# Optical Properties of a Total-Reflection-Type One-Dimensional Photonic Crystal

Hideyuki Inouye, Mariko Arakawa, Jing Yong Ye, Toshiaki Hattori, Hiroki Nakatsuka, and Kazuyuki Hirao

***Abstract*—We produced an asymmetric Fabry–Perot microcavity using total reflection, and its optical properties were investigated. The structure is considered to be a total-reflection-type 1-D photonic crystal. An electric-field enhancement of incident light in a defect layer installed inside the photonic crystal was observed by fluorescence emission from dye molecules doped into the defect layer division. We confirmed that the incident light intensity was strengthened by about 63 times in the defect layer.**

***Index Terms*—Asymmetric micro cavity, photonic crystal, total reflection.**

## I. Introduction

AS IN THE CASE of multilayer dielectric mirrors, some periodic structures composed of proper dielectrics show interesting light transmission characteristics. In the case of a high-reflection dielectric mirror, some frequencies of incident light are unable to pass through the structure because there are no photon modes in the frequency region inside the structure. This behavior resembles that of electrons in crystals. Therefore, such dielectric structures are called photonic crystals (PCs) and the stop-band is called a photonic band-gap (PBG) [1]. PC structures have been studied intensively since the formal similarity between Schrödinger's equation for electrons and Maxwell equation for photons was pointed out [1]–[5]. In particular, if a modulation of the dielectrics in the structure is in only one direction, the simplest structure is considered to be a one-dimensional photonic crystal (1-D PC) [6]. On the other hand, such a structure has also been investigated as a microcavity [7], [8].

When a defect layer is inserted into the center of such a multilayer system, a localized-optical mode appears in the PBG as a defect level. This structure can be considered as a Fabry–Perot microcavity, and the optical electric field of the incident light that is resonant with the defect level is enhanced in the defect layer by about the $Q$ value of the resonator that is formed by the dielectric multilayer [9], [10]. It is expected that the nonlinearity would be enhanced by the enhancement of the optical electric field at the defect layer if the defect layer includes nonlinear optical material, such as semiconductor quantum dots or metal nanoparticles, or the defect layer itself is made of nonlinear optical material [11], [12].

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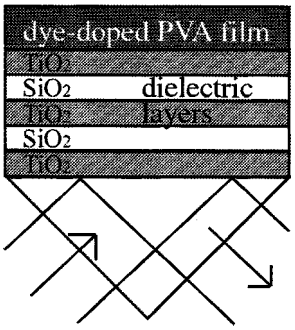


Fig. 1. Structure of the TR 1-D PC.

In the development of optical nonlinear devices, a high optical nonlinearity and a fast response are required of the nonlinear optical material. In general, however, it is difficult to satisfy both requirements at the same time [13]. The combination of the 1-D PC and an existing fast-response nonlinear-material might solve this difficulty. Recently, Tsurumachi *et al.* demonstrated the fast-time response and the high optical nonlinearity of a Fabry–Perot type 1-D PC with semiconductor quantum dots dispersed in the defect layer [12].

Although such a structure is very useful, it is quite difficult to control the nonlinearity of the defect layer microscopically, since the defect layer is inserted in the center of the 1-D PC structure. In order to investigate another possibility, we pay attention to a sample structure that is used in the attenuated-total reflection (ATR) method. The ATR method is used in a measurement such as an absorption measurement of a thin film. Because of the attenuation originated from the localization of light in the thin film, high sensitivity can be expected in the absorption measurement [14], [15]. In the ATR method, the total reflection on a surface of the sample plays an important role. By integrating this technique and a 1-D PC structure, we can simplify the 1-D PC structure.

In this paper, we produce a total-reflection type 1-D PC (TR 1-D PC) composed of a dielectric multilayer system with an exposed defect layer and investigate the optical properties of the TR 1-D PC.

