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

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Abstract. – We describe a practical implementation of a (semi-deterministic) photon gun based on stimulated Raman adiabatic passage pumping and the strong enhancement of the photonic density of states in a photonic band-gap material. We show that this device allows *deterministic* and *unidirectional* production of single photons with a high repetition rate of the order of 100 kHz. We also discuss specific 3D photonic micro-structure architectures in which our model can be realized and the feasibility of implementing such a device using Er^{3+} ions that produce single photons at the telecommunication wavelength of 1.55 μm.

In recent years, quantum optical information processing has attracted much attention, mostly for its applications to secure communication protocols [1] and the possibility of solving efficiently computational tasks impossible to solve on a classical computer [2]. Exploiting true single-photon sources —rather than coherent pulses, is a goal of eavesdropper-proof quantum cryptography [3]. High-fidelity single-photon sources are also a requirement for scalable linear optical quantum computing [4].

Present-day research considers photon emission from single atoms or molecules (either in cavity QED [5–7] or emission from color centers [8]) quantum dot structures [9], mesoscopic p-n diode structures [10], chemical compounds [11], or micro-pillars [12]. Also, spontaneous parametric down-conversion may be used as a pseudo–single-photon source, conditioned upon detection of one photon out of the pair [13]. In the present proposal, we focus on the possibility

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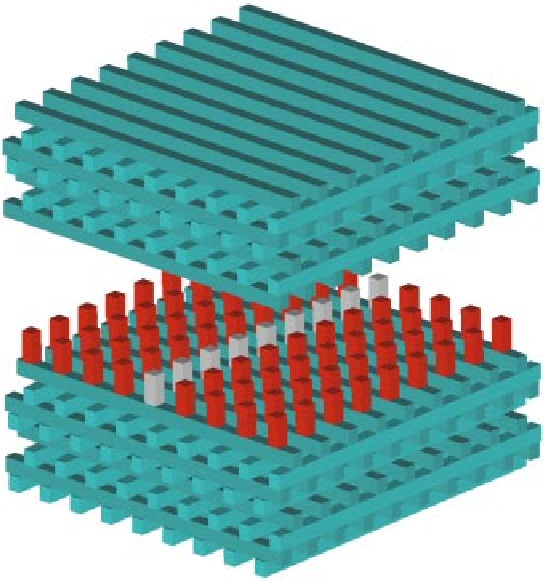

Fig. 1 – Photonic band-gap waveguide architecture for single-photon generation. The micro-structure consists of a waveguide channel in a 2D photonic crystal, which is embedded in a 3D photonic crystal [17]. In this example, the 2D photonic crystal consists of Si square rods of width $a_{2\mathrm{D}}/a = 0.3$ and thickness $h_{2\mathrm{D}}/a = 0.3$, respectively (here a is the dielectric lattice constant of the embedding 3D photonic crystal). The linear waveguide is generated by replacing one row of rods in the longitudinal direction with a low-dielectric material (silica, polymer material or, simply, air) row of rods. The 3D photonic crystal is assumed to be a woodpile structure that presents a photonic band-gap of about 18% of the mid-gap frequency [17]. The width and the height of the stacking rods in the woodpile structure are $a_{3\mathrm{D}}/a = 0.25$ and $h_{3\mathrm{D}}/a = 0.3$, respectively.

of modifying spontaneous emission by placing the radiation source inside a 3D dielectric photonic crystal heterostructure. It is known that the rate of spontaneous decay of an excited atom or ion can be tailored by the Purcell effect, whereby a cavity alters the density of modes of the vacuum radiation field, which, in turn, can lead to enhancement or inhibition of spontaneous decay of an atom inside the cavity [14].

