Journal of Quantitative Spectroscopy & Radiative Transfer 112 (2011) 2584–2591

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Infrared radiative properties of two-dimensional square optical black holes

J. Qiu [a], J.Y. Tan [b], L.H. Liu [a,b,*], P.-f. Hsu [c]

[a] School of Energy Science and Engineering, Harbin Institute of Technology, 92 West Dazhi Street, Harbin 150001, People's Republic of China
[b] School of Automobile Engineering, Harbin Institute of Technology at Weihai, 2 West Wenhua Road, Weihai 264209, People's Republic of China
[c] Department of Mechanical and Aerospace Engineering, Florida Institute of Technology, FL 32901, USA

ARTICLE INFO

Article history:
Received 11 May 2011
Received in revised form
6 July 2011
Accepted 2 August 2011
Available online 7 August 2011

Keywords:
Square optical black hole
Geometric optics
FDTD
Infrared radiative properties

ABSTRACT

Optical black hole (OBH) is a special optical structure, in which the dielectric function or refractive index of media becomes gradually larger from the outside to the core. The circular optical black holes (COBH) have been proved remarkably useful for broadband omnidirectional light absorption. The main goal of this paper is to propose an alternative square structure of OBH due to fabrication consideration. The infrared radiative properties of two-dimensional SOBHs are numerically studied with geometric optics approximation (GOA) and the finite-difference time-domain (FDTD) method. A critical wavelength is found in this paper: when the wavelength is smaller than half of the inner core side length, the Poynting vectors obtained by the FDTD method agree well with the ray trajectories calculated by the GOA, and the absorptance is nearly 100% with a proper refractive index gradient. While the wavelength is increasing, the net energy flows do not agree with the ray trajectories and the absorptance will be decreased. The reason is attributed to the diffraction effect, which is discussed in detail in this paper.

1. Introduction

The concept of a black hole is a region of space from which nothing, not even light, can escape. Einstein's general theory of relativity predicts that a sufficiently compact mass will deform spacetime to form a black hole. Similar to the gradient gravitation of perfect black body, the artificial optical black hole (OBH) is designed with gradient index materials, which absorbs almost all the light [1,2]. There has recently been considerable interest in OBH, which is designed as a broadband and omnidirectional light absorber for efficient solar energy harvesting, thermal light emitting, infrared sensing, and other areas [1–13]. Cheng et al. [2] reported the first experimental demonstration of OBH in the microwave frequencies. The proposed OBH can absorb electromagnetic waves efficiently coming from all directions due to the local control of electromagnetic fields. Circular structure of OBH (COBH) has been proved remarkably useful for broadband omnidirectional light absorption [1,2,4]. Argyropoulos et al. [3] demonstrated excellent absorption for different angles of wave incidence and illumination excitation types using a parallel, radially dependent FDTD simulation technique. Qiu et al. [4] proposed an alternative approach to wavelength selective light absorption (both TE and TM waves), based on an optical board periodically embedded with OBHs using the FDTD method. Gradient index materials have been extensively used in the optical fibers and other optical devices, its combination with optical black hole occurs only a few years ago. The spherical and cylindrical structures of OBHs are the only structures that have been considered so far [1–4,7]. To ensure the feasibility of fabricating the optical black holes, we need to consider the typical lithography and etching processes used in semiconductor or MENS devices' fabrications, which are most likely

* Corresponding author at: School of Energy Science and Engineering, Harbin Institute of Technology, 92 West Dazhi Street, Harbin 150001, People's Republic of China. Tel.: +86 451 86402237; fax: +86 451 86221048.
E-mail address: lhliu@hit.edu.cn (L.H. Liu).