## II. Experimental With a TR 1-D PC

The TR 1-D PC was composed of a dielectric mirror covered with a defect layer and a prism guiding incident light to the dielectric multilayer system. The structure is shown in Fig. 1. This simple structure shows a form folded at the center of a 1-D PC. The structure can be considered as a kind of 1-D PC structure with an exposed defect layer. The dielectric multilayer system was composed of five dielectric layers—$SiO_2$ and $TiO_2$ layers

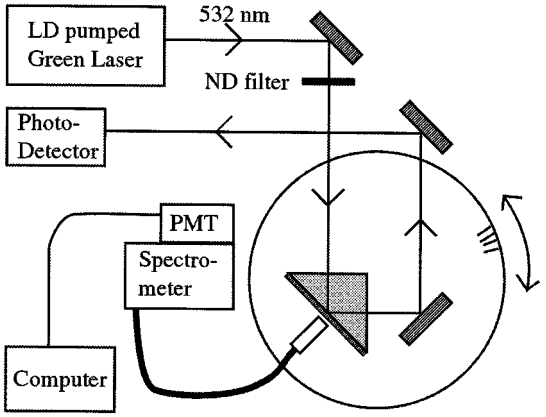


Fig. 2. Experimental setup.

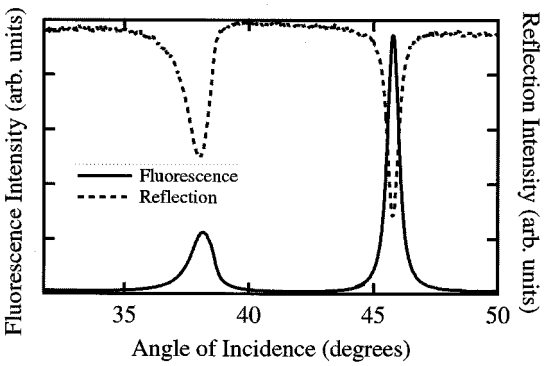


Fig. 3. Typical incident angle dependencies of reflectance and the fluorescence intensity.

were stacked alternately. The dielectric mirror was designed to have high reflectivity (95%) at 514 nm for 45 degrees of incidence. As a defect layer, we applied a dye-doped poly-vinyl alcohol (PVA) film. The film was made on the dielectric mirror by a spin-coat method and the typical thickness of the defect layer was $\sim$1 $\mu$m. We doped Eosin-Y dye molecules into the PVA film. The electric field enhancement was observed through the intensity change of the fluorescence in the dye-doped PVA film.

Fig. 2 shows an experimental setup. We used a laser diode-pumped CW green laser (532 nm) as a pump source. The polarization of the incident light was adjusted to $s$-polarization. The sample was set on a turn table, and the reflected light was detected. The fluorescence spectrum and the intensity were measured with a spectrometer through an optical fiber that was adjacent to the surface of the defect layer and a photomultiplier tube. The dependence of the fluorescence intensity on the angle of incidence was measured by rotating the turn table. The typical power of the incident light was about 1 $\mu$W.

## III. Results and Discussion

Fig. 3 shows typical angle dependencies of the fluorescence intensity (solid curve) and the reflectance (dashed curve). In both cases, sharp peaks or dips are clearly observed at angles of 38 and 46 degrees. Such angle dependencies basically originate from the localization of light inside the defect layer. For the

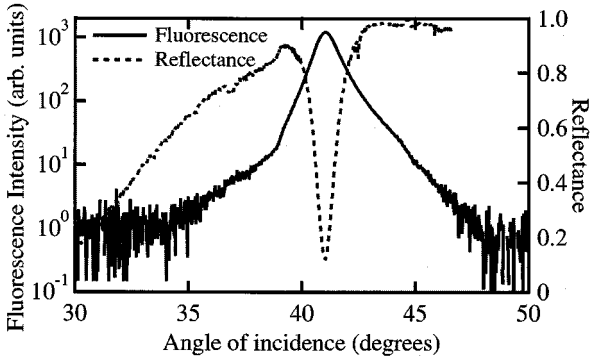


Fig. 4. Incident angle dependencies of the fluorescence intensity (solid curve) and reflectance (dashed curve). This figure shows the largest enhancement of the fluorescence intensity in the present experiment.

