Chin. Phys. B Vol. 22, No. 8 (2013) 080304

Effect of excess noise on continuous variable entanglement sudden death and Gaussian quantum discord*

Su Xiao-Long(苏晓龙)†

State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, *China*

(Received 10 January 2013; revised manuscript received 6 March 2013)

A symmetric two-mode Gaussian entangled state is used to investigate the effect of excess noise on entanglement sudden death and Gaussian quantum discord with continuous variables. The results show that the excess noise in the channel can lead to entanglement sudden death of a symmetric two-mode Gaussian entangled state, while Gaussian quantum discord never vanishes. As a practical application, the security of a quantum key distribution (QKD) scheme based on a symmetric two-mode Gaussian entangled state against collective Gaussian attacks is analyzed. The calculation results show that the secret key cannot be distilled when entanglement vanishes and only quantum discord exists in such a QKD scheme.

Keywords: continuous variable, entanglement, quantum key distribution

PACS: 03.67.Hk, 03.67.Dd, 42.50.Dv, 42.50.–p **DOI:** 10.1088/1674-1056/22/8/080304

1. Introduction

Quantum entanglement is a basic resource for quantum information processing. A troublesome problem in practical application is that quantum entanglement is sensitive to environment-induced loss. In the discrete variable case, it has been shown that entanglement can be completely lost after a finite time of interaction with the environment for a two-qubit system, which is known as entanglement sudden death (ESD).[1,2] The continuous variable (CV) system is an alternative system to investigate quantum information and has obtained remarkable progress.[3,4] It has been observed that losses may lead to ESD in Gaussian CV systems too.[5–7]

Quantum correlation, which is measured by quantum discord,[8] can also be used as the quantum resource in some types of quantum information processing tasks. It has been shown that some quantum computational tasks based on a single qubit can be carried out by separable (that is, non-entangled) states that nonetheless carries non-classical correlations.[9–11] Recently, quantum discord was extended to a two-mode Gaussian state.[12,13] A two-mode Gaussian state is entangled with Gaussian quantum discord $D > 1$, while when $0 \leq D \leq 1$ it is either a separable or entangled state. Gaussian quantum discord has been experimentally demonstrated by several groups.[14–16]

Quantum key distribution (QKD) allows two legitimate parties, Alice and Bob, who are linked by a quantum channel and an authenticated classical channel, to establish the secret key only known by themselves. Generally CV QKD uses a Gaussian quantum resource state, such as entangled state, squeezed state, and modulated coherent state, as the resource state, along with a reconciliation and privacy amplification procedure to distill the secret key.[4,17,18] In the practical applications, quantum channels not only are lossy, but also have excess Gaussian noises on the quadrature distribution. For a given tolerable channel efficiency T, there exists a lower limit for excess noise δ, which is given by $\delta < 2T$.[19] CV QKD protocols have been shown to be unconditionally secure, that is, secure against arbitrary attacks[20] and have been proved to be unconditionally secure over long distance.[21] Besides the traditional one-way CV QKD scheme, a two-way CV QKD scheme has been proposed and proved to be able to tolerate more excess noise than one-way CV QKD scheme.[22,23] Recently, a CV QKD scheme with thermal states was also proposed and proved to be secure against collective Gaussian attacks.[24] The CV QKD exploiting coherent state[25–31] and entangled state[32–34] have been experimentally realized in recent years.

In Ref. [7], it is shown that a symmetric two-mode Gaussian entangled state is a fully robust state, which means that entanglement never vanishes with any type of loss in the channel. However, the practical quantum channels not only are lossy, but also have excess Gaussian noises. In this paper, we analyze the effect of the excess noise in the channel on ESD and Gaussian quantum discord of a symmetric two-mode Gaussian entangled state. The calculation shows that the excess noise in the channel is the key factor that leads to ESD for a symmetric two-mode Gaussian entangled state. The excess noise also leads to a decrease of the Gaussian quantum discord, but it never makes the quantum discord vanish.[12,13] As an example of practical application, the security of a QKD scheme based on a symmetric two-mode Gaussian entangled state is also analyzed. The relation among the secret key rate,

*Project supported by the National Basic Research Program of China (Grant No. 2010CB923103), the National Natural Science Foundation of China (Grant Nos. 11174188 and 61121064), and the Fund from the Shanxi Scholarship Council of China (Grant No. 2012-010).

