

Narrow-Band Omnidirectional Structural Color

Debasish Banerjee and Minjuan Zhang

Toyota Motor Engineering & Manufacturing North America

Masahiko Ishii

Toyota Motor Corporation

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ABSTRACT

Automotive pigments consist of absorptive materials which absorb most of the wavelengths of light in the visible range (400-800 nm) except one particular range which gets reflected and seen as color. This coloring mechanism based on light absorption due to their molecular structure generally reflects a broader range of wavelength with a moderate reflectivity (50-60%). However in nature we find many magnificent colors in insects, butterflies, birds and fishes. These colors in nature are not based on the absorptive pigments, but on the nanoscopic regular structures that interfere light reflected from those periodic sites. Since animals contain no solid metals, to produce metallic-like reflections they also rely on interference of light.^[1] Most common and well-known form of animal reflector is the multilayer type where alternating high and low refractive index layers are formed. Such nanostructure assembly can reflect light up to 100%. In order to use this technology for color application one need to design a narrow band omnidirectional reflector to avoid angle dependent reflectivity. In the present work we conducted theoretical simulation of multilayer stack formed by alternating high and low refractive index layers to identify the key parameters that allows control of the reflection band width and predicted structural parameters necessary for the narrow-band design.

INTRODUCTION

When white light, i.e. light having a roughly equal mixture of the entire visible spectrum of wavelengths, encounters a pigment, some wavelengths are absorbed by the chemical bonds of the pigment and other wavelengths are reflected. The reflected wavelengths determine the color of the pigment. This coloring mechanism based on light absorption due to their molecular structure generally reflects a broader range of wavelength with a moderate reflectivity (50-60%). Brilliant colors in the living world^[2, 3] are not based on the absorptive pigments, but on interference of light reflected from periodic structure comparable to the visible wavelength of light. This type of 'structural' colors is have been studied by researchers for a long time.^[1, 4] People have been able to replicate these

colors mimicking the nanostructures of the natural world.^[5] Although these colors are with pure quality and have good aesthetic beauty, they change reflective wavelength (color) when viewed from different angles.^[6]

If two dielectric materials with high and low indices of reflection, n_H and n_L are alternatively stacked and each layer has an optical thickness (refractive index multiplied by the layer thickness) = quarter-wavelength ($\lambda_0/4$, where λ_0 is the free-space wavelength), this dielectric stack can reflect light of specific wavelength band (centered at λ_0). This is the simplest type of 1D photonic crystal (PC) also known as Bragg reflector. Using this principle there have been commercialization of 'Flex Product' pigments also known as 'Color by Physics'.^[6] Such pigments contain multilayer structure to form 'Bragg reflectors'. In this case associated angle dependent reflectivity has been used to enhance aesthetic value of the pigment. However to maintain the purity of a particular color one has to avoid angle dependent reflectivity, in other words make omnidirectional reflectors. The high reflectivity of Bragg reflectors is known for a long time. However, just recently the conditions for omnidirectionality of reflection for arbitrary polarization of light have been developed.^[7] It was recognized that omnidirectional reflection is possible only by well-designed 1D PCs and does not necessarily require 2D or 3D PCs. The simplicity of designing 1D PCs opens up numerous possibilities to use omnidirectional reflectors (ODRs) in wide range of applications. However, main stream research of ODRs is limited to optoelectronic devices for telecommunication that requires broad reflection band in the near to short IR (1000-3000 nm) regime.^[7-17] The use of multilayer structures has not been exploited for producing narrow omnidirectional reflection (ODR) bands. When targeted at the visible range (400-800 nm) such reflectors can be used as 'omnidirectional structural color'. In this report we describe the theoretical aspect of omnidirectional 1D PC reflectors to demonstrate a way to choose realistic fabrication parameters for the narrow band design. Calculation showed that to design narrow band omnidirectional reflector in visible region the thickness of individual stack should be tailored between 40 to 80 nm.

MAIN SECTION

THEORETICAL FORMULATIONS FOR BAND STRUCTURE

Let us consider a multilayer structure of alternate high and low refractive index material with refractive index and layer thickness are n_H , d_H and n_L , d_L respectively (Fig 1). Light is an electromagnetic wave consisted of an electric (E) and a magnetic (B) component of vector perpendicular to each other. Light fall on the multilayer top surface can be distinguished between two independent electromagnetic modes or polarizations: transverse electric (TE) modes and transverse magnetic (TM) modes. For the TE mode, the electric field is perpendicular to the plane, as is the magnetic field for the TM mode.

