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Bloch Surface Wave-Coupled Emission from Quantum Dots by Ensemble and Single Molecule Spectroscopy

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Abstract

We report the spectral properties and spatial distribution of quantum dot (QD₅₇₅) emission on a one-dimensional photonic crystal (1DPC). Our 1DPC substrate consists of multiple layers of dielectrics with a photonic band gap (PBG) near the QD₅₇₅ emission maximum. The 1DPC was designed to display a surface-trapped electromagnetic state known as a Bloch surface wave (BSW) at the 1DPC-air (sample) interface. Ensemble angle-dependent emission intensities revealed a sharp angular emission peak near 41° from the normal which is consistent with the BSW resonance at 575 nm. We further examined the emission from single QDs on the 1DPC. A notable increase in fluorescence intensity from QD₅₇₅ particles was observed on BSW substrate compared to the glass substrate from the scanning confocal fluorescence images and from the intensity-time trajectories of single QD₅₇₅ particles. The intensity-decays showed substantially faster decay (4-fold decrease in emission lifetime) from the single QD₅₇₅ particles on 1DPC substrate (~4.8 nsec) as compared to the glass substrate (~18 nsec). We observed the spectral characteristics of the individual QD₅₇₅ particles on 1DPC and glass substrates, by recording the single particle emission spectra through the 1DPC. The emission spectra of the single QD₅₇₅ particles are similar (with emission maxima around 575 nm) on both substrates except a substantial increase in intensity (over 10-fold) on the BSW substrate. Our results demonstrate that quantum dots can interact with Bloch Surface Waves (BSW) on a 1DPC. To the best of our knowledge, this is the first report on the single particle fluorescence studies on 1DPC substrate. The 10-fold increase in intensity in combination with 4-fold reduction in emission lifetime suggest 1DPCs with BSW modes have potential use in sensing and single molecule spectroscopy.

Graphical abstract

This paper reports on the spectral properties and spatial distribution of quantum dot (QD₅₇₅) emission on a one-dimensional photonic crystal (1DPC) which consists of multiple layers of dielectrics with a photonic band gap near the QD₅₇₅ emission maximum. Single molecule fluorescence study further demonstrates that 1DPC substrate can increase the brightness and reduce the emission lifetime of individual QD₅₇₅ molecules.

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Keywords

Quantum dots; single molecule fluorescence; photonic crystal; Bloch surface wave; Bloch surface wave-coupled emission

1. Introduction

Fluorescence methods have made substantial contributions to the advances in biological and medical research. Fluorescence technology has advanced greatly during the past decades. The technology has matured and current advances are more incremental than revolutionary. To bypass the current limitations there is now a strong interest in the near-field interactions of fluorophores with a variety of nanofabricated plasmonic structures or structures with nano scale features. With the aid of near-field coupling of fluorophores to nano sized objects it is possible to modify the processes of excitation and emission and to obtain spectral resolution originating at the site of emission. Additionally, near-field interactions can alter the decay rates of fluorophores which in turn impacts their quantum yields, lifetimes and photostability. To date most of these effects have been obtained using the interaction of fluorophores with plasmons on metallic surfaces and/or particles.¹⁻⁵

