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Preparing pure states with lossy beam splitters using quantum coherent absorption of squeezed light

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ABSTRACT

We investigate coherent perfect absorption (CPA) of squeezed coherent states of light by an absorbing beam splitter. First we derive the absorption coefficients for quantum coherence and for intensity, which generally differ. Secondly, we present the remarkable properties of a CPA-gate: two identical but otherwise arbitrary incoming squeezed coherent states can be completely stripped off their coherence, producing a pure entangled squeezed vacuum state at the output. Importantly, this output state of light is not entangled with the absorbing beam splitter by which it was produced. This makes the CPA gate potentially interesting for continuous-variable quantum state preparation.

Keywords: Quantum state preparation, coherent perfect absorption, QED of lossy environments, input-output relations, squeezed light, beam splitter

1. INTRODUCTION

Coherent perfect absorption (CPA) of light¹ is interference-assisted absorption that in its simplest form can take place using an absorbing beam splitter with a carefully designed absorption strength. With input light from only one side, light would leave the beam splitter, but no light emerges if there is equal input from both sides. In essence, the reflected part of one of the incident beams interferes destructively with the transmitted part of the other, and vice versa.¹ With CPA one can control light with light in linear optics.²

CPA has been successfully demonstrated in many setups, for example in a silicon cavity with two counter-propagating waves,³ using a pair of resonators coupled to a transmission line,⁴ and using graphene to observe CPA of optical⁵ and of terahertz radiation.⁶ CPA can be used to strongly couple light to surface plasmons,⁷ and may play a role in photodetection,^{8,9} sensing,¹⁰ photovoltaics¹¹ and cloaking.^{12,13} Further applications can be found in the excellent review by Baranov et al.²

Investigations of CPA in the quantum regime (also known as Quantum CPA²) have only recently begun, predominantly with entangled few-photon input states.^{14–17} Here we consider instead squeezed coherent states of light¹⁸ and report the effects of quadrature squeezing on the absorption profile of the system, and how the absorbing beam splitter affects the output states of light. This conference proceedings contains a selection and summary of main results of our recent research article on continuous-variable quantum states in the context of CPA,¹⁹ and we refer to that original work for further results and explanations.

Squeezed states have reduced noise in one field quadrature at the expense of larger noise in the other.²⁰ Squeezed states of light play indispensable roles in quantum information, communication and optics protocols. In particular, for quantum teleportation,^{21–23} quantum key distribution,²⁴ quantum metrology,²⁵ quantum cryptography,²⁶ quantum dense coding,²⁷ quantum dialogue protocols,²⁸ quantum laser pointers,²⁹ and quantum memories.^{30,31} They are used to increase the sensitivity of gravitational wave detectors³² as well. Squeezed light may also be produced by (pairs of) individual emitters in optical nanostructures.³³

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Figure 1. Comparison of the action in classical optics of (a) the lossless fifty-fifty beam splitter and (b,c) the lossy CPA beam splitter. In (b), with input from one port, 25 percent of the intensity is transmitted, 25 percent reflected, and 50 percent absorbed. In (c), with coherent light of equal intensity arriving in phase on the CPA beam splitter, all light is absorbed. The question addressed in the main text is about the action of this CPA beam splitter in continuous-variable quantum optics: with two incoming squeezed coherent states, how much intensity and coherence are lost, and what is the two-port optical output state? Surprisingly, that state can be pure despite the interaction with the lossy optical device.

For squeezed coherent input states we show that a one- and two-mode combined squeezed vacuum state^{34–37} is produced at the output. Importantly, we will show that in the output state the light is not entangled with the beam splitter even though the latter is lossy. These and further intriguing properties may make the lossy CPA beam splitter a useful element in continuous-variable protocols.

In Sec. 2, we introduce CPA and distinguish between the absorption of quantum coherence and intensity. Sec. 3 describes coherent absorption of coherent states and Sec. 4 of squeezed coherent states. In Sec. 5 we derive and discuss the remarkable quantum state transformation that can be performed by the CPA beam splitter, and we conclude in Sec. 6.