†Corresponding author. E-mail: suxl@sxu.edu.cn

 http://iopscience.iop.org/cpb http://cpb.iphy.ac.cn

entanglement, and quantum discord is analyzed. What we are interested in is whether the secret key can be distilled when entanglement vanishes and only quantum correlation exists. The calculation results show that it is impossible to distill the secret key when entanglement vanishes and only quantum correlation exists. It confirms that entanglement is a precondition for QKD with a two-mode Gaussian entangled state.[35] It also supplies a possible way to destroy, instead of eavesdrop, this type of CV QKD scheme where a two-mode Gaussian entangled state is used as a resource state.

The paper is organized as follows. In Section 2, the physical model used to investigate the effect of excess noise on CV ESD and Gaussian quantum discord is presented. In Section 3, the ESD and Gaussian quantum discord under influence of excess noise are analyzed. In Section 4, the security of CV QKD scheme based on a symmetric two-mode Gaussian entangled state is proved, and the relation between secret key rate, ESD, and Gaussian quantum discord is analyzed. In Section 5, we conclude the paper.

2. Physical model

The physical model used to analyze the effect of excess noise on ESD and Gaussian quantum discord is shown in Fig. 1. A symmetric two-mode Gaussian entangled state with a variance of V, such as a symmetric Einstein–Podolsky–Rosen (EPR) entangled state, is used as the resource state, which is distributed between Alice and Bob. One of the two-mode Gaussian states ($\hat{b}$) is transmitted through a lossy channel, which is modeled by a beam splitter with transmission efficiency T. The excess noise in the channel is modeled by an environmental thermal state $\rho_{\rm E}$ with variance W, which corresponds to $\delta = W-1$ in Ref. [19] and $\varepsilon = (W-1)(1-T)/T$ in Ref. [29]. $W = 1$ means there is no excess noise ($\delta = 0$) in the channel, only loss exists. When $W > 1$, there is excess noise in the channel.

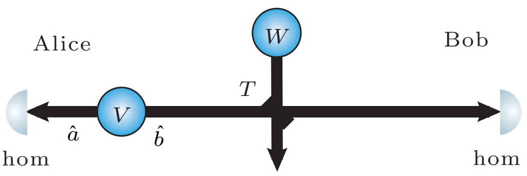

Fig. 1. (color online) Schematic plot of a symmetric two-mode Gaussian entangled state distributed between Alice and Bob through a lossy channel with excess noise. The transmission efficiency of quantum channel is modeled by a beam splitter with transmission T. Excess noise in the channel is modeled by an environmental thermal state $\rho_{\rm E}$ with variance W. Alice and Bob perform homodyne (hom) detection on the mode they hold, respectively.

The amplitude and phase quadratures of an optical mode $\hat{a}$ is defined as $\hat{X}_a = \hat{a}+\hat{a}^\dagger$ and $\hat{Y}_a = (\hat{a}-\hat{a}^\dagger)/\mathrm{i}$, respectively. A Gaussian state is fully characterized by its covariance matrix. The covariance matrix is constructed using the following definitions of its matrix elements

$$V_{lm} :\ = \frac{1}{2}\langle \hat{O}_l\hat{O}_m + \hat{O}_m\hat{O}_l\rangle - \langle \hat{O}_l\rangle\langle \hat{O}_m\rangle, \tag{1}$$

$$V_{ll} = \langle \hat{O}_l^2\rangle - \langle \hat{O}_l\rangle^2 :\ = V(\hat{O}_l), \tag{2}$$

where $\hat{O}_l$ is the l-th element of the quadrature row vector $\hat{O} = (\hat{X}_1, \hat{Y}_1, \ldots, \hat{X}_N, \hat{Y}_N)$ which describes the bosonic system of N modes. The covariance matrix of a symmetric two-mode Gaussian state is given by

$$\boldsymbol{\sigma} = \begin{pmatrix} V\boldsymbol{I} & C\boldsymbol{Z} \\ C\boldsymbol{Z} & V\boldsymbol{I} \end{pmatrix}, \tag{3}$$

where $V = \cosh 2r$ with squeezing parameter $r \in [0,\infty)$ is the noise variance of EPR entangled modes $\hat{a}$ and $\hat{b}$, $C = \sqrt{V^2-1}$, $\boldsymbol{I}$ and $\boldsymbol{Z}$ are the Pauli matrices

$$\boldsymbol{I} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \quad \boldsymbol{Z} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}. \tag{4}$$

