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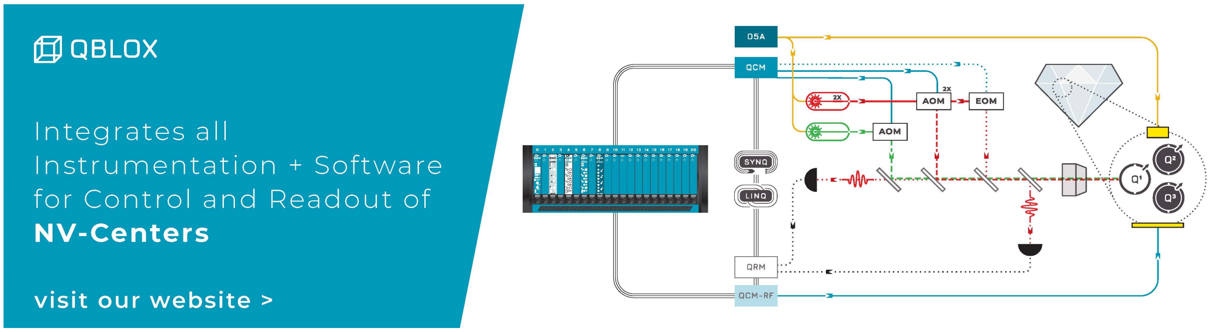

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Photon-number state on-demand source by cavity parametric downconversion

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The authors propose a realizable scheme for an arbitrary photon-number state on-demand source based on parametric downconversion in a doubly resonant photonic cavity. The signal-wavelength resonance serves as storage for signal photons and the idler-wavelength resonance generates time separation between exiting idler photons, enabling photon-number-resolving detection. The counting of idler photons indicates the desired signal photon-number state, which can be released from the cavity on demand. They analyze the statistics of photon-number states generation and estimate the maximal repetition rates. Performance of the monolithic cavity for signal-storage and idler time spacing is limited, however, by external devices, namely, the long recovery time of existing single-photon detectors. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2364877]

Photon-number states are required in many optical applications of quantum information and quantum computing. Single-photon states are necessary for security-proven quantum cryptography,[1] and other Fock states with fixed number of photons can be used to generate multiparticle entanglement.[2] Furthermore, these states represent the most distinct from the classical description of radiation and can contribute to fundamental light-matter interaction research.

Some experiments generating Fock states have been conducted by cavity quantum electrodynamics using superconducting cavities.[3] Nonlinear optics may provide a somewhat simpler approach. Optical parametric amplification process was suggested as a photon-number state source due to the fact that idler and signal photons are produced in pairs, and thus counting the idler photons enables the generation of the same number of signal photons.[4] In particular, single-photon sources based on spontaneous parametric downconversion (SPDC) were shown to improve significantly the performance of quantum cryptography versus the weak coherent pulse version of a photon source.[1] SPDC produces the photon pairs at random and the signal photons emitted are heralded, but unpredictable. Different solutions were proposed to implement synchronous on-demand single-photon sources by time multiplexing[5] or space multiplexing[6] multiple SPDC sources. Using very low pump intensity in order to reduce the multiple pair generation probability, the SPDC emits no pairs most of the time, and very rarely a single pair of photons. Multiplexing a large number of such emitters provides almost an on-demand source. Another solution is to switch the heralded signal photon into a storage loop for a later use.[5,7] However, a finite probability of producing multiple pairs still exists, and hence this type of a single-photon source must employ a photon-number-resolving (PNR) detector and postselection in the receiver.[8] PNR detectors were designed for small photon-number states using multiple detectors with beam splitters in a "tree" configuration,[5] multiple optical delay lines,[9] or visual photon light counters.[10] However, improving the accuracy of these PNR detectors or scaling them for large photon-number states would require significant design complications.

In this letter we propose a simple, room-temperature, SPDC-based photon-number state on-demand source. In this scheme the SPDC generates the signal and the idler photons inside a monolithic single cavity, having two wavelength resonances (Fig. 1). The pump pulse intensity is adjusted to produce on average n SPDC pairs. The resonance at the signal wavelength is designed to have a long photon lifetime and serves as storage for signal photons, which are generated inside the cavity and are automatically coupled into the storage. The resonance at the idler wavelength is designed to form time separation between the idler photons such that the idler photon lifetime τ_p is larger than the idler detector's recovery time. Given enough time, all the idler photons can be detected, and with sufficient time separation every photon can be counted. Cavity-enhanced SPDC produces photons only at the desired wavelengths due to the spectral selectivity, thus improving the conversion efficiency with increasing cavity quality factors (Q).

The photon number-generation protocol is as follows.

(1) If the number of idler photons counted equals the desired n, then the output mirror of the cavity is abruptly spoiled, thus reducing the Q factor and enabling the emission of the n signal photons in a very short period of time.