0022-4073/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jqsrt.2011.08.002

Nomenclature

E	electric field vector
H	magnetic field vector
k	wave vector
k_z	wave vector component in the z-direction
$\hat{n}$	complex refractive index, $\hat{n}=n+i\kappa$
r	position of an incident ray
Δs	step length
L	outer side length
L_c	inner core side length
s	abscissa along the ray trajectory
S	Poynting vector
TE	transverse electric wave
TM	transverse magnetic wave

Greek symbols

ε	relative (electric) permittivity or dielectric function
ε_0	permittivity of vacuum
κ	imaginary part of $\hat{n}$
λ	wavelength
μ	relative (magnetic) permeability
μ_0	permeability of vacuum
θ	angle
x, y, or z	x, y, or z axis in the Cartesian coordinate system

Superscripts

$\hat{}$	complex variable
$*$	complex conjugate

to be the same scheme used in the optical black hole fabrication. It is not easy to fabricate curved profiles in the depth direction in the lithography and etching or focused ion beam processes as shown in Fig. 1, although curved patterns are possible [14]. As such, it is reasonable to consider other geometry for optical black hole design. This is one of the motivations to study optical black holes with square cross section.

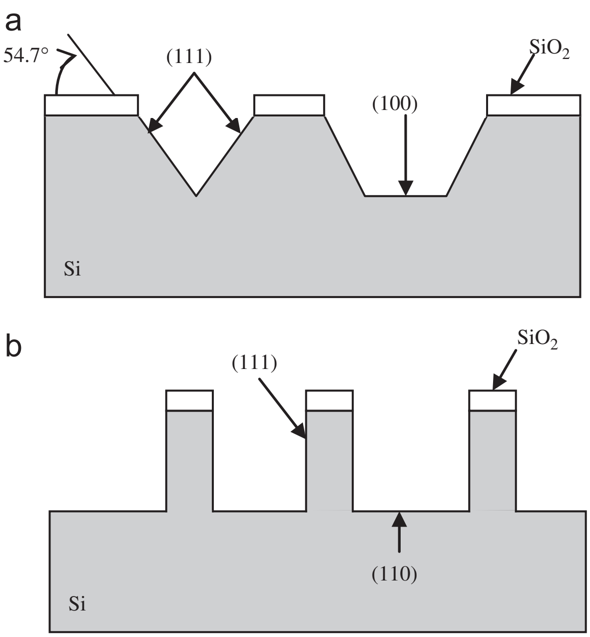

Fig. 1. Orientation-dependent etching. (a) Through window patterns on ⟨100⟩-oriented silicon; (b) through window pattern on ⟨1 1 0⟩-oriented silicon [14].

In this paper, a square cross section structure of OBH (SOBH) is presented and its infrared radiative properties are numerically studied. A geometric optics approximation (GOA) of studying the alternative structures of OBHs is proposed in this paper, which uses the ray equation to calculate ray trajectories of OBHs with different refractive index gradient structures. The ray trajectories are compared with the Poynting vectors obtained with the FDTD method. The diffraction effect of electromagnetic waves has also been discussed in detail by illustrating the Poynting vector distribution within and around the SOBH. The results demonstrate the advantages of SOBH and the proposed GOA and FDTD method can be directly and easily extended to the design of other alternative structures of OBHs.

2. Square optical black hole and theoretical formulation

2.1. Geometry description

The geometry of a 2-D SOBH is shown in Fig. 2. In this figure L ($=30\ \mu$m) and L_c ($=8.4\ \mu$m) represent the outer side length and the inner core side length of the square cross section of OBH, respectively. Assuming that the fabrication method chosen for this proposed structure allows for the local values of the refractive index in the range $n_0<n<n_c$ and $n_0=1$ [1], we define the "fundamental" square black holes via

$$n(x,y)=\begin{cases} n_0, & |x|>\frac{L}{2} \text{ or } |y|>\frac{L}{2} \\ n_0\left(\frac{L}{2|x|}\right)^m, & \frac{L_c}{2}\le|x|\le\frac{L}{2} \text{ and } |x|\ge|y| \\ n_0\left(\frac{L}{2|y|}\right)^m, & \frac{L_c}{2}\le|y|\le\frac{L}{2} \text{ and } |x|<|y| \\ n_c+i\kappa_c, & |x|<\frac{L_c}{2} \text{ and } |y|<\frac{L_c}{2} \end{cases} \tag{1}$$

where m represents the different orders of refractive index. The complex refractive index of the inner core is