2. ABSORPTION OF COHERENCE AND OF INTENSITY

Let us consider a lossy beam-splitter in free space which superposes two incident quantized modes of light and creates two outgoing modes as shown in Fig. 1. The incident modes are described by the discrete annihilation operators $\hat{a}_1$ and $\hat{a}_2$. The field operators $\hat{b}_1$ and $\hat{b}_2$ of the outgoing modes are, then, given by the relations^{38–41}

$$\hat{b}_1 = t\hat{a}_1 + r\hat{a}_2 + \hat{L}_1, \quad (1a)$$

$$\hat{b}_2 = r\hat{a}_1 + t\hat{a}_2 + \hat{L}_2, \quad (1b)$$

where t and r are the beam-splitter's transmission and reflection amplitudes. The $\hat{L}_1$ and $\hat{L}_2$ describe Langevin-type noise operators corresponding to device modes of the beam splitter where the absorption takes place. We discuss this quantum noise in Sec. 5. In the lossy beam splitter, the light will typically lose part of its coherence and also part of its intensity, both due to a combination of destructive interference and dissipation. We define the total intensities of incoming and outgoing fields as

$$\mathcal{I}_{\text{in}} \equiv \langle \hat{a}_1^\dagger \hat{a}_1 \rangle + \langle \hat{a}_2^\dagger \hat{a}_2 \rangle \quad \text{and} \quad \mathcal{I}_{\text{out}} \equiv \langle \hat{b}_1^\dagger \hat{b}_1 \rangle + \langle \hat{b}_2^\dagger \hat{b}_2 \rangle, \quad (2)$$

and the lost intensity as $\Delta\mathcal{I} \equiv \mathcal{I}_{\text{in}} - \mathcal{I}_{\text{out}}$. The coefficient of absorption of intensity is

$$\mathcal{A}_{\text{coh}}^{\mathcal{I}} \equiv 1 - \mathcal{I}_{\text{out}}/\mathcal{I}_{\text{in}}, \quad (3)$$

being the fraction of intensity that gets lost. Analogously, we choose to quantify the input coherent amplitudes through the quantity

$$\mathcal{C}_{\text{in}} \equiv |\langle \hat{a}_1 \rangle|^2 + |\langle \hat{a}_2 \rangle|^2 \quad (4)$$

i.e. as the sum of the absolute values squared of the expectation values $\langle \dots \rangle$, the latter taken with respect to the initial quantum state $|\psi\rangle_{\text{in}}$. This state describes both the quantum state of light in both arms and of the internal

states of the beam splitter. Correspondingly, we quantify the output coherent amplitude, $\mathcal{C}_{\text{out}} \equiv |\langle \hat{b}_1 \rangle|^2 + |\langle \hat{b}_2 \rangle|^2$, and the net loss in coherent amplitudes as $\Delta\mathcal{C} \equiv \mathcal{C}_{\text{in}} - \mathcal{C}_{\text{out}}$. We define the coefficient of absorption of coherent amplitudes as

$$\mathcal{A}_{\text{coh}}^{\mathcal{C}} \equiv \Delta\mathcal{C}/\mathcal{C}_{\text{in}} = 1 - \mathcal{C}_{\text{out}}/\mathcal{C}_{\text{in}}. \quad (5)$$

We are interested in the two extreme situations: Coherent perfect absorption, corresponding to $\mathcal{A}_{\text{coh}}^{\mathcal{I}} \equiv 1$ (no output intensity), as opposed to perfect absorption of coherence, or $\mathcal{A}_{\text{coh}}^{\mathcal{C}} \equiv 1$ (vanishing output coherent amplitudes). We will refer to $\mathcal{A}_{\text{coh}}^{\mathcal{C}}$ as the absorption of coherence.

