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Prediction of photonic crystal emitter efficiency using an optimized fuzzy learning approach

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Abstract

Photonic crystals (PC) have attracted much attention over the last decade for their unique ability to control light propagation. Researchers suggested the use of metallic photonic crystal with network topology as high efficiency thermal emitters. A necessary precursor to the deployment of such crystals in practical systems is fast accurate prediction of the emission characteristics and efficiency from a photonic lattice. Conventional models that simulate the photonic response of PC are computationally expensive and can take up to a few hours on several parallel processors to realize the emitter efficiency for a given PC structure. Therefore, a practical design process with trial and error cannot be done in a reasonable amount of time.

In this article we suggest the use of a fuzzy learning approach to establish a model that can be used to predict emitter efficiency from such systems. The widely studied metallic PC Lincoln log structure is used as a case study. We show that the proposed method can estimate the efficiency of any PC Lincoln log structure much faster than any existing method and is by no means bound to this specific geometry. The case study presented here was chosen only because of recent high interest in it and the abundance of literature data on the example structure. The learning process using Fuzzy set Theory is explained. A multi-objective optimization method to enhance the fuzzy learning process is also outlined. An exemplar case showing the ability of the proposed model to predict the emitter efficiency of a tungsten PC with a bandgap at (10–11.5 μm) is illustrated. We show that once the fuzzy learning is performed, the proposed method can predict the emitter efficiency with 95% accuracy without the need for any expensive computations.

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Keywords: Photonic crystal; Emitter efficiency; Power efficiency; Thermo-photovoltaics (TPV); Fuzzy set Theory

1. Introduction

Photonic crystals are artificial structures with a periodically varying refractive index. Much like their semiconductor counterparts and their effect on free electrons, this periodicity enables them to uniquely manipulate and control light propagation in all directions due to the opening of a frequency gap (bandgap) where light is forbidden to propagate [1,2]. This property enables one to control light and produce effects that are not possible with conventional optics [1]. In particular researchers suggested the use of metallic photonic crystal with network topology as high

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efficiency thermal emitters [3,4]. This is due to their ability to suppress unwanted long wavelength radiation and funnel all thermal radiation into a pre-designated (by design) tunable narrow band. This unique capability aligns such crystals to impact greatly all applications that mandate sources with narrow thermal emission, such as thermo-photovoltaics and infrared scene generators.

A necessary precursor to the deployment of such crystals in practical systems is fast accurate prediction of the emission characteristics and efficiency from a photonic lattice. Computational models that simulate the photonic response of PC such as finite difference time domain (FDTD), transfer matrix method (TMM), and rigorous coupled wave analysis (RCWA), to mention a few, are computationally expensive and can take up to a few hours on several parallel processors to realize the emitter efficiency for a given PC structure. Therefore, a practical design process with trial and error cannot be done in a reasonable amount of time.

In this article we focus our attention on metallic Lincoln log photonic crystals as shown in Fig. 1 because of the recent demonstrations of large infrared bandgaps [3–6] which aligns them well with thermal emission applications, in addition to the available wealth of literature on the subject. It has been shown that such crystals are able to modify and manipulate the density of photon states [7]. At the boundary of the gap, the group velocity of light is greatly reduced and as a result the photon density of states peaks in value. This results in a preferential emission in the pass band frequencies closest to the bandedge associated with a complete suppression of emission within the gap. In a metallic

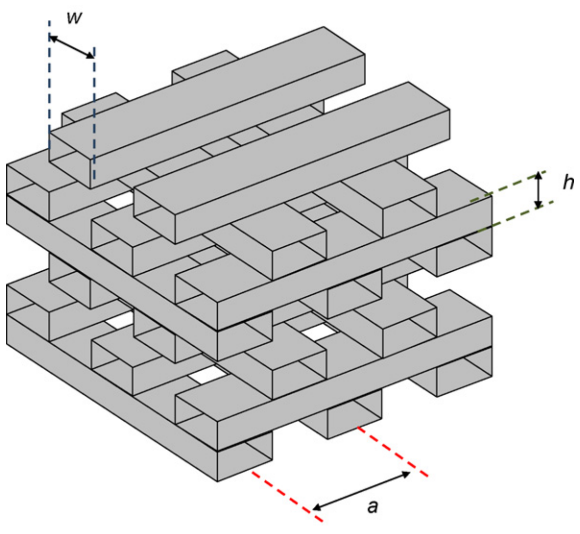

Fig. 1. A schematic of a Lincoln log PC: a represents the lattice constant, w the rod width, and h the rod height.

photonic crystal this gap extends from a pre-designed tunable bandedge frequency down to zero (infinite wavelength). Thus, if designed to have a bandedge matching that of a photovoltaic (PV) cell and/or detector, a metallic PC would suppress, in principle, all undesirable (waste) long wavelength emission. Because of its conductive metallic behavior, the thermal phonon populations with energies matching the suppressed long wavelengths are forced to undergo multi-phonon frequency conversion processes and relax their radiation in the allowed emission bands. Thus, unlike a conventional filter, a metallic PC recycles this undesirable (waste) long wavelength emission that would otherwise reduce the efficiency of the whole device. The maximum possible efficiency enhancement from a metallic PC emitter would thus be primarily dictated by the narrowness of the emission profile. This far, the maximum reported estimation of efficiency enhancement is $\sim$40% from one face of the PC lattice over a conventional blackbody emitter [4].

In the context of this paper a model based on Fuzzy set Theory for prediction of the emitter efficiency of photonic crystal (PC) structures is presented. First the methods used for simulation of PC photonic response are discussed. We then introduce the concept of fuzzy learning from example data and we present a method for enhancing the performance of the fuzzy-based model using a multi-objective optimization method. Finally, a case study presenting the ability of the proposed method to predict the PC response for a variety of Lincoln log microstructures that are *not used* in developing the model is presented and discussed. It is worth pointing out that the methods described here are by no means bound to the specified geometry which was primarily chosen because of recent interest in it and the abundance of literature data on the example structure [1–8].

1.1. PC simulation: background

There is an abundance of numerical methods available for PC simulation, these include: finite difference time domain [9], modal expansion [10], Green's function integral equations [11] and transfer matrix methods [12]; all possess advantages and disadvantages. In this paper however, our focus is directed towards the ability to evaluate the thermal emission performance from a PC emitter once a sufficient amount of example cases are calculated. As such we are not biased to one method over the other, what we are interested primarily in is a fast, accurate method for the generation of these example cases. Because of the topological structure of the Lincoln log