Recently we have started investigations on the interaction of fluorophores with one-dimensional photonic crystals (1DPCs).^{6, 7} These multilayer structures contain only dielectric materials and thus do not display the energy dissipation known to occur with metals. Photonic crystals (PCs) are defined according to their dimensionality.⁸ 1DPCs are multilayers of dielectrics with different refractive indices. PCs can display photonic band gaps (PBG), which are optical frequencies (or wavelengths) that cannot propagate in a given structure.^{8, 9} The PBGs give a colored appearance to structures without the presence of chromophores. There are relatively few reports on the use of PCs to modify fluorescence.¹⁰⁻¹⁵ Most of these reports are focused on the optics, with some on sensing using two dimensional photonic crystals (2DPCs).¹⁰ A frequent goal is to use the PBG to prevent emission.¹⁶ An excited fluorophore (or dipole) in a perfect three-dimensional (3D) PBG is expected to remain indefinitely in the excited state because there is no local photonic mode density (PMD) to allow emission. A fluorophore in a 3DPC is difficult to excite because the PBG prevents entry of incident light. Also, for the same reason it is difficult to acquire the emission from the 3DPC structure. Two-photon excitation has been used to allow excitation from outside the 3D PBG.¹⁷ Additionally, fabrication of 2D and 3DPCs involves nano-scale structural features requires complex nanofabrication using either top-down or self-assembly methods. Herein we selected 1DPCs because they are relatively easy to fabricate using vapor deposition and can be prepared with large surface areas. Our structure was shown to enhance the RhB emission coupled to the BSW mode.⁷ Liscidini

et.al. also reported the directional emission from rhodamine monolayer on the surface of a planar photonics crystal substrate.¹⁴ The enhanced emission was observed at the angle where the emitters are evanescently coupled to a BSW demonstrating the possibility of coupling of fluorophores to BSW at the ensemble level. The enhancement was observed due to the resonant coupling of the emitter to the BSW and from the strong field confinement near the surface of the structure. These features will facilitate 1DPCs to be useful in bioassays, array applications and cell imaging^{7, 15, 18-20}.

In the present report we focused on the emission properties of QDs when placed within the near-field distances of the top surface of the 1DPC. The 1DPC was designed to display a trapped surface-bound state, Bloch surface wave (BSW). We questioned if the excited QDs would couple with the BSWs which could result in changes in intensity, lifetime or spatial distribution of the emission. Ensemble measurements with the QDs provided the information on the spectral distribution of the emission. Single QDs were observed to illuminate ambiguities present in typically ensemble spectral measurements. Our results show highly directional emission consistent with coupling to BSWs. We observed increased brightness and photostability and decreased lifetimes of the single QDs on 1DPC. We believe 1DPC structures have high potential for improved sensitivity and novel device formats for sensing, diagnostics and imaging.

2. Materials and Methods

The 1DPC substrate was made by plasma-enhanced chemical vapor deposition (PECVD) of SiO₂ and Si₃N₄ on 170 µm thick Corning microscope cover slips. This structure consisted of alternating layers of SiO₂, (with a low (L) refractive index), and Si₃N₄ (as the (H) refractive index dielectric), and a top SiO₂(L) layer, which has a thickness of 152 nm (Figure 1). The targeted thicknesses were chosen because this structure was previously shown to display BSWs. The actual thickness and optical constants of the SiO₂, Si₃N₄ and polyvinyl alcohol (PVA) layers were determined using a N and K spectrophotometer (Model 1200). Simulations of transmission and reflectance spectra were performed using TFCalc from Software Spectra, Inc., based on the Transfer Matrix method.

Water soluble CdSe/ZnS core-shell, -COOH functionalized quantum dots (6 nm in diameter) emitting at 575 nm (here after referred as QD₅₇₅) were purchased from Sigma Aldrich. Subsequently, aliquots of approximately 100 µl of QD₅₇₅ were spin coated from aqueous solution at 3000 rpm (Specialty Coating System Inc., Speedline Technologies, Indiana) on the surface of the 1DPC and glass substrates for single molecule experiments. For ensemble measurements, QD₅₇₅ were dispersed in 0.5% aqueous PVA solution (MW 16,000-23,000) and spin coated at 3000 rpm on glass and 1DPC surfaces which yielded a thickness of ~ 15 nm.^{7, 21}

The angle-dependent emission from the spin-casted QD₅₇₅ on the fabricated 1DPC substrates was recorded using a home-made set-up.^{7, 22} Excitation was achieved with a CW 470 nm laser with polarizers between the laser and sample. The emission was collected with a 1 mm diameter fiber positioned 2 cm from the sample with a polarizer between the sample and fiber input. Emission spectra were measured using an Ocean Optics spectrometer

(Model SD2000) with 1 nm resolution. A 500 nm long-pass emission filter (Chroma) was also placed between the sample and fiber input to remove scattered excitation light.

