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利用双模压缩真空态实现量子态的远程传输*

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借助于双模压缩真空态在 EPR 纠缠态表象中的表示,研究了用双模压缩真空态作为量子通道实现任意的单模和双模量子态的远程传输.

关键词:量子隐形传态,EPR 纠缠态,压缩真空态
PACC:4250

1. 引　言

随着量子信息科学的蓬勃发展,量子纠缠态找到了施展作为的主战场.现在,量子纠缠态已经被广泛地用于量子隐形传态,量子浓缩编码,量子计算等领域的研究中[1—7].1993 年,Bennett 等人提出了利用量子态的纠缠特性实现远程隐形传态的理论方案[3].Bennett 等人的开创性文章掀起了研究量子隐形传态的高潮,关于量子隐形传态的各种理论方案相继出现[8—11].但是,现有的关于量子隐形传态的研究大都限于分立量子态的传输,对于连续变量的量子隐形传态则少见报道.最近,山西大学的研究小组提出了利用明亮压缩光实现连续变量的量子隐形传态的方案[12],Fan 等人利用 EPR 纠缠态作为量子通道,从理论上研究了双模压缩真空态的隐形传态[13].本文利用双模压缩态作为量子通道,研究任意的单模和双模量子态的隐形传态(包括分立的和连续的量子态).

2. EPR 纠缠态

近年来,量子纠缠态的性质及其应用逐渐成为人们的热门话题. 从历史上讲,纠缠态的概念最早是由爱因斯坦等人提出来的.为了说明在承认局域性和实在性的前提下,量子力学的描述是不完备的,爱因斯坦等人提出如下一个量子态[14]:

$$\psi(x_1,x_2) = \int_{-\infty}^{\infty} \exp[\mathrm{i}p(x_1 - x_2 + x_0)]\,\mathrm{d}p, \tag{1}$$

其中 x_1, x_2 分别表示两个粒子的坐标.很容易看出,$\psi(x_1,x_2)$是两个粒子的相对坐标 $\hat{X}_1 - \hat{X}_2$ 和总动量 $\hat{P}_1 + \hat{P}_2$ 的共同本征态,它的基本特征是不能写成两个子系统量子态的直积形式.在文献[15]中,Fan 等人给出了两个粒子的相对坐标 $\hat{X}_1 - \hat{X}_2$ 和总动量 $\hat{P}_1 + \hat{P}_2$ 的共同本征态在双模 Fock 空间的表达式

$$|\eta\rangle_{12} = \exp\Big[-\frac{1}{2}|\eta|^2 + \eta a_1^{+} - \eta^{*} a_2^{+} + a_1^{+} a_2^{+}\Big]|00\rangle_{12}, \tag{2a}$$

$$(\hat{X}_1 - \hat{X}_2)|\eta\rangle_{12} = \eta_1|\eta\rangle_{12}, \tag{2b}$$

$$(\hat{P}_1 + \hat{P}_2)|\eta\rangle_{12} = \eta_2|\eta\rangle_{12}, \tag{2c}$$

$$X_i = \frac{1}{\sqrt{2}}(a_i + a_i^{+}),$$

$$P_i = \frac{1}{\sqrt{2}\mathrm{i}}(a_i - a_i^{+}), \tag{2d}$$

其中 $\eta = (\eta_1 + \mathrm{i}\eta_2)/\sqrt{2}$,$|00\rangle$是双模真空态.可以证明,$|\eta\rangle_{12}$是纠缠态,它在坐标表象和动量表象中的 Schmidt 分解分别为

$$|\eta\rangle_{12} = \exp\Big(-\frac{\mathrm{i}}{2}\eta_1\eta_2\Big)\int_{-\infty}^{\infty}\mathrm{d}x\,|x\rangle_1 \otimes |x - \eta_1\rangle_2 \exp(\mathrm{i}\eta_2 x), \tag{3}$$

$$|\eta\rangle_{12} = \exp\Big(-\frac{\mathrm{i}}{2}\eta_1\eta_2\Big)\int_{-\infty}^{\infty}\mathrm{d}p\,|p + \eta_2\rangle_1 \otimes |-p\rangle_2 \exp(-\mathrm{i}p\eta_1), \tag{4}$$

