Dye molecules as single-photon sources and large optical nonlinearities on a chip

J Hwang\(^1\) and E A Hinds

Centre for Cold Matter, Blackett Laboratory, Imperial College London, Prince Consort Road, London SW7 2AZ, UK
E-mail: j hwang@imperial.ac.uk

New Journal of Physics 13 (2011) 085009 (11pp)
Received 28 April 2011
Published 10 August 2011
Online at http://www.njp.org/
doi:10.1088/1367-2630/13/8/085009

Abstract. We point out that individual organic dye molecules, deposited close to optical waveguides on a photonic chip, can act as single-photon sources. A thin silicon nitride strip waveguide is expected to collect 28% of the photons from a single dibenzoterrylene molecule. These molecules can also provide large, localized optical nonlinearities, which are enough to discriminate between one photon or two through a differential phase shift of 2° per photon. This new atom–photon interface may be used as a resource for processing quantum information.

Contents

1. Introduction

2. Single molecules as quantum optical dipoles

3. Design of a waveguide for large coupling to molecules

4. Photon emission into the waveguide

5. Phase shift of a guided photon by molecule

6. Conclusions

Acknowledgments

References

1 Author to whom any correspondence should be addressed.
1. Introduction

Single photons are exceedingly attractive as a basis for quantum information processing (QIP) because they are robust against dephasing and are able to encode information in several degrees of freedom such as polarization, time bin and path [1]. The main challenge for photonic QIP lies in implementing efficient interactions between photons. Since ordinary materials are not sufficiently nonlinear to achieve this, it was initially believed that sophisticated methods such as electromagnetically induced transparency [2] or cavity QED [3] would be essential [4]. In 2001, however, Knill et al [5] suggested a fundamentally different approach, known as linear optical quantum computing (LOQC). They proved that it is possible to create a universal quantum computer with linear optics alone, using Hong–Ou–Mandel (HOM) interference [6], feed-forward and photodetection. Two of these requirements were recently realized on a photonic chip by the group of O’Brien [7]. Optical waveguides on the chip provide networks of interconnected interferometers with high visibility and with excellent control over the alignment and purity of the optical elements. These chips promise a robust platform for quantum logic that is scalable in principle, but only at the cost of prohibitively large resources. By introducing a nonlinear element into the chip, dramatic savings in the required resources can be obtained. As a simple, practical way to achieve this, one might want to use single organic dye molecules in a transparent organic matrix as the nonlinear material. At cryogenic temperature, each molecule behaves as a two-level quantum system and has a strong nonlinear interaction with passing photons, provided these are confined within an area comparable to the resonant interaction cross section [8, 9]. High-index dielectric waveguides can provide such small mode-field areas. To create a two-dimensional (2D) network of nonlinearities, single organic dye molecules may be deposited on top of pre-fabricated networks of waveguides. The molecules are expected to induce substantial nonlinear phase shifts in the light. For a realistic geometry that we discuss below, the phase shift of one photon changes by more than a degree when a second photon is present. This strong nonlinearity offers a possible way to avoid the overhead of LOQC on a chip.

To realize the full potential of photonic QIP, sources and detectors must be integrated into the chip in a scalable way. Many groups are working on the development of suitable detectors; see, for example, [10]. By contrast, the single photons used for QIP on a chip have so far been generated externally using parametric down-conversion, which does not seem to be a scalable approach. Semiconductor III–V quantum dots show promise as single-photon sources on a chip; however, it remains challenging to scale up to a large number of emitters [11, 12]. Alternatively, trapped atoms or ions could also act as single-photon sources, but these atomic systems have not yet emerged as a practical way to implement quantum logic on an optical chip because the complex functions of laser cooling and atom trapping are not easily integrated into the chip. By contrast, individual dye molecules offer a simple way to integrate several single-photon sources into an optical chip. When a short laser pulse excites one or more of these molecules, each molecule emits a single photon into the nearby waveguide, thereby acting as a source of transform-limited single photons with high fidelity and high repetition rate [13]. The method we suggest here is considerably simpler than existing schemes and is scalable. The waveguides are fabricated first, the molecules are then deposited on top and finally those of interest are selectively addressed and coupled to the waveguides.
2. Single molecules as quantum optical dipoles