Observations of single molecule fluorescence were made with a stage-scanning confocal Picoquant MicroTime 200 microscope with time-correlated single-photon counting capabilities. The psec pulsed excitation laser (510 nm, 20-MHz repetition rate, 80-psec FWHM) was directed through a 10 nm bandpass excitation filter and reflected by a dichroic mirror into an inverted microscope (Olympus, IX 71). A water immersion objective (Olympus 60×, 1.2 NA) was used for focusing the laser light onto the sample and for collecting the fluorescence emission from the sample. The fluorescence signal that passed through the dichroic mirror and a band-pass filter (550-600 nm, Chroma) was focused through a 75 μm pinhole to a single-photon avalanche photodiode (SPAD) (SPCM-AQR-14, Perkin Elmer Inc) detector. Fluorescence images were recorded by raster scanning (in a bidirectional manner) the sample through the excitation light focal point by means of a linearized piezo scanner. The colors in the recorded images are all false color. The data acquisition was performed by the TimeHarp 200 TCSPC PC-board working in the Time-Tagged Time-Resolved (TTTR) mode, which stores all relevant information for every detected photon (100-nsec resolution) for further data analysis, i.e. the photon arrival time at the detector relative to the corresponding laser excitation pulse (37-ps resolution), the position of the sample and the number of the detection channel. All the analyses were performed using PicoQuant Symphotime software.

The intensity decays were analyzed in terms of the multi-exponential model ²³:

$$I(t) = \sum_{i=1}^n \alpha_i \exp(-t/\tau_i) \quad (1)$$

where, τ_i are the lifetimes with amplitudes α_i and $\sum_i \alpha_i = 1.0$. The contribution of each component to the steady-state intensity is given by:

$$f_i = \frac{\alpha_i \tau_i}{\sum_j \alpha_j \tau_j} \quad (2)$$

The average lifetime is represented by:

$$\bar{\tau} = \sum_i f_i \tau_i \quad (3)$$

and the amplitude-weighted lifetime is given by:

$$\langle \tau \rangle = \sum_i \alpha_i \tau_i \quad (4)$$

The values of α_i and τ_i were determined using the PicoQuant Symphotime software with nonlinear least squares fitting. Lifetimes were estimated by fitting to a χ^2 value of less than 1.2 and a residual trace that was symmetrical about the zero axis.

3. Results and Discussion

Excited-state fluorophores can interact with 1DPCs in several ways. To explore the spectral properties and spatial distributions of QD₅₇₅ emission from the 1DPC, we performed the ensemble angular emission measurements using the setup described previously.⁷ A spin-coated PVA film containing QD₅₇₅ on 1DPC is placed on a hemi-cylindrical prism with an index matching fluid. The prism is needed to admit the incident light above the critical angle (θ_c). The light was incident through the prism which is called the Kretschmann (KR) configuration. Illumination at the BSW resonance angle is expected to excite the QD₅₇₅ on the surface of the 1DPC. The BSWs have a narrow angular distribution. The emission is observed through the 1DPC and prism. Figure 1 shows the angular distribution of emission from QD₅₇₅ on 1DPC using KR illumination. The incident angle was adjusted to obtain the highest emission intensities and thus corresponds to a reflectivity minimum to be in resonances with BSW mode in the 1DPC. In accordance with the KR illumination, the sample illuminated through the prism yields an evanescent wave and selectively excites QD₅₇₅ by the evanescent field of the BSW. We observed the emission intensities to depend on the incident polarization. For 1DPC structures, the S- and P-polarizations are defined relative to the planar surfaces of the sample. Emission polarized in the plane of the sample (perpendicular to the plane of incidence) is called S. Emission polarized in the plane of incidence is called P. We measured the coupled and free-space emission of QD₅₇₅. We observed major fraction (over 90%) of the total emission from the QD₅₇₅ appeared through the prism. This can be seen from the low emission intensity on the sample side of the structure.