Photonic crystals are periodically ordered dielectric materials that allow a very precise control of the flow of light and of the light-matter interaction. In this study, we make use of a photonic crystal structures exhibiting a photonic band-gap (PBG) [15]. In particular, we focus on a simplified 1D model [16] of a complex 3D heterostructure introduced in [17]. In the context of single-photon devices, PBG materials provide the possibility of unidirectional enhancement of the atomic emission. As shown in fig. 1, a 1D photonic-crystal model can be physically realized in a waveguide channel in a 2D photonic crystal that is embedded in a 3D PBG material. The electromagnetic field is confined vertically by the PBG of the 3D structure (here, for example, we consider a woodpile crystal [18]) and in-plane by the stop gap of the 2D photonic crystal (a square lattice in this case) [17]. By tuning the characteristics of the micro-structure (geometry and index of refraction contrast) [16], the linear defect in the 3D PBG can support a single waveguide mode, which experiences a sharp cutoff in the gap of 3D photonic crystal as shown in fig. 2. In this case, the sub-gap generated by the waveguide channel has a true one-dimensional character, since there is only one direction available for wave propagation. For an infinite structure, the sharp cutoff of the guided mode

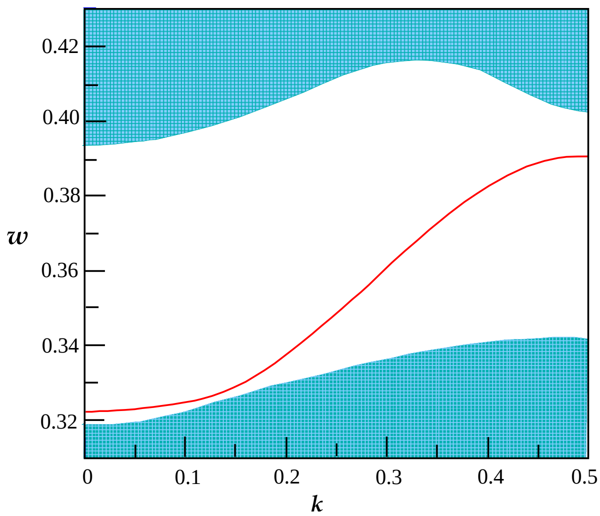

Fig. 2 – Schematic dispersion relation of a PBG heterostructure similar to the one presented in fig. 1 for propagation along the waveguide direction ($\boldsymbol{w} = \omega a/2\pi c$, $\boldsymbol{k} = k_{\|}a/2\pi$). By removing one row of rods, the linear defect supports a single wave-guided mode and, by appropriately choosing the unit cell size, the mode will experience a sharp cutoff in the spectral region around the $|2\rangle \rightarrow |1\rangle$ transition frequency.

at the Brillouin zone boundary gives rise to a low-group velocity, which, combined with the one-dimensional character of the system, generates a divergent density of states (DOS), a physical square-root singularity in the photonic density of states (DOS) near the cutoff of the waveguide modes [19]. For a real structure, the divergence is removed by the finite-size effects [20]. However, the strong variation with frequency of the photonic DOS remains [16]. Alternatively, a 1D photonic-crystal model can be implemented using the concept of omni-directional mirrors —one-dimensional periodic dielectric structures that reflect light from all incident angles and polarizations, and extend it to systems with cylindrical symmetry [21]. These cylindrical omni-directionally reflecting waveguides structures have been fabricated in fiber form [22], and show enhancement of the LDOS following a sharp $1/\sqrt{(\omega - \omega_{\mathrm{c}})}$ type singularity, as predicted for one-dimensional systems.