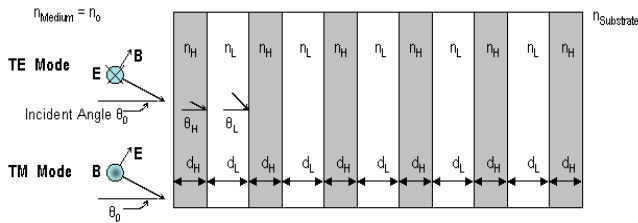


Figure 1: Multilayer structure of high and low refractive index material. Concept of TE and TM polarization of light is also visualized.

The refractive index of the medium and the substrate are n_0 (1 for air), and n_s (1.5 for glass). When light falls on the top surface at an angle θ_0 , the angle it makes on the high and low refractive index layers are θ_H and θ_L respectively. By Snell's law,

$$n_0 \sin \theta_0 = n_L \sin \theta_L = n_H \sin \theta_H \quad \dots (1)$$

When a light of wavelength λ falls on a multilayer sample at an angle θ_0 the propagation of light in a bi-layer can be expressed in the form characteristic translation matrix (F_T) which is given by equation 2^[17]

$$F_T = \frac{1}{1 - \rho_T^2} \begin{vmatrix} e^{i(\delta_L + \delta_H)} - \rho_T^2 e^{-i(\delta_H - \delta_L)} & -2i\rho_T e^{-i\delta_H} \sin \delta_L \\ 2i\rho_T e^{i\delta_H} \sin \delta_L & e^{-i(\delta_L + \delta_H)} - \rho_T^2 e^{-i(\delta_H - \delta_L)} \end{vmatrix}$$

Where, ... (2)

$$\delta_L = \frac{2\pi}{\lambda} n_L d_L \cos \theta_L, \quad \delta_H = \frac{2\pi}{\lambda} n_H d_H \cos \theta_H,$$

$$\rho_T = \frac{n_{HT} - n_{LT}}{n_{HT} + n_{LT}},$$

$$n_{HT} = \begin{cases} \frac{n_H}{\cos \theta_H} \\ n_H \cos \theta_H \end{cases}, n_{LT} = \begin{cases} \frac{n_L}{\cos \theta_L} \\ n_L \cos \theta_L \end{cases} \text{ For TM Polarization} \\ \text{For TE Polarization}$$

The boundary condition that determines the band edge equation between reflection and transmission band of the band structure is given by,

$$\text{Trace}|F_T| = -1 \quad \dots\dots\dots (3)$$

Setting trace of matrix elements to negative one, band-edge equations can be deduced for TM and TE polarizations. The term 'long' and 'short' corresponds to the long wavelength and short wavelength edges of total reflection band. The band edge equations are given by equation 4.1 and 4.2,

In TE mode:

$$\lambda_{Long}^{TE}(\theta_0) = \frac{\pi L_+(\theta_0)}{\cos^{-1} \left| \rho_{TE}(\theta_0) \cos \left(\frac{\pi L_-}{\lambda_{Long}^{TE}} \right) \right|}$$

$$\lambda_{Short}^{TE}(\theta_0) = \frac{\pi L_+(\theta_0)}{\cos^{-1} \left| \rho_{TE}(\theta_0) \cos \left(\frac{\pi L_-}{\lambda_{Short}^{TE}} \right) \right|} \quad \dots\dots\dots (4.1)$$

In TM mode:

$$\lambda_{Long}^{TM}(\theta_0) = \frac{\pi L_+(\theta_0)}{\cos^{-1} \left| \rho_{TM}(\theta_0) \cos \left(\frac{\pi L_-}{\lambda_{Long}^{TM}} \right) \right|}$$

$$\lambda_{Short}^{TM}(\theta_0) = \frac{\pi L_+(\theta_0)}{\cos^{-1} \left| \rho_{TM}(\theta_0) \cos \left(\frac{\pi L_-}{\lambda_{Short}^{TM}} \right) \right|} \quad \dots\dots\dots (4.2)$$

Where, $L_+ = n_H d_H \cos \theta_H + n_L d_L \cos \theta_L$,
 $L_- = n_H d_H \cos \theta_H - n_L d_L \cos \theta_L$,

Equation 4.1 and 4.2 can not be solved analytically; hence numerical methods have been used to understand the band structure. Figure 2 illustrates TE and TM band-

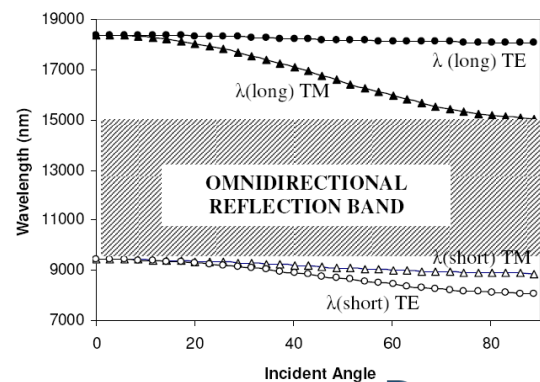


Figure 2: Band structure of an omnidirectional reflector.