A convenient operating wavelength might lie in the wavelength range of 780–900 nm, where silicon photodiodes have high quantum efficiency and high-index waveguide materials such as SiN and GaP have good transparency. A suitable molecule for this purpose is dibenzoterrylene (DBT) operating in the vicinity of 785 nm, whose structure is illustrated in figure 1(a). The photophysical properties of DBT have been thoroughly studied in an anthracene matrix \[14, 15\]. It is more convenient to work with matrices that are liquid at room temperature, such as n-hexadecane \[16\] or methyl methacrylate (MMA) \[17\] so that the molecules can be introduced onto the photonic chip in droplets or spin coated. These matrix molecules are also shown in figure 1(a). On insertion into the cryostat, the matrix material crystallizes to form a Sh’polskii matrix \[18\], moulded to the shape of the nanoscale surface structures. At temperatures below 2 K, the DBT molecule acts as a simple two-level system with a strong electric dipole transition. Each molecule can be individually addressed and remains trapped indefinitely in the solidified solvent.

Figure 1(b) shows the level scheme of a single DBT molecule in the host matrix. The zero-phonon line (ZPL) of the molecule connects the ground state \(S_{0,v=0}\) to the ground state of the first electronically excited manifold \(S_{1,v=0}\). This forms the two-level quantum system of interest, with a lifetime-limited linewidth of 30 MHz. Since the non-radiative decay from the \(S_{1,v=0}\) state is negligible, the molecule can be made to emit a single photon simply by exciting it with a short laser pulse \[13\]. Excitation on the \((0–1)\) transition, shown by the dash-dotted line in figure 1(b), is followed by fast vibrational relaxation to \(S_{1,v=0}\) and subsequent decay to \(S_{0,v=0}\). This conveniently separates the excitation frequency from the frequency of the decay photons. A fraction of the spontaneous decays are red-shifted lines as shown by the dashed line in figure 1(b). Because the vibrationally excited \(S_{0,v≠0}\) states relax rapidly to \(S_{0,v=0}\), these lines are broad and not useful for our purpose. The branching ratio for emitting a ZPL photon varies from one DBT molecule to another over the range 0.1–0.5 \[13, 19\], depending on the local environment. There is also some inhomogeneous variation of the ZPL frequency. Thus, although a given molecule emits identical photons into the waveguide, these photons may not interfere with photons from another molecule. This inhomogeneous shift can be removed by applying a local electric field to each molecule that Stark-shifts them to a common resonance frequency, as was recently demonstrated with two molecules \[20\]. Individual molecules, tuned
to have identical transition frequencies and coupled to waveguides, can serve as integrated photon sources for QIP on an optical chip.

Molecules that have a strong electric dipole transition can also be used as sources of optical nonlinearity on a chip. It was recently demonstrated that a single dibenzanthanthrene (DBATT) molecule embedded in n-hexadecane can obscure a substantial part of the light in a beam whose cross section is comparable with the scattering cross section of the molecule [21]. In such a beam, it was shown that the molecule behaves as a two-level quantum emitter whose nonlinear response is appreciable even at very low light intensity. This was seen through the appearance of Mollow sidebands in the fluorescence spectrum of the molecule [21]. In another proof of the large dipolar coupling, Rabi flopping of the two-level molecule could be observed in weak light pulses, where only a few hundreds of photons were enough to generate a \( \pi \)-pulse [22]. More recently, it was shown that the single molecule can act as an absorber whose absorption coefficient can be manipulated by a control laser and can also be turned into gain when the population of the molecule is inverted [9].

In comparison with other solid state emitters such as nanocrystals containing diamond N–V centres [23], colloidal quantum dots [24] and self-assembled quantum dots [25], the very small size of the organic dye molecules offers a significant advantage. At practical concentrations, there can be several hundreds of molecules in an illuminated volume of 1 \( \mu \text{m}^3 \), compared with only a few for the other emitters. This greatly increases the probability of finding a molecule exactly where it is needed. Since the frequency of the ZPL is inhomogeneously distributed over \( \sim 1 \text{ THz} \), whereas the natural width is only about 30 MHz, there is no difficulty in identifying the individual molecules within this volume by their laser-induced fluorescence, using simple far-field optics and a tuneable, narrow-band laser. One is almost bound to find a suitable molecule closely coupled to the waveguide at any desired position along its length. At each position where a molecule is needed, the resonance frequency of the selected molecule can be shifted to the desired photon frequency by the Stark tuning using small electrodes deposited on each side of the waveguide.

