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Nonlinear tuning of 3D photonic band-gap structures for single-photon on demand sources

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Abstract

We describe a practical implementation of a semi-deterministic photon gun based on the stimulated Raman adiabatic passage pumping and the nonlinear tuning 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 microstructure 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.

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Keywords: Photonic crystals; Single-photon sources; Linear optics quantum computation

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1. Introduction

During the last years, the quantum optical information processing has generated a strong scientific interest brought about by its applications to secure communication protocols [1] and quantum computation [2]. In this context, high-fidelity single-photon sources constitute a requirement for eavesdropper-proof quantum cryptography [3] and scalable linear optical quantum computing [4].

Current research considers single photon emission from single atoms in microcavities [6,7], color centers in diamond [8], quantum dots embedded in microcavities [9], quantum wells in mesoscopic p–n diode structures [10], single molecules in chemical compounds [11], or quantum dots in 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 context of single-photon devices, it is well-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 radiation field, which in turn can lead to the enhancement or the inhibition of spontaneous decay of an atom inside the cavity [14]. Photonic crystals constitute an ultimate example of confined photonic systems, in which the photonic density of states and photonic mode spatial distribution can be tailored with great accuracy. Active sources placed in microcavities formed inside photonic crystals [15] provide the possibility of unidirectional enhancement of the radiation emission and, consequently, may become ideal systems for highly controlled single photon production [16]. In the present proposal, we focus on the possibility of modifying spontaneous emission by placing the radiation source inside a 3D dielectric photonic crystal heterostructure. In particular, we focus on a simplified 1D model of a complex 3D heterostructure introduced in Ref. [5]. As shown in Fig. 1, a 1D photonic

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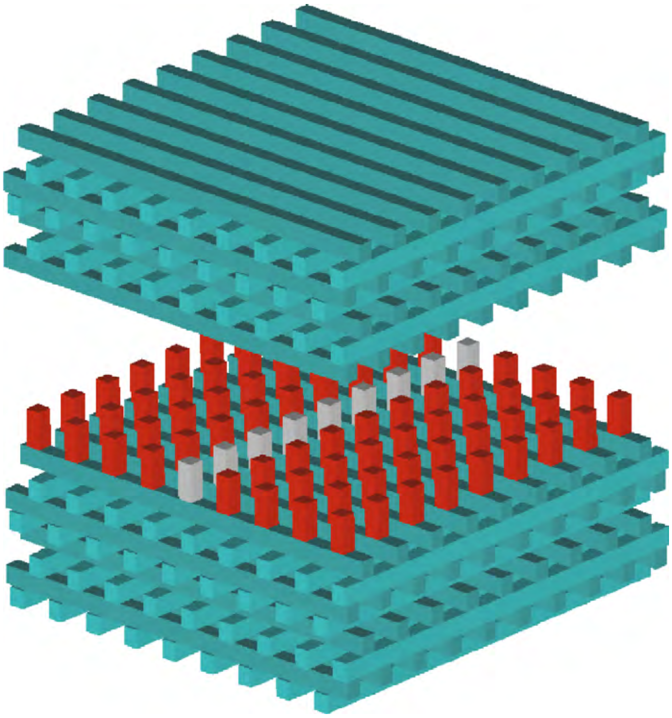

Fig. 1. Photonic band gap waveguide architecture for single-photon generation. The microstructure consists of a waveguide channel in a 2D photonic crystal, which is embedded in a 3D photonic crystal [5].