3. CPA OF COHERENT STATES

We assume that initially the internal device modes of the beam splitter are in their ground states, denoted as $|\rangle_{\text{BS}}$. For the incident optical modes, let us first consider that both are prepared in coherent states.⁴² A coherent state (for example of mode 1) is defined as $|\alpha\rangle_1 = \hat{D}_1(\alpha)|\rangle$ in terms of the optical vacuum state $|\rangle$ and the displacement operator

$$\hat{D}_1(\alpha) \equiv \exp(-|\alpha|^2/2) \exp(\alpha \hat{a}_1^\dagger) \exp(-\alpha^* \hat{a}_1). \quad (6)$$

The total input state can then be written as $|\psi\rangle_{\text{in}} = |\alpha\rangle_1 \otimes |\beta\rangle_2 \otimes |\rangle_{\text{BS}}$ with $\alpha = |\alpha| \exp(i\theta_1)$ and $\beta = |\beta| \exp(i\theta_2)$. For the input coherence of these coherent states we then find

$$\mathcal{C}_{\text{in}} = |\alpha|^2 + |\beta|^2, \quad (7)$$

and for the output coherence

$$\mathcal{C}_{\text{out}} = (|\alpha|^2 + |\beta|^2)(|t|^2 + |r|^2) + 2 \cos(\theta) |\alpha| |\beta| (tr^* + rt^*),$$

where we used the input-output relations 1 and defined $\theta \equiv \theta_2 - \theta_1$ as the phase difference between the coherent states. The coefficient of absorption of quantum coherence then reads

$$\mathcal{A}_{\text{coh}}^{\mathcal{C}} = 1 - \left[|t|^2 + |r|^2 + \frac{2|\alpha||\beta|(tr^* + rt^*)}{|\alpha|^2 + |\beta|^2} \cos(\theta) \right], \quad (8)$$

which reduces to the conventional expression for incoherent absorption $\mathcal{A} = 1 - (|t|^2 + |r|^2)$ when replacing $\cos(\theta)$ by its average value of zero. For two coherent incident states, the quantum coherence lost is in fact equal to the lost intensity, because the identities $\mathcal{C}_{\text{in}} = \mathcal{I}_{\text{in}}$ and $\mathcal{C}_{\text{out}} = \mathcal{I}_{\text{out}}$ hold in that case. This then immediately implies $\Delta\mathcal{C} = \Delta\mathcal{I}$ and $\mathcal{A}_{\text{coh}}^{\mathcal{C}} = \mathcal{A}_{\text{coh}}^{\mathcal{I}}$. This equality does not hold for incident squeezed states of light, as we shall see below.

4. COHERENT ABSORPTION OF SQUEEZED COHERENT STATES

We will now investigate the effects of squeezing on the coherent absorption of light. Mathematically, a squeezed coherent state $|\alpha, \zeta\rangle$ is obtained by the action of a squeeze operator on a coherent state,⁴² for example for mode 1

$$|\alpha_1, \zeta_1\rangle_1 = \hat{S}_1(\zeta_1)|\alpha_1\rangle = \hat{S}_1(\zeta_1)\hat{D}_1(\alpha_1)|\rangle. \quad (9)$$

Here the squeeze operator is defined as

$$\hat{S}_1(\zeta_1) \equiv e^{\frac{1}{2}\zeta_1^* \hat{a}_1^2 - \frac{1}{2}\zeta_1 \hat{a}_1^{\dagger 2}}, \quad (10)$$

in terms of the mode creation and annihilation operators $\hat{a}_1^\dagger$ and $\hat{a}_1$. The degree of squeezing is determined by the complex coefficient $\zeta_1 = \xi_1 \exp(i\phi_1)$. Here, ξ_1 is called the squeezing parameter, while the angle ϕ_1 quantifies the amount of rotation of the field quadratures in the corresponding quantum optical phase space.

Let us now assume two squeezed coherent states $|\alpha, \zeta_1\rangle_1$ and $|\beta, \zeta_2\rangle_2$ as the input states of a general lossy beam splitter. The input states are then characterized by in total four complex parameters: the coherence parameters $\alpha = |\alpha| \exp(i\theta_1)$ and $\beta = |\beta| \exp(i\theta_2)$, and the squeezing parameters $\zeta_1 = \xi_1 \exp(i\phi_1)$ and $\zeta_2 = \xi_2 \exp(i\phi_2)$. The total input state has the form $|\psi\rangle_{\text{in}} = |\alpha, \zeta_1\rangle_1 \otimes |\beta, \zeta_2\rangle_2 \otimes |\rangle_{\text{BS}}$.