Figure 2 shows the coupled emission spectra for QD₅₇₅ in PVA film on 1DPC. For the easy interpretation of the data, we divided the coupled emission, based on the observation angle, into Range 1 (~ 38 to ~ 44 degrees) and Range 2 (~ 45 to ~ 70 degrees). In both angle ranges we found the S-polarized emission wavelength to depend strongly to the observation angle whereas the corresponding P-polarized emission is relatively insensitive to the observation angle. Additionally, the S-polarized emission in both the Ranges (although it is more pronounced in Range 2 as compared to Range 1) has narrow band width as compared to the P-polarized emission from the 1DPC or the QD₅₇₅ emission from the glass. This observation is consistent with the emission coupled to the BSWs.^{7, 18, 19, 24, 25} Based on the previous studies using other probes,⁷ and the calculations presented in Figure 3, we presume the Range 1 emission is due to coupling to BSW and that for Range 2 is resulted from the QD₅₇₅ emission coupled to the internal mode (IM) of our 1DPC. The observed spectral changes are similar to the spectral dispersion observed in surface plasmon coupled emission (SPCE) where emission from fluorophores couple to the planar metal film by near-field interaction.^{26, 27} The occurrence of spectral dispersion in SPCE was thought to be originated from the dispersion in optical properties of metals. The angle dispersion for Bloch wave coupled-emission (BWCE) is considerably larger than for SPCE. Additionally, the widths of the recorded spectra were narrower for Range 2 than for Range 1. We believe the different

widths are due to coupling to a BSW (Range 1) or an internal mode (IM) of the PC with higher dispersion (Range 2). The emission through the prism is expected to be polarized due to coupling to various modes in the 1DPC. It is important to mention that the smaller angle emission band is S-polarized. This is in contrast to the SPCE where the smallest angle emission is P-polarized. We interpret this difference is due to the different polarizations of the modes for plasmons or BSWs. We have observed similar emission profiles for both BSW and IM modes using both KR and reverse Kretschmann (RK) excitation. For RK excitation, the directional emission is observed only due to the coupling of different modes (BSW and IM modes in the present case). More detail studies need to be performed to make a comparison for BSW- versus IM- mode coupled emission intensities.

Figure 3A presents the calculated angle-dependent reflectivity for the fabricated 1DPC structure with 575 nm incident light for KR illumination. The calculated reflectivity at 575 nm matches to the emission maxima of the probe QD₅₇₅. The incident angle was adjusted to obtain the highest emission intensities and thus corresponds to a reflectivity minimum or to be in resonances with a mode in the 1DPC. The reflectivity profile clearly shows the existence of three peaks (modes) for S-polarized incident light. Based on the field location, the sharp drop in reflection at an angle of 41.5° is assigned as BSW. We assigned the other two peaks as internal mode 1 (IM1) and internal mode 2 (IM2) appearing at 58° and 68°. To find out the occurrence of PBG for this 1DPC structure, we calculated the reflectivity spectrum at 0° plane wave incidence which is shown in the inset of Figure 3A displaying PBG near 590 nm to 850 nm. Figure 3B presents the calculated electric field intensity distributions for BSW at 575 nm (emission maxima) and 470 nm (excitation wavelength). The E²-field due to the BSW penetrates into the sample and that optical energy accumulates at the SiO₂-PVA interface. This provides opportunities for both selective excitation of surface-bound fluorophores and for a sharp angular distribution in the coupled emission. These selective excitation and sharp emission profiles are especially valuable for developing single molecule fluorescence based surface assays. Figures 3C and 3D show the electric field intensity distributions of IM1 and IM2 respectively. In contrary to BSW, the E²-fields for IM1 and IM2 are located inside the 1DPC structures. It is pertinent to note here that the angular distribution shown in Figure 1 with maximum emission at 41 degrees is in accordance with the calculated BSW angle (41.5 degrees) shown in Figure 3A. The small discrepancy in the angle may be due to the difference in the optical parameters used in the calculation to that of the actual parameters of the structure.