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 photonic crystal [17]) and in-plane by the stop gap of the 2D photonic crystal (a square lattice in this case) [5]. By tuning the characteristics of the microstructure (geometry and index of refraction contrast) [5], 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. In this case, the subgap generated by the waveguide channel has a true 1D character, since there is only one direction available for wave propagation. The sharp cutoff of the guided mode at the Brillouin zone boundary gives rise to a low group velocity ($d\omega/dk \to 0$), which combined with the 1D character of the system generates a divergent density of states (DOS) ($\rho(\omega) \propto dk/d\omega \to \infty$). For an infinite structure, there is a physical squareroot singularity in the photonic DOS near the cutoff of the waveguide modes [18]. For a finite structure, the divergence is removed by the finite-size effects. However, the strong variation with frequency of the photonic DOS remains [5]. We limit the present analysis to an idealized 1D photonic crystal in which the single-mode waveguide channel is modeled as an *effective* 1D photonic crystal consisting of alternating double-layer of quarter wave plates (the electromagnetic field in the guided mode in Fig. 1 encounters a periodic 1D effective variation of the dielectric constant as it propagates along the waveguide channel).

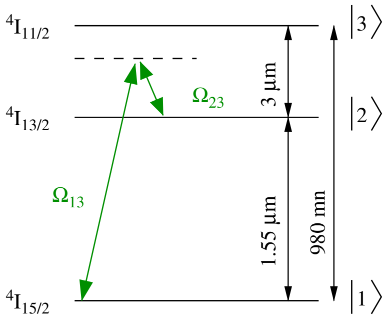

Fig. 2. Schematic level diagram of Er^{3+} ion discussed in the context of the deterministic STIRAP pumping scheme. Using the technique of STIRAP, the population transfer to the level $|2\rangle$ does not depend on the branching ratio and can be implemented with unit efficiency.

2. Single-photon generation in photonic band gap materials

We consider an Er^{3+} ion embedded in the dielectric backbone of the PBG (Fig. 2). The ion could be placed with an atomic-force microscope or by sparse ion implantation midway during the structure's growth [19]. An 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 [20]. This method allows, in principle, for a 100% population transfer even for a strongly decaying intermediate state $|3\rangle$. 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. Let us assume that we could arrange the properties of the dielectric microstructure in such a way that the transition $|2\rangle \to |1\rangle$ frequency is placed in the spectral region surrounding the cutoff frequency of the waveguide mode. After the excitation process, the ion will feel a large density of modes and will decay very rapidly. We call this type of process "on demand" since the onset of spontaneous decay can be controlled externally.

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 of the waveguide channel, the linear defect may support additional guided modes. These additional modes can be used to convey the external laser fields that drive the pumping process.

For concreteness, we consider the model whereby the radiating ion is placed in the middle of an effective 40-layer dielectric structure with $n_1 = 1$ and $n_2 = 2$. Since 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., we could use in our simulations a larger n_2/n_1 [$n_2 \in (3.14, 3.5)$] 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. The most relevant features of the photonic crystals for realization of single photon "gun"

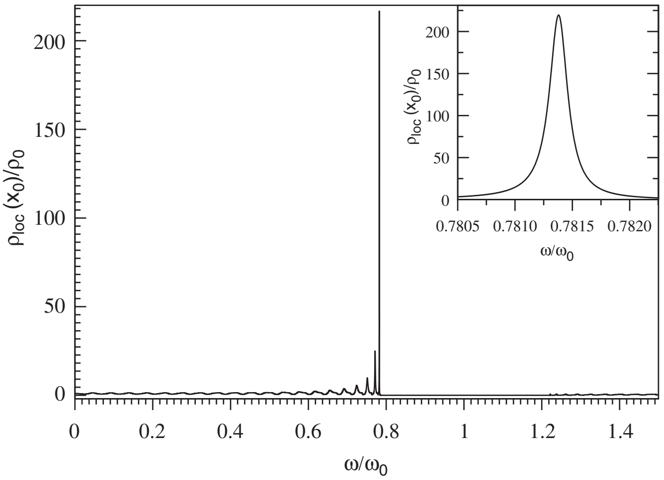

Fig. 3. Normalized local mode density at the ion position for a 40-layer stack with $n_1 = 1$, $n_2 = 2$. The ion is placed in the middle of the dielectric slab situated halfway between the longitudinal boundaries of the structure. The inset shows an expanded view of the spectral region surrounding the band edge frequency.

devices (the rapid variation with frequency of the DOS and the unidirectional operation) are easily recaptured in the simplified 1D model. Fig. 3 shows the normalized spontaneous emission rate (with respect to the low frequency emission rate) as function of the scaled frequency ($\omega_0 = 2\pi c/a$, with a the unit cell length), which is proportional to the local DOS at the ion position (in this example, the ion is placed in the middle dielectric slab of the *effective* 1D photonic crystal). Note that due to the effective 1D 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 a telecom fiber or other waveguide.