4.1 Perfect coherent absorption of coherence

The expected values of the input operators with respect to the state $|\psi\rangle_{\text{in}}$ read

$$\langle \hat{a}_1 \rangle = |\alpha| (e^{i\theta_1} \cosh(\xi_1) - e^{-i\theta_1} e^{i\phi_1} \sinh(\xi_1)), \quad (11a)$$

$$\langle \hat{a}_2 \rangle = |\beta| (e^{i\theta_2} \cosh(\xi_2) - e^{-i\theta_2} e^{i\phi_2} \sinh(\xi_2)). \quad (11b)$$

For the input coherence (4) it then follows that

$$\mathcal{C}_{\text{in}} = \gamma_1^2 |\alpha|^2 + \gamma_2^2 |\beta|^2, \quad (12)$$

where $\gamma_1^2 = \cosh(2\xi_1) - \cos(\eta_1) \sinh(2\xi_1)$, $\gamma_2^2 = \cosh(2\xi_2) - \cos(\eta_2) \sinh(2\xi_2)$ with $\eta_1 \equiv 2\theta_1 - \phi_1$ and $\eta_2 \equiv 2\theta_2 - \phi_2$. Similarly, by using the input-output relations (1), we obtain the output coherence

$$\mathcal{C}_{\text{out}} = (|t|^2 + |r|^2) \mathcal{C}_{\text{in}} + \Gamma(tr^* + rt^*), \quad (13)$$

where $\Gamma = \langle \hat{a}_1 \rangle \langle \hat{a}_2 \rangle^* + \langle \hat{a}_2 \rangle \langle \hat{a}_1 \rangle^*$. Therefore, by Eq. (5), the fraction of the coherence that gets lost is

$$\mathcal{A}_{\text{sq}}^{\mathcal{C}} = 1 - \left(|t|^2 + |r|^2 + \frac{\Gamma(tr^* + rt^*)}{\gamma_1^2 |\alpha|^2 + \gamma_2^2 |\beta|^2} \right). \quad (14)$$

In the following we will analyze whether it is possible that all coherence gets lost at the absorbing beam splitter, i.e. whether $\mathcal{A}_{\text{sq}}^{\mathcal{C}} = 1$ can be achieved with two incoming squeezed states.

We study how squeezing affects the coherent absorption of quantum coherence by exploring Eq. (14) for two special cases. For the CPA beam splitter with $t = 1/2$ and $r = -1/2$, and two input states with equal coherent amplitudes ($\alpha_1 = \alpha_2 = \alpha$), a nonvanishing coherent phase difference ($\theta_1 = \theta$ and $\theta_2 = 0$), equal squeezing amplitudes $\xi_1 = \xi_2 = \xi$ and vanishing squeezing phases ($\phi_1 = \phi_2 = 0$), we obtain

$$\mathcal{A}_{\text{sq}}^{\mathcal{C}} = \frac{1}{2} + \frac{\cos(\theta)}{1 + e^{2\xi} [\cosh(2\xi) - \cos(2\theta) \sinh(2\xi)]}. \quad (15)$$

Thus, for all phase differences θ , in the limit $\xi \rightarrow +\infty$ (amplitude squeezing), the coefficient of absorption of quantum coherence converges to the maximum incoherent absorption of $\mathcal{A} = 1/2$. With squeezing up to $\xi \approx 5$, almost perfect absorption of quantum coherence is recovered for θ equal to a multiple of 2π . In the opposite limit $\xi \rightarrow -\infty$ (phase squeezing), the coefficient of absorption becomes $\mathcal{A}_{\text{sq}}^{\mathcal{C}} = 1/2 + (\cos(\theta)/[1 + (1/2)(1 + \cos(2\theta))])$, similar to the bare coherent states, with total loss of coherence ($\mathcal{A}_{\text{sq}}^{\mathcal{C}} = 1$) in the case of equal phases ($\theta = 0$).