3. Design of a waveguide for large coupling to molecules

If the cross-sectional area of a light beam is small, the electric field of one photon is correspondingly large. Efficient molecule–waveguide coupling therefore requires a waveguide designed to have as small a mode cross section as possible. A molecule positioned suitably close to such a waveguide may be so strongly driven that one photon begins to saturate the molecular polarizability, leading to an effective interaction between photons. Large dipolar coupling also leads to preferential emission of photons into the waveguide mode.

The key parameter to maximize is the strength of the electric field per photon at the position of the molecule, which controls both the probability of photon emission into the guide mode and the degree of saturation of the molecule when one or two photons pass it. For a simple rectangular ridge waveguide, a good strategy is to choose high index contrast and a width of roughly half the wavelength. Given this fixed width, there exists an optimum thickness of the waveguide, which maximizes the field at the surface where the molecules are located.

Figure 2(a) shows an example of a suitable waveguide design. The waveguide is a high-index rectangular strip on a lower-index substrate. We consider silicon nitride (Si_3N_4), with a refractive index of 2, on silica with a refractive index of 1.45. The molecules dissolved in their molecular matrix are deposited on top. After cooling in a cryostat, the solvent forms a top layer
Figure 2. (a) An example of waveguide design and an illustration of molecular emission channels. A 120 nm thick Si$_3$N$_4$ core (refractive index $n = 2$) is deposited on SiO$_2$ ($n = 1.445$) and covered with a molecular matrix such as n-hexadecane ($n = 1.434$) or MMA ($n = 1.42$). A molecule on the top surface of the core emits photons into the waveguide mode at a rate $\Gamma_{wg}$ in each direction. It also emits into the rest of the space. (b) Calculated transverse mode for such a strip waveguide, covered by n-hexadecane and operating at the ZPL frequency of the DBT molecule ($f/c = 785$ nm). Propagation is into the page, and the colour indicates the magnitude of the electric field along $x$ in quasi-TE operation. MMA gives a similar result. Inset: the same waveguide but with a 40 nm gap filled with n-hexadecane.

of very similar index as silica: 1.434 for n-hexadecane and 1.42 for MMA. The Si$_3$N$_4$ layer is readily deposited on silica using plasma-enhanced chemical vapour deposition (PECVD), which allows the thickness to be controlled accurately. At 785 nm wavelength of DBT, we calculate that a thickness of 120 nm maximizes the evanescent field per photon at the position $\vec{r}_0$ of a molecule, taken as 20 nm above the strip. We choose a width of 600 nm to ensure single-mode operation. Figure 2(b) shows the calculated mode distribution when the top layer is n-hexadecane. Using this distribution, we calculate that the effective mode cross section $A_{eff}$ for coupling to the molecule is

$$A_{eff} = \iint \frac{\varepsilon(\vec{r})|\vec{E}(\vec{r})|^2 dA}{\varepsilon(\vec{r}_0)|\vec{E}(\vec{r}_0)|^2} = 0.42 \lambda^2,$$

$\varepsilon(\vec{r})$ being the relative permittivity at position $\vec{r}$ and $\lambda$ the transition wavelength in free space. This indicates that large coupling is possible between the molecule and the waveguide, since $A_{eff}$ is comparable with the free-space optical cross section for the molecular ZPL transition, $\sigma_{ZPL} = \frac{3\lambda^2}{2\pi}$.

Even larger coupling may be achieved by cutting a narrow slot along the waveguide in the propagation direction, as shown in the inset of figure 2(b) for a gap of 40 nm. With such a narrow gap, our simulation shows that the propagating mode is largely unaffected, while the electric field in the gap is enhanced by the ratio of guide and slot permittivities [26]. Thus, the effective mode area for coupling to a molecule in this slot is only 0.10$\lambda^2$.

