Partial collimation of diffuse light from a diffusely reflective source

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Abstract

A general purpose collimator capable of collimation of radiation from an arbitrary thermal source of diffuse light is incompatible with the second law of thermodynamics. It is known, however, that diffusion of coherent light from a particular ground glass can be reversed holographically. A new collimator is presented which produces a partially collimated beam of increased radiance when placed close to a white (diffusely reflective) source.

1. Introduction

Light can be readily diffused by a ground glass or other scattering medium, but the inverse process of collimating diffuse light is not as readily accomplished. A simple light baffle can reject the oblique rays, leaving only the ones in a desired range of directions, at the expense of much loss of light; such a baffle does not collimate the light since no rays are redirected. One may envisage holographic Bragg planes which diffract oblique rays into the direction normal to the plate, but such Bragg planes also diffract the normal rays in an oblique direction, so that no collimation is achieved. In this article we examine conditions under which collimation of diffuse light is possible, present a design for such a collimator, and present experimental results.

2. Limitations associated with the second law of thermodynamics

A collimator for a diffuse source will transform a disordered system into a more ordered one. Consequently limitations associated with the second law of thermodynamics are to be considered. The second law states that the entropy change in processes in a closed system must be nonnegative. This is equivalent to requiring that the transfer of heat from a cooler object to a hotter one cannot occur spontaneously [1]. There are several degrees of freedom in a beam of light. for the purpose of this discussion of diffusion, we consider only the distribution of directions of rays in the limit of ray optics.

Let there be a thermal blackbody source at absolute temperature T. The radiancy R [power per unit area] is given by $R=\sigma T^4$, in which σ is the Stefan Boltzmann constant. Suppose a perfect collimator exists for the diffuse blackbody radiation from an area A. The collimated radiation can then be focused by a lens, to a diffraction limited spot. The power density at this spot is approximately (for an f/1 system) $R_{spot} = R[A/\pi\lambda_o^2]$, in which λ_o is the wavelength of the peak of the Planck radiation distribution. The spot power density substantially exceeds the radiancy R of that blackbody, since the area ratio $[A/\pi\lambda_o^2]$ can be made very large. Therefore, energy will be pumped from one reservoir at temperature T to an identical one at temperature T, heating it in violation of the second law of thermodynamics. Collimation of diffuse incandescent radiation is therefore not possible.

A second argument involves two cavity radiators connected by a hole of area $A = a^2$ which is a distance d from the back wall of one cavity. The flux at the back wall due to the radiation passing through the hole is: Flux = $\pi RA \sin^2\theta \approx \pi RA[a/d]^2$ by virtue of the Lambertian emissivity of a blackbody. A general purpose collimator placed at the connecting hole would direct upon the back wall all the flux πRA passing through the hole. The ratio of these fluxes is $[d/a]^2$. Consequently the region on the back wall of one cavity will be heated above the ambient blackbody temperature T without any external input of free energy, in violation of the second law of thermodynamics. Collimation of thermal radiation is therefore forbidden by the second law. As for nonthermal radiation, one might suppose that by placing some constraints on the light, e.g. to have a narrow spectral bandwidth, collimation of diffuse light might be achieved, perhaps by an ensemble of oblique Bragg planes to redirect the off-axis rays. Such collimation is excluded by repeating the above argument but with a narrowband filter between the cavity radiators as is done to demonstrate [1] that all cavity radiators which are at the same temperature must have the same spectral radiance. Thermodynamic aspects of diffusion and other operations upon a beam of light has been considered elsewhere [2].

3. Examples of collimating diffuse coherent light

Partially coherent sources can produce a far-field intensity distribution as directional as that of a laser [3-5]. These 'Collett-Wolf' sources are based on temporally coherent light for which the spatial intensity distribution and degree of spatial coherence are both gaussian. Laboratory realizations of such sources have been constructed as follows. A laser was used to illuminate a diffuser in a controlled manner, giving a near-field diffuse, spatially incoherent light which appears directional at large distances [5]. However, since the original source is a coherent laser source, the procedure is not collimation of diffuse light.

