

## Single photons on demand from tunable 3D photonic band-gap structures

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In this article we propose to build a (semi-)deterministic photon gun by modifying the spontaneous decay in a photonic band-gap material. We show that such a device allows for deterministic and unidirectional single-photon emission with a repetition rate of the order of 100 kHz. We describe a specific realization of the 1D band-gap model by means of a 3D photonic-crystal heterostructure and the feasibility of implementing such a device using  $\text{Er}^{3+}$  ions that produce single photons at the telecommunication wavelength of  $1.55\ \mu\text{m}$ , important for many applications.

### 1. Introduction

Single photons are an indispensable tool in many branches of physics such as metrology and quantum information processing. Important metrological applications include the use of photon counting to define a ‘quantum candela’ or the use of twin photons in quantum imaging. Single photons in well-defined Fock states provide the basic ingredient for all-optical quantum information processing [1–3] and are key to unconditional security in quantum key distribution [4].

Producing single photons on demand in a well-controlled manner is a notoriously difficult task as quantum-state engineering is a highly nonlinear process. Most current proposals make use of photon emission from atomic or molecular systems such as in cavity QED [5], nitrogen-vacancy colour centres in diamond [6, 7], quantum dots [8–10], or micropillars [11] to name only a few. Our proposal focuses on the possibility of modifying spontaneous emission of an atom by suitably modifying the quantum vacuum. It has been known for a long time that dielectric materials can alter the spontaneous decay process by the Purcell effect [12]. Essentially, the dielectric environment alters the local mode density around the radiating atom which leads either to enhancement [12] or inhibition [13] of spontaneous decay. Resonant cavities and micropillars use this effect to break the

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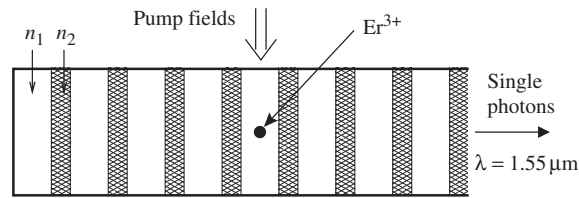


Figure 1. A periodic double-layer of quarter-wave plates with refractive indices  $n_1$  and  $n_2$  create a 1D band gap. As explained later in this paper, an intensity-dependent shift of the refractive index  $n_2$  creates a shift in the band gap. The atom or ion goes from a regime of strongly inhibited spontaneous emission to strongly enhanced emission and thus releases a photon.

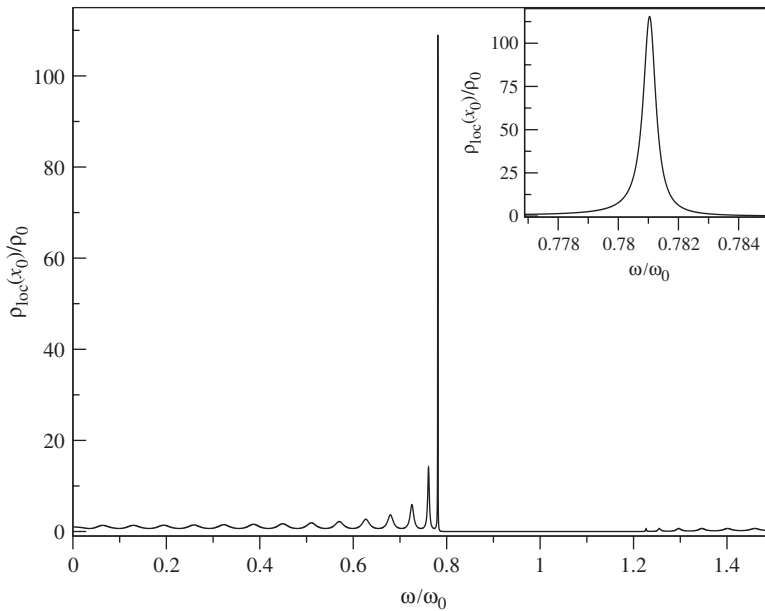


Figure 2. Normalized local mode density at the ion position for a 29-layer stack with  $n_1 = 1$ ,  $n_2 = 2$ . The ion is placed in the middle of the dielectric slab situated halfway between the longitudinal boundaries of the structure. The inset shows an expanded view of the spectral region surrounding the band edge frequency.

isotropy of spontaneous emission and introduce a preferred direction into which the emitted photon is radiated.