In addition to having small mode volume, the waveguide must have low loss if it is to be useful for practical applications. In a silicon nitride waveguide similar to the one we propose...
here, a loss of 1.5 dB cm\(^{-1}\) has been measured \[27\]. Since the circuits under consideration in this paper will typically be smaller than 1 mm in size, the losses should be at the level of a few per cent.

4. Photon emission into the waveguide

Figure 2(a) illustrates an excited DBT molecule placed 20 nm above the integrated waveguide. When the DBT molecule in n-hexadecane or MMA is excited at 785 nm, its decay is almost entirely radiative. Photons are radiated as travelling waves in the waveguide at a rate \(\Gamma_{WG}\) for each direction. There is also radiation into the rest of space.

Let us first consider the rate of radiation into the waveguide using Fermi’s golden rule

\[
\Gamma(r, \omega) = 2\pi |g(r, \omega)|^2 D(\omega),
\]

where \(g(r, \omega)\) is the dipolar coupling constant per photon for an emitter at position \(r\) with transition frequency \(\omega\), and \(D(\omega)\) is the photonic density of states. We note that the dipole approximation is appropriate here because the size of the molecule is much less than the wavelength of the light and because non-radiative decay is negligible. \[15\] The waveguide supports only one transverse mode at the transition frequency, so the density of waveguide modes is found by counting longitudinal modes \[28, 29\]. For waves travelling in one direction with a periodic boundary condition over a large length \(L\),

\[
D(\omega) = \frac{L}{2\pi v_g},
\]

where \(v_g\) is the group velocity in the guide. For the same travelling wave mode, the rotating-wave dipole coupling is given by

\[
|g|^2 = \frac{\omega d^2}{2\hbar \varepsilon_0 n^2 L A_{\text{eff}}}
\]

when we treat the substrate, coated by matrix material, as a homogeneous dielectric of real permittivity \(\varepsilon = n^2\) at the transition frequency of the molecule. Here, \(d\) is the dipole transition matrix element that couples to the \(x\)-polarized waveguide mode and \(A_{\text{eff}}\) is defined in equation (1). As pointed out by Barnett et al \[30\], an additional factor of \((\frac{n^2+2}{3})^2\) is introduced by the local field correction in the dielectric. Collecting these terms together, we arrive at the spontaneous emission rate of travelling wave photons in one direction in the guide:

\[
\Gamma_{WG} = \frac{d^2 \omega}{2\hbar n^2 \varepsilon_0 A_{\text{eff}} v_g} \left(\frac{n^2 + 2}{3}\right)^2.
\]

It is convenient to compare this with the radiation rate in the matrix material without any waveguide, given by \[30\]

\[
\Gamma_{\text{rad}} = \frac{d^2 \omega^3}{3\pi \hbar \varepsilon_0 c^3 n} \left(\frac{n^2 + 2}{3}\right)^2.
\]

The first factor is the usual formula for radiative decay into free space, with \(d^2 = d_x^2 + d_y^2 + d_z^2\). The effect of the dielectric is contained in the last two factors. The ratio of these two radiation rates is

\[
\frac{\Gamma_{WG}}{\Gamma_{\text{rad}}} = \frac{1}{4} \frac{d^2_x}{4 d^2} \frac{\frac{3\lambda^2}{2\pi n^2}}{A_{\text{eff}} v_g} \approx \frac{1}{4} \frac{\frac{3\lambda^2}{2\pi n^2}}{A_{\text{eff}}}.
\]

New Journal of Physics 13 (2011) 085009 (http://www.njp.org/)
Figure 3. (a) Finite-difference time-domain simulation of dipole radiation coupled to the waveguide. The propagation axis is horizontal on the page. The dipole, placed 20 nm above the strip, is pointing out of the page (the $x$-direction) exciting the quasi-TE mode. (b) Unidirectional launch of single-molecule emission using a Bragg reflector: a quarter wave stack of n-hexadecane blocks alternating with $\text{Si}_3\text{N}_4$ blocks. The molecule is placed inside the rightmost trench, 20 nm away from the end face of the strip.

