Correlation and squeezing for optical transistor and intensity router applications in diamond NV center

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We study an optical transistor (switch and amplifier) and router by spontaneous parametric four-wave mixing and fluorescence in diamond nitrogen-vacancy (NV) center. The routing results from three peaks of fluorescence signal in the time domain, while the switching and amplification are realized by correlation and squeezing. The intensity switching speed is about 17 ns. The optical transistor and router are controlled by the power of incident beams. Our experimental results provide that the advance technique of peak division and channel equalization ratio of about 90% are applicable to all optical switching and routing. ©2017 Optical Society of America

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Photon correlation and squeezing have been extensively studied theoretically and experimentally. Entanglement between classical and non-classical photons is identified as a useful resource for optical quantum information processing [1]. Photon entanglement also has potential applications for quantum information processing and long distance communication [2,3] and quantum metrology [4,5]. However, for the actual implementation of quantum technology, some challenges still remain. First, quantum computation and quantum communication require extended period of coherence time [5]. The Pr3+:Y2SiO5 and diamond nitrogen-vacancy (NV) crystals have ‘atom-like’ properties, with long coherence times and narrow spectral width, compared to traditional spontaneous parametric down conversion process [6,7]. The negatively charged nitrogen-vacancy (NV−) center in diamond is an individually addressable electronic spin that can be initialized and read out optically at room temperature [8]. The motivation behind this Letter is that optical manipulation techniques are important for the development of integrated nanophotonic systems for diamond-based scalable quantum optical devices and quantum networks [9,10]. The second incentive is lifetime of multi-order fluorescence (FL) and spontaneous parametric four-wave mixing (SP-FWM) processes, which are controlled by the nonlinear effect in a NV center crystal [11].

We used two tunable dye lasers (narrow scan with a 0.04 cm−1 linewidth) pumped by an injection-locked single-mode Nd:YAG laser (Continuum Powerlite DLS 9010, 10 Hz repetition rate, 5 ns pulse width), which are used to generate the pumping fields $E_1(\omega_1, \Delta_1)$, 575 nm and $E_2(\omega_2, \Delta_2)$, 637 nm with the frequency detuning $\Delta_1 = \Delta_1^G + \Delta_2$ and $\Delta_2 = \Delta_2^G$, respectively, and $\Delta_1^G = \omega_{\text{ina}} - \omega_1 (i = 1, 2)$, where $\omega_{\text{ina}}$ denotes the transition frequency between levels $\Delta_2^G$ and the detuning corresponding phonon relaxation.

The sample used in this experiment is doped nitrogen in bulk diamond crystal, which generated two sites due to two different charge states. The NV center is treated as a three-level system with ground triplet state $|3A_2\rangle$, and two sublevels in a triplet excited state $|3E\rangle$. The ground and excited states of NV0 are labeled by $^2E$ and $^2A_1$. Our major focus in this Letter is NV−; the triplet ground state $^3A_2$ splits due to spin-spin interaction of $D_{ij} = 2.88$ GHz [12] between $|^3A_2, m_i = 0\rangle$ and $|^3A_2, m_i = \pm 1\rangle$. Now we discuss a $V$-type system, by opening fields $E_1$ and $E_2$, FL signal is generated via perturbation chain as $\rho_{00} \rightarrow \rho_{10} \rightarrow \rho_{11} \rightarrow \rho_{20} \rightarrow \rho_{21}$, [13]

$$ (a_1)\rho_{21}^{(4)} = G_{1}^2 G_{2}^2 (\Gamma_{10} + i \Delta_{2}^G) \Gamma_{00} (\Gamma_{20} + i \Delta_{2}^G) \Gamma_{22}^G, \quad (1) $$

$$ (a_2)\rho_{21}^{(4)} = G_{1}^2 G_{2}^2 (\Gamma_{10} + i \Delta_{2}^G) \Gamma_{00} (\Gamma_{20}^* + i \Delta_{2}^G) \Gamma_{22}^G \quad (2) $$

where a single steric defines the decay rates from direct transition, and double steric is the decay rate after considering the lattice relaxation. Similarly for a two-level system with a field $E_1$, FL signal is generated through the perturbation chain, which can be defined as
By opening field $\Gamma$, moment $V$ will occur in the paraxial direction due to phase-matching. Meanwhile the two step lifetimes, $\Gamma_c = \Gamma_{10}^* + \Gamma_{11}$ and $\Gamma_b = \Gamma_{10}^* + \Gamma_{11}^*$, are for a two-level system.

