 3 has a slope proportional to λ^{-2}, and corresponds to the Rayleigh region of behavior. This reduction of effective cross section at a rate of λ^{-2} is mechanism for attenuating long wavelength emission. The rippled response in the left of Fig. 3 is the Mie region of behavior. In the following section, the Rayleigh/Mie response of Fig. 3 is combined with the blackbody emission spectrum.

3. Results

Drawing upon the previous section, the total blackbody emission of a nanosphere can be modeled by combining the radar cross section behavior of the radiator in Fig. 3 with the blackbody radiation spectrum of Fig. 2. In effect, the electromagnetic radiation behavior of the sphere is combined the blackbody emission spectrum.

The combination of the blackbody emission characteristics of Fig. 2 with the Rayleigh/Mie characteristics of Fig. 3 results in the Rayleigh/Mie enhanced blackbody radiation spectrum shown in Fig. 4. The solid red lower-left curve in Fig. 4 corresponds to the spectral radiance $I_\lambda(\lambda,T)$ of a normal 300 K blackbody, as before. The upper-left dashed blue curve in Fig. 4 corresponds to the blackbody radiation of a 500 nm

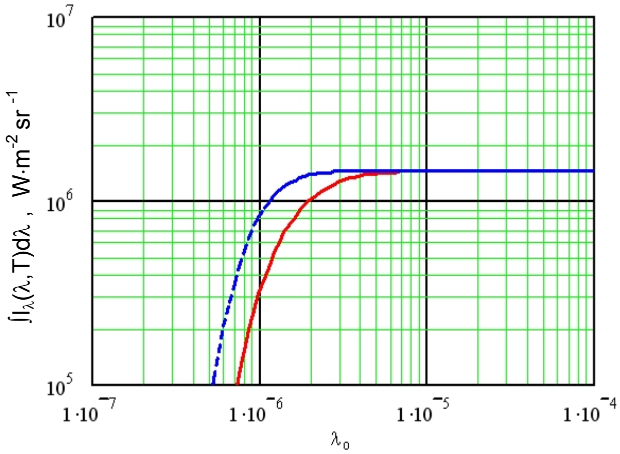

Fig. 5. Integral of blackbody spectral radiance $\int I_\lambda(\lambda,T)d\lambda$ in $W{\cdot}m^{-2}{\cdot}sr^{-1}$ as a function of wavelength in meters. Lower red solid trace is 3000 K blackbody; upper-left dashed blue trace is 3000 K blackbody of radius 10 nm adjusted for Rayleigh/Mie effect (rescaled by factor of 35). Rayleigh/Mie effect causes a shift to the left, to approximately 45% shorter wavelength.

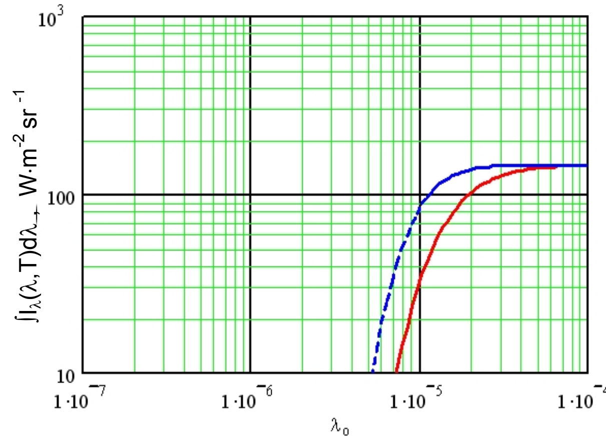

Fig. 6. Integral of blackbody spectral radiance $\int I_\lambda(\lambda,T)d\lambda$ in $W{\cdot}m^{-2}{\cdot}sr^{-1}$ as a function of wavelength in meters. Lower red solid trace is 300 K blackbody; upper-left dashed blue trace is 300 K blackbody of radius 100 nm adjusted for Rayleigh/Mie effect (rescaled by factor of 35). Rayleigh/Mie effect causes a shift to the left, to approximately 45% shorter wavelength.

spherical blackbody at 300K, including the Rayleigh/Mie effects of Fig. 3. In particular, note that the radiation is suppressed at wavelengths longer than 10 μm, due to Rayleigh/Mie effects for the 500 nm radius particle size. In addition, the peak radiation wavelength is shifted to the left, corresponding to an emission peak at a shorter wavelength. For temperature T=300 K, the theoretical peak wavelength is λ=2898/T=9.6 μm, and the observed peak of the 500 nm blackbody in Fig. 4 is approximately λ=7 μm, resulting in a shift of 27% in peak wavelength.

Another way to visualize the effect of the Rayleigh/Mie enhancement is to plot the integral of the spectral radiance, $\int I_\lambda(\lambda,T)d\lambda$. In Fig. 5, the integral of spectral radiance is shown in the lower solid red curve for a normal 3000 K blackbody, without Rayleigh/Mie enhancement. The upper-left dashed blue curve of Fig. 5 shows the integral of spectral radiance for a 3000 K spherical blackbody with 10 nm radius, including the effects of Rayleigh/Mie enhancement. It is apparent that the emission wavelengths of the dashed blue Rayleigh/Mie-enhanced blackbody are shifted left to shorter wavelengths. The two curves in Fig. 5 cross the radiance value of 10^6 $W{\cdot}m^{-2}{\cdot}sr^{-1}$ at λ=1.1 μm and λ=2.0 μm, corresponding to a wavelength reduction of 45%. Thus, the Rayleigh/Mie effect has reduced the integrated emission wavelength by nearly a factor of one half.

In Fig. 6, the integrated spectral radiance in the lower solid red curve is for a normal 300 K blackbody, without Rayleigh/Mie enhancement. The upper-left dashed blue curve of Fig. 6 shows the integral of spectral radiance of a 300 K spherical blackbody with 100 nm radius, including the effects of Rayleigh/Mie enhancement. Again, the Rayleigh/Mie effect has reduced the integrated emission wavelength by nearly a factor of one half, as seen on the logarithmic axes. Finally, note that he Rayleigh/Mie blue traces in Figs. 5 and 6 were rescaled by a factor of 35 to allow easier comparison and to compensate for the net reduction in emission caused by the Rayleigh/Mie attenuation of long wavelengths. If energy is conserved in isolated nanospheres, the rescaling should not be taken to represent lost energy.

4. Conclusion

The results illustrate scenarios where blackbody emission at long wavelength is suppressed by proper sizing of constituent nanoscale devices. In this, the Rayleigh/Mie suppression of long wavelength radiation is used to cause an apparent shift to shorter wavelengths in the blackbody emission spectrum. Results show potential wavelength reduction in the range of 25% to 50%. Although nanospheres were considered for simplicity in Rayleigh/Mie behavior, other geometries can be similarly treated. The results also suggest a large number of potential applications in energy conversion systems, incoherent photon wavelength conversion systems, solar cell efficiency improvement, and incandescent lighting. Finally, recent success by other investigators with thermal energy conversion in tungsten photonic crystals [6] suggest the potential of shaping blackbody emission, as the present Rayleigh/Mie approach undergoes further examination for potential limitations such as quantum effects for nanometer scale devices.

5. References

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