The anisotropy of the molecule concentrates most of its transition moment along a particular direction. In making the last step, we assume that the molecule is suitably oriented with respect to the waveguide, so that $d^2/d^2 \approx 1$. In general, the molecules will be randomly distributed in the $x$–$z$ plane of figure 2, but their density will be high enough to find one whose orientation is optimum, as detected by its coupling to the waveguide mode. For the thin waveguides we are considering here, much of the field mode is in the matrix material, of refractive index $n$, and this makes $v_g \approx c/n$, except when the frequency is close to the waveguide cutoff. Equation (5) gives us some insight into the requirements for creating photons efficiently in the waveguide. Specifically, the molecule should be aligned with respect to the waveguide, the effective mode area $A_{\text{eff}}$ should be small and the group velocity $v_g$ should be low. For the waveguide considered in section 2, equation (5) gives $\Gamma_{\text{wg}}/\Gamma_{\text{rad}} = 0.14$. This expression does not directly determine the ratio of photons in the guide to photons in the substrate/matrix because the rate for the latter is not equal to $\Gamma_{\text{rad}}$; it is affected by the presence of the guide.

In order to address this point, we simulated the problem numerically, using MEEP program [31] to calculate the power radiated by a classical dipole in a dielectric medium, both with and without the waveguide. The result with the waveguide, shown in figure 3(a), confirms that the power in each guided direction is indeed 14% of the power radiated into a homogeneous dielectric with no waveguide. We also find that the total radiated power remains almost unchanged (there is a 5% increase) when the waveguide is present. This indicates that the power coupled into the guide is diverted from power that would otherwise be part of $\Gamma_{\text{rad}}$; indeed, it is evident that the angular distribution of the radiation in the bulk is strongly modified by the presence of the guide. We conclude therefore that 28% of the photons emitted are coupled into the waveguide, 14% in each direction.
In order to deliver all these photons to the target, we consider placing a mirror on the left side of the molecule, so that the left-going field is reflected and adds constructively to the right-going field. With the molecule positioned at the antinode of the interference pattern, the coupling to the travelling output should increase from $\Gamma_{WG}$ to $4\Gamma_{WG}$, producing a rate that is 56% of $\Gamma_{rad}$. The corresponding numerical simulation, shown in figure 3(b), demonstrates that this idea works when we make a Bragg reflector by modulating the waveguide. Over 50% of the radiation is now coupled into the right-going waveguide and again the total radiation rate is well approximated by $\Gamma_{rad}$. We find that the Bragg mirror scatters some of the power into the matrix material, but this is not a large loss. Further simulations are required to optimize the guided photon yield and to take advantage of the more strongly coupled geometries, such as the 40 nm-wide nano trench discussed in section 2. With these it should be possible to reach still higher photon yields into the waveguide.

5. Phase shift of a guided photon by molecule

When a guided ZPL photon passes a molecule it produces a Stark shift

$$U(t) = \frac{\hbar g^2 \delta}{\delta^2 + (\Gamma/2)^2 + 2g^2},$$

where $g$ is the coupling between the molecule and the field, $\delta$ is the detuning of the light from the molecular resonance and $\Gamma$ is the total decay rate of the excited molecule. Assuming that the photon is produced by another molecule, as described above, the coupling takes the form $g^2 = g_0^2 e^{-\Gamma t}$. The peak coupling is given by

$$g_0^2 = \eta d_0^2 \omega \frac{n^2 + 2}{3} \eta \Gamma_{wg} \Gamma,$$

where $\eta$ is the branching ratio for the ZPL and the last step makes use of equation (3). The phase shift induced in the molecule by the passage of this photon is

$$\phi(1) = -\frac{\delta}{2m} \ln \left(1 + \frac{2m \eta \Gamma_{wg} \Gamma}{\delta^2 + (\Gamma/2)^2}\right),$$