For simplicity, we limit the present analysis to an idealized 1D system in which the single-mode waveguide channel is modeled as an *effective* 1D photonic crystal consisting of alternating double-layer of quarter-wave plates. As argued above, this model can be implemented in carefully designed 3D dielectric heterostructures, in which the electromagnetic field of the guided mode encounters a periodic 1D effective variation of the dielectric constant as it propagates along the waveguide channel. The most relevant features of the photonic crystals for the realization of single-photon "gun" devices, namely, the rapid variation with frequency of the DOS and the unidirectional operation, are easily recaptured in our simplified 1D model. Essentially, for an $N = 29$ period stack with an index of refraction contrast of $2:1$, the spontaneous decay rate at the band edge frequency is enhanced by a factor of 115 compared to inside the bulk dielectric. We emphasize that only in one-dimensional systems the low-group velocity modes give rise to variations with the frequency of the optical DOS strong enough to drive an "on-demand" emission of photons and that there are photonic band-gap architectures, such as the one presented in fig. 1, in which these one-dimensional models can be practically implemented. In conventional 3D photonic crystals, the contribution of the low-group velocity

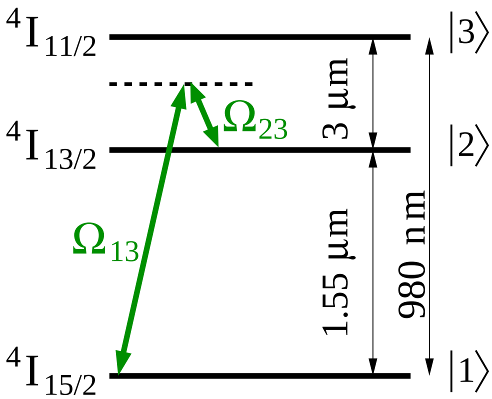

Fig. 3 – Schematic level diagram of Er^{3+} ion discussed in the context of the deterministic STIRAP pumping scheme. Using the technique of STIRAP, the population transfer to the level $|2\rangle$ does not depend on the branching ratio and can be made with unit efficiency.

modes to the DOS is of an integrable form and the DOS, while presenting discontinuities of the slope, $\mathrm{d}\rho/\mathrm{d}\omega$, remains finite and continuous as a function of frequency [23].

We now consider an Er^{3+} ion embedded with an atomic-force microscope or by sparse ion implantation midway during the structure's growth [24] in the dielectric backbone of the photonic crystal. The wavelength of 1.55 μm of the Er^{3+} ion ${}^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition ($|2\rangle \rightarrow |1\rangle$, for short) is most convenient for quantum communication with optical fibers. Excitation can be performed by pumping at 980 nm, corresponding to the ${}^4I_{11/2} \rightarrow {}^4I_{15/2}$ transition ($|3\rangle \rightarrow |1\rangle$), as shown in fig. 3. However, even a 100% efficient population transfer to the upper state $|3\rangle$ does not guarantee that the Er^{3+} ion will decay to the state $|2\rangle$. For example, the level ${}^4I_{11/2}$ decays to ${}^4I_{15/2}$ about six times faster than to the level ${}^4I_{13/2}$ [25]. Alternatively, in-band pumping at 1480 nm may be used [26]. Nevertheless, due to the relatively small radiative decay rate of the $|2\rangle \rightarrow |1\rangle$ transition, the in-band pumping mechanism is not very efficient and does not have a deterministic character.

A more efficient and *deterministic* preparation of the emission-ready state $|2\rangle$ of the Er^{3+} ion can be carried out by using stimulated Raman adiabatic passage (STIRAP) from the ground state [27]. This method allows, in principle, for a 100% population transfer even for a strongly decaying intermediate state $|3\rangle$. A *deterministic* population transfer is achieved by first turning on the external laser field that drives the transition $|2\rangle \rightarrow |3\rangle$ (denoted by Ω_{23} in fig. 3), and then turning on the laser field that drives the transition $|1\rangle \rightarrow |3\rangle$ (denoted by Ω_{13} in fig. 3), while the Ω_{23} driving field is turned off, all done adiabatically. Here, Ω_{ij} denote the Rabi frequencies of the STIRAP fields coupling the levels $|i\rangle$ and $|j\rangle$. If both laser pulses have the same Gaussian shape, the most efficient transfer is achieved when their peaks are separated by a time interval of about τ, and the adiabaticity condition $\tau\sqrt{\Omega_{13}^2 + \Omega_{23}^2} > 10$ is fulfilled [27]. For atoms with dipole transitions in the IR range considered here, the adiabaticity and optimization requirements are easily satisfied for relatively low-power, nanosecond pulses with nearly transform-limited spectral width [27]. The STIRAP process provides both the pump and the trigger mechanisms of the single-photon–gun device. After the *deterministic* excitation process, the ion is left in its $|2\rangle$ state for a time that is inversely proportional to the spontaneous decay rate of the metastable state. Assume now we could arrange the properties of the dielectric micro-structure in such a way that the transition $|2\rangle \rightarrow |1\rangle$ frequency is placed in the spectral region surrounding the cutoff frequency of the wave-guided photonic crystal mode. Subsequently to the excitation process, the ion will feel a large density of modes and will decay