As the second special case to illustrate loss of coherence in the presence of squeezing, we revert the situation and take the coherence phases and amplitudes to be equal, but different squeezing amplitudes (and again $\delta = \phi = 0$ and the same beam splitter with $t = 1/2$ and $r = -1/2$). This gives

$$\mathcal{A}_{\text{sq}}^{\mathcal{C}} = 1 - \frac{1}{2} \left(1 - \frac{2e^{-\xi'}}{e^{-2\xi_1} + e^{-2\xi_2}} \right). \quad (16)$$

This formula implies that in the absence of phases, squeezing always works against absorption provided that $\xi_1 \neq \xi_2$. Indeed, the perfect absorption of coherent photons occurs only if $\xi_1 = \xi_2$.

4.2 Coherent absorption of intensity

For a fair comparison of coherence and intensity absorption, we now consider the same special cases that we already investigated in our analysis of the coefficient of absorption of quantum coherence. First, we choose $\theta_1 = \theta$, $\xi_1 = \xi_2 = \xi$, $\theta_2 = \phi_1 = \phi_2 = 0$ and $t = 1/2$ and $r = -1/2$ with equal coherent amplitudes. We obtain

$$\mathcal{A}_{\text{sq}}^{\mathcal{I}} = \frac{1}{2} + \frac{(\cos(\theta)/2)e^{-2\xi}}{e^{-2\xi} + \left[\frac{1 - \cos(2\theta)}{2} \right] \sinh(2\xi) + \frac{\sinh^2(\xi)}{|\alpha|^2}}, \quad (17)$$

which should be compared with Eq. (15) that gives $\mathcal{A}_{\text{sq}}^{\mathcal{C}}$ for the same input states. Notice that $\mathcal{A}_{\text{sq}}^{\mathcal{I}}$ depends on $|\alpha|$ while $\mathcal{A}_{\text{sq}}^{\mathcal{C}}$ does not. In the limit $\xi \rightarrow +\infty$, we have $\mathcal{A}_{\text{sq}}^{\mathcal{I}} = 1/2$ as before. Thus, in this limit all the quantum contributions due to quantum coherence and squeezing are lost and the corresponding absorption coefficients reduce to that of maximum incoherent one, i.e., $\mathcal{A}_{\text{sq}}^{\mathcal{C}} = \mathcal{A}_{\text{sq}}^{\mathcal{I}} = \mathcal{A}$. In the opposite limit of $\xi \rightarrow -\infty$, we obtain $\mathcal{A}_{\text{sq}}^{\mathcal{I}} = (1/2) + 2 \cos(\theta)/[3 + \cos(2\theta) + (1/|\alpha|^2)] < 1$ for all $\alpha \in \mathbb{C}$. Perfect absorption of intensity is possible if and only if there is no squeezing, while coherence could be fully absorbed also in the presence of squeezing.

5. CONTINUOUS-VARIABLE QUANTUM STATE PREPARATION WITH CPA

We would like to know the quantum states of light produced at the output of a beam splitter that exhibits CPA. For equal coherent states $|\alpha\rangle_1$ and $|\alpha\rangle_2$ as input, we found that there is no intensity in the output, so the output state for the two optical output modes is the vacuum state, whatever the coherence amplitude $|\alpha|$ of the input states. Quantum state preparation becomes even more interesting for squeezed coherent input states, which we write in terms of squeezing and displacement operators as

$$\begin{aligned} |\psi\rangle_{\text{in}} &= |\alpha, \zeta_1\rangle_1 \otimes |\beta, \zeta_2\rangle_2 \otimes |\rangle_{\text{BS}} \\ &= e^{\frac{1}{2}(\zeta_2^* \hat{a}_2^2 + \zeta_1^* \hat{a}_1^2) - \frac{1}{2}(\zeta_2 \hat{a}_2^{\dagger 2} + \zeta_1 \hat{a}_1^{\dagger 2})} \hat{D}_1(\alpha) \hat{D}_2(\beta) |\rangle \otimes |\rangle_{\text{BS}}. \end{aligned} \quad (18)$$

In the previous section we saw that for equal input amplitudes and squeezing, and for $t = -r = 1/2$, all coherence can be coherently absorbed but some output intensity will always remain. We will now use the input state (18), specify $\beta = \alpha$ and $\zeta_2 = \zeta_1 = \zeta$, and then determine the output state for this specific case.