Then, $\Gamma_c = \Gamma_{10}^* + \Gamma_{00} + \Gamma_{20}^* + \Gamma_{22}^*$ and $\Gamma_d = \Gamma_{10}^* + \Gamma_{00} + \Gamma_{20}^* + \Gamma_{22}^*$ are for the $V$-level system, where $\Gamma_i = -\mu_i E_i/\hbar$ is the Rabi frequency of $E_i$ with the electric dipole moment $\mu_i$ between levels $|i\rangle$ and $|j\rangle$, and $\Gamma_{ij}$ is the transverse decay rate. In addition to the FL signals, the SP-FWM signal will occur in the paraxial direction due to phase-matching of the FWM process in two-levels and the $V$-type system.

By opening field $E_1$, Stokes $E_s$ and anti-Stokes $E_{as}$ are generated with phase-matching conditions $k_{as} = k_1 + k_2 - k_3$, and $k_3 = k_2 + k_1 - k_{as}$ respectively. Both $E_s$ and $E_{as}$ are detected by a pair of points that are symmetrical at photomultiplier tube PMT1 and PMT3, as depicted in Fig. 1(a). The perturbation chain for respective Stokes and anti-Stokes in the $V$-type level system are $\rho_{00} \rightarrow \rho_{10} \rightarrow \rho_{20} \rightarrow \rho_{20} \rightarrow \rho_{00}$, and $\rho_{00} \rightarrow \rho_{10} \rightarrow \rho_{00} \rightarrow \rho_{20} \rightarrow \rho_{00}$. The density matrix for Stokes and anti-Stokes in a $V$-type system can be written as

\[
(a_0, \rho_{10})_{\rho_{10}(S)} = -i G_{1S} G_{1/2} (\Gamma_{10} + \Delta_2^s) \times \{\Gamma_{00} + i(\Delta_2^s - \Delta_1)\} (\Gamma_{10} + i\Delta_2^s),
\]

\[
(b_0, \rho_{10})_{\rho_{20}(S)} = -i G_{1S} G_{1/2} (\Gamma_{10} + \Delta_1) \times \{\Gamma_{00} + (\Delta_2 - \Delta_1)\} (\Gamma_{20} + 1\Delta_1).
\]

Similarly, the density matrix for Stokes and anti-Stokes in two-level system can be written as

\[
(a_0, \rho_{10})_{\rho_{10}(S)} = -i G_{1S} G_{1/2} (\Gamma_{10} + \Delta_2^s) \times \{\Gamma_{00} + i(\Delta_2^s - \Delta_1)\} (\Gamma_{10} + i\Delta_2^s),
\]

\[
(b_0, \rho_{10})_{\rho_{20}(S)} = -i G_{1S} G_{1/2} (\Gamma_{10} + \Delta_1) \times \{\Gamma_{00} + (\Delta_2 - \Delta_1)\} (\Gamma_{20} + 1\Delta_1).
\]

\[
(c_0, \rho_{10})_{\rho_{10}(S)} = -i G_{1S} G_{1/2} (\Gamma_{10} + \Delta_2^s) \times \{\Gamma_{00} + i(\Delta_2^s - \Delta_1)\} (\Gamma_{10} + i\Delta_2^s),
\]

\[
(d_0, \rho_{10})_{\rho_{20}(S)} = -i G_{1S} G_{1/2} (\Gamma_{10} + \Delta_1) \times \{\Gamma_{00} + (\Delta_2 - \Delta_1)\} (\Gamma_{20} + 1\Delta_1).
\]

\[
(e_0, \rho_{10})_{\rho_{10}(S)} = -i G_{1S} G_{1/2} (\Gamma_{10} + \Delta_2^s) \times \{\Gamma_{00} + i(\Delta_2^s - \Delta_1)\} (\Gamma_{10} + i\Delta_2^s),
\]

\[
(f_0, \rho_{10})_{\rho_{20}(S)} = -i G_{1S} G_{1/2} (\Gamma_{10} + \Delta_1) \times \{\Gamma_{00} + (\Delta_2 - \Delta_1)\} (\Gamma_{20} + 1\Delta_1).
\]