For the 785 nm transition of DBT in a matrix of MMA, the spontaneous emission rate at a temperature of 2 K is typically $\Gamma_0 = 2\pi \times 30 \times 10^6$ s$^{-1}$ [15] and the branching ratio for the ZPL line is $\eta = 0.5$ in favourable cases. Taking $\Gamma_{WG} = 0.5\Gamma$, the phase shift $\phi(1)$ (dashed) of a single photon passing the molecule peaks at 180 mrad (10$^\circ$), as shown in figure 4, whereas $\phi(2)$ (dotted) is appreciably less because of the saturation of the molecule. The difference $\phi(1) - \phi(2)$ (solid) peaks at 40 mrad (2$^\circ$). The real part of the phase shift necessarily brings with it an imaginary part that attenuates the light, reducing the intensity to $\exp(-\frac{1}{2}\phi)$. The percentage of power lost is also shown in figure 4 (dash-dotted), where we see that the peak phase shifts are in the region of 20–30% extinction. In principle, this level of nonlinearity is sufficient to provide a useful photon–photon interaction for optical quantum information processing. [32] The differential phase shift increases with stronger coupling arising from reduced mode area. For example, with 0.1$\lambda$$^2$ mode area using a slot, the maximum differential phase shift rises...
Figure 4. Phase shift and extinction of light in the waveguide due to the presence of one DBT molecule. Dashed line: phase shift $\varphi(1)$ of one photon; dotted line: phase shift per photon $\varphi(2)$ of two photons; solid line: differential shift $\varphi(1) - \varphi(2)$; dash-dotted line: extinction.

Figure 5. (a) HOM experiment with molecules acting as two single-photon sources. Blue lines: waveguides; red dots: single molecules; green boxes: detectors; grey boxes: Stark electrodes; V1 and V2: voltage sources. (b) Nonlinear phase gate. Light in the pump input phase shifts light in the upper arm of the interferometer, changing the output port reached by the probe light.

6. Conclusions

We have shown that organic molecules placed close to a microfabricated optical strip waveguide offer a very promising addition to optical quantum information processing. In one application, they can act as photon sources integrated on a chip. Figure 5(a) shows a two-photon source, using molecules embedded in Bragg mirrors, coupled to a beam splitter formed by an optical directional coupler [33]. When the molecules are Stark tuned to the same frequency, the identical...
photons will exhibit HOM interference [6], and will go as a pair to one or the other detector. The probability of producing a ZPL photon on any given shot of the source is limited by the branching ratio to 50%; however, it may be possible by more subtle engineering of the photonic environment to inhibit emission on the red-shifted sidebands, or there may be a host–guest system with a more favourable branching ratio.

We have also shown that the molecule can impose a phase shift on each photon, and that this shift can change according to the number of photons because of the saturation of the molecule. Figure 5(b) illustrates a rudimentary gate based on the phase shift. A single photon is fed into a Mach–Zehnder interferometer through the port marked ‘probe’. The probability of arriving at detector 0 (or 1) is determined by the difference in propagation phase for the upper and lower arms. Since a separate ‘pump’ single-photon pulse controls the phase shift on the upper arm by saturating the polarizability of the molecule (red dot), there is an effective photon–photon interaction that controls which detector the probe photons reach. A complete switch from one detector to the other would require a larger phase shift than we have demonstrated here, but nevertheless, it is possible in principle to construct useful logic gates from this building block [32, 34]. Losses in such a circuit are a necessary consequence of the Kramers–Kronig relations and reduce the efficiency of the computation, but are a relatively benign form of decoherence because they are readily detected [35]. It seems, on theoretical grounds, associated with the fluctuation-dissipation theorem, that the single-photon phase gate may not work as well as it was described here [36]. However, it may be that in the nonlinear response regime of strong coupling this can be circumvented. We see this as a promising area for further research.

Acknowledgments

We thank Benoit Bertrand for assistance with the numerical simulations and Alex Crosse, Myungshik Kim and Terry Rudolph for fruitful discussions.