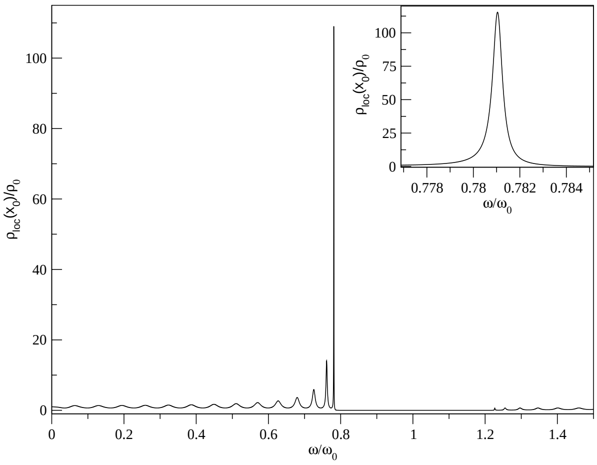

Fig. 4 – Normalized local mode density at the ion position for a 29-layer stack with $n_1 = 1$, $n_2 = 2$. The ion is placed in the middle of the dielectric slab situated halfway between the longitudinal boundaries of the structure. The inset shows an expanded view of the spectral region surrounding the band edge frequency. The low-temperature (10 K) linewidth of the Er^+ ion itself is about 0.0001 in these dimensionless units [28].

very rapidly. This type of process is called to be "on demand", since the onset of spontaneous decay can be controlled externally. The process becomes more deterministic the higher the local density of modes is, that is, the sharper the band edge becomes. This increase in mode density can be, in turn, achieved by increasing the longitudinal size of the photonic crystal.

We also note that the photonic-crystal heterostructure architecture in fig. 1 has an additional advantage for practical implementations of a single-photon–gun device. By increasing the transverse size or changing the topology of the waveguide channel, the linear defect can support more guided modes: for a specific spectral range, the linear defect supports three waveguide modes [16], one of which experiences a sharp cutoff in the middle of the 3D PBG, while, on the same spectral range, the second and the third guided modes have a very large dispersion. The low group velocity of the first mode gives rise to a strong enhancement of the photonic LDOS as discussed above, whereas the high group velocity (large dispersion) of the second and third guided modes makes them suitable for conveying the pumping field to the emitter system [16]. Moreover, the 3D PC heterostructure we propose is in fact amenable to include other emitter systems such as quantum dots: the dielectric rows surrounding the waveguide channel may include quantum dots that couple evanescent to the guided radiation modes [16].

For concreteness, consider the model whereby the radiating ion is placed in the middle of an effective 29-layer dielectric structure made out of alternating quarter-wave long dielectric layers of index of refraction $n_1 = 1$ and $n_2 = 2$, respectively. The value of $n_2 = 2$ is somewhat arbitrary. The woodpile structure can be made out of very high index of refraction materials in an air matrix, such as Si or III-IV semiconductors, GaAs or InP, etc. This means that we could use in our simulations a larger n_2 [$n_2 \in (3.14, 3.5)$] index of refraction contrast. However, we employ an effective 1D model, and we expect the effective index of refraction to be somewhat lower than the actual index of refraction of the dielectric backbone. Suppose the ion is in the excited state $|2\rangle$ and the transition frequency ω_A corresponds to $0.781\omega_0$ (here ω_0 is the mid-gap frequency). Figure 4 shows the normalized spontaneous emission rate (with respect to the homogeneous dielectric emission rate) that is proportional to the local DOS at the ion position. We note that due to the effective one-dimensional character of the device, the enhancement of the mode density preferentially occurs at a single mode of propagation. Correspondingly, the emission is highly directional along the waveguide channel and may be easily mode-matched to, for example, a telecom fiber or other waveguide.