Similar to fluorescence, the generation process of Stokes and anti-Stokes also have three transition pathways and the three steps lifetimes, which are $\Gamma_{(s)} = \Gamma_{20} + \Gamma_{00} + \Gamma_{10}; \Gamma_{(as)} = \Gamma_{10} + \Gamma_{00} + \Gamma_{20}$ for $V$-type and $\Gamma_{(s)} = \Gamma_{10} + \Gamma_{00} + \Gamma_{20}$, for a two-level system. The coupling Hamiltonian for the SP-FWM process is defined as $H = \Delta_3 \Delta_3^s + \Delta_3 \Delta_3^s$, where $\Delta_3^s$ and $\Delta_3^s$ are creation and annihilation operators acting on Stokes and anti-Stokes signals, respectively, while $\nu$ is the velocity of the field in the nonlinear medium. The nonlinear gain $g = |\langle -i \nu S_{as} \rangle^\dagger S_{as}^\dagger E_1 E_2/2\rangle|$, where $i = 1, 2$, depends on the nonlinear susceptibility $\chi^{(3)}_{S.;as}$ and the pumping field amplitude, where $\chi^{(3)}_{S.;as} = (N \mu_{S.;as} \rho_{3,(S.;as)}^S) / (c_0 E_1 E_2 E_{S.;as})$. We fit our time domain multi-peak signals in Fig. 2 with

\[
I_1(t) \propto \rho_{10}(S)^2 e^{\nu t/\Gamma_{1}} \times \rho_{20}(S)^2 e^{-\nu t/\Gamma_{2}} + \rho_{00}(S)^2 e^{-\nu t/\Gamma_{0}} \times \rho_{20}(S)^2 e^{-\nu t/\Gamma_{2}},
\]

where the different delay times $t_{0}$ and $t_{0}'$ correspond to different population transitions from the excited state back to the ground state manifold. $\Gamma_{1,2,3}$ is the decay rate of signal intensity for three peaks.

Figures 2(a) and 2(b) show the time domain composition of SP-FWM and FL with increasing power of $E_1$, from low to high.
high in the two-level and $V$-type systems, respectively. Figure 2(a7) is a zoomed-in figure of Fig. 2(a3). From Fig. 2(a7), one can see that each signal has two peaks. The first sharp peaks, dotted in the blue line, show SP-FWM, while the second broad peaks with the red dotted line shows FL. With power increasing, the total intensity of the composite signal increases, while the proportion of SP-FWM in the composite signal decreases as power increases. At low power, the sharp peaks are more obvious in contrast to broad peaks, which can be exploited for controlled amplification. We observed that the highest amplification ratio of an optical transistor is about 8.5 from Fig. 2(b) [14].

Figures 2(c) and 2(d) show the third peak in time domain in the two-level and $V$-type systems, respectively. It results from the phonon-assisted transition from the triplet state to the metastable singlet state (MS), which then repopulates to the triplet state with FL emission. So it has a time delay in the time domain, as shown in Figs. 2(g) to 2(a2). We can clearly find that the intensity of the third peak is proportional to the power of $E_1$. The transistor switch is realized by the results observed in Figs. 2(c) and 2(d) in the time domain, where FL is input $a_{\text{input}}$, $E_1$ is a control signal (analogous to the gate voltage and base current in the case of MOSFET and BJT, respectively), and $a_{\text{output}}$ is output of the transistor. We can say that the time domain FL in Fig. 2(d) shows analogy with the $p$-type emitter and collector and $n$-type base (PNP) switch transistor. When the input beam $E_1$ is fixed at low power, the gain effect will be off-logic at the baseline shown in Fig. 2(d1), and when power is high, the gain effect is in the ON-state, as shown in Fig. 2(d3). Furthermore, the transistor switch will remain in the ON-state as $I > 0$, and it will remain in the OFF-state until $I \leq 0.3$, as shown in Fig. 2(d1), where $I$ is the intensity. Our experiment result defined the switching contrast as $C = (I_{\text{off}} - I_{\text{on}}) / (I_{\text{off}} + I_{\text{on}})$, then $C = 90\%$. The speed of the transistor switch in the FL time domain can be given by the OFF-state, and it is observed to be 6 ns at Fig. 2(d1), followed by 11 ns as rising time, and 6 ns, given by ON-state at Fig. 2(d3), followed by 11 ns of falling time. The $E_1$ field is controlled by an electro-optical modulator, and the speed is 10 ns. The switching speed is controlled by the atomic coherence time that is mutable by the phonon effect from microseconds to nanoseconds. The total switching speed (17 ns) is taken to be the quadrature sum of several independent contributions.