References

[1] 2009 Focus Issue on Quantum Optics Nature Photon. 3 669–740
[2] Schmidt H and Imamoglu A 1996 Opt. Lett. 21 1936
[3] Turchette Q A, Hood C J, Lange W, Mabuchi H and Kimble H J 1995 Phys. Rev. Lett. 75 4710
[4] Ladd T D, Jelezko F, Laflamme R, Nakamura Y, Monroe C and O’Brien J L 2010 Nature 464 45
[5] Knill E, Laflamme R and Milburn G J 2001 Nature 409 46–52
[6] Hong C K, Ou Z Y and Mandel L 1987 Phys. Rev. Lett. 59 2044
[7] Politi A, Cryan M J, Rarity J G, Yu S and O’Brien J L 2008 Science 320 646
[8] Horak P, Klappauf B G, Haase A, Folman R, Schmiedmayer J, Domokos P and Hinds E A 2003 Phys. Rev. A 67 043806
[9] Hwang J, Pototschnig M, Lettow R, Zumofen G, Renn A, Götzinger S and Sandoghdar V 2009 Nature 460 76
[10] Natarajan C M, Peruzzo A, Miki S, Sasaki M, Wang Z, Baek B, Nam S, Hadeld R H and O’Brien J L 2010 Appl. Phys. Lett. 96 211101
[11] Khitrova G, Gibbs H M, Kira M, Koch S W and Scherer A 2006 Nature Phys. 2 81
[12] Fushman I, Englund D, Faraon A, Stoltz N, Petroff P and Vuckovic J 2008 Science 320 769
[13] Trebbia J-B, Ruf H, Tamarat Ph and Lounis B 2009 Opt. Express 17 23986
[14] Nicolet A, Bordat P, Hofmann C, Kol’chenko M A, Kozankiewicz B, Brown R and Orrit M 2007 Chem. Phys. Chem. 8 1926–36

New Journal of Physics 13 (2011) 085009 (http://www.njp.org/)
[15] Nicolet A, Hofmann C, Kol’chenco M A, Kozankiewicz B and Orrit M 2007 *Chem. Phys. Chem.* **8** 1215–20
[16] Boiron A-M, Lounis B and Orrit M 1996 *J. Chem. Phys.* **105** 3969
[17] Walser A, Renn A, Götzinger S and Sandoghdar V 2009 *Chem. Phys. Lett.* **472** 44
[18] Moerner W E, Plakhotnik T, Imgartinger T, Croci M, Palm V and Wild U P 1994 *J. Phys. Chem.* **98** 7382
[19] Deperasinska I, Karpink E, Banasiewicz M, Makarewicz A and Kozankiewicz B 2011 *Phys. Chem. Chem. Phys.* **13** 1872
[20] Lettow R, Rezus Y, Renn A, Zumofen G, Ikonen E, Götzinger S and Sandoghdar V 2010 *Phys. Rev. Lett.* **104** 123605
[21] Wrigge G, Gerhardt I, Hwang J, Zumofen G and Sandoghdar V 2008 *Nature Phys.* **4** 60
[22] Gerhardt I, Wrigge G, Zumofen G, Hwang J, Renn A and Sandoghdar V 2009 *Phys. Rev. A* **79** 011402
[23] Jelezko F and Wrachtrup J 2006 *Phys. Status Solidi a* **203** 3207
[24] Empedocles S A, Norris D J and Bawendi M G 1996 *Phys. Rev. Lett.* **77** 3873
[25] Vamivakas A N, Atature M, Dreiser J, Yilmaz S T, Badolato A, Swan A K, Goldberg B B, Imamoglu A and Unlu M S 2007 *Nano Lett.* **7** 2892
[26] Robinson J T, Manolatou C, Chen L and Lipson M 2005 *Phys. Rev. Lett.* **95** 143901
[27] Daldosso N, Melchiorri M, Riboli F, Girardini M, Pucker G, Crivellari M, Bellutti P, Lui A and Pavesi L J 2004 *Lightwave Technol.* **22** 1734
[28] Jun Y C, Briggs R M, Atwater H A and Brongersma M L 2009 *Opt. Express* **17** 7479
[29] Quan Q, Bulu I and Loncar M 2009 *Phys. Rev. A* **80** 011810
[30] Barnett S M, Huttner B and Loudon R 1992 *Phys. Rev. Lett.* **68** 3698
[31] Oskooi A F, Roundy D, Ibanescu M, Bermel P, Joannopoulos J D and Johnson S G 2010 *Comput. Phys. Commun.* **181** 687
[32] Munro W J, Nemoto K and Spiller T P 2005 *New J. Phys.* **7** 137
[33] Lifante G 2003 *Integrated Photonics: Fundamentals* (New York: Wiley)
[34] Jeong H, Kim M S, Ralph T C and Ham B 2004 *Phys. Rev. A* **70** 061801
[35] Varnava M, Browne D E and Rudolph T 2006 *Phys. Rev. Lett.* **97** 120501
[36] Shapiro J H 2006 *Phys. Rev. A* **73** 062305

*New Journal of Physics* **13** (2011) 085009 (http://www.njp.org/)