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Sensitivity Analysis of a Bioinspired Refractive Index Based Gas Sensor

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Abstract

It was found out that the change of refractive index of ambient gas can lead to obvious change of the color of *Morpho* butterfly's wing. Such phenomenon has been employed as a sensing principle for detecting gas. In the present study, Rigorous Coupled-Wave Analysis (RCWA) was described briefly, and the partial derivative of optical reflection efficiency with respect to the refractive index of ambient gas, *i.e.*, sensitivity of the sensor, was derived based on RCWA. A bioinspired grating model was constructed by mimicking the nanostructure on the ground scale of *Morpho didius* butterfly's wing. The analytical sensitivity was verified and the effect of the grating shape on the reflection spectra and its sensitivity were discussed. The results show that by tuning shape parameters of the grating, we can obtain desired reflection spectra and sensitivity, which can be applied to the design of the bioinspired refractive index based gas sensor.

Keywords: bioinspired gas sensor, sensitivity, diffraction gratings, refractive index, subwavelength structures

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1 Introduction

The *Morpho* butterfly wing has attracted people for a long time due to its bright blue appearance. In fact, this color is generated by the multilayer asymmetric nanostructure on the wing surface due to the manipulation of electromagnetic waves in subwavelength regime[1,2]. As a result, such kind of color is called "structure color" since it has nothing to do with pigments but closely related to the complex nanostructure, as shown in Fig. 1.

It was found out that the reflection spectrum of *Morpho* butterfly wing is sensitive to ambient gas, or more specifically, the refractive index of the ambient gas. Even slight change of the refractive index can lead to obvious change of the color. Potyrailo found out that the wing of *Morpho sulkowskyi* butterfly can respectively give different optical reflections to vapor of water, methanol, ethanol and isomers of dichloroethylene[3]. The sensors that use such mechanism as sensing principle for detecting chemical or biological substances have been described in the literatures[4,5]. This simple sensing principle can simplify the sensing process and reduce the costs as compared with the conventional sensing principle that based on modulation of electrical property[6,7]. As a result, the nanostructure of butterfly wing has caught a lot of attention in the study of novel optical gas sensor. In the present study, the typical nanostructure on

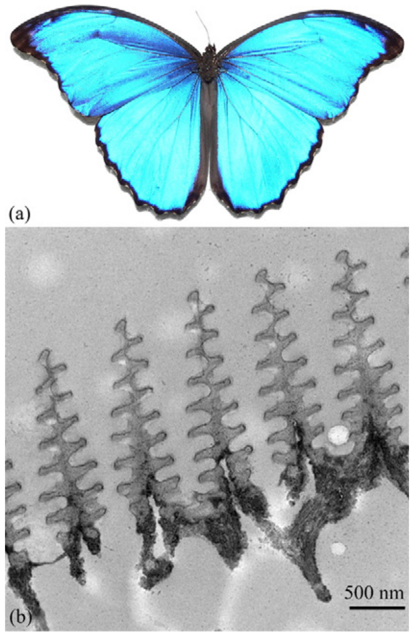

Fig. 1 (a) *Morpho didius* butterfly, (b) TEM image of cross section through a ground scale.

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the wing surface of *Morpho didius* butterfly is mimicked and simplified for constructing a refractive index based gas sensor.

For the refractive index based sensor in the present study, the sensitivity describes how the optical reflection efficiency will behave when the refractive index of ambient gas changes slightly. A lot of studies have been carried out to improve the sensitivity of similar sensors, and people found out that sensitivity concerns closely with material and shape of the nanostructure. Rong *et al.* and Bonanno *et al.* independently studied porous structures and came to similar conclusions that the performance of a sensor will be better when the size of pores is about 100 nm[8,9]. The study results of Block *et al.* showed that the sensitivity of photonic-crystal-based chemical or biological sensors can be improved by four-fold by using high-index polymer instead of low-index porous dielectric[10]. Ganesh *et al.* optimized the structure parameters of Bragg stack which is essentially an one-dimensional (1D) photonic crystal and made the sensitivity of sensor tunable[11]. The mechanism of response in these references involves optics, which is related to the refractive index of the ambient medium fills in the sensors' cavities. In the literature, there also exist some studies that aim to improve the sensitivity by using chemically selective surface[12,13], which relies on surface adsorption and capillary condensation effects for some special ambient media, and thus amplifies the response of sensors to the change of refractive index. In these cases, the mechanism involves not only optics but also chemistry and thermotics. In our study, we focus on the optical analysis and do not regard the chemical and thermal effects, and we derive the partial derivative of the optical reflection efficiency with respect to the refractive index of ambient gas, *i.e.* sensitivity, by using the Rigorous Coupled-Wave Analysis (RCWA) method[14–19]. Then, the effects of the grating nanostructure on the reflection spectra and its partial derivative are analyzed. The results can be applied to the design of the bioinspired refractive index based gas sensor.