In Eq. (1), output operators were defined in terms of input operators. We need instead the input operators in terms of the output operators. Thereby we can obtain the sought output state by writing the input state in terms of the output operators. We will use the known quantum optical input-output theory for absorbing beam splitters,^{38–41,43} in particular Ref.,⁴¹ and identify what is special about quantum state transformation by absorbing beam splitters that exhibit CPA. Following Ref.⁴¹ we write the input-output operator relations Eq. (1) in matrix notation as

$$\hat{\mathbf{b}} = \mathbf{T}\hat{\mathbf{a}} + \mathbf{A}\hat{\mathbf{g}}. \quad (19)$$

Here $\mathbf{T}$ is the 2×2 transmission matrix. The Langevin noise of the absorbing beam splitter is accounted for by linear combinations of bosonic device input operators $\hat{g}_1$ and $\hat{g}_2$ that together form the vector $\hat{\mathbf{g}}$. The corresponding linear coefficients form the 2×2 absorption matrix $\mathbf{A}$. Besides optical output operators $\hat{b}_{1,2}$, there are device output operators $\hat{h}_{1,2}$. Also the latter pair can be written as a linear combination of all four input operators. The 4×4 matrix that relates all four output operators in terms of the four input operators is restricted by the requirement that output operators satisfy standard bosonic commutation relations and are canonically independent. This restricts $\mathbf{A}$ once $\mathbf{T}$ is given, for example.

The formalism of Ref.⁴¹ simplifies particularly for the CPA beam splitter because $\mathbf{T}$ is a real symmetric matrix in this special case, and the absorption matrix $\mathbf{A}$ is then also easily found:

$$\begin{aligned} \mathbf{T}_{\text{cpa}} = \begin{pmatrix} t & r \\ r & t \end{pmatrix} &= \frac{1}{2} \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix} = \frac{1}{2} (\mathbf{1} - \sigma_x), \\ \mathbf{A}_{\text{cpa}} &= \frac{1}{2} \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} = \frac{1}{2} (\mathbf{1} + \sigma_x), \end{aligned} \quad (20)$$

both in terms of the 2×2 unit matrix $\mathbf{1}$ and the Pauli matrix σ_x . For the CPA beam splitter, the inverse relationship of Eq. (19) becomes

$$\hat{\mathbf{a}} = \mathbf{T}_{\text{cpa}} \hat{\mathbf{b}} - \mathbf{A}_{\text{cpa}} \hat{\mathbf{h}}. \quad (21)$$

Now we can use these relations to write $\hat{a}_1$ and $\hat{a}_2$ in the input state (18) in terms of the four output operators $\hat{b}_{1,2}$ and $\hat{h}_{1,2}$. We thereby obtain as one of our main results the output state

$$|\psi\rangle_{\text{out}} = e^{\frac{1}{4}\zeta^* (\hat{b}_1 - \hat{b}_2)^2 - \frac{1}{4}\zeta (\hat{b}_1^\dagger - \hat{b}_2^\dagger)^2} |\rangle \otimes e^{\frac{1}{4}\zeta^* (\hat{h}_1 + \hat{h}_2)^2 - \frac{1}{4}\zeta (\hat{h}_1^\dagger + \hat{h}_2^\dagger)^2} |\alpha, \alpha\rangle_{\text{BS}}.$$

This is a direct-product state of optical output states and beam splitter device states. In other words, the optical output state is *not entangled* with the absorbing beam splitter that was used to produce it. This leaves the reduced output state of only the light in a pure state, rather than the usual mixed state. This is the main reason why the CPA beam splitter, although lossy, could become a useful component in continuous-variable quantum state engineering.