Here we will focus on modifying the spontaneous emission of a radiation source by placing it inside a dielectric structure that exhibits a photonic band gap (PBG). Such materials are known to show both enhancement and inhibition effects for different frequencies [14, 15]. A band gap occurs in periodic media; the simplest example being an alternating stack of planar layers with refractive indices  $n_1$  and  $n_2$  (figure 1). The thickness of the layers is chosen such that they form

quarter-wave plates. The 1D PBG arises due to destructive interference of multiply reflected waves inside the layered material [16].

As a numerical example, we consider a 29-layer stack with  $n_1 = 1$  and  $n_2 = 2$  surrounded by vacuum. This value of  $n_2$  is somewhat arbitrary. However, possible candidates for high-index materials such as Si or GaAs possess refractive indices in the range  $n_2 \sim 3 \dots 3.5$  so that large refractive index contrasts are indeed possible. Analytical results show that the transmittivity at the mid-gap frequency  $\omega_0$  decreases exponentially with the number  $N$  of layers in the stack [17, 18]. Similarly, the density of modes shows a strong frequency dependence. At the band-edge resonance (BER), the density of modes increases as  $\rho_{\text{BER}} \propto N^2 \rho_{\text{bulk}}$ , whereas at mid-gap it decreases asymptotically as  $\rho_{\text{MG}} \propto N^{-1} \rho_{\text{bulk}}$  (figure 2) [17, 18]. Hence, the contrast of the density of modes can be adjusted by increasing the number of quarter-wave plates in the stack.

## 2. 3D Photonic band-gap structures for single-photon generation

The 1D model described above only shows the main principle for enhancing and inhibiting spontaneous decay. For a realistic implementation a confinement in the transverse directions is also necessary. For that purpose, we propose to place the radiating atom inside a waveguide channel inside a 2D photonic crystal which itself is embedded in a 3D PBG structure [19]. The 1D model can be realized in a waveguide channel in a 2D photonic crystal that is embedded in a 3D PBG host structure [20]. The vertical confinement is achieved by the 3D woodpile structure [21, 22] and the horizontal confinement

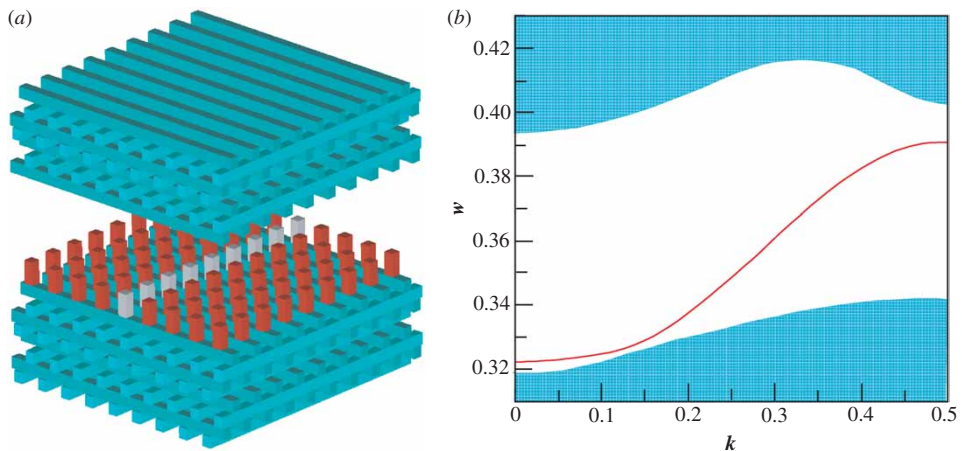


Figure 3. (a) Photonic band-gap architecture for single-photon generation. The radiating atom or ion is placed in a waveguide channel inside a 2D photonic crystal which itself is embedded in a 3D PBG structure. (b) Schematic dispersion relation of a photonic band-gap heterostructure ( $\omega = \omega a/2\pi c$ ,  $\mathbf{k} = k_1 a/2\pi c$ ). The geometry of the structure is described in the text. (The colour version of this figure is included in the online version of the journal.)

by the stop-gap of the 2D photonic crystal. By adjusting the geometry and refractive index contrast of the 3D woodpile structure [23, 24] the defect can support a single mode that can propagate along the 1D waveguide channel (figure 3(b)).