3. Nonlinear switching of the band-edge frequency in photonic crystals

An alternative option for triggering the single photon emission process is to make use of an intensity-dependent Kerr nonlinear medium 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 available 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 location), the ion transition frequency will now be located within the continuum of modes near the photonic band edge, and will suddenly feel a strong DOS and will spontaneously decay very rapidly. Our calculations show that for a dielectric structure consisting of 40 unit cells the required nonlinear relative change of the refraction index necessary to achieve single photon generation processes is $\Delta n/n \approx 6 \times 10^{-3}$. The shift of the band gap can be performed in principle by choosing a nonlinear medium with a intensity-dependent (Kerr) nonlinearity $n(I) = n_{\mathrm{L}} + n_{\mathrm{NL}} I$, where I is the intensity of an externally applied electric field.

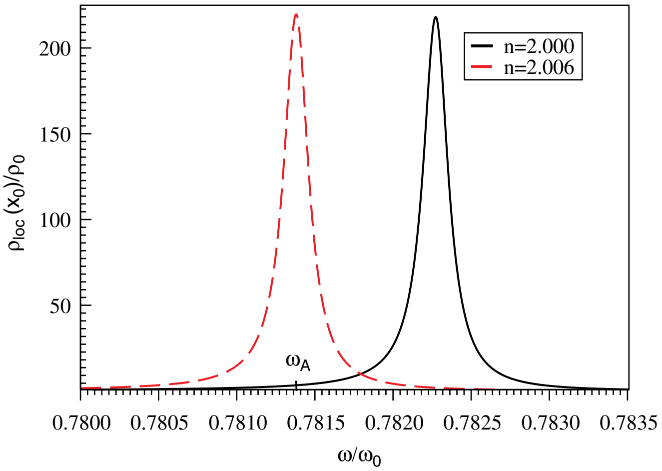

Fig. 4. Normalized mode density for a 40-layer stack with $n_1 = 1$, $n_2 = 2$ (solid line) and $n_2 = 2.006$ (dotted line).

We assume that the radiating ion is placed in a 40-layer stack with $n_1 = 1$ and $n_2 = 2$, whereby n_2 can be tuned via the nonlinearity $n_2(I) = n_2 + \Delta n_2$. Suppose the ion is in the excited state $|2\rangle$ and the transition frequency ω_A corresponds to $0.7814\,\omega_0$. Then, when $n_2 = 2$, ω_A lies in the band gap. If we change n_2 by increasing the intensity of the field driving the nonlinear medium, the range of the band gap is changed accordingly. Note that by changing n_2, the quarter-wave stack condition $n_2 d_2 = \lambda_0/4$ is no longer satisfied. When $n_2 = 2.006$, ω_A lies at the band edge as depicted in Fig. 4.

We 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 metastable ion state. For mode-locked laser diodes the repetition rate can be as high as 1 GHz, but is certainly in the 100 MHz range. This 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 [21], the enhanced spontaneous decay rate of the erbium ion can be of the order of 100 kHz, which can be further increased by increasing the longitudinal size of the photonic crystal waveguide channel.

4. Conclusions

In summary, we have proposed a source of single photons using a STIRAP pumping process of a monoatomic source placed in a light confining dielectric structure and triggered by the nonlinear tuning of the photonic density of states. The atomic source can be rapidly switched, at will, with a high repetition rate. The virtue of the mode confinement effect in the architecture presented in Fig. 1 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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