The entanglement between Alice and Bob is contaminated by loss and excess noise in the channel. After transmission, the amplitude and phase quadratures at Bob's station are given by

$$\hat{X}_{\rm B} = \sqrt{T}\hat{X}_{\rm b} + \sqrt{1-T}\hat{X}_W, \tag{5}$$

$$\hat{Y}_{\rm B} = \sqrt{T}\hat{Y}_{\rm b} + \sqrt{1-T}\hat{Y}_W, \tag{6}$$

where $\hat{X}_W$ and $\hat{Y}_W$ are the amplitude and phase quadratures of the environmental thermal state $\rho_{\rm E}$. Then the covariance matrix of the two-mode Gaussian state distributed between Alice and Bob is given by

$$\boldsymbol{V}_{\rm AB} = \begin{pmatrix} V\boldsymbol{I} & C'\boldsymbol{Z} \\ C'\boldsymbol{Z} & V_{\rm B}\boldsymbol{I} \end{pmatrix}, \tag{7}$$

where $V_{\rm B} = TV + (1-T)W$, $C' = \sqrt{T(V^2-1)}$.

3. Entanglement and quantum discord of the system

The symplectic spectrum of a covariance matrix

$$\boldsymbol{\sigma} = \begin{pmatrix} \boldsymbol{A} & \boldsymbol{C} \\ \boldsymbol{C} & \boldsymbol{B} \end{pmatrix} \tag{8}$$

is given by[36,37]

$$\nu_{\pm} = \sqrt{\frac{\Delta \pm \sqrt{\Delta^2 - 4\det\boldsymbol{\sigma}}}{2}}, \tag{9}$$

where $\boldsymbol{A}$ ($\boldsymbol{B}$) denotes the covariance matrix of mode $\hat{a}$ ($\hat{b}$), $\boldsymbol{C}$ contains correlations between quadratures of the two modes, $\det\boldsymbol{\sigma}$ is the determinant of covariance matrix and $\Delta = \det\boldsymbol{A} + \det\boldsymbol{B} + 2\det\boldsymbol{C}$.

PPT criterion is a necessary and sufficient criterion for entanglement of a Gaussian state.[38,39] A Gaussian state is entangled iff $\tilde{\nu}_- < 1$, where $\tilde{\nu}_-$ is the smallest symplectic eigenvalue of partially transposed covariance matrix for a two-mode Gaussian state, which is given by[36,37]

$$\tilde{\nu}_- = \sqrt{\frac{\tilde{\Delta} - \sqrt{\tilde{\Delta}^2 - 4\det\boldsymbol{\sigma}}}{2}}, \tag{10}$$

where $\tilde{\Delta} = \det \boldsymbol{A} + \det \boldsymbol{B} - 2\det \boldsymbol{C}$. Substituting the corresponding terms of matrix $\boldsymbol{V}_{\rm AB}$ in Eq. (7) into Eq. (10), we can verify whether the two-mode Gaussian state is entangled or not after the transmission.

Quantum discord is defined as the difference between two quantum analogues of classically equivalent expression of the mutual information. The Gaussian quantum discord of a two-mode squeezed thermal state is given by[12]

$$D_{\rm AB} = f(\sqrt{I_2}) - f(\nu_-) - f(\nu_+) + f\left(\frac{\sqrt{I_1} + 2\sqrt{I_1 I_2} + 2I_3}{1 + 2\sqrt{I_2}}\right), \tag{11}$$

where

$$f(x) = \left(x + \frac{1}{2}\right)\log_2\left(x + \frac{1}{2}\right) - \left(x - \frac{1}{2}\right)\log_2\left(x - \frac{1}{2}\right),$$

$I_1 = \det \boldsymbol{A}$, $I_2 = \det \boldsymbol{B}$, and $I_3 = \det \boldsymbol{C}$. When $D_{\rm AB} > 1$, the state is an entangled state, while when $0 \le D_{\rm AB} \le 1$, the state is either separable or entangled. When $D_{\rm AB} < 0$, there is no quantum correlation, only classical correlation between two modes. Substituting the corresponding terms of matrix $\boldsymbol{V}_{\rm AB}$ in Eq. (7) into Eq. (11), we can calculate the Gaussian quantum discord between Alice and Bob.