The rest of this paper is organized as follows. In section **2**, the RCWA method with enhanced transmittance matrix is briefly introduced. In section **3**, the derivation of sensitivity of a 1D grating is described. In section **4**, numerical examples are presented, verification of the analytical sensitivity as well as discussions on the effect of the grating shape on the reflection spectra and its sensitivity are presented. In section **5**, we come to the conclusion.

2 Rigorous coupled-wave analysis method

Fig. 2 is an illustration of an arbitrarily profiled periodical 1D dielectric grating with period Λ along the x-axis. A polarized electromagnetic plane wave with a vacuum wavelength λ_0 transmits into the grating with an angle of incidence θ to z-axis, and the electric field is independent of y-axis in Transverse Electric (TE) mode and the magnetic field is also independent of y-axis in Transverse Magnetic (TM) mode. The refractive indexes of the media of the input region, ridge of grating and output region are n_{I}, n_{r}, and n_{II}, respectively. The grating can be decomposed into many layers, and each layer is treated as an individual rectangular grating. Then, the electromagnetic fields in all the layers are described, and the boundary conditions are applied at the interfaces.

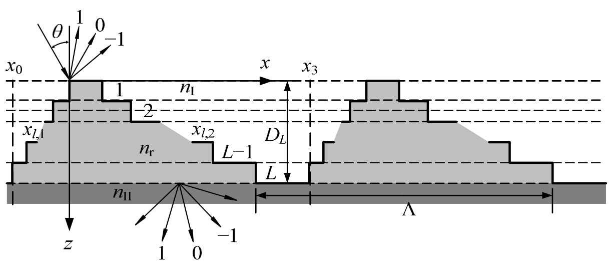

Fig. 2 A sketch of a periodical arbitrary-profiled periodical 1D dielectric grating.

For TE mode, the normalized electric fields in region I ($z < 0$) and region II ($z \geq D_{\mathrm{L}}$) are

$$E_{\mathrm{I},y} = \exp\left[-jk_0 n_{\mathrm{I}}\left(x\sin\theta + z\cos\theta\right)\right] + \sum_i R_i \exp\left[-j\left(k_{xi}x - k_{\mathrm{I},zi}z\right)\right], \quad (1)$$

$$E_{\mathrm{II},y} = \sum_i T_i \exp\left\{-j\left[k_{xi}x + k_{\mathrm{II},zi}\left(z - D_L\right)\right]\right\}, \quad (2)$$

and for TM mode, the normalized magnetic fields in region I and region II are

$$H_{\mathrm{I},y} = \exp\left[-jk_0 n_{\mathrm{I}}\left(x\sin\theta + z\cos\theta\right)\right] + \sum_i R_i \exp\left[-j\left(k_{xi}x - k_{\mathrm{I},zi}z\right)\right], \quad (3)$$

$$H_{\mathrm{II},y} = \sum_i T_i \exp\left\{-j\left[k_{xi}x + k_{\mathrm{II},zi}\left(z - D_L\right)\right]\right\}, \quad (4)$$

where D_L is total height of the grating ridge, $k_0 = 2\pi/\lambda_0$, $k_{xi} = k_0[n_{\mathrm{I}}\sin\theta - i(\lambda_0/\Lambda)]$, R_i is the normalized amplitude of the i-th reflected wave in region I, T_i is the normalized amplitude of the i-th transmitted wave in region II.