In this example, the width and height of the rods in the woodpile structure are  $a_{3D} = 0.25a$  and  $h_{3D} = 0.3a$ , respectively, where  $a$  is the lattice constant of the 3D photonic crystal. We assume here that the 3D photonic crystal generates a band gap of  $\sim 18\%$  of the mid-gap frequency [20]. The 2D photonic crystal consists of Si rods of width  $a_{2D} = 0.3a$  and  $h_{2D} = 0.3a$ , respectively. One row of the 2D photonic crystal is removed to form the linear defect that supports a single propagating mode which is truly one dimensional. By appropriately choosing the unit cell size  $a$ , one can achieve that the mode will experience a sharp cutoff in the spectral region surrounding the chosen atomic transition frequency. With this physical implementation of an effective 1D model in mind, we can continue using the idealized 1D model to describe single-photon generation in such a system.

Let us now suppose that an atom or ion with transition frequency  $\omega_A$  near the band edge is placed inside the PBG structure. For example, an  $\text{Er}^{3+}$  ion can be embedded with an atomic-force microscope or by sparse ion implantation halfway during the structure's growth into the waveguide channel [25]. The schematic level diagram is depicted in figure 4. The wavelength of  $1.55\mu\text{m}$  of its  ${}^4I_{13/2} \rightarrow {}^4I_{15/2}$  transition ( $|2\rangle \rightarrow |1\rangle$  for short) is most convenient for communication with optical fibres [26]. Excitation to level  $|2\rangle$  could, in principle, be performed by irradiating the ion with  $980\text{ nm}$  light corresponding to the  ${}^4I_{11/2} \rightarrow {}^4I_{15/2}$  transition ( $|3\rangle \rightarrow |1\rangle$ ). However, the branching ratio between relaxation on the  $|3\rangle \rightarrow |1\rangle$  transition and relaxation on the  $|2\rangle \rightarrow |1\rangle$  transition is  $6:1$  [27] which makes direct pumping very inefficient.

A more efficient and deterministic way of preparing the intermediate state  $|2\rangle$  is by using stimulated Raman adiabatic passage (STIRAP) from the ground state  $|1\rangle$  [28]. The method allows, in principle, for a  $100\%$  population transfer even for a strongly decaying intermediate state. A lossless (and therefore deterministic) population transfer is achieved by first switching on the  $\Omega_{23}$ , and then the  $\Omega_{13}$  driving field while the  $\Omega_{23}$  field is being turned off. The whole process has to

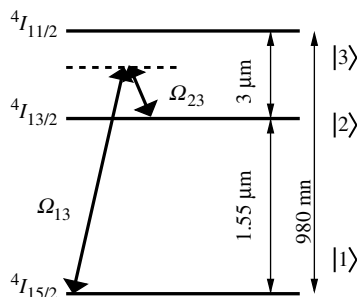


Figure 4. Schematic level diagram of the  $\text{Er}^{3+}$  ion. The  $|2\rangle \rightarrow |1\rangle$  transition is initially suppressed by the photonic band-gap. Optical pumping into level  $|2\rangle$  can be performed using the STIRAP method described in the text.

be done adiabatically. Adiabaticity is ensured if both pulses (assumed to have the same Gaussian shape) have a temporal width  $\tau$  that satisfies  $\tau(\Omega_{13}^2 + \Omega_{23}^2)^{1/2} > 10$ . For the atoms with dipole transitions in the optical IR range, the adiabaticity and optimization requirements are easily fulfilled for relatively low-power nanosecond pulses with nearly transform-limited spectral width. After the STIRAP cycle the ion is in an emission-ready state but unable to decay due to the strong Purcell inhibition.