Figure 2(a) shows the smallest symplectic eigenvalues of partially transposed covariance matrix for $r = 0.35$ (3-dB quantum correlation, solid line) with $W = 1$, $r = 1.15$ (10-dB quantum correlation) with $W = 1$ (dotted line), and $W = 1.5$ (dashed line), respectively. For $r = 0.35$ and $r = 1.15$ with $W = 1$, we have $\tilde{\nu}_- < 1$ at any transmission efficiency, which clearly shows that entanglement is robust against loss. When $r = 1.15$ with $W = 1.5$, i.e. there is excess noise $\delta = 0.5$ in the channel, $\tilde{\nu}_-$ is larger than 1 when transmission efficiency is smaller than 0.2, which means that entanglement vanishes due to excess noise in the channel. This result confirms that excess noise can lead to ESD of a symmetric Gaussian entangled state. For avoiding ESD, we have to eliminate or minimize the excess noise in the transmission channel.

Figure 2(b) shows the Gaussian quantum discords for $r = 0.35$ (solid line) with $W = 1$, $r = 1.15$ with $W = 1$ (dotted line) and $W = 1.5$ (dashed line), respectively. In all the cases, we see that Gaussian quantum discord increases with the increase of transmission efficiency of the channel. For $r = 0.35$ with $W = 1$, $D_{\rm AB}$ is always smaller than 1, which means that the transmitted state is either separable or entangled state. For $r = 1.15$ with $W = 1$ and $W = 1.5$, $D_{\rm AB}$ is larger than 1 when transmission efficiency is larger than 0.68 and 0.85, respectively. It means that for higher transmission efficiency, the state is an entangled state ($D_{\rm AB} > 1$). With the decreasing of transmission efficiency and increasing of excess noise, the state may be turned into either separable or entangled state.

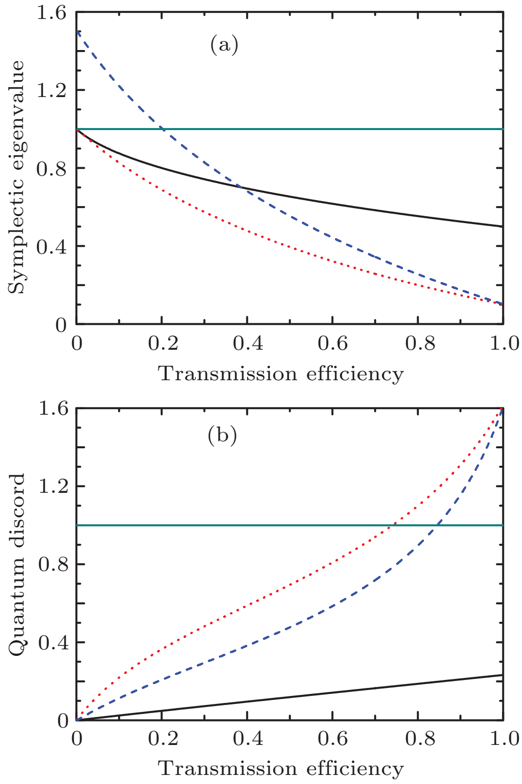

Fig. 2. (color online) (a) Symplectic eigenvalues with different variances of resource state and (b) Gaussian quantum discords with different variances of resource state. Dotted (red) and solid (black) lines in panels (a) and (b) correspond to $r = 1.15$ and $r = 0.35$ with $W = 1$, respectively. Dashed (blue) lines in panels (a) and (b) correspond to $r = 1.15$ with $W = 1.5$.