Figure 2(e) shows the delay time of the third peak changes with the power of $E_1$; we can observe the shifting of the peak to the right as the power of $E_1$ decreases in Figs. 2(e1)–2(e4) in the two-level system. This is because the population transfer rate assisted by the phonon for the third peak increases with larger laser power. Figure 2(f) shows a similar phenomenon in the $V$-type system. We can use such multiple channel signals as routing in the time domain. Our experiment provides a physical mechanism to realize all optical routing in the time domain by controlling laser power. By proceeding this, we can see the division of the first peak ($\delta_0$) into two peaks due to the power of $E_1$, as shown in the zoomed out curve 2 [Fig. 2(e5)] of Fig. 2(e3). Therefore, the corresponding switching ratio of our routing is about 3. Such results can be exploited for time division multiplexing (TDM) or routing. Here, we use the channel equalization ratio $P = 1 - \sqrt{\sum_{n=1}^{N}(S_n - S)^2 / S}$ [14] to measure the de-multiplexing effect, where $s_n$ is the area of each peak, $s$ is the area of each peak or gap between peaks, and $N$ is the total number of peaks after conversion. When $P$ is near 100\%, we shall obtain more balanced and stable spatial channels. Here the channel equalization $P$ can approach 80\%–90\%. For conversion modulations, we can obtain the contrast index $\eta$ in this experiment. It can be expressed as $\eta = (t^\prime - t) / (t^\prime + t)$, where $(t^\prime - t)$ is delay time or time gap (blank area) between two neighboring peaks in the area of Fig. 2(e5). If $\eta$ is larger, the peaks will become more separated, the de-multiplexing effect will be better for the all optical routing de-multiplexer, and there will be little crosstalk between them, indicating greater accuracy of information. In this experiment, contrast index $\eta$ can reach about 80\%–90\%, and the average power of our routing can be operated at 0.7–2.0 $\mu$W.

Subsequently, we shall discuss two-mode correlation and squeezing between $E_1$, $E_{as}$, and FL signals. By changing the power of $E_1$, as described in Fig. 2(a), the intensity noise correlation of Stokes and anti-Stokes are calculated using their time-dependent intensity fluctuation traces of SP-FWM evaluation at low (1.5 mW), medium (5.5 mW), and high power (10 mW). The intensity noise correlation function $G^{(2)}_{E_1as}(\tau)$ between Stokes and anti-Stokes can be described as $G^{(2)}_{E_1as}(\tau) = (\langle \delta I_s(t_1) \delta I_{as}(t_2) \rangle / \langle \delta I_s(t_1) \rangle^2 < (\delta I_{as}(t_2) \rangle)^2$, where $\tau$ is the selected time delay and $\delta I_s(t_2)$, $\delta I_{as}(t_2)$ are intensity fluctuations.

Figure 3(b) shows the two-mode intensity difference squeezing calculated by $S_q^{(2)} = \log_2(\delta^2(\hat{I}_s - \hat{I}_{as}) / \delta^2(\hat{I}_s + \hat{I}_{as}))$. The black and red lines represent the intensity sum squeezing and intensity difference squeezing, respectively. Consequently, we can analyze our amplification result by squeezing “$S_q$” between the black and red lines displayed in Figs. 3(b1)–3(b4). We can see that the difference at low power is $S_q = -1$ in Fig. 3(b1); at medium power it is $S_q = -2$ in Fig. 3(b2); and at high power it is $S_q = -5$ and -6 in Figs. 3(b3) and 3(b4), respectively. By considering the result-oriented judgments of squeezing, we shall now discuss the transistor realization as an amplifier, as shown in Fig. 1(d). Here the second mode correlation function, or second order squeezing, are treated as input $a_{\text{input}} = a_{\text{(as)}}$, or $a_{\text{input}} = a_{\text{(as)}}^*; E_1$ is the control signal and $a_{\text{output}}$ is the output of transistor, while $N$ is the internal noise. Thus, one can model the transistor as an amplifier with the output $a_{\text{output}} = a_{\text{input}}G + N$. When $E_1$ power reaches from 5.5 mW to 10 mW, the output $a_{\text{output}}$ will be amplified via gain ($G$), as shown in Figs. 3(a1)–3(a4). This phenomenon can be termed as optical amplifier.