### 3. Shifting the band gap by nonlinear processes

The release of the photon can be achieved in a variety of different ways. If, for example, the dielectric structure was tuned such that the transition frequency falls within the spectral region surrounding the cutoff frequency of the waveguide mode, after excitation via the STIRAP process the ion would rapidly decay due to the large Purcell enhancement [19]. In this case the photonic crystal is used only to direct the emitted photon in a prescribed direction. This is similar to what is used in cavity QED [5].

Here we want to describe a different effect that can be used to release a photon on demand [29]. Suppose the radiating ion is placed in a dielectric structure with  $n_1 = 1$  and  $n_2 = 2$  whereby  $n_2$  can be tuned via a Kerr nonlinearity  $n_2(I) = n_2 + \Delta n_2$  [30]. For the photonic-crystal model depicted in figure 3 that means that the material used for the rods should exhibit a non-vanishing third-order nonlinear susceptibility. An additional advantage of the 3D photonic-crystal structure compared to a homogeneous bulk medium is that the same variation of the nonlinear index of refraction can be achieved with a fraction of the power [23, 24].

A change in the index of refraction of the host material leads to a shift of the position of the photonic band gap along the frequency axis (note that by changing  $n_2$  the quarter-wave condition is not exactly fulfilled). In figure 5 we show the normalized mode density for a 40-layer stack with  $n_1 = 1$  and  $n_2 = 2$  (solid line), and  $n_2 = 2.006$  (dashed line), respectively, for the spectral region around the cutoff frequency. We see that already with  $\Delta n_2 = 0.006$  and  $N = 40$  layers the band edge can be shifted by around  $0.001\omega_0$ . This is certainly enough to switch the ion from being in a regime of strongly inhibited spontaneous decay to strongly enhanced spontaneous decay, and vice versa. For the current numerical example, the local density of modes at  $\omega = 0.7822\omega_0$  changes by a factor of  $\sim 50$ . This value can be increased by increasing the number of layers  $N$ , the refractive index contrast  $n_2 - n_1$ , and the size of the nonlinear shift  $\Delta n_2$ . For the process of single-photon generation this means that, if the ion's excitation process is performed during the presence of the laser light which induced the nonlinear shift, the onset of spontaneous decay can be externally controlled by switching off the nonlinear shift  $\Delta n_2$  (here we do not assume that one can induce a negative shift of the refractive index).

Note that optical switches work on the basis of the same underlying physical principle [23, 24, 31–34]. In this context, it has been shown that nonlinear effects of the same order of magnitude as the one required by our proposal (change in the index of refraction  $\Delta n_2/n_2 \approx 10^{-3}$ ) can be achieved using nonlinear materials with

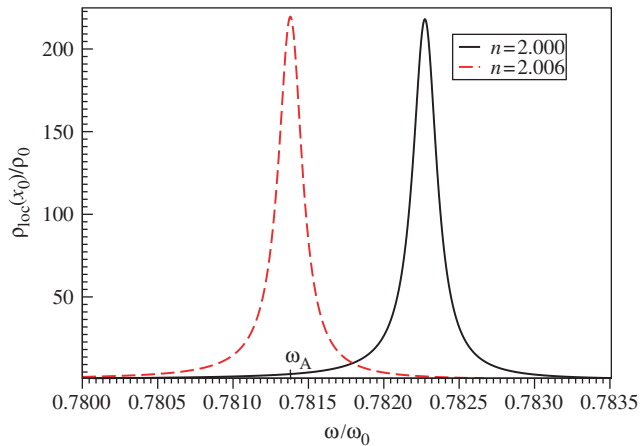


Figure 5. Normalized mode density for a 40-layer stack with  $n_1 = 1$ ,  $n_2 = 2$  (solid line) and  $n_1 = 1$ ,  $n_2 = 2.006$  (dashed line). The ion is placed in the middle of the dielectric slab situated halfway between the longitudinal boundaries of the structure. (The colour version of this figure is included in the online version of the journal.)