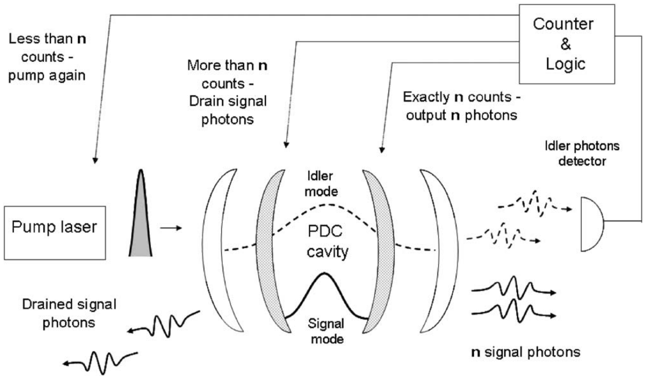

FIG. 1. Arbitrary n-photon state generation scheme.

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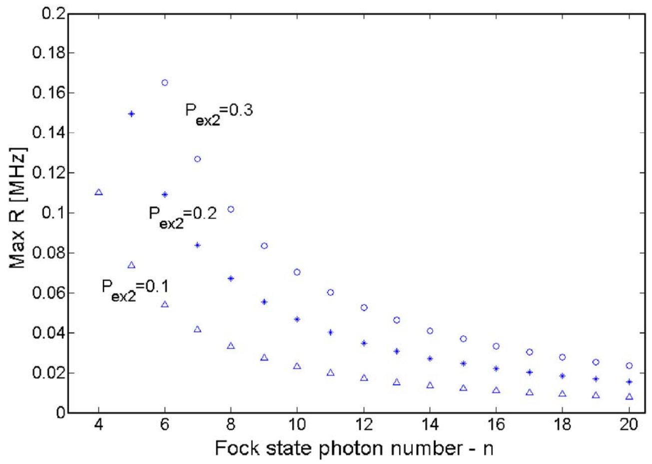

FIG. 2. (Color online) Maximal repetition rate of n-state generation vs photon number for various double-detection probabilities $P_{\mathrm{ex\_2}}$ for $P_{\mathrm{ex\_}n}=99.8\%$, detector efficiency $\eta_d=1$, and detector's recovery time of $\tau_d=10$ ns.

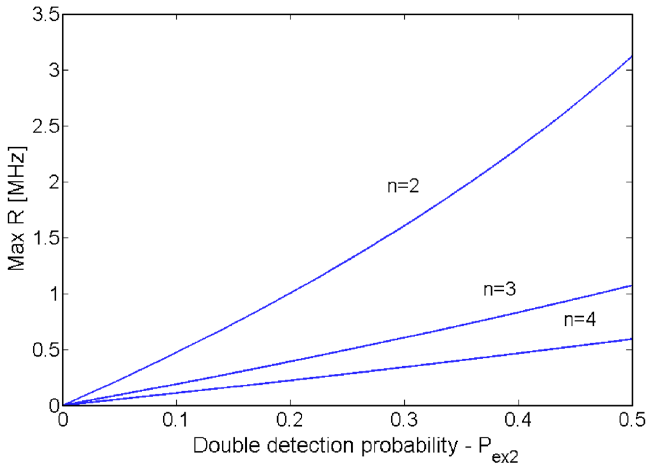

FIG. 3. (Color online) Maximal repetition rate of n-state generation vs double-detection probabilities $P_{\mathrm{ex\_2}}$ for various photon-number states, $P_{\mathrm{ex\_}n}=99.8\%$, detector efficiency $\eta_d=1$, and detector's recovery time of $\tau_d=10$ ns.

(2) If the counted number is different from n, the drain mirror of signal cavity is switched off and the signal photons are drained and subsequently the cavity is pumped again.

Emission time-resolving capability of the cavity for idler photons stems from its idler photon lifetime τ_p. Given n idler photons in the cavity, after the first photon is emitted the probability of emitting the second photon during a short time period t is

$$P_{\mathrm{ex\_2}}(t,n)=(1-e^{-t/\tau_p})(n-1). \tag{1}$$

Thus $P_{\mathrm{ex\_2}}$ is the double-detection probability. This probability should be kept low enough for the interval $t=\tau_d$, where τ_d is the idler detector's recovery time required for high photon-number resolution. Hence the smallness of this probability determines the required idler photon cavity lifetime and thus the cavity's Q factor,

$$\tau_p=\frac{-\tau_d}{\ln(1-P_{\mathrm{ex\_2}}(t,n)/(n-1))}. \tag{2}$$

A given probability $P_{\mathrm{ex\_}n}$ that all the idler photons exit the cavity and are counted determines the detector's wait-time T_w according to

$$P_{\mathrm{ex\_}n}(T_w,n)=\eta_d(1-e^{-T_w/\tau_p}), \tag{3}$$

where η_d is the detector efficiency.

