Voltage-tunable integrated quantum entanglement device via nonlinear Fano resonances

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Integration of devices generating nonclassical states (such as entanglement) into photonic circuits is one of the major goals in achieving integrated quantum circuits (IQCs). This is demonstrated successfully in the past decades. Controlling the nonclassicality generation in these micron-scale devices is also crucial for robust operation of the IQCs. Here, we propose a micron-scale quantum entanglement device whose nonlinearity (so the generated nonclassicality) can be tuned by several orders of magnitude via an applied voltage. The level-spacing of quantum emitters (QEs), which can be tuned by voltage, are embedded into the hotspot of a metal nanostructure (MNS). QE-MNS coupling introduces a Fano resonance in the “nonlinear response”. Nonlinearity, already enhanced extremely due to localization, can be controlled by the QEs’ level-spacing. Nonlinearity can either be suppressed (also when probe is on the device) or be further enhanced by several orders. Fano resonance takes place in a relatively narrow frequency window so that \textasciitilde meV voltage-tunability for QEs becomes sufficient for a continuous tuning on/off of the nonclassicality. This provides orders of magnitude modulation depths.

Recently, the efforts on the scalable integration of the quantum optics features into photonic chips—integrated quantum circuits—which allows the operation of quantum computation and quantum communication on a single medium\textsuperscript{8}. Such an integration (and miniaturization) necessitates the controlled generation and manipulation of entangled and/or squeezed light at much smaller (micron-scale) dimensions. This stimulated the intense research on the micron-scale generation of quantum states, for instance, quadrature-squeezed states on silicon-nitrite chips\textsuperscript{9} (continuous-variable entanglement\textsuperscript{10,12} and single-photon operations on semiconductor quantum dots\textsuperscript{13,15}) (discrete-variable entanglement\textsuperscript{16}). Both approaches (also the hybrid approach\textsuperscript{17}) utilize nonlinear interactions in a chip component. Nonlinear frequency conversion rate is either fixed\textsuperscript{15}; or it can be controlled by auxiliary light\textsuperscript{19}, by tuning the resonances\textsuperscript{20} and optical filters\textsuperscript{21} (i.e., voltage-controlled preparation of two-photon states\textsuperscript{22}), and by adjusting phase-matching condition\textsuperscript{23}. The control on the production (switching) of quantum nonclassicality in a circuit is quite important for the robust operation of an integrated quantum circuit.

In this Letter, we study a micron-scale entangler where nonclassicality generation can not only be switched on/off, but also tuned continuously by an applied voltage. Furthermore, one can achieve modulation depths as large as several orders of magnitude. The entanglement (nonclassicality) switch is based on the Fano-control of nonlinear response of a metal nanostructure (MNS). A quantum emitter (QE) is positioned at the hot spot of the MNS and creates the Fano resonance in the nonlinear response. The level-spacing of the QE can be tuned via an applied voltage\textsuperscript{20,21,26}, which also controls the rate of the nonlinear conversion—thus, the nonclassicality of the system. Here, as an example, we work the squeezing and entanglement generation at the fundamental frequency ($\omega$) of a Fano-controlled second harmonic generation (SHG) process. However, such a control can be achieved also in other nonlinear processes\textsuperscript{27,28}.

Fano resonances appear at relatively sharp frequency bands\textsuperscript{29}. This feature may be disadvantageous in achieving broadband nonlinearity enhancements in MNSs. Here, however, we turn the sharpness of the Fano resonances into an advantage, because a smaller voltage tuning for the QE level-spacing ($\omega_{eg}$), \textasciitilde meV\textsuperscript{20,24,26}, comes to be sufficient for turning on and off the nonclassicality.

We consider a micron-sized photonic crystal cavity into which a MNS, e.g., a bow-tie antenna, is embedded, see Fig. 1. The QE(s), whose level-spacing is voltage-tuned\textsuperscript{26}, is positioned at the nm-sized hotspot (occurs at the gap). A Fano resonance appears due to the MNS-QE coupling, see the inset of Fig. 2. When $\omega_{eg}$ is tuned to $2\omega$, the SHG process (so the nonclassicality generation) is suppressed, e.g., 3-4 orders of magnitude. In contrast, when the $\omega_{eg}$ is tuned to 2.001$\omega$, the SHG is enhanced.
FIG. 1. Micron-scale voltage-tunable integrated entanglement device. Nonlinearity of the MNS is already extremely enhanced due to localization at the hotspot [20]. QE(s) positioned to the hotspot induces a Fano resonance which can suppress (turn off) the localization-enhanced nonlinearity by several orders at \( \omega_{eg} = 2\omega \) or enhance it 10-100 times at \( \omega_{eg} = 2.001. \) Level-spacing (\( \omega_{eg} \)) is tuned by an applied voltage [20] [21] [20]. \( \hat{a}_{in} \) is the input field (integrated laser), \( \hat{a}_{out} \) and \( \hat{b}_{out} \) are the output fields whose entanglement (Fig. 2) and nonclassicality (Fig. 3) are investigated.