a Kerr coefficient of about  $n_2 = 1.5 \times 10^{-17} \text{ m}^2 \text{ W}^{-1}$ , that are achievable in, for example, AlGaAs systems [35]. The Kerr coefficient can be enhanced in more complex systems, such as GaAs/AlGaAs multiple quantum wells (MQW), up to values of  $n_2 = 3.6 \times 10^{-14} \text{ cm}^2 \text{ W}^{-1}$  [36], with a corresponding reduction in the control field intensities.

The power level required to achieve the necessary change in the index of refraction in the photonic crystal architecture we proposed is many orders of magnitude lower than it will be in a conventional nonlinear material. The main reasons for that are related to the transverse area of the photonic modes used to drive the nonlinear medium in the photonic crystal in question which is extremely small (a few wavelengths squared). Consequently, to achieve the same-size nonlinear effects, which depend on field intensity, we need much less power than in other systems that have larger transverse modal area. Practically, one will need to change the index of refraction not throughout the whole photonic crystal structure, but only in about three rows of rods surrounding the waveguide yielding further confinement of the driving field. The exact value of the intensity of light required to achieve the demanded change in the index of refraction depends very much on this level of confinement and requires precise simulations, but calculations in similar systems [23, 24, 34] suggest electric fields of  $E \approx 5 \text{ pJ}/\mu\text{m}$  would suffice (see figure 6 from [34]). The wavelength of the control radiation is determined by the specific nonlinear material used, and for the example considered here (AlGaAs and GaAs/AlGaAs MQW) it would be around  $1.68 \mu\text{m}$  [36].

Given the fact that the wavelength of the control field required to drive the nonlinear medium and the operating wavelength of the  $\text{Er}^{3+}$  ion are relatively close, one would expect the control field to affect the  $\text{Er}^{3+}$  dynamics as well. In our proposal, the Er ion is placed in a waveguide channel, surrounded by

a two-dimensional photonic crystal structure. To achieve the nonlinear change in the index of refraction required for the single photon source operation, we will need to apply a control field only to about three rows of cylinders in the neighbourhood of the waveguide channel. This field would be applied using the carrier (propagating) photonic modes available in the photonic crystal architecture considered. It has been shown that the specific photonic crystal architecture we consider supports carrier modes that are very well localized either in the high index material (the dielectric cylinders) or the waveguide channel (see figures 4 and 11 in [24]). Therefore, the control field can be delivered using modes localized in the cylinder region with minimal effect on the  $\text{Er}^{3+}$  ion located in the waveguide channel, and the  $\text{Er}^{3+}$  ion can be driven (in the STIRAP scheme) and the single photon collected using modes that are highly localized in the waveguide region.

Let us finally turn to the question of the speed of such a device. There are several key factors that limit the possible repetition rate of the photon gun. The repetition rate of ion excitation is determined by the repetition rate of the exciting laser which, for mode-locked diode lasers, can be as high as 100 MHz and more. More important is the limitation due to the spontaneous decay rate of the ion. In bulk material, the lifetime of  $\text{Er}^{3+}$  is typically 1 ms. Due to the Purcell enhancement near the photonic band edge this decay rate can increase to 100 kHz and more. As mentioned earlier, this rate can be further increased by sharpening the band edge by adding more quarter-wave layers to the stack or increasing the refractive index contrast. The increase of the local mode density near the band edge scales as  $N^2$ , whereas at mid-gap it decreases as  $N^{-1}$  [17, 18].

#### 4. Conclusions

In summary, we have proposed a source of single photons from mono-atomic emitters such as  $\text{Er}^{3+}$  placed in a dielectric micro-structure that, due to the presence of a single waveguide mode, provides the necessary unidirectionality of the source. The ions are excited by a (semi-)deterministic STIRAP pumping process and the photons are released by shifting the photonic band gap through an intensity-dependent refractive index change. The source can be rapidly switched with a repetition rate that can easily exceed 100 kHz.

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