4. Security of the QKD with a symmetric two-mode Gaussian entangled state

As an example, we apply a symmetric two-mode Gaussian entangled state to be the resource state for a QKD scheme, which is shown in Fig. 3. In the QKD scheme, Alice holds mode $\hat{a}$, and transmits mode $\hat{b}$ to Bob over the quantum channel with transmission efficiency T. Alice and Bob perform homodyne detection on their own beam randomly to measure amplitude or phase quadrature, respectively. The secret key is established by the quantum fluctuation of each quadrature. There are two advantages of this QKD scheme, one is that the true random numbers resulting from the quantum fluctuations are used to establish the secret key. The other is that no signal modulation is

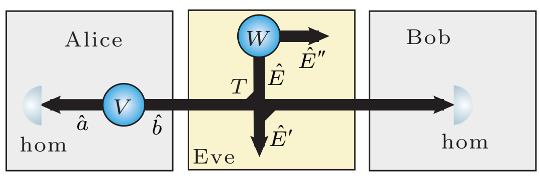

Fig. 3. (color online) Schematic of the QKD scheme with an EPR entangled state. The transmission efficiency of the quantum channel is modeled by a beam splitter with transmission T. Eve performs an entangling cloner attack, where the variance of the EPR state is W. Alice and Bob perform homodyne (hom) detection on the mode they hold, respectively.

needed in the QKD scheme. The proof-of-principle experimental demonstration of this QKD scheme has been demonstrated in Ref. [32], in which the post-selection technique is utilized to distill the secret key.[40]

We assume that Eve performs the entangling cloner attack,[41] which is the most important and practical example of a collective Gaussian attack,[20,42–44] to steal the information. She prepares an ancilla EPR entangled state with variance W. She keeps one mode $\hat{E}''$ and mixes the other mode $\hat{E}$ with the transmitted mode $\hat{b}$ in the quantum channel by a beam splitter, leading to the output mode $\hat{E}'$. Eve's output modes are stored in a quantum memory and detected collectively at the end of the protocol. Eve's final measurement is optimized based on Alice and Bob's classical communication.

The 3-dB loss limit on the transmission line in the CV QKD[45] can be beaten with the reverse reconciliation[25] or the post-selection.[40] In reverse reconciliation, Alice attempts to guess what was received by Bob rather than Bob guessing what was sent by Alice. Such a reverse reconciliation protocol gives Alice an advantage over a potential eavesdropper Eve. In the following, we use the variable X to represent amplitude or phase quadrature of an optical mode to analyze the secret key without losing the generality.

In reverse reconciliation, the secret key rate is given by

$$K_{\mathrm{RR}} = I(X_{\mathrm{A}} : X_{\mathrm{B}}) - I(X_{\mathrm{B}} : E), \tag{12}$$

where

$$I(X_{\mathrm{A}} : X_{\mathrm{B}}) = H(X_{\mathrm{B}}) - H(X_{\mathrm{B}}|X_{\mathrm{A}}) \tag{13}$$

is the mutual information between Alice and Bob, with

$$H(X_{\mathrm{B}}) = (1/2)\log_2 V(X_{\mathrm{B}})$$

and

$$H(X_{\mathrm{B}}|X_{\mathrm{A}}) = (1/2)\log_2 V(X_{\mathrm{B}}|X_{\mathrm{A}})$$

being the total and conditional Shannon entropies. Eve's information is given by

$$I(X_{\mathrm{B}} : E) = S(E) - S(E|X_{\mathrm{B}}), \tag{14}$$

where $S(\cdot)$ is the von Neumann entropy. The von Neumann entropy of a Gaussian state ρ can be expressed in terms of its symplectic eigenvalues[46]

$$S(\rho) = \sum_{k=1}^{n} g(\nu_k), \tag{15}$$

where

$$g(\nu) = \left(\frac{\nu+1}{2}\right)\log_2\left(\frac{\nu+1}{2}\right) - \left(\frac{\nu-1}{2}\right)\log_2\left(\frac{\nu-1}{2}\right), \tag{16}$$

with $\boldsymbol{\nu} = \{\nu_1, \ldots, \nu_n\}$ being the symplectic eigenvalues of Gaussian state ρ.