Figure 4 shows the single molecule scanning confocal images of QD₅₇₅ spin coated on glass and 1DPC substrates. The samples were excited by a 510 nm picosecond pulsed laser with an excitation power of 10 μw. The fluorescence images were recorded with a 550-600 nm bandpass emission filter. As discussed in earlier section, the BSW coupled emission for QD₅₇₅ occurs at 41° and we could collect this emission through the 60× water objective (NA ~ 1.2). IMCE occurs at larger angles (Range 2). Since the maximum collection angle of the objective is 64 degrees, the images may contain along with BWCE, some contribution from the IMCE. Well-separated bright spots are observed as a result of the fluorescence from the individual QD₅₇₅ on the 1DPC and glass substrates. We observed notable difference in the emission intensities between the two images (Figure 4A and B). This suggests that 1DPCs are highly effective in enhancing the BSW coupled emission of single QD₅₇₅ particles. As a

control substrate to determine the background count rates, we recorded the images of 1DPC substrate without QD₅₇₅ under similar excitation-emission conditions. We have not observed any substantial background from the fabricated 1DPC substrate as shown in Figure 4C. It is important to note that the highest enhancement of QD₅₇₅ on 1DPC is expected while the probes are placed right at the surface as the calculated electric field intensity distribution shows highest field intensity at the surface and decays exponentially.

To explore the changes in the underlying photophysics of single QD₅₇₅ molecules on glass and 1DPC surfaces, the fluorescence intensity of individual QD₅₇₅ molecules as a function of time was recorded while under continuous excitation. While observing the single QD₅₇₅ molecules under continuous illumination on the glass substrate, the emission intensity from the QD₅₇₅ molecules fluctuates dramatically. An example of blinking^{28, 29} from the individual QD₅₇₅ particle on glass substrate is shown as intensity-time trace of Figure 5A. Figure 5B shows the intensity-time trace of an individual QD₅₇₅ molecule on 1DPC substrate. A notable increase in fluorescence intensity (over 6-fold) from QD₅₇₅ particles was observed on BSW substrate compared to the glass substrate as evident from the images as well as from the intensity-time trajectories of individual single particles. While the QD₅₇₅ particles are placed on the 1DPC, we not only observed a significantly higher count rate but a complete elimination in blinking (Figure 5B).

The emission intensity decays from individual QD₅₇₅ molecules on glass and 1DPC substrates are shown in Figure 5C & D. The lifetimes of single QD₅₇₅ molecules were measured using the time-correlated single-photon counting (TCSPC) method and were recovered by nonlinear least-squares (NLLS). The intensity decays of QD₅₇₅ on glass (Figure 5C) could be fitted with a mono-exponential function, however the intensity decays on 1DPC substrate (Figure 5D) are much rapid and could only be bi-exponentially fitted with two components. The lifetime for faster component is 0.8 nsec (45% contribution in amplitude) whereas for slower component it is 8.3 nsec (55% contribution in amplitude). Overall, the intensity-decays showed a substantial faster decay (~4-fold decrease in amplitude weighted emission lifetime) from the single QD₅₇₅ particles on the 1DPC substrate (4.8 nsec) in comparison to the glass substrate (18 nsec). This result indicates that the 1DPC structure is not slowing the decay rate due to an altered density of states (DoS). The more rapid decays on the 1DPC suggest that coupling of the QD₅₇₅ with the 1DPC provide a pathway for faster decay, which we presume is due to an increased DoS near the short wavelength of PBG (Insert in Figure 3A). Since we do not expect the emission of QD₅₇₅ to be quenched by the dielectric 1DPC and the observed brightness is increased on the 1DPC, it seems likely that the more rapid decay is due to an increase in the radiative decay rate (Γ) and not due to an increased rate of non-radiative decay (k_{nr}).