proper angle of incidence, a resonator is formed for some frequency of the incident light inside the TR 1-D PC and the incident light localizes there. The increase of the fluorescence intensity and the decrease of the reflectance were caused by absorption of the localized light inside the defect layer. Therefore, the change of the fluorescence intensity directly reflects a change of the electric field amplitude of the incident light in the defect layer. If the angle is not proper and is not tuned to the resonant mode, the reflectance is determined primarily by that of the dielectric mirror. In such cases, the fluorescence almost vanishes because there is no photon mode inside the TR 1-D PC. Furthermore, the full width at half maximum (FWHM) of the dip and the peak at 38 degrees are broader than those at 46 degrees. In the present sample, total reflection occurs when the angle of incidence is larger than 40 degrees. When the angle of incidence is 38 degrees, the total reflection does not occur and the $Q$ value of the resonator is relatively smaller, thus causing a broader and smaller dip and peak in Fig. 3.

The largest enhancement of the fluorescence measured in the present experiment is shown in Fig. 4 (solid curve). The reflectance is also shown as a dashed curve. The concentration of dye molecules was 0.5% wt. and the thickness of the defect layer was estimated as about 870 nm from the peak separation of the incident angle dependence. The pump power was 1 $\mu$W. The intensity of the fluorescence is normalized at the bottom far away from resonance, and the vertical axis is a logarithmic scale to emphasize a change in the fluorescence intensity. It is clearly shown that the fluorescence intensity increases when a resonator is formed in the defect layer. When the incident light is resonant with a cavity mode of the TR 1-D PC, the fluorescence intensity is enhanced more than one thousand times compared with that far from resonance. This means that a large enhancement of the optical electric field is realized in the defect layer.

In order to understand the behavior of the electric field inside the TR 1-D PC, we apply a matrix treatment [16]. By using this method, we can directly calculate the electric field of the incident light inside the multilayer system. We consider a multilayer dielectric system as follows. There are $k+1$ interfaces when the number of layers is $k$. These boundaries are numbered from 1 to $k+1$. The incident light passes through the structure from layer 1 to layer $k$. At the $g+1$th boundary between $g$th and $g+1$th

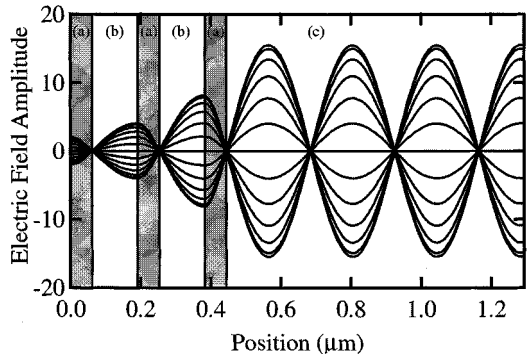


Fig. 5. Calculated field pattern of light at the frequency on resonance to the TR 1-D PC resonant mode. The layers (a) and (b) stand for a $TiO_2$ layer and a $SiO_2$ layer, respectively. Layer (c) is the exposed defect-layer composed of a dye-doped PVA film.