10-100 times. We remark that the localization (hotspot) already enhances the SHG, for instance, by \( 10^6 \) times [20]. The pronounced Fano-enhancement (suppression) factors multiplies the \( 10^6 \) localization enhancement [20] [31]. The cavity is pumped by an integrated microlaser [15] [32] on the left hand side.

Here, we show that the SHG process taking place inside the cavity (entanglement device) generates two kinds of nonclassicality. (i) The two pulses emitted from the cavity in the opposite directions (\( \hat{a}_{out} \) and \( \hat{b}_{out} \) in Fig. 1), at the fundamental frequency \( \omega, \) are entangled, see Fig. 2. (ii) The transmitted light \( \hat{b}_{out} \) is single-mode nonclassical, see Fig. 3. Thus, one can either (i) use the two entangled light beams or (ii) create entanglement (on the right hand side) from the nonclassicality inherited in \( \hat{b}_{out} \) using an integrated beam-splitter [33]. Beyond the generation of nonclassicality [34] [35], the most important thing our device can provide is the continuous tunability of the quantum nonclassicality (by several orders of magnitude) via an applied voltage.

Cavity system and Hamiltonian. — Dynamics of the voltage-controlled entanglement device can be described as follows. An integrated laser of frequency \( \omega \) excites the fundamental cavity mode (\( \hat{c}_1 \)) on the left hand side, \( \hat{H}_L = \hbar \hat{c}_1 (\hat{c}_1^\dagger e^{-i\omega t} + H.c.) \). The cavity mode couples with the first (lower-energy) plasmon mode (\( \hat{a}_1 \), resonance \( \Omega_1 \)) of the bow-tie MNS, \( \hat{H}_1 = \hbar g_1 \hat{a}_1^\dagger \hat{c}_1 + H.c. \). The \( \hat{a}_1 \) plasmon excitation is localized within the nm-sized hotspot located at the gap between the two metal nanoparticles. Orders of magnitude enhanced electromagnetic field (\( \omega \)), at the hotspot, yield the SHG process [36]. Two localized excitations (\( \omega \)) in the \( \hat{a}_1 \) plasmon mode combine to produce a single \( 2\omega \) plasmon in the second (higher energy) plasmon mode \( \hat{a}_2 \), \( \hat{H}_{2\text{a}2} = \hbar \chi(2) \hat{a}_2^\dagger \hat{a}_1^\dagger \hat{a}_1 + H.c. \). The hotspot of the \( \hat{a}_2 \) mode, of resonance \( \Omega_2 \), is also at the center (gap). The SHG conversion takes place over the plasmons [37] because overlap integral for this process is extremely larger due to the localization [31] [35]. As both incident (\( \omega \)) and converted (\( 2\omega \)) fields are localized the SHG process can be enhanced as large as \( 10^6 \) times — localization enhancement [20]. The level-spacing of the QE (\( \omega_{eg} \)) is around the second harmonic (SH) frequency \( 2\omega \) and the resonance \( \Omega_2 \) of the second plasmon mode \( \hat{a}_2 \), so that it is off-resonant to the fundamental frequency. The localized \( \hat{a}_2 \) plasmon mode couples with the QE(s) \( \hat{H}_2 = \hbar f |\psi\rangle \langle \psi | \hat{a}_2 + H.c. \), which introduces a Fano resonance in the SH conversion, see inset of Fig. 2. The SHG process can be controlled by the level-spacing of the QE(s), \( \omega_{eg} \) which is tuned by an applied voltage [20]. When voltage tunes to \( \omega_{eg} = 2\omega \), the localization enhanced (e.g., about \( 10^6 \) times) SHG is suppressed, for instance, \( 10^{-4} \) times. That is, the switch turns the SHG off. When \( \omega_{eg} \approx 2.001\omega \), this time the localization enhanced SHG is further multiplied by a factor of \( 10^{-10^2} \).

The SHG process \( \langle \hat{a}_2^\dagger \hat{a}_1 + H.c. \rangle \) generates the nonclassicality (e.g., squeezing) in the \( \hat{a}_1 \) plasmon mode. The nonclassicality of the \( \hat{a}_1 \) mode is transferred back to the fundamental cavity mode \( \hat{c}_1 \) via the beam splitter like interaction. Nonclassicality introduces in the \( \hat{c}_1 \) mode. The cavity mode couples to the left (\( \hat{a}_{out} \)) and right (\( \hat{b}_{out} \)) hand sides of the cavity. \( \hat{a}_{out} \) and \( \hat{b}_{out} \) are related to the cavity field \( \hat{c}_1 \) via input-output relations [39]. Because of the common interaction with the cavity mode (entanglement swap [40]) and the nonclassicality of \( \hat{c}_1 \), the \( \hat{a}_{out} \) and \( \hat{b}_{out} \) modes get entangled, see Fig. 2. In addition to this entanglement, the nonclassicality (squeezing) in the cavity mode is transferred also to the \( \hat{b}_{out} \) on the right hand side. Thus, \( \hat{b}_{out} \) is also single-mode nonclassical (squeezed) as well as it is entangled with the \( \hat{a}_{out} \) mode. (Not all of the total nonclassicality can be converted into entanglement in beam-splitter like interactions, but some single-mode nonclassicality remains within the transferred mode [41].) One does not have to use the entanglement of the \( \hat{a}_{out} \) and \( \hat{b}_{out} \) modes, but can also convert the single-mode nonclassicality of the transmitted \( \hat{b}_{out} \) mode into entanglement by placing an integrated beam splitter on the right hand side [42].