The state (22) is produced by perfect coherent absorption of coherence: all coherence of the input state $|\psi\rangle_{\text{in}} = |\alpha, \zeta\rangle_1 \otimes |\alpha, \zeta\rangle_2 \otimes |\rangle_{\text{BS}}$ ends up in the material modes of the beam splitter. The optical output state does not depend on the input coherence amplitude α at all. This explains that we found $A_{\text{sq}}^C = 1$ in Sec. 4.1.

For vanishing squeezing we indeed find standard CPA behavior: for the 2-mode coherent input state $|\psi\rangle_{\text{in}} = |\alpha\rangle_1 \otimes |\alpha\rangle_2 \otimes |\rangle_{\text{BS}}$ we find from Eq. (22) the corresponding output state $|\psi\rangle_{\text{out}} = |\rangle \otimes |\alpha, \alpha\rangle_{\text{BS}}$. This is a direct product of indeed the optical vacuum state and coherent states for the device modes of the beam splitter. So for coherent states the coherent absorption is indeed perfect, no photons leave the CPA beam splitter and $A_{\text{sq}}^{\mathcal{I}} = 1$.

Back to the general case of squeezed coherent input, the optical output state $e^{\frac{1}{4}\zeta^*(\hat{b}_1 - \hat{b}_2)^2 - \frac{1}{4}\zeta(\hat{b}_1^\dagger - \hat{b}_2^\dagger)^2}|\rangle$ in Eq. (22) is a one- and two-mode combined squeezed vacuum state. The one-mode squeezing corresponds to quadratic operators in the exponent such as $\hat{b}_2^2$, and the two-mode squeezing to the products of different operators such as $\hat{b}_1\hat{b}_2$. Squeezed vacuum states have non-vanishing intensities, and since a beam splitter under CPA conditions emits squeezed vacuum states of light, coherent perfect absorption of intensity is not possible, and $A_{\text{sq}}^{\mathcal{I}} < 1$ for non-vanishing squeezing. This optical output state is independent of the coherence amplitude α of the incident squeezed coherent states. This quantum property explains why the coherent absorption coefficient $A_{\text{sq}}^{\mathcal{I}}$ in Eq. (17) became dependent on the input intensity via $|\alpha|^2$, while such a nonlinear dependence is absent for $A_{\text{sq}}^{\mathcal{C}}$ in Eq. (15). The one- and two-mode combined squeezed vacuum states have been studied in different settings before.^{34–37}

6. CONCLUSIONS

In conclusion, we investigated the coherent absorption of light when two squeezed coherent beams are superposed on an absorbing beam splitter. We first reconsidered the generic case of two incoming bare coherent states and distinguished two types of absorption, namely of quantum coherence and of intensity. We showed that the corresponding absorption coefficients are identical for the case of bare coherent state inputs

In the case of squeezed coherent beams, the coherent degree of freedom is completely absorbed, provided that the CPA conditions hold. Furthermore, we find that an entangled squeezed vacuum state is produced at the output, leaving the absorber in a squeezed coherent state.

We propose to test and use the lossy CPA gate as a new tool for quantum state preparation. Since quite remarkably the CPA gate produces a direct-product state of an optical output state and an internal beam-splitter state [see Eq. (22)], it does not suffer from the usual disadvantage of lossy optical components that they become entangled with optical fields, producing mixed reduced quantum states for the light fields. Instead, the optical output states of the CPA gate are pure quantum states.

It is interesting to compare the CPA gate with the usual practical implementation of “phase-space displacement” by which a squeezed vacuum state and a strong coherent state are mixed on a low-reflectivity non-lossy beam splitter,⁴⁴ resulting in a squeezed coherent output state. Our CPA gate does more or less the reverse, separating squeezing from coherence, but the crucial difference is that it does so for *arbitrary* (but equal) input coherence amplitudes. This arbitrariness constitutes a useful robustness of this gate. In particular, the CPA gate would work in a small-signal regime where saturation effects in absorption can safely be neglected.

Our proposal of the CPA quantum gate is part of an interesting wider trend to engineer quantum dissipation and to use it for quantum state preparation and other quantum operations.^{45–52} Also for our CPA gate for continuous-variable quantum state preparation, loss is a resource to obtain new functionality.

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