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ScienceDirect
Photonics and Nanostructures – Fundamentals and Applications 6 (2008) 81–86
PHOTONICS AND NANOSTRUCTURES Fundamentals and Applications
www.elsevier.com/locate/photonics

Emissivity measurements of 3D photonic crystals at high temperatures

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Received 2 July 2007; received in revised form 30 August 2007; accepted 8 October 2007
Available online 13 October 2007

Abstract

An accurate methodology is presented to measure photonic crystal emissivity using a direct method. This method addresses the issue of how to separate the emissions from the photonic crystal and the substrate. The method requires measuring two quantities: the total emissivity of the photonic crystal–substrate system, and the emissivity of the substrate alone. Our measurements have an uncertainty of 4% and represent the most accurate measure of a photonic crystal's emissivity. The measured results are compared to, and agree very well with, the independent emitter model.

PACS : 42.70.Qs; 44.40.+a; 42.72.Ai

Keywords: Photonic crystal; Emissivity; Measurements; High temperature

1. Introduction

The emittance of photonic crystals [1] has been a subject of intense study because of the potential use of photonic crystals as high-temperature emitters for thermophotovoltaic applications [2,3]. This potential is due to the fact that photonic crystals (PC) are artificial materials with densities of states and spectral shapes that can be engineered. For an non-opaque objects, the "*extended*" Kirchhoff's law must be used to obtain the emissivity, e, such that $e = 1 - R(\lambda) - T(\lambda)$, with $R(\lambda)$ and $T(\lambda)$ being the total reflectivity and transmissivity of the material, respectively. Theoretical predictions based on this approach are called indirect methods [4,5]. In essence this approach calculates the effective absorptivity of the material that makes up the photonic crystal, convoluting it with the slow light effect of the photonic crystal, itself. This approach does not include the interplay between radiative and non-radiative relaxations of the emitters interacting with the electromagnetic fields inside the photonic crystal field. Alternatively, direct approaches based on quantum optics [6,7], or stochastic Langevin electrodynamics [8,9], do not assume an *a priori* maximum of 1 for the emissivity. None of these theoretical approaches consider the fact that photonic crystal often is built on a substrate and has finite number of periods. Therefore, theoretical transmittance and reflectance calculations are often for free-standing photonic crystals of infinite extent. Finally, the question remains whether the thermal excitation of a photonic crystal, with a strongly modified density of states, can be driven out of equilibrium; thus raising the possibility that the emissivity in a certain spectral range can exceed unity [3,7,6,10,11–14].

Previous measurements performed on a tungsten photonic crystal in the temperature range of 404–546 K

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1569-4410/$ – see front matter
doi:10.1016/j.photonics.2007.10.002

[14] have shown that the emissivity is independent of temperature, and can be described approximately by $1 - R(\lambda)$. The remaining small discrepancy was attributed to the use of specular reflectance for the $1 - R(\lambda)$ calculation rather than, more correctly, the total reflectance. In these measurements, the transmittance of the photonic crystal–substrate system has not been properly accounted for because of the difficulty in measuring effective transmittance. In addition, the transmittance of the silicon substrate can change significantly with temperature along with resistivity, especially in the temperature range being investigated. Since silicon is a semi-transparent material, the emissivity of the heater block can also affect the measured emissivity. As such, in these experiments the measured emissivity was that of a conglomeration of emitters constituting the heater block, the substrate and the PC lattice. At the end the question remains: how does the reflectance of the photonic crystal–substrate system relate to the inherent reflectivity of a free-standing photonic crystal?

In this paper we report on our high-temperature photonic crystal emissivity measurements, and derive the expression for the emissivity of a photonic crystal–substrate system in terms of the separate photonic crystal and substrate emissivities, and the photonic crystal reflectance based on an "*extended*" Kirchhoff's law. The detailed measurement methodology, and a comparison with a theoretical calculation, is presented.

2. Emissivity of combined photonic crystal–substrate system

A photonic crystal supported by a substrate allows for convenient handling of the photonic crystal. However, the substrate effect is often not considered in theoretical calculations of the reflectivity and transmissivity. In this case, a tungsten photonic crystal is built on top of a partially transparent silicon substrate with an unpolished backside. The light scattering effect from the backside of the substrate, and the partial transparency of the substrate itself, introduce tremendous complications in modeling the transmission and reflection of the system [15,16]. For a uniform semi-transparent material, the emissivity is expressed in terms of reflectivity and transmissivity [16]. In principle one can obtain the emissivity by measuring the reflectivity and transmissivity of the object; this is called an indirect measure (not to be confused with indirect method in the theoretical approaches). To measure the total reflectance and transmittance of a highly scattered object, an integrating sphere is needed [17]. If the sample also needs to be in vacuum to avoid oxidation, this method becomes impractical. Furthermore, this method is incompatible with measuring angular-dependent emission. Therefore, we chose to measure the emission from the sample directly, and obtain the emittance by comparing the emission from a reference object with known emissivity; this is called the direct method. A common method of heating the sample is by clamping it to a solid, heated block, to achieve an isothermal condition with the block, itself. The temperature of the sample surface is determined by comparison to a characterized reference sample mounted next to the sample under test. However, when a sample is attached directly on top of a solid block it introduces an emitter additional to the photonic crystal and the substrate. Therefore, we chose to heat the sample from the edge, but the inevitable temperature profile across the photonic crystal presents a serious challenge to determining the photonic crystal temperature. In the later part of this paper, we will describe, in detail, the methodology of how this challenge was met and mitigated.

To determine the emissivity of the photonic crystal–substrate system, we consider the photonic crystal and the substrate as two-independent isothermal emitters, as shown in Fig. 1. For the moment we consider the perturbation posed by having one side of the photonic crystal in contact with the silicon substrate to be small

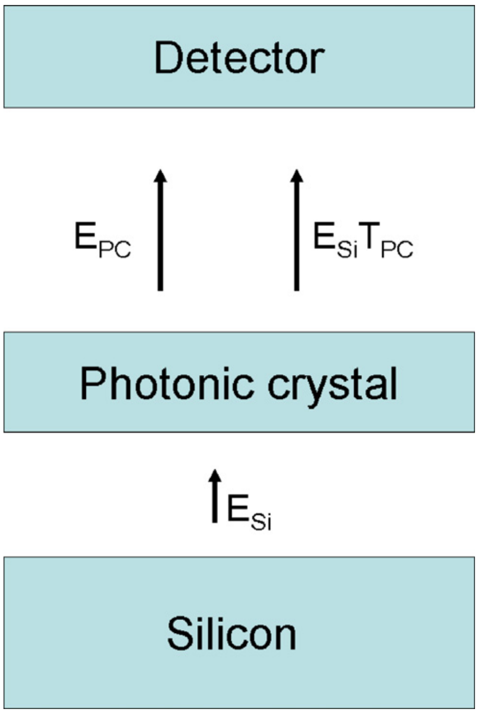

Fig. 1. Independent emitter model for the photonic crystal–substrate system emission.