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其中$|x\rangle_i$和$|p\rangle_i$分别是坐标算符$\hat{X}_i$和动量算符$\hat{P}_i$的本征态

$$|x\rangle_i = \pi^{-1/4}\exp\left[-\frac{1}{2}x^2+\sqrt{2}xa_i^+-\frac{1}{2}a_i^{+2}\right]|0\rangle_i, \tag{5}$$

$$|p\rangle_i = \pi^{-1/4}\exp\left[-\frac{1}{2}p^2+\mathrm{i}\sqrt{2}pa_i^+ +\frac{1}{2}a_i^{+2}\right]|0\rangle_i. \tag{6}$$

利用正规乘积内的积分技术(IWOP)[16]和真空态投影算符的正规乘积形式

$$|0\rangle\langle 0| = :\mathrm{e}^{-a^+a}:, \tag{7}$$

其中::表示正规乘积,可以证明$|\eta\rangle_{12}$满足下列完备性关系和正交关系:

$$\int\frac{\mathrm{d}^2\eta}{\pi}|\eta\rangle_{12\,12}\langle\eta| = 1, \tag{8}$$

$$_{12}\langle\eta'|\eta\rangle_{12} = \pi\delta(\eta-\eta')\delta(\eta^*-\eta'^*). \tag{9}$$

因此,$|\eta\rangle_{12}$构成一个新的量子力学表象,称之为EPR纠缠态表象.可以证明:在EPR纠缠态表象中,双模压缩算子可以表示为[17]

$$\begin{aligned}S_{12}(\mu) &= \exp[\lambda(a_1^+a_2^+-a_1a_2)]\\ &= \frac{1}{\mu}\int\frac{\mathrm{d}^2\eta}{\pi}|\eta/\mu\rangle_{12\,12}\langle\eta|, \qquad \mu = \exp(\lambda),\end{aligned} \tag{10}$$

因此,双模压缩真空态可以表示为

$$\begin{aligned}S_{12}(\mu)|00\rangle_{12} &= \frac{1}{\mu}\int\frac{\mathrm{d}^2\eta}{\pi}|\eta/\mu\rangle_{12\,12}\langle\eta|00\rangle_{12}\\ &= \frac{1}{\mu}\int\frac{\mathrm{d}^2\eta}{\pi}|\eta/\mu\rangle_{12}\exp\left[-\frac{1}{2}|\eta|^2\right].\end{aligned} \tag{11}$$

3. 单模量子隐形传态

假定发送者Alice有粒子1处于任意的量子态

$$|\psi\rangle_1 = \sum_n C_n|n\rangle_1, \tag{12}$$

根据坐标表象的完备性关系

$$\int_{-\infty}^{\infty}|q\rangle\langle q|\mathrm{d}q = 1, \tag{13}$$

方程(12)可以表示为

$$\begin{aligned}|\psi\rangle_1 &= \sum_n C_n|n\rangle_1 = \sum_n C_n\int_{-\infty}^{\infty}\mathrm{d}q|q\rangle_{1\,1}\langle q|n\rangle_1\\ &= \sum_n C_n\frac{1}{\sqrt{2^n n!\sqrt{\pi}}}\int_{-\infty}^{\infty}\mathrm{d}q|q\rangle_1 H_n(q)\exp\left(-\frac{1}{2}q^2\right),\end{aligned} \tag{14}$$

其中,利用了

$$\langle q|n\rangle = \frac{1}{\sqrt{2^n n!\sqrt{\pi}}}H_n(q)\exp\left(-\frac{1}{2}q^2\right). \tag{15}$$

Alice想将此态传送给接受者Bob,但粒子1本身不被传送.粒子2和3事先制备成双模压缩真空态

$$\begin{aligned}|\mu\rangle_{23} &= S_{23}(\mu)|00\rangle_{23}\\ &= \frac{1}{\mu}\int\frac{\mathrm{d}^2\eta}{\pi}|\eta/\mu\rangle_{23}\exp\left[-\frac{1}{2}|\eta|^2\right],\end{aligned} \tag{16}$$

它构成Alice和Bob之间的量子通道,然后粒子2传送给Alice,粒子3传送给Bob.由于粒子2和3处于纠缠态,发送者Alice对粒子2的任何操作,必然导致粒子3发生相应的演变.