The conditional variance is defined as[47] $V_{X|Y} = V(X) - |\langle XY\rangle|^2/V(Y)$. So Bob's conditional variance is given by

$$V_{\mathrm{B|A}} = V_{\mathrm{B}} - \frac{T(V^2-1)}{V}. \tag{17}$$

Then according to Eq. (13), we obtain the mutual information between Alice and Bob.

Eve interacts her mode $\hat{E}$ with the transmitted mode $\hat{b}$ on the beam splitter to eavesdrop information. The amplitude and phase quadratures of mode $\hat{E}'$ are

$$\hat{X}_{E'} = \sqrt{T}\hat{X}_{\mathrm{E}} - \sqrt{1-T}\hat{X}_{\mathrm{b}}, \tag{18}$$

$$\hat{Y}_{E'} = \sqrt{T}\hat{Y}_{\mathrm{E}} - \sqrt{1-T}\hat{Y}_{\mathrm{b}}. \tag{19}$$

Eve's covariance matrix is made up from the modes $\hat{E}'$ and $\hat{E}''$, which is

$$\boldsymbol{V}_{\mathrm{E}} = \begin{pmatrix} e_\nu \boldsymbol{I} & \varphi \boldsymbol{Z} \\ \varphi \boldsymbol{Z} & W\boldsymbol{I} \end{pmatrix}, \tag{20}$$

where $e_\nu = (1-T)V + TW$, $\varphi = \sqrt{T(W^2-1)}$.

The conditional covariance matrix $\boldsymbol{V}_{E|X_{\mathrm{B}}}$, which represents the covariance matrix of a system where one of the modes has been measured by homodyne detection (in this case Bob), is given by[4,48,49]

$$\boldsymbol{V}_{E|X_{\mathrm{B}}} = \boldsymbol{V}_E - (V_{\mathrm{B}})^{-1}\boldsymbol{D}\boldsymbol{\Pi}\boldsymbol{D}^{\mathrm{T}}, \tag{21}$$

where

$$\boldsymbol{\Pi} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}. \tag{22}$$

Here $\boldsymbol{D}$ is the matrix describing the correlations between Eve's modes and Bob's mode, which is given by

$$\boldsymbol{D} = \begin{pmatrix} \langle \hat{E}' X_{\mathrm{B}}\rangle \boldsymbol{I} \\ \langle \hat{E}'' X_{\mathrm{B}}\rangle \boldsymbol{Z} \end{pmatrix} = \begin{pmatrix} \mu \boldsymbol{I} \\ \theta \boldsymbol{Z} \end{pmatrix}, \tag{23}$$

where $\mu = \sqrt{T(1-T)}(W-V)$, $\theta = \sqrt{(1-T)(W^2-1)}$.

Substituting the corresponding terms of matrix in Eqs. (20) and (21) into Eq. (9), the symplectic eigenvalues of $\boldsymbol{V}_{\mathrm{E}}$ and $\boldsymbol{V}_{E|X_{\mathrm{B}}}$ are obtained. Then substituting these eigenvalues into Eqs. (15) and (16), we obtain $S(E)$ and $S(E|X_{\mathrm{B}})$, which are substituted into Eq. (14) to calculate Eve's information. Finally, the secret key rate is obtained from Eq. (12).

Figure 4 shows the secret key rates for $r = 0.35$ (solid line) with $W = 1$, $r = 1.15$ with $W = 1$ (dotted line) and $W = 1.5$ (dashed line), respectively. By comparing the secret key rates of different entanglement level, we see that the higher entanglement is, the higher the secret key rate is, which means that entanglement helps to increase the secret key rate. When the excess noise exists in the channel ($W > 1$), for example, $W = 1.5$, the secret key can be distilled for $T > 0.53$. It means that Eve can destroy the secure communication between Alice and Bob by adding sufficient excess noise in the channel.

Comparing dashed lines in Fig. 2(a) and Fig. 4, we find that after entanglement died ($T < 0.2$), none of any secret key can be distilled, although the Gaussian quantum discord still exists ($D_{AB} > 0$ in Fig. 2(b)). The results confirm that entanglement is a necessary precondition for CV QKD and point out that Gaussian quantum discord itself has no contribution to the secret key in such a CV QKD scheme.