We now consider the issues related to the speed of such a photon gun. The maximum repetition rate of that device is limited by the following factors: 1) the repetition rate of the ion excitation, and 2) the spontaneous decay rate (inverse lifetime of the excited state) of the metastable ion state. For mode-locked laser diodes the repetition rate is usually in the 100 MHz range, but can be as high as 1 GHz. That means that the limiting factor is the enhanced spontaneous decay rate of the erbium ion. Taking the lifetime of the excited ion to be 1 ms in the bulk, the enhanced spontaneous decay rate of the erbium ion can be of the order of 100 kHz, using the model above. But, as mentioned earlier, this rate can be further increased by sharpening the band edge with the addition of more periods or by increasing the index contrast. The increase of the mode density scales as N^2, where N is the number of the periods. The total repetition rate of the device then can be as high as several MHz for realistic N. Moreover, since there is no fundamental limitation on the emitter system, it is possible to improve the performance of the single-photon device by using other emitter systems, such as other rare-earth ions [7], quantum dots [9]. For some of these systems, the requirements for the enhancement of the local DOS can be relaxed and the repetition rate of the single-photon production can be easily enhanced.

We also note that our 3D PBG waveguide-based single-photon device proposal eliminates the inverse relationship between the magnitude of the defect-mode DOS and the repetition rate of the device that would be present in a 3D PBG single defect-mode–based proposal for a single-photon gun (along the lines of ref. [29]). In such a defect-mode device, the repetition rate is unfavorably limited by the cavity build-up time, which is inversely proportional to the quality factor of the defect-mode, whereas the enhancement of the DOS is proportional to the the quality factor of the defect-mode.

An alternative option for triggering the single-photon emission process would be to use an intensity-dependent Kerr nonlinearity embedded in the dielectric backbone of the photonic crystal. If initially the ion frequency ω_A falls inside the photonic band-gap, the ion cannot decay due to the lack of photonic modes. By applying an external optical or electric field (that induces a prescribed change of the refraction index of the nonlinear material and shifts the band-gap to a different frequency interval), the ion transition frequency will now be located within the continuum of modes near the photonic band edge. Subsequently, the excited ion will suddenly feel a strong DOS and will spontaneously decay very rapidly. Our calculations show that for a dielectric structure consisting of 39 unit cells, the required nonlinear relative change of the refraction index necessary to achieve single-photon generation processes is $\Delta n/n \approx 6 \times 10^{-3}$. Moreover, using the photonic crystal architecture presented in fig. 1, we argue that the external laser field power required to achieve the necessary change in the index of refraction may be strongly reduced. By a suitable engineering, it is possible to achieve very strong local field enhancement at the nonlinear medium location, and, implicitly, a strong variation of the nonlinear index of refraction with only a fraction of the power that would have been required to obtain the same variation in the case of a homogeneous medium [16].

In summary, we have proposed a source of single photons switched by a STIRAP pumping process of a mono-atomic source placed in a light-confining dielectric structure. The atomic source can be rapidly switched, at will, with a high repetition rate. The virtue of the mode confinement effect in the PBG architecture is that the single-photon–gun device can be made small and compact. The unidirectional operation of the single-photon device is achieved by tailoring the PBG geometry, while the repetition rate of the device is dramatically increased due to the strong enhancement of the optical DOS near a photonic band edge.

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