为了把$|\psi\rangle_1$传送给接受者Bob,Alice对粒子1和2实施联合测量,这导致另一个双模压缩真空态,记作

$$\begin{aligned}|\sigma\rangle_{12} &= S_{12}(\sigma)|00\rangle_{12}\\ &= \frac{1}{\sigma}\int\frac{\mathrm{d}^2\eta}{\pi}|\eta/\sigma\rangle_{12}\exp\left[-\frac{1}{2}|\eta|^2\right].\end{aligned} \tag{17}$$

联合测量后,粒子3的投影态为

$$\begin{aligned}&_{12}\langle\sigma|\mu\rangle_{23}\otimes|\psi\rangle_1\\ &= \frac{1}{\mu\sigma\pi^2}\int\mathrm{d}^2\eta'\mathrm{d}^2\eta\exp\left[-\frac{1}{2}(|\eta'|^2+|\eta|^2)\right]\\ &\quad\times{}_{12}\langle\eta'/\sigma|\eta/\mu\rangle_{23}\otimes|\psi\rangle_1.\end{aligned} \tag{18}$$

把方程(3)和(14)代入方程(18)得

$$\begin{aligned}&_{12}\langle\sigma|\mu\rangle_{23}\otimes|\psi\rangle_1\\ &= \frac{1}{\mu\sigma\pi^2}\int\mathrm{d}^2\eta'\mathrm{d}^2\eta\exp\left[-\frac{1}{2}(|\eta'|^2+|\eta|^2)\right]\\ &\quad\times\exp\left(\frac{\mathrm{i}\eta'_1\eta'_2}{2\sigma^2}\right)\int_{-\infty}^{\infty}\mathrm{d}x'\,{}_1\langle x'|\otimes{}_2\langle x'-\eta'_1/\sigma|\\ &\quad\times\exp\left(-\frac{\mathrm{i}\eta'_2x'}{\sigma}\right)\exp\left(-\frac{\mathrm{i}\eta_1\eta_2}{2\mu^2}\right)\int_{-\infty}^{\infty}\mathrm{d}x|x\rangle_2\\ &\quad\otimes|x-\eta_1/\mu\rangle_3\exp\left(\frac{\mathrm{i}\eta_2x}{\mu}\right)\otimes\sum_n C_n\frac{1}{\sqrt{2^n n!\sqrt{\pi}}}\\ &\quad\times\int_{-\infty}^{\infty}\mathrm{d}q|q\rangle_1 H_n(q)\exp\left(-\frac{1}{2}q^2\right)\\ &= \frac{1}{\mu\sigma\pi^2}\int\mathrm{d}^2\eta'\mathrm{d}^2\eta\exp\left[-\frac{1}{2}(|\eta'|^2+|\eta|^2)\right.\\ &\quad\left.-\frac{\mathrm{i}}{2}\left(\frac{\eta'_1\eta'_2}{\sigma^2}+\frac{\eta_1\eta_2}{\mu^2}\right)\right]\sum_n C_n\frac{1}{\sqrt{2^n n!\sqrt{\pi}}}\\ &\quad\times\int_{-\infty}^{\infty}\mathrm{d}qH_n(q)\exp\left(-\frac{1}{2}q^2\right)\int_{-\infty}^{\infty}\mathrm{d}x\exp\left[\mathrm{i}x\left(\frac{\eta_2}{\mu}-\frac{\eta'_2}{\sigma}\right)\right],\\ &\quad{}_1\langle x+\eta'_1/\sigma|q\rangle_1\otimes|x-\eta_1/\mu\rangle_3\end{aligned}$$