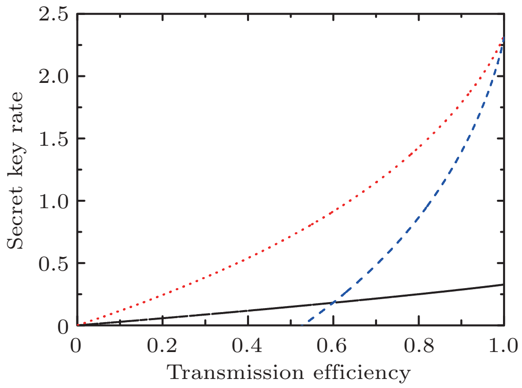

Fig. 4. (color online) Secret key rates with different variances of resource state. Dotted (red) and solid (black) lines correspond to $r = 1.15$ and $r = 0.35$ with $W = 1$, respectively. Dashed (blue) lines correspond to $r = 1.15$ with $W = 1.5$.

5. Conclusion

In conclusion, by considering a symmetric two-mode Gaussian entangled state transmitted through a lossy channel with excess noise, we show that excess noise in the channel can lead to ESD. Although the excess noise also decreases Gaussian quantum discord, it never totally vanishes. Therefore in order to distribute Gaussian entanglement over a long distance, we have to control the excess noise in the quantum channel. For CV QKD with a symmetric two-mode Gaussian entangled state, the secret key cannot be distilled when entanglement vanishes ($\tilde{\nu}_- > 1$) and only Gaussian quantum discord exists ($D_{AB} > 0$). The result supplies a possible way to destroy, instead of eavesdrop, the CV QKD with a symmetric two-mode Gaussian entangled state.