![Figure 3](image-url)
In Fig. 4, we discuss the two-mode correlation and squeezing between a composite signal with Stokes (anti-Stokes) and fluorescence. We acquired these results by changing the power of $E_1$ in the V-type system. In Figs. 4(a1)–4(a4), the value of the correlation varies with the generating field $E_1$. The switching correlation can be explained by the effect of many factors at the same time, such as population fluctuations, the nonlinear phase, and the initial phase. Here the correlation increases with the increase in power, $P_1$, due to the gain effect of generating field $E_1$.

When power, $P_1$, of $E_1$ is set at medium power, the correlation function $G^{(2)}_{\text{FL}}(\tau)$ is negative at delay time $\tau = 0$ µs, as shown in Figs. 4(a1) and 4(a2), due to a small population fluctuation of $f^{(2)}(t) \rightarrow 0$ as predicted by $G^{(2)}_{\text{FL}}(0) = -[f(t) + f^2(t)]/\sqrt{|f(t) + f^2(t)|^2}$, where $f = |\sqrt{i}|$. Now we evaluate the squeezing to find our switching results. In Figs. 4(b1)–4(b4), the black line defines the sum and the red line elaborates on the difference. The difference at 0.7 mW between the distinct lines is $S_q = -2$ in Fig. 4(b1) and $S_q = 1$ in Fig. 4(b2); at 1 mW, the results are $S_q = -4$ and $-7$ in Figs. 4(b3) and 4(b4), consecutively. The model of the transistor is shown in Fig. 1(c), where the composite signal is illustrated in the time domain and can be treated as input ($a_{\text{input}}$) for the model transistor. $E_1$ is a control signal (analogous to the gate voltage and base current in the case of metal oxide semiconductor field effect transistor [MOSFET] and bipolar junction transistor [BJT], respectively) and $a_{\text{output}}$ is the output of the transistor. Further, we can define switching contrast by our experiment as $C = -1$, where $I_{\text{on}}^\text{eff}$ is the OFF-state when $G^{(2)}_{\text{FL}}(\tau) < 0.2$, while $I_{\text{off}}$ is the ON-state when $G^{(2)}_{\text{FL}}(\tau) > 0.2$.

Figure 5 shows the experimental results of the three-mode correlation and squeezing in the $V$-type system. The total intensity of the composite signal is $\rho = \rho_{\text{FL}} + \rho_{\text{SP-FWM}}$, where $\rho_{\text{FL}}$ is from PMT2 and $\rho_{\text{SP-FWM}} = \rho_{\text{S}}^{(3)}$ or $\rho_{\text{S}}^{(1)}$ is from PMT1 and PMT3, respectively. The intensity fluctuations $\delta \hat{I}_j(\tau_j)$, $\delta \hat{I}_S(\tau_S)$, and $\delta \hat{I}_\text{FL}(\tau)$ are recorded, and intensity noise correlation among $E_1$, $E_\text{S}$, and FL can be defined as $G^{(3)}(\tau_1, \tau_2, \tau_3) = \langle (\delta \hat{I}_j(\tau_j))(\delta \hat{I}_j(\tau_j))(\delta \hat{I}_\text{FL}(\tau)) \rangle / \sqrt{\langle (\delta \hat{I}_j(\tau_j))^2 \rangle \langle (\delta \hat{I}_j(\tau_j))^2 \rangle \langle (\delta \hat{I}_\text{FL}(\tau))^2 \rangle}$. We can see in Fig. 5(a) that the peak intensities decrease continuously from left to right with the power of $E_1$ decreasing. Figure 5(b) shows three-mode intensity difference squeezing calculated from

$$S_q^{(3)} = \text{Log}_{10}(\text{Stokes} - \text{anti-Stokes}/\text{fluorescence})$$

which has a similar dependence on the power of $E_1$.

In summary, we have presented a model of switching/routing and amplification by using compositional signals of multiorder FL and SP-FWM in NV center.

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