

# **Notes of Quantum Optics**

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# Preface

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## Chapter 1

# Field quantization

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## 1.1 Electrodynamics review

### 1.1.1 Plane waves and algebra

### 1.1.2 Helmholtz and potentials

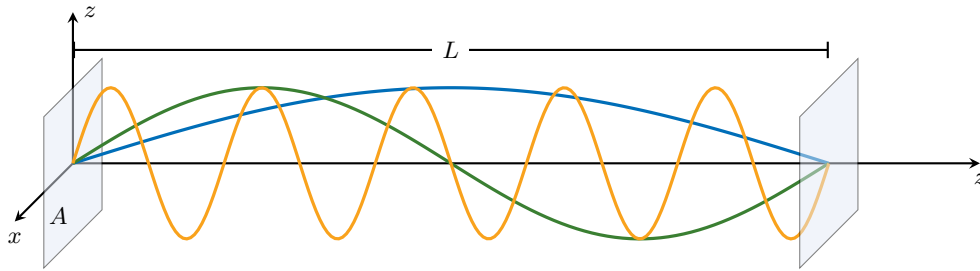
### 1.1.3 Wave equations

## 1.2 Quantization of a single-mode field

### 1.2.1 Fields in a cavity

Lets consider the following one-dimensional problem, where a cavity of length  $L$  is oriented along the  $z$ -axis.

A linear polarized E-field is assumed, the medium is free space, perfect conducting walls and there is no free charges nor free current. The scheme is shown in figure 1.1.



**Figure 1.1** One-dimensional cavity problem. Perfect conducting walls.

Our goal is to find the E- and B-field inside the cavity. Maxwell's equations in this case are:

$$\text{Maxwell's equations with free sources} \quad \begin{cases} \nabla \cdot \mathbf{E} = 0 \\ \nabla \cdot \mathbf{B} = 0 \\ \nabla \times \mathbf{E} = -\partial_t \mathbf{B} \\ \nabla \times \mathbf{B} = \frac{1}{c^2} \partial_t \mathbf{E} \end{cases} \quad (1.1)$$

The E-field will be assumed to be  $\mathbf{E}(z,t) = \mathbf{e}E(z,t)$ , where  $\mathbf{e}$  is the polarization vector. Because fields depends only on  $z$ ,  $\nabla = \hat{z}\partial_z$ . First Maxwell equation yields:

$$\nabla \cdot \mathbf{E} = \partial_z(\hat{z} \cdot \mathbf{E}) = \partial_z(\hat{z} \cdot \mathbf{e}E) = 0 \implies \mathbf{e} \cdot \hat{z} = 0.$$

This implies that the polarization vector must be unitary in the transverse plane:

$$\mathbf{e} = \cos \phi \hat{\mathbf{x}} + \sin \phi \hat{\mathbf{y}}.$$

Third Maxwell's equation yields

$$\nabla \times \mathbf{E} = (\hat{z}\partial_z) \times (\mathbf{e}E) = (\hat{z} \times \mathbf{e})\partial_z E = -\partial_t \mathbf{B}.$$

Taking the curl of this equation, using Fourth Maxwell's equation and vector identities:

$$\begin{aligned} \nabla \times (\nabla \times \mathbf{E}) &= -\partial_t (\nabla \times \mathbf{B}) \\ \nabla(\nabla \cdot \mathbf{E}) - \nabla^2 \mathbf{E} &= -\frac{1}{c^2} \partial_t^2 \mathbf{E} \\ -\partial_z^2 \mathbf{E} &= -\frac{1}{c^2} \partial_t^2 \mathbf{E}. \end{aligned}$$

From here, we have the E-field wave equation for this particular problem.

$$\partial_z^2 E - \frac{1}{c^2} \partial_t^2 E = 0. \quad (1.2)$$

Before solving this equation, we need the boundary condition set by the PEC condition. We need to  $\hat{n} \times \mathbf{E} = 0$  on the surface. Because the normal surface unit vector is  $\hat{n} = \pm \hat{z}$ , we have

$$\text{Boundary condition} \quad \hat{n} \times \mathbf{E} = \hat{z} \times (\mathbf{e} E) = 0 \implies E(z=0, t) = E(z=L, t) = 0.$$

In order to solve the PDE, we assume a product form  $E(z, t) = Z(z)q(t)$ . Then, by replacing in it in (1.2):

$$\begin{aligned} \partial_z^2 [Z(z)q(t)] - \frac{1}{c^2} \partial_t^2 [Z(z)q(t)] &= 0 \\ Z''(z)q(t) - \frac{1}{c^2} Z(z)\ddot{q}(t) &= \bigg/ [Z(z)q(t)]^{-1} \\ \frac{Z''(z)}{Z(z)} &= \frac{1}{c^2} \frac{\ddot{q}(t)}{q(t)}. \end{aligned}$$

Left side depends only on  $z$ , while the right side only on  $y$ . The only way this can be true is if both are a constant, say,  $-k^2$ . Then,

$$\text{Spatial and temporal differential equations} \quad \left\{ \begin{array}{l} \frac{Z''}{Z} = -k^2 \longrightarrow Z'' + k^2 Z = 0 \\ \frac{1}{c^2} \frac{\ddot{q}}{q} = -k^2 \longrightarrow \ddot{q} + \omega^2 q(t) = 0 \end{array} \right.$$