Holographic reversal of the diffusion of light is possible [6]. The procedure involves holographically recording the detailed structure of a *particular* diffuser. The object behind the diffuser must emit or reflect coherent light; it could be a point source of laser light. It is possible to correct a diffused or aberrated image by making a hologram of the object [which could be a point source] through the diffuser and reconstructing it with a coherent conjugate beam. Such a procedure would not be transferable to the general problem of collimating incoherent light from an arbitrary diffuser, since a small change in the reconstruction conditions abolishes the effect. This holographic approach could not be used in the second law examples since the holographic corrector plate is specific to the diffuser in question. Thermal blackbody sources by contrast have no distinguishing features beyond their temperature.

4. Design of a collimator for diffuse light from a diffusely reflecting source

In this article we present a collimator for diffuse light from a diffusely reflective white source. As the following quantitative analysis will show, the performance of the collimator depends on the diffuse reflectance of the source being sufficiently high. The collimator consists of a short wave pass interference filter which transmits light of a given wavelength provided it is incident at a relatively small angle with respect to the normal [7], otherwise the light is reflected back to be diffusely reflected again. Some of these rays will be within the acceptance angle of the filter and will be transmitted, resulting in an enhanced brightness in the normal direction. The interference filter is placed close to or in contact with the diffuse source. Those rays which exit from the source at angles normal or near normal to the source are transmitted by the filter. Oblique rays are reflected by the filter back to the diffuse source where they are diffusely reflected. Some of those rays will then exit in the desired near normal directions, enhancing the brightness in the 'forward' direction, while oblique rays are again reflected back.

To predict the degree of collimation, consider [8] the flux $d\Phi_{eye}$ entering the eye pupil of area dS_2 from source area dS_1 of luminance L, at angle θ and at distance r. The diffuse source is assumed to be a Lambertian emitter. The diffuser transmits light with an efficiency ε_t and reflects light with an efficiency ε_r.

$$d\Phi_{eye} = [1/r^2]L\, dS_2\, dS_1 \cos\theta \qquad (1)$$

Consider the increment of flux leaving the diffuser $d\Phi_{dif}$ over some range of angle.

$$d\Phi_{dif} = 2\pi L\, dS_1 \cos\theta \sin\theta\, d\theta, \qquad (2)$$

so that, by integration the flux in a cone of angle θ_o is:

$$\Phi_{dif}^{in} = \pi L\, dS_1 \sin^2\theta_o, \qquad (3)$$

and outside that cone angle the flux is:

$$\Phi_{dif}^{out} = \pi L\, dS_1 (1 - \sin^2\theta_o). \qquad (4)$$

Now suppose that the collimator transmits light (with transmittance T) of a particular wavelength within a cone of angle θ_o and which perfectly reflects that light outside that angle. The reflectance within that cone is 1-T, and losses are assumed to be negligible. Any light which does not exit within the given cone angle is reflected back by the collimator to be diffusely reflected again. Considering all the multiple reflections, the increments to the luminance have the form

$\Xi = (1 - \sin^2\theta_o)\, \varepsilon_r + (\sin^2\theta_o)\, \varepsilon_r\, (1 - T) = (1 - T\sin^2\theta_o)\, \varepsilon_r$. (5)

However, not all of the light is transmitted. So the enhancement factor is:

$L_{app}/L = T\, [1 + \Sigma_n \Xi^n] = T\, [1 + \Sigma_n [\, (1 - T\sin^2\theta_o)\varepsilon_r]^n]$. (6)

This expression, which was obtained assuming a transmittance varying as a step function of angle, is readily generalized to the case of continuously varying transmittance. Predicted behavior is shown in Fig. 1. Observe that enhancement of the diffuser's brightness is still possible even if the collimator does not have 100% transmittance on axis; nevertheless, $T \approx 1$ is desirable. Perfect collimation, which corresponds to an unbounded enhancement factor, is possible in principle as the diffuse reflectance of the source approaches unity and the cone angle of the filter approaches zero. The predicted enhancement was also found to converge slowly to its asymptotic value with number n of reflections as shown in Fig. 2. For a 95% reflective diffuser, about 19 reflections are needed to achieve 90% of maximum enhancement for a 15° acceptance angle filter, and 37 reflections for a 5° acceptance angle. Further analysis disclosed that, for a backlit diffuser, the intensity of the collimated light is bounded from above by the intensity of the backlighting source.