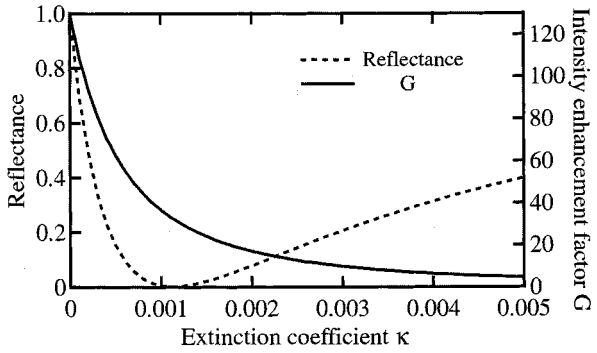


Fig. 6. $\kappa$ dependence of the intensity enhancement factor $G$ and reflectance.

layers in the system, the boundary condition of the electric and magnetic fields are described as

$$\begin{bmatrix} E_g \\ H_g \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \begin{bmatrix} E_{g+1} \\ E_{g+1} \end{bmatrix} \equiv M_g \begin{bmatrix} E_{g+1} \\ E_{g+1} \end{bmatrix} \tag{1}$$

$$M_g = \begin{bmatrix} \cos\Delta_g & i\cos i_g \sin\Delta_g/\tilde{n}_g \\ i\tilde{n}_g \sin\Delta_g/\cos i_g & \cos\Delta_g \end{bmatrix}$$

$$\Delta_g = \frac{2\pi d_g \tilde{n}_g}{\lambda} \tag{2}$$

where $M_g$ is the characteristic matrix, $i_g$ is the refraction angle, $\Delta_g$ is the phase-shift angle upon one transversal of the $g$th layer, $\tilde{n}_g$ stands for the complex refractive index, and $d_g$ is the thickness of the $g$th layer. From (1) and (2), we obtain a relationship among the incident light, the refracted light, and the transmitted light. Here, only the TE mode corresponding to the $s$-polarized light was considered. To observe the total behavior of the electric field in the multilayer system, we carried out this calculation at each interface.

Fig. 5 shows a calculated result of an electric field pattern inside the TR 1-D PC. The layers (a) and (b) stand for a $TiO_2$ layer and a $SiO_2$ layer, respectively. Layer (c) is a defect layer composed of a dye-doped PVA film. In the calculation, the refractive indices of $SiO_2$ and $TiO_2$ were assumed to be 1.46 and 2.35, respectively, and the thicknesses of $SiO_2$ and $TiO_2$ layers were set as 130 nm and 61 nm, respectively, by taking into account the angle of incidence at each layer. The thickness of the defect layer and the index were assumed to be 870 nm and 1.5. In this calculation, the extinction coefficient of the defect layer, $\kappa$, was assumed to be zero for simplification. The electric field amplitude of the incident light was set to be unity. In Fig. 5, it is clearly shown that the electric field is enhanced by about 16 times at the defect layer. This strong enhancement of the electric field is caused by the localization of the incident light at the defect layer. The localization of the incident light is one of the most important features of the photonic crystal with a defect layer [10].

In the present experiment, the enhancement of the electric field is directly observed as an increase of the fluorescence intensity of dye molecules inside the defect layer. The spatially-averaged intensity of the light in the defect layer provides a proper comparison with the experimental result. We define an intensity-enhancement factor $G$ that reflects the average light intensity inside the defect layer as

$$G \equiv \frac{1}{d_{\text{defect}}} \int_{-d_{\text{defect}}/2}^{d_{\text{defect}}/2} \frac{|E_{\text{defect}}(z)|^2}{|E_{\text{incident}}|^2}\, dz \tag{3}$$

where $d_{\text{defect}}$ is the thickness of the defect layer, $E_{\text{defect}}(z)$ is the optical electric field in the defect layer expressed as a function of position, and $z$, $E_{\text{incident}}$ is the optical electric field of the incident light.

To understand the optical properties of the TR 1-D PC, we have to take into account an extinction coefficient, $\kappa$, in the defect layer. $\kappa$ strongly affects the enhancement of the light intensity, because the enhancement is caused by multiple reflections inside the defect layer. In Fig. 6, we show a calculated result of the $\kappa$ dependencies of the reflectance and the intensity enhancement factor $G$. The incident light is resonant with the defect mode. When $\kappa$ is zero, both the reflectance and the value of $G$ take on the maximum values of 1.0 and about 130, respectively. This means that the average intensity of the light is enhanced by about 130 times at the defect layer. As $\kappa$ increases, the reflectance decreases to a minimum value around $\kappa = 0.001$ and subsequently increases with $\kappa$. On the other hand, it can be seen that the value $G$ rapidly and monotonically decreases with $\kappa$, and that $\kappa$ should be kept low enough to make full use of the electric-field enhancement at the defect layer.