It is known that single quantum dots display blinking which occurs when the quantum dot transition between “on” and “off” states. We observed strong blinking of our QD₅₇₅ on a glass slide (Figure 5A). This blinking was completely eliminated when the QD₅₇₅ was placed on the 1DPC (Figure 5B). The absence of blinking may contribute to part of the increased intensity we observed on the 1DPC. The enhancement in the emission intensity occurs concurrently with a decrease in the lifetime of the emission. As a result of the shortened lifetime (Figure 5D), the fluorophore does not remain in the excited state long

enough for the inter-system crossing into the triplet state to occur and thus we observed reduced blinking.³⁰

To quantitatively compare the emission and the origin of fluorescence from individual QD⁵⁷⁵ particles and explore the changes in underlying photophysics of QD⁵⁷⁵ on glass and 1DPC substrates, we recorded the fluorescence spectra by positioning the excitation beam on the individual QD⁵⁷⁵ particles on BSW and glass substrates in our stage-scanning confocal microscope. The single molecule spectra were recorded with an EMCCD camera coupled to an Acton spectrograph. The spectral properties of these single QD⁵⁷⁵ particles are similar (emission maxima) on both substrates except a substantial increase in intensity (over 10-fold) from the particles on the BSW substrate. We believe this is the first observation of the spectra of individual fluorescent probes on 1DPC substrates. Figures 6 also point out that there is a significant spectral overlap between the emission spectra of QD⁵⁷⁵ molecules from glass and 1DPCs thus further confirming that the emission spectra collected were indeed from the QD⁵⁷⁵ molecules and not corrupted by any noise in the system (such as background emission from 1DPC substrate).

We confirmed the validity of our single particle observation by recording intensities or decay times of a large number of QD₅₇₅. Figure 7 shows the intensity and lifetime histograms of over 50 QD₅₇₅ molecules on glass or 1DPC substrates. Examination of intensity histograms shows that on average the QD₅₇₅ molecules were more than 10-fold brighter on the 1DPC than on glass. These results indicate that 1DPC substrate can increase the brightness of QD₅₇₅ molecules on 1DPC when compared to glass in ensemble as well as single particle measurements. This result also shows that there is a relative uniform increase in single particle brightness and not higher enhancements of a small fraction of the QD₅₇₅. We recorded the lifetimes of over 50 QD₅₇₅ molecules on glass control and 1DPC substrate to determine the range of lifetimes present in each substrate. As discussed earlier, the intensity decays of QD₅₇₅ on 1DPC could only be fitted with two components. In this lifetime histogram (Figure 7B) we have included the amplitude weighted average lifetime. The mean of the lifetime distribution on the 1DPC substrate is ~ 4.5 nsec, and that on glass is 18 nsec. From the histograms it is obvious that on average the lifetimes are about 4-fold shorter on the 1DPC than on glass. An important observation is that the QD₅₇₅ particles with the shorter lifetimes had higher intensities on 1DPC, which implies that the radiative decay rate of the QD₅₇₅ is much larger on the 1DPC than on glass.

Although we observed about 10-fold enhanced intensities from QDs on 1DPCs, it is important to note (Figure 3B) that the field accumulation is high on the surface of 1DPC. A comparative analysis of the field distributions between the 1DPC and plasmonic substrate was shown in our previous paper.⁷ Further study is required to attain the maximum enhancement from fluorophores on the 1DPCs. The advantages of using photonic structures are that there is no quenching regime as opposed to the plasmonic substrates. In fact, the highest field for the 1DPC substrate is right at the surface for the BSW mode as shown in Figure 3B (calculated electric field intensity distribution profiles). The distance dependence study of metal-enhanced fluorescence (MEF) suggests an optimal distance of about 10 nm from the metal surface because fluorophores at closer distances are often quenched.^{31, 32} For MEF, the metal must display a plasmon resonance at wavelengths where its intrinsic

absorption is low. Subsequently, different metals have diverse optical constants. As a result, different metals or metal nanostructures have to be chosen to match the wavelength region of interest. Additionally, metals are lossy and quickly dissipate the optical energy. Some of these shortcomings with plasmonic substrates could be circumvented by using dielectric 1DPCs, for example the structure used in the present study.