5. Experiment

In tests of anti-diffusion the diffuser was back-illuminated with white light, through an opaque mask (to reduce the cone angle of rays from the diffuse source), and the filter placed in contact with it (Fig. 3). The transmitted light orthogonal to the diffuser was passed through a monochromator (Jarrell Ash, Monospec 18; with FWHM determined to be 1 nm) and measured with a silicon detector. The purpose of the monochromator was to determine the anti-diffusion as a function of wavelength. Measurements were made of the diffuse source alone and of the source with the interference filter directly over it, and the numbers divided to obtain the enhancement factor.

In an experimental study of anti-diffusion, we used a high reflectance diffuser, 50 mm in diameter and masked to 25 mm square, for which nominal characteristics were 5% transmittance and 95% reflectance [9]. An interference filter 50 mm square, of custom design [10] was used as a collimator. It was designed to have a sharp cutoff of transmitted light as a function of angle and high transmittance at the band edge. The cut-off angle for 50% transmittance was 14° and the transmittance for normal incidence at 550 nm was 87%. The transmittance of the interference filter was determined as a function of wavelength and angle.

Results for the filter transmittance are shown in Fig. 4. The enhancement of light intensity in the forward direction was measured as described above. Results are shown in Fig. 5. Enhancements of a factor of six were observed near 550 nm; while this is an imperfect state of collimation, it is nevertheless a substantial ordering of the rays.

The filter was then moved away from the diffuser. It was observed that light leaked out the edges and that the enhancement factor decreased precipitously if the filter were moved by a few millimeters. This observation is consistent with the predictions in Fig. 3 in that a large number of multiple reflections is required for significant anti-diffusion to occur.

We emphasize that the nature of the source and the proximity of the interference filter play a crucial role in this experiment. Indeed one could view the experiment as modifying diffuser characteristics rather than collimating diffuse light.

6 Discussion and conclusions

We conclude that it is possible to collimate diffuse light under special circumstances. Light from a 'white' diffuser can be collimated using an angle sensitive reflector, such as an interference filter. The degree of collimation depends on the diffuser having a high diffuse reflectance, the angle sensitive reflector transmitting light over a narrow angle with high transmittance in the forward direction, and being placed sufficiently close to the source (in relation to its width) that excessive light does not leak out the edges. While the present realization provides collimation for a narrow band of wavelength, neither a three-color device nor a wideband device covering the visible spectrum would violate any known physical laws. Neither the present collimator nor the holographic variety contradict the second law of thermodynamics since they would not work for blackbody radiation. Light reflected back into a cavity radiator from its small aperture does not enhance its emissivity.

Collimation of diffuse light by the present method may find application in fluorescent light sources which, in a thick layer, can have a high diffuse reflectivity [11], up to 97%, for visible light. Collimation of diffuse light from a backlit diffuser may not be practical since it will only work for a diffusely reflective, hence inefficient, diffuser. The situation is different in the case of fluorescent lamps in which ultraviolet light is absorbed strongly in the white phosphor, and visible light is emitted. The lamp can be very efficient even if the white phosphor is thick enough to be very diffusely reflective.

We remark in a related vein that the thermodynamic aspects of ray optics have been considered in the context of solar concentrators [12]. Arguments based on the second law of thermodynamics give a limit to the maximum achievable concentration.