The pump pulse is regarded as a coherent state:

$$|\alpha\rangle=\sum_{n=0}^{\infty}\alpha^n\frac{e^{-|\alpha|^2/2}}{\sqrt{n!}}|n\rangle, \tag{4}$$

with the Poissonian photon-number statistics

$$P_{\mathrm{pump}}(n)=|\alpha|^{2n}\frac{e^{-|\alpha|^2}}{n!} \tag{5}$$

and a mean photon number of $|\alpha|^2$.

The configuration under discussion supports three modes at the signal, the idler, and the pump wavelengths. Thus the second-order ($\chi^{(2)}$) nonlinear process Hamiltonian in the interaction picture is

$$H_{\mathrm{int}}=i\hbar\eta(a_s^\dagger a_i^\dagger a_p-a_s a_i a_p^\dagger), \tag{6}$$

where η is the process efficiency.

Generally the downconverted states are squeezed with the squeezing parameter r proportional to η. For the short pulse low process efficiency, r is close to zero and the downconverted states can be approximated as coherent states. The pair number statistics is then[5]

$$P_{\mathrm{pair}}(n)=|\beta|^{2n}\frac{e^{-|\beta|^2}}{n!}, \tag{7}$$

where $|\beta|^2$ is the mean downconverted pair number, which depends on the interaction time, pump strength, and the process efficiency. The generated pairs may undergo upconversion to a photon at the pump wavelength by the same second-order nonlinearity. However, this process does not change the original Poissonian distribution and has a negligible probability.

The generation probability of n pairs during a single pumping attempt is

$$P_g(n)=P_{\mathrm{pair}}(n)P_{\mathrm{ex\_}n}(T_w,n). \tag{8}$$

Hence the expectation value for the number of pumping attempts until the generation of n pairs is

$$N_s=1/P_g(n). \tag{9}$$

After the generation, n signal photons are stored in the signal cavity and may be released on demand. However, the maximal repetition rate of the source is limited by the number of attempts and the duration of each attempt:

$$R=\frac{1}{T_wN_s}. \tag{10}$$

The variance of the Poissonian pair number distribution is proportional to the mean photon number. Hence the maximal generation rate is expected to decrease for higher photon-number states. Furthermore, double-detection probability $P_{\mathrm{ex\_2}}$ determines the cavity lifetime, and reducing it to a desired value results in longer detector wait time and thus in lower repetition rate.

Calculation of the maximal repetition rate R with a given double-detection probability $P_{\mathrm{ex\_2}}$ and idler detector recovery time τ_d shows a monotonic decrease in R for larger photon-number states (Fig. 2). Whereas allowing larger values of $P_{\text{ex\_2}}$ results in higher R for a given photon-number state (Fig. 3). Photon-number state generation with kilohertz repetition rates is expected for photon-number states up to $n=10$ with high idler photon counting probability $P_{\text{ex\_}n}$ of 99% and a reasonably low double-detection probability of 1%. Less strict error requirements and smaller photon-number states enable operating the source with generation rates in the megahertz range.

Available room-temperature photon counters have typical recovery times of tens of nanoseconds, which determine the required idler cavity photon lifetime. Free-space cavity, 1 m long, can provide tens of nanoseconds idler photon lifetimes using dielectric mirrors with reflectivity of ~90% at the idler wavelength and microsecond-scale signal photon lifetime with ~99.5% mirror reflectivity at the signal wavelength. Signal photon switching out the free-space cavity can be done, e.g., by a fast Pockels cell.[5]

Integrated photonics may provide an alternative approach. Very high finesse ($Q > 10^4$) microcavities are feasible,[11] and employing distributed gratings technology with centimeter-long cavities may yield photon lifetimes as long as a few microseconds at the signal wavelength for storage and tens of nanoseconds at the idler wavelength for photon-number resolving detection. Fast Q switching by applying voltage to the distributed reflector,[12] can enable on-demand immediate release of the signal photons out of the cavity.

In conclusion, we have demonstrated a realizable photon-number state on-demand source based on SPDC process in a doubly resonant compound cavity, which provides both time separation between exiting idler photons and storage for signal photons generated inside the cavity with no need for coupling into the storage. The scheme enables photon-number resolved detection of idler photons and the release on demand of stored signal photon-number states. Photon statistics calculations validate the source's operation for number states as high as 10 with kilohertz repetition rates and less than 1% error rates. Both free-space and integrated optics implementations of the source appear feasible, and the only principal limitation on the repetition rate and the generated photon number is due to an external element, namely, the detector's recovery time. The proposed scheme may help developing real-world applications of quantum information processing such as telecommunication bit-rate quantum cryptography and scalable quantum computing.

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