$$= \frac{1}{\mu\sigma\pi^2}\int d^2\eta' d^2\eta \exp\Big[-\frac{1}{2}(|\eta'|^2+|\eta|^2) + \frac{i}{2}\Big(\frac{\eta'_1\eta'_2}{\sigma^2}-\frac{\eta_1\eta_2}{\mu^2}-\frac{2\eta'_1\eta_2}{\mu\sigma}\Big)\Big]\sum_n C_n\frac{1}{\sqrt{2^n n!\sqrt{\pi}}}$$

$$\times\int_{-\infty}^{\infty} dq H_n(q)\exp\Big[-\frac{q^2}{2}+iq\Big(\frac{\eta_2}{\mu}-\frac{\eta'_2}{\sigma}\Big)\Big]$$

$$\times|q-\eta_1/\mu-\eta'_1/\sigma\rangle_3$$

$$=\hat{F}(\hat{X}_3,\hat{P}_3)\sum_n C_n\frac{1}{\sqrt{2^n n!\sqrt{\pi}}}$$

$$\times\int_{-\infty}^{\infty} dq|q\rangle_3 H_n(q)\exp\Big(-\frac{1}{2}q^2\Big), \quad (19)$$

其中

$$\hat{F}(\hat{X}_3,\hat{P}_3) = \frac{1}{\mu\sigma\pi^2}\int d^2\eta' d^2\eta\exp\Big[-\frac{1}{2}(|\eta'|^2+|\eta|^2) + \frac{i}{2}\Big(\frac{\eta'_1\eta'_2}{\sigma^2}-\frac{\eta_1\eta_2}{\mu^2}-\frac{2\eta'_1\eta_2}{\mu\sigma}\Big)\Big]$$

$$\times\exp\Big[i\hat{P}_3\Big(\frac{\eta_1}{\mu}+\frac{\eta'_1}{\sigma}\Big)\Big]$$

$$\times\exp\Big[i\hat{X}_3\Big(\frac{\eta_2}{\mu}-\frac{\eta'_2}{\sigma}\Big)\Big]. \quad (20)$$

比较方程(14)和(17)可以看出:发送者 Alice 将测量的结果通过经典通道告诉接收者 Bob,后者通过幺正变换 $\hat{F}^{-1}(\hat{X}_3,\hat{P}_3)$,便可使得粒子 3 处于欲传送的量子态,从而实现了将未知量子态从 Alice 处发送到 Bob 处,留在 Alice 处的粒子 1 的原始态在测量之后被破坏,这是量子不可克隆性的表现.

4. 双模量子隐形传态

让发送者 Alice 和接收者 Bob 共享两个双模压缩真空态 $|\tau\rangle_{13}=S_{13}(\tau)|00\rangle_{13}$ 和 $|\sigma\rangle_{24}=S_{24}(\sigma)|00\rangle_{24}$,其中 S_{ij} 相应于模 i 和 j 的双模压缩算子,它们构成发送者 Alice 和接收者 Bob 之间的两个量子通道.为了传送双模量子态 $|\psi\rangle_{56}$,发送者 Alice 对粒子(3,5)和(4,6)实施联合测量,这导致另外两个双模压缩真空态,记作 $|\tau'\rangle_{35}=S_{35}(\tau')|00\rangle_{35}$ 和 $|\sigma'\rangle_{46}=S_{46}(\sigma')|00\rangle_{46}$[13].联合测量后,粒子 1 和 2 的投影态为

$${}_{35}\langle\tau'|\otimes{}_{46}\langle\sigma'|\tau\rangle_{13}\otimes|\sigma\rangle_{24}\otimes|\psi\rangle_{56}$$

$$={}_{35}\langle 00|\otimes{}_{46}\langle 00|S^+_{35}(\tau')S^+_{46}(\sigma')S_{13}(\tau)\times S_{24}(\sigma)|00\rangle_{13}\otimes|00\rangle_{24}\otimes|\psi\rangle_3$$