References

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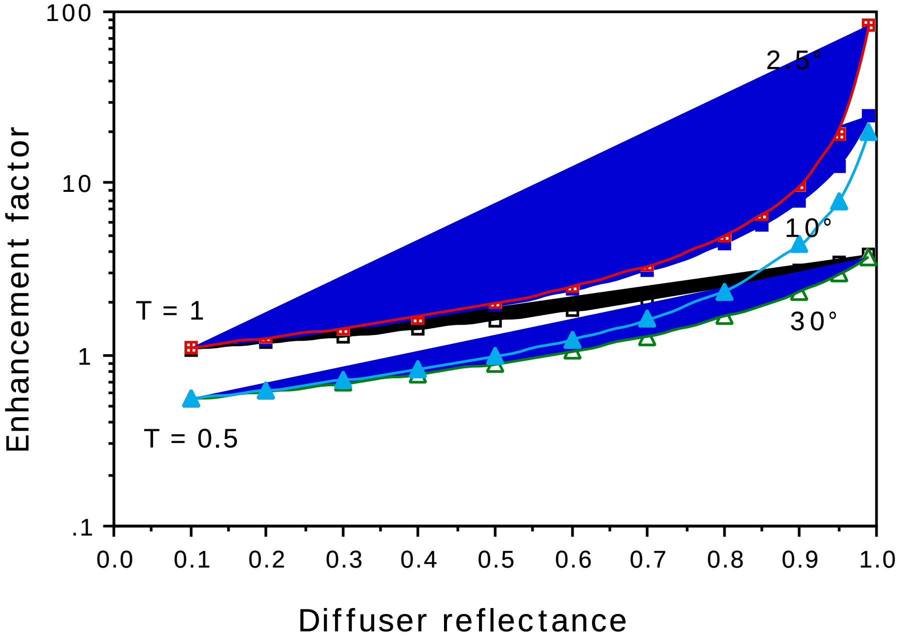
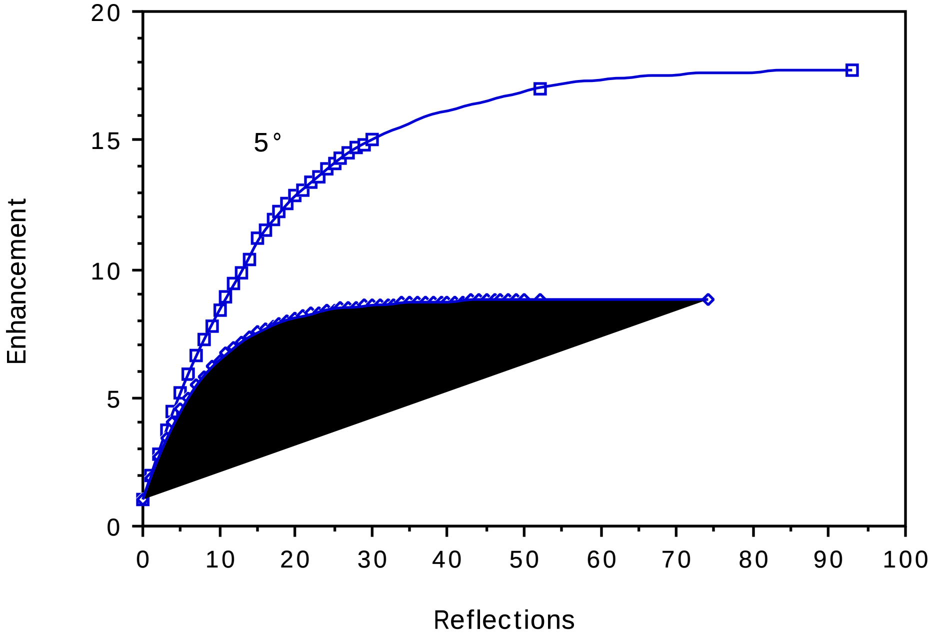
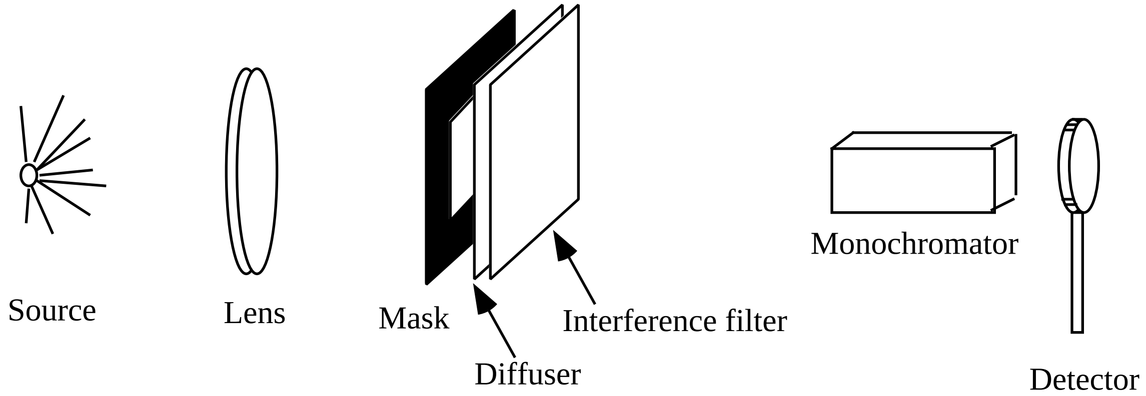
Figures