References

[1] Yu T and Eberly J H 2009 *Science* **323** 598
[2] Almeida M P, De Melo F, Hor-Meyll M, Salles A, Walborn S P, Souto Ribeiro P H and Davidovich L 2007 *Science* **316** 579
[3] Braunstein S L and Van Loock P 2005 *Rev. Mod. Phys.* **77** 513
[4] Weedbrook C, Pirandola S, García-Patrón R, Cerf N J, Ralph T C, Shapiro J H and Llyod S 2012 *Rev. Mod. Phys.* **84** 621
[5] Coelho A S, Barbosa F A S, Cassemiro K N, Villar A S, Martinelli M, and Nussemzveig P 2009 *Science* **326** 823
[6] Barbosa F A S, Coelho A S, De Faria A J, Cassemiro K N, Villar A S, Nussemzveig P and Martinelli M 2010 *Nat. Photon.* **4** 858
[7] Barbosa F A S, De Faria A J, Coelho A S, Cassemiro K N, Villar A S, Nussemzveig P and Martinelli M 2011 *Phys. Rev. A* **84** 052330
[8] Ollivier H and Zurek W H 2001 *Phys. Rev. Lett.* **88** 017901
[9] Knill E and Laflamme R 1998 *Phys. Rev. Lett.* **81** 5672
[10] Ryan C A, Emerson J, Poulin D, Negrevergne C and Laflamme R 2005 *Phys. Rev. Lett.* **95** 250502
[11] Lanyon B P, Barbieri M, Almeida M P and White A G 2008 *Phys. Rev. Lett.* **101** 200501
[12] Giorda P and Paris M G A 2010 *Phys. Rev. Lett.* **105** 020503
[13] Adesso G and Datta A 2010 *Phys. Rev. Lett.* **105** 030501
[14] Gu M, Chrzanowski H M, Assad S M, Symul T, Modi K, Ralph T C, Vedral V and Lam P K 2012 *Nat. Phys.* **8** 671
[15] Blandino R, Genoni M G, Etesse J, Barbieri M, Paris M G A, Grangier P and Tualle-Brouri Rosa 2012 *Phys. Rev. Lett.* **109** 180402
[16] Madsen L S, Berni A, Lassen M and Andersen U L 2012 *Phys. Rev. Lett.* **109** 030402
[17] Chen J J, Han Z F, Zhao Y B, Gui Y Z and Guo G C 2006 *Physics* **35** 785 (in Chinese)
[18] Zhu J, He G Q and Zeng G H 2007 *Chin. Phys.* **16** 1364
[19] Namiki R and Hirano T 2004 *Phys. Rev. Lett.* **92** 117901
[20] Renner R and Cirac J I 2009 *Phys. Rev. Lett.* **102** 110504
[21] Leverrier A and Grangier P 2009 *Phys. Rev. Lett.* **102** 180504
[22] Su X L, Jing J T, Pan Q and Xie C D 2006 *Phys. Rev. A* **74** 062305
[23] Pirandola S, Mancini S, Lloyd S and Braunstein S L 2008 *Nat. Phys.* **4** 726
[24] Weedbrook C, Pirandola S and Ralph T C 2012 *Phys. Rev. A* **86** 022318
[25] Grosshans F, Van Assche G, Wenger J, Brouri R, Cerf N J and Grangier P 2003 *Nature* **421** 238
[26] Lorenz S, Korolkova N and Leuchs G 2004 *Appl. Phys. B* **79** 273
[27] Lance A M, Symul T, Sharma V, Weedbrook C, Ralph T C and Lam P K 2005 *Phys. Rev. Lett.* **95** 180503
[28] Symul T, Alton D J, Assad S M, Lance A M, Weedbrook C, Ralph T C and Lam P K 2007 *Phys. Rev. A* **76** 030303
[29] Lodewyck J, Bloch M, García-Patrón R, Fossier S, Karpov E, Diamanti E, Debuisschert T, Cerf N J, Tualle-Brouri R, McLaughlin S W and Grangier P 2007 *Phys. Rev. A* **76** 042305
[30] Qi B, Huang L L, Qian L and Lo H K 2007 *Phys. Rev. A* **76** 052323
[31] Shen Y, Zou H X, Tian L, Chen P X and Yuan J M 2010 *Phys. Rev. A* **82** 022317
[32] Su X L, Wang W Z, Wang Y, Jia X J, Xie C D and Peng K C 2009 *Europhys. Lett.* **87** 20005
[33] Eberle Tobias, Händchen Vitus, Duhme J, Franz T, Werner R F and Schnabel R arXiv: 1110.3977v1 [quant-ph]
[34] Madsen L S, Usenko V C, Lassen M, Filip R and Andersen U L 2012 *Nature Commun.* **3** 1083
[35] Curty M, Lewenstein M and Lütkenhaus N 2004 *Phys. Rev. Lett.* **92** 217903
[36] Serafini A, Illuminati F and De Siena S 2004 *J. Phys. B: At. Mol. Opt. Phys.* **37** L21
[37] Adesso G, Serafini A and Illuminati F 2004 *Phys. Rev. A* **70** 022318
[38] Simon R 2000 *Phys. Rev. Lett.* **84** 2726
[39] Werner R F and Wolf M M 2001 *Phys. Rev. Lett.* **86** 3658
[40] Silberhorn Ch, Ralph T C, Lütkenhaus N and Leuchs G 2002 *Phys. Rev. Lett.* **89** 167901
[41] Grosshans F, Cerf N J, Wenger J, Tualle-Brouri R and Grangier P 2003 *Quantum Inf. Comput.* **3** 535
[42] Navascués M, Grosshans G and Acín A 2006 *Phys. Rev. Lett.* **97** 190502
[43] García-Patrón R and Cerf N J 2006 *Phys. Rev. Lett.* **97** 190503
[44] Pirandola S, Braunstein S L and Lloyd S 2008 *Phys. Rev. Lett.* **101** 200504
[45] Grosshans F and Grangier P 2002 *Phys. Rev. Lett.* **88** 057902
[46] Holevo A S, Sohma M and Hirota O 1999 *Phys. Rev. A* **59** 1820
[47] Grangier P, Levenson J A and Poizat J P 1998 *Nature* **396** 537
[48] Eisert J, Scheel S and Plenio M B 2002 *Phys. Rev. Lett.* **89** 137903
[49] Fiuràšek J 2002 *Phys. Rev. Lett.* **89** 137904