$$=\frac{1}{\tau\tau'\sigma\sigma'\pi^4}\int d^2\eta d^2\eta' d^2\eta'' d^2\eta'''\exp\Big[-\frac{1}{2}(|\eta|^2 + |\eta'|^2+|\eta''|^2+|\eta'''|^2)\Big],$$

$${}_{35}\langle\eta'/\tau'|\otimes{}_{46}\langle\eta''/\sigma'|\eta'''/\tau\rangle_{13}\otimes|\eta/\sigma\rangle_{24}\otimes|\psi\rangle_{56}$$

$$=\frac{1}{\tau\tau'\sigma\sigma'\pi^4}\int d^2\eta d^2\eta' d^2\eta'' d^2\eta'''$$

$$\times\exp\Big[-\frac{1}{2}(|\eta|^2+|\eta'|^2+|\eta''|^2+|\eta'''|^2)\Big]$$

$$\times\exp\Big[\frac{i}{2}\Big(\frac{\eta'_1\eta'_2}{\tau'^2}+\frac{\eta''_1\eta''_2}{\sigma'^2}+\frac{\eta'''_1\eta'''_2}{\tau^2}+\frac{\eta_1\eta_2}{\sigma^2}\Big)\Big]$$

$$\times\int_{-\infty}^{\infty}dx_1dx_2\,{}_5\langle x_1-\eta'_1/\tau_1|\otimes{}_6\langle x_2-\eta''_1/\sigma'|\psi\rangle_{56}$$

$$\otimes|x_1+\eta'''_1/\tau\rangle_1\otimes|x_2+\eta_1/\sigma\rangle_2$$

$$\times\exp\Big[-i\Big(\frac{\eta'_2}{\tau'}-\frac{\eta'''_2}{\tau}\Big)x_1-i\Big(\frac{\eta''_2}{\sigma'}-\frac{\eta_2}{\sigma}\Big)x_2\Big]. \quad (21)$$

假定发送者 Alice 有粒子 5 和 6 处于任意的量子态 $|\psi\rangle_{56}$,

$$|\psi\rangle_{56}=\sum_{k,l}C_{kl}|k\rangle_5\otimes|l\rangle_6. \quad (22)$$

根据坐标表象的完备性关系(13),$|\psi\rangle_{56}$ 可以表示为

$$|\psi\rangle_{56}=\sum_{k,l}C_{kl}\frac{1}{\sqrt{2^{k+l}k!l!\pi}}$$

$$\times\int_{-\infty}^{\infty}dqdq'|q\rangle_5\otimes|q'\rangle_6 H_k(q)H_l(q')$$

$$\times\exp\Big[-\frac{1}{2}(q^2+q'^2)\Big]. \quad (23)$$

把方程(23)代入方程(21)得

$${}_{35}\langle\tau'|\otimes{}_{46}\langle\sigma'|\tau\rangle_{13}\otimes|\sigma\rangle_{24}\otimes|\psi\rangle_{56}$$

$$=\frac{1}{\tau\tau'\sigma\sigma'\pi^4}\int d^2\eta d^2\eta' d^2\eta'' d^2\eta'''$$

$$\times\exp\Big[-\frac{1}{2}(|\eta|^2+|\eta'|^2+|\eta''|^2+|\eta'''|^2)\Big]$$

$$\times\exp\Big[\frac{i}{2}\Big(-\frac{\eta'_1\eta'_2}{\tau'^2}-\frac{\eta''_1\eta''_2}{\sigma'^2}+\frac{\eta'''_1\eta'''_2}{\tau^2}+\frac{\eta_1\eta_2}{\sigma^2}+\frac{2\eta'_1\eta'''_2}{\tau\tau'}+\frac{2\eta''_1\eta_2}{\sigma\sigma'}\Big)\Big]\sum_{k,l}C_{kl}\frac{1}{\sqrt{2^{k+l}k!l!\pi}}$$

$$\times\int_{-\infty}^{\infty}dqdq'H_k(q)H_l(q')\exp\Big[-\frac{1}{2}(q^2+q'^2)\Big]$$

$$\times|q+\eta'_1/\tau'+\eta'''_1/\tau\rangle_1\otimes|q'+\eta''_1/\sigma'+\eta_1/\sigma\rangle_2$$