From Fig. 6, we estimated the extinction coefficient $\kappa$ of the present sample as 0.0005 from the dip depth of the reflectance shown in Fig. 4. To compare with the experimental result, we calculated the dependence of the enhancement factor $G$ on the angle of incidence by taking into account the fact that $\kappa = 0.0005$. Fig. 7 shows the calculated incident angle dependence of the enhancement factor $G$. As the incident angle approaches the resonance angle, the $G$ value increases sharply. The maximum value of $G$ is 63. This result clearly shows that the intensity of the incident light is enhanced by 63 times. This large enhancement causes an increase of the fluorescence intensity. If we compare the value of $G$ on resonance with that far away from resonance, the value on resonance is over two thousand times larger than that far away from resonance. This means that the fluorescence intensity would be enhanced by more than two thousand times. This result roughly agrees with the experimental result of the enhancement of the fluorescence intensity

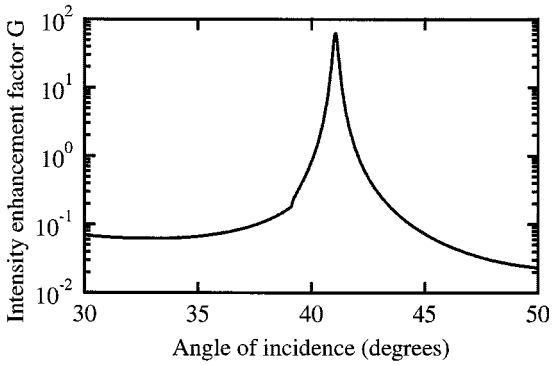


Fig. 7. Incident angle dependence of the intensity enhancement factor $G$.

by a factor of 1000. The smaller enhancement in the experiment and the difference between the shapes of the experimental (Fig. 4) and the simulated (Fig. 7) fluorescence curves might be attributed to optical imperfections at the interfaces of the TR 1-D PC or the inhomogeneity of the thickness of the dye-doped PVA film.

## IV. Conclusion

We successfully demonstrated an optical field enhancement in a TR 1-D PC. When the incident light was tuned to the defect mode, the intensity of the incident light was enhanced by a factor of 63 in the defect layer composed of the dye-doped polymer film. When the angle of incidence was on resonance, the intensity of the fluorescence in the defect layer was enhanced by about 1200 times compared with that far away from resonance. If we apply more dielectric layers in a dielectric multilayer part of the TR 1-D PC, we can obtain a greater enhancement of the signal as reported elsewhere in case of a microcavity [17]. In our case, a five-layer dielectric system is suitable for coupling with a short-pulse laser system whose output pulse has a broad spectral width.

The enhancement of the electric field in the TR 1-D PC suggests if we use an optical nonlinear material as the defect layer, we can expect a great enhancementin nonlinear processes such as degenerate four-wave mixing (DFWM) [12]. But, in some cases such as second-harmonic or third-harmonic generation, it would not be a simple problem. Because the phase matching condition is more complicated, we have to design the dielectric layers properly.

A special feature of the TR 1-D PC is that it facilitates direct access to the defect layer for microscopic control of the nonlinear effect. For example, this feature makes it possible to control the nonlinearity of the defect layer by an extra control pulse which is irradiated from outside the photonic crystal. When the irradiation induces a change of index at the defect layer, the index change causes shifts of the resonance frequency and the resonance angle of the TR 1-D PC. The TR 1-D PC might be an interesting structure for achieving a high-efficiency optical-switching device.

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