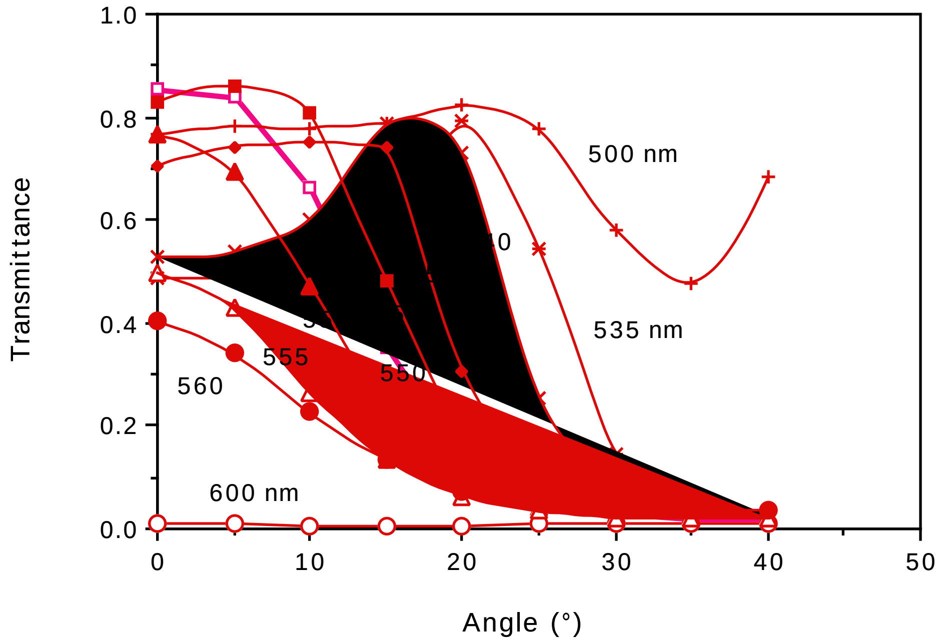
1. Predicted enhancement factor L_{app}/L vs diffuser reflectance ε_r for different cut off angles θ_o, and different transmittances T in the forward direction.
Squares, T = 1; solid squares $\theta_o = 10°$, open squares, $\theta_o = 30°$, squares with cross, $\theta_o = 2.5°$.
Triangles, T = 0.5; solid triangles $\theta_o = 10°$, open triangles, $\theta_o = 30°$.



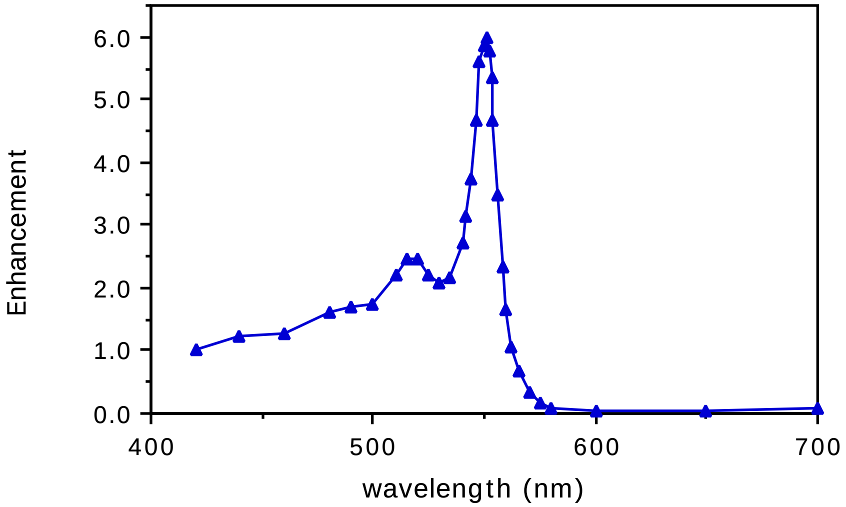
2. Predicted enhancement factor for light in the forward direction vs number of reflections, for two acceptance cone angles.



3. Experimental configuration.



4. Transmittance of collimator filter as it depends on wavelength and angle. 550 nm, indicated by the thick line, is the design wavelength.



5. Experimental enhancement of diffuse light intensity in the forward direction, vs wavelength.