$$\times\exp\Big[-i\Big(\frac{\eta'_2}{\tau'}-\frac{\eta'''_2}{\tau}\Big)q-i\Big(\frac{\eta''_2}{\sigma'}-\frac{\eta_2}{\sigma}\Big)q'\Big]$$

$$=\hat{F}(\hat{X}_1,\hat{X}_2,\hat{P}_1,\hat{P}_2)\sum_{k,l}C_{kl}\frac{1}{\sqrt{2^{k+l}k!l!\pi}}\int_{-\infty}^{\infty}dqdq'H_k(q)$$

$$\times H_l(q')|q\rangle_1\otimes|q'\rangle_2\exp\Big[-\frac{1}{2}(q^2+q'^2)\Big]. \quad (24)$$

其中

$$
\begin{aligned}
&\hat{F}(\hat{X}_1,\hat{X}_2,\hat{P}_1,\hat{P}_2)\\
&=\frac{1}{\tau\tau'\sigma\sigma'\pi^4}\int d^2\eta d^2\eta' d^2\eta'' d^2\eta''' \exp\Big[-\frac{1}{2}(|\eta|^2\\
&\quad+|\eta'|^2+|\eta''|^2+|\eta'''|^2)\Big]\\
&\quad\times\exp\Big[\frac{i}{2}\Big(-\frac{\eta'_1\eta'_2}{\tau'^2}-\frac{\eta''_1\eta''_2}{\sigma'^2}+\frac{\eta'''_1\eta'''_2}{\tau^2}\\
&\quad+\frac{\eta_1\eta_2}{\sigma^2}+\frac{2\eta'_1\eta'''_2}{\tau\tau'}+\frac{2\eta''_1\eta_2}{\sigma\sigma'}\Big)\Big]\\
&\quad\times\exp\Big[-i\Big(\frac{\eta'_1}{\tau'}+\frac{\eta'''_1}{\tau}\Big)\hat{P}_1-i\Big(\frac{\eta''_1}{\sigma'}+\frac{\eta_1}{\sigma}\Big)\hat{P}_2\Big]\\
&\quad\times\exp\Big[-i\Big(\frac{\eta'_2}{\tau'}-\frac{\eta'''_2}{\tau}\Big)\hat{X}_1-i\Big(\frac{\eta''_2}{\sigma'}-\frac{\eta_2}{\sigma}\Big)\hat{X}_2\Big].
\end{aligned}
\tag{25}
$$

比较方程(23)和(24)可以看出:发送者 Alice 将测量的结果通过经典通道告诉接收者 Bob,后者通过幺正变换 $\hat{F}^{-1}(\hat{X}_1,\hat{X}_2,\hat{P}_1,\hat{P}_2)$,便可使得粒子 1 和 2 处于欲传送的量子态,从而实现了将未知的双模量子态从 Alice 处发送到 Bob 处.

5. 结论和讨论

量子隐形传态是没有经典对应的信息传递方法,传递前,发送者和接收者共享一个(或多个)纠缠态,即量子通道.文献[13]已经提出了利用具有连续变量的 EPR 纠缠态作为量子通道,实现双模压缩真空态的隐形传态的理论方案,我们利用双模压缩态作为量子通道,研究了任意的单模和双模量子态的隐形传态(包括分立的和连续的量子态),比较而言,双模压缩真空态更容易在实验上实现.在理论计算过程中,我们利用了双模压缩真空在 EPR 纠缠态表象中的表示和 EPR 纠缠态在坐标表象中的 Schmidt 分解,这使得问题大为简化.

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Teleportation of quantum states by means of two-mode squeezed vacuum*

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Abstract

By means of the expression of two-mode squeezed vacuum in electron paramagnetic resonance (EPR) entangled state representation, we study the teleportation of any form of single-mode and two-mode quantum states by using two-mode squeezed vacuum as quantum channels.

Keywords: quantum teleportation, EPR entangled state, squeezed vacuum
PACC: 4250

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