Langevin equations. — Time evolution of the operators can be determined using the Heisenberg equations of motion, e.g., \( \hat{a}_1 = [\hat{a}_1, \hat{H}] \) as

\[
\begin{align*}
\dot{\hat{c}}_1 &= -(\kappa_1 + i\omega_1)\hat{c}_1 - ig_1 \hat{a}_1 + \varepsilon L e^{-i\omega t}, \\
\dot{\hat{c}}_2 &= -(\kappa_2 + i\omega_2)\hat{c}_2 - ig_2 \hat{a}_2, \\
\dot{\hat{a}}_1 &= -(\gamma_1 + i\Omega_1)\hat{a}_1 - ig_1 \hat{c}_1 - 2\chi(2)\hat{a}_1^\dagger \hat{a}_2, \\
\dot{\hat{a}}_2 &= -(\gamma_2 + i\Omega_2)\hat{a}_2 - ig_2 \hat{c}_2 - \chi(2)\hat{a}_1^\dagger \hat{a}_1 - i\hat{\rho}_{ge}, \\
\dot{\hat{\rho}}_{ge} &= -(\gamma_{eg} + i\omega_{eg})\hat{\rho}_{ge} + i\hat{a}_2 \hat{\rho}_{cc} - \hat{\rho}_{gg}, \\
\dot{\hat{\rho}}_{cc} &= -(\gamma_{ec} + i\omega_{eg})\hat{\rho}_{cc} + i\hat{a}_2^\dagger \hat{\rho}_{eg} - H.c.],
\end{align*}
\]
QE coupling and population inversion are when sharper resonance QE(s) are used. = rate [20], e.g., by the second term of the presence of the QE, the SHG of the MNS is governed depicted in the inset of Fig. 2. We remark that without unity (1 = 0.05), we observe that the log-neg can be tuned continuously by 5-orders of magnitude (∆ω ≈ 10⁴) compared to their decay rates controlling field amplitudes. For this reason, empirically, we need to consider a smaller decoherence rate Γ, for the noise operators (a_1, a_2). (We also present our results with Γ = 1, which is for convenience, though not reliable physically.)

First, we calculate the entanglement between the reflected (a_{out}) and transmitted (b_{out}) pulses, see Fig. 1. We calculate the logarithmic-negativity (EN), which is an entanglement measure for Gaussian states [31]. As we use the standard linearization method [32] for calculating the evolution of the noise operators, the fields stay Gaussian and EN can be employed as a measure. In Fig. 2, we observe that the log-neg can be tuned continuously on and off between ω_{eg} = 2ω and ω_{eg} = 2.001ω.
Next, we also calculate the single-mode nonclassicality of the transmitted wave $b_{\text{out}}$. We employ the entanglement potential \[ \mathcal{N}_{\text{SMNC}} \] as measure for the single-mode nonclassicality. Only a nonclassical single-mode state can create entanglement at the output of a beam-splitter. Entanglement potential is the degree of entanglement a nonclassical state creates at the beam-splitter output, which can also be quantified in terms of log-neg. We remind that not all of the nonclassicality of a mode could be converted into entanglement at the beam splitter output. In Fig. 3 we observe that $\mathcal{N}_{\text{SMNC}}$ can similarly be continuously tuned by several orders of magnitude via a $\sim$ meV adjustment of the QE level-spacing. Such a modulation in the quantized energy level spacing of the colloidal quantum dots up to 25 meV is succeeded in Ref. [24].

Therefore, one can use the (i) entanglement of two pulses propagating in opposite directions or (ii) convert the nonclassicality of the transmitted $b_{\text{out}}$ pulse into entanglement on the right hand side using an integrated beam splitter. Such a modulation is important for generating the nonclassicality when the desired pulse is passing through the device, but turning it off for an unwanted pulse. We note that the sample setup, Fig. 1 can also be placed into a smaller cavity.

In summary, we introduce a micron-scale quantum entanglement device which can be integrated into (quantum) photonic circuits. The nonclassicality can be supplied into the integrated quantum circuit on demand by applying a voltage on the device. Unlike the integrable quadrature squeezing generators presented in the literature [9, 57–59], the nonclassicality can be turned off also when a pulse is passing through the device. The voltage can also continuously tune the degree of the generated entanglement/nonclassicality. The linear response of the device is not altered by voltage. Although we study the tuning of nonclassicality on a second harmonic generation process here, the same method can be applied also on the the voltage-tuning of other nonlinear processes. The details of our calculations following the standard methods can be found in the SM [13].

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