4. Conclusion

We investigated the emission properties of quantum dots when placed within near-field distances of the top surface of a 1DPC. These multilayer dielectric structures are easily fabricated using well-established vapor deposition methods. The substrate dimensions and the dielectric thickness are selected based on simulations of the reflectance spectra to match the desired emissive structure for the QD₅₇₅. The angular emission measurements of the QD₅₇₅ on the fabricated 1DPC substrate clearly showed the BSW-coupled emission occurring at an angle of 41°. We also observed IMCE at higher angles (58 and 68 deg). We investigated single QD₅₇₅ particles on planar 1DPC substrates to resolve the heterogeneity of the emitting population. The results obtained from the present single molecule fluorescence study clearly indicate that 1DPC substrate can increase the brightness and reduce the lifetime of individual QD₅₇₅ molecules. To the best of our knowledge this paper reports the first study of single molecule imaging and spectroscopy of individual nanoparticles on one-dimensional (1D) photonic crystals (PCs) substrates. Single molecule detection has advantages over ensemble studies and provides spectral insights of individual particles that are otherwise masked in the ensemble averaging. This paper includes the time-resolved fluorescence studies of single quantum dot nanoparticles on 1DPC. Performing time-resolved fluorescence studies at the single molecule level is of great importance to understand the radiative decay rates and interaction of single probe with 1DPC.

Further study is warranted to reveal the detail information about the radiative decay rates and how it correlates with the PBG. The decrease in lifetime suggests that fluorophores can potentially have higher photostability on 1DPC substrate when compared to glass. The observation of single molecule fluorescence on the 1DPC substrate suggests the feasibility of these 1DPC substrates for detecting single surface bound probes in the presence of other labeled freely diffusing molecules. This implication is further supported by the calculated electric field intensity distribution on the present 1DPC substrate where the BSW penetrates into the probe layer, but the other E²-fields (IM modes) are inside the 1DPC. We believe that this 1D-photonic layered structures will play an important role in the next generation of devices and will offer a wide range of opportunities for the control of light and luminescence at nanoscale dimensions.

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Figure 1. Schematic of the one-dimensional photonic structure with QD_{575} in 15 nm thick PVA layer (Left panel). Angular distribution of QD_{575} S- and P-polarized emission with 470 nm KR excitation at an angle of 50° . The intensities were measured at the angle of maximum emission (Right panel).

Figure 2.

Effect of observation angle in Range 1 (38-44 degrees) on the QD₅₇₅ S-polarized (Panel A) and P-polarized emission spectra (Panel B) with KR excitation. Bottom panels (C and D) show the QD₅₇₅ emission spectra in Range 2 (46-70 degrees) for S- and P- polarized emission, respectively.

Figure 3.

(A) Calculated angle-dependent reflectivity for the BSW structure shown in Figure 1 with 575 nm incident light, KR illumination. The calculated electric field intensity distributions for (B) BSW with 470 nm (50°) and 575 nm (41.5°); (C) IM1 (58°) and (D) IM2 (68°) with 575 nm illumination.

Figure 4. Schematics of single molecule fluorescence measurements of QD₅₇₅ on 1DPC. Single QD₅₇₅ particle fluorescence images (false color) on A) 1DPC and B) glass. C) BSW substrate without any probe was used to determine the background signal from the fabricated 1DPC substrate.

Figure 5. Intensity-time traces (left panels) and intensity-decays (right panels) from individual QD₅₇₅ on glass (A & C) or 1DPC (B & D) substrates.

Figure 6.
Representative emission spectra from individual QD₅₇₅ on glass or BSW substrates.

Figure 7. Emission intensity (left panel) and lifetime (right panel) histograms generated from single QD₅₇₅ particles on glass or BSW substrates.