For the spatial ODE, we assume a solution of the form

$$Z(z) = A \sin(kz) + B \cos(kz), \quad Z(0) = Z(L) = 0.$$

Setting the boundaries:

$$\begin{aligned} Z(0) &= A \sin(0) + B \cos(0) = 0 \implies B = 0 \\ Z(L) &= A \sin(kL) = 0 \implies k_m = \frac{m\pi}{L}, \quad m \in \mathbb{N}. \end{aligned}$$

We left the temporal ODE unsolved. Finally, putting all together yields the initial E-field:

$$\mathbf{E}_{\mathbf{k},\lambda}(z, t) = \mathbf{e}_\lambda \sqrt{\frac{2\omega^2}{V\varepsilon_0}} q_{\mathbf{k},\lambda}(t) \sin(kz), \quad k_m = \frac{m\pi}{L}, \quad \omega = ck.$$

We have includnig the subscript  $\lambda$  and  $\mathbf{k}$  to consider multiple mode  $\mathbf{k}$  varied with  $m$  and  $\lambda$ . Also, the coefficient in red is for better results in the future. Using Faraday's law:

$$\mathbf{B}_{\mathbf{k},\lambda}(z, t) = (\mathbf{k} \times \mathbf{e}_\lambda) \frac{1}{kc^2} \sqrt{\frac{2\omega^2}{V\varepsilon_0}} \dot{q}_{\mathbf{k},\lambda}(t) \sin(kz).$$

The term  $\dot{q}(t)$  will play the role of a canonical momentum for a particle of unit mass,  $p(t) = \dot{q}(t)$ .

### 1.2.2 Single-mode Hamiltonian

The classical field energy, or Hamiltonian  $H$ , of the single-mode field is given by

$$\begin{aligned}
 H_{\mathbf{k},\lambda} &= \frac{1}{2} \int dV \left[ \epsilon_0 \mathbf{E}_{\mathbf{k},\lambda}^2 + \frac{1}{\mu_0} \mathbf{B}_{\mathbf{k},\lambda}^2 \right] \\
 &= \frac{1}{2} A \int_0^L dz \left[ \frac{2\omega^2}{V\epsilon_0} q_{\mathbf{k},\lambda}^2(t) \sin^2(kz) + \frac{1}{\mu_0} \frac{1}{k^2 c^4} \frac{2\omega^2}{V\epsilon_0} p_{\mathbf{k},\lambda}^2(t) \cos^2(kz) \right] \\
 &= \frac{A}{V} \int_0^L dz \left[ \omega^2 q_{\mathbf{k},\lambda}^2(t) \sin^2(kz) + p_{\mathbf{k},\lambda}^2(t) \cos^2(kz) \right] \\
 &= \frac{1}{L} \left[ \omega^2 q_{\mathbf{k},\lambda}^2(t) \frac{L}{2} + p_{\mathbf{k},\lambda}^2(t) \frac{L}{2} \right] \\
 H_{\mathbf{k},\lambda} &= \frac{1}{2} \left[ \omega^2 q_{\mathbf{k},\lambda}^2(t) + p_{\mathbf{k},\lambda}^2(t) \right].
 \end{aligned}$$

It is apparent that a single-mode field is formally equivalent to a harmonic quantum oscillator of unit mass, where the E- and B-fields play the roles of canonical position and momentum.

$$H_{\text{harmonic oscillator}} = \frac{1}{2} m \omega^2 x^2 + \frac{p^2}{2m}.$$

To begin the quantization, we make  $q, p$  operators  $\hat{q}, \hat{p}$ , which needs to satisfy the canonical commutation relations

$$[\hat{q}_{\mathbf{k},\lambda}, \hat{p}_{\mathbf{k},\lambda}] = i\hbar. \quad (1.3)$$

The EM fields with the operators are:

$$\begin{aligned}
 \hat{\mathbf{E}}_{\mathbf{k},\lambda}(z, t) &= \mathbf{e}_{\mathbf{k},\lambda} \sqrt{\frac{2\omega^2}{V\epsilon_0}} \hat{q}(t) \sin(kz) \\
 \hat{\mathbf{B}}_{\mathbf{k},\lambda}(z, t) &= (\mathbf{k} \times \mathbf{e}_{\mathbf{k},\lambda}) \frac{1}{kc^2} \sqrt{\frac{2\omega^2}{V\epsilon_0}} \hat{p}(t) \cos(kz)
 \end{aligned} \quad (1.4)$$

Quantized EM fields

The operators  $\hat{q}, \hat{p}$  are Hermitian and therefore correspond to observable quantities. It is convenient to introduce the ladder operators to simplify the expression:

$$\begin{aligned}
 \hat{a}_{\mathbf{k},\lambda} &= \sqrt{\frac{1}{2\hbar\omega}} (\omega \hat{q}_{\mathbf{k},\lambda} + i \hat{p}_{\mathbf{k},\lambda}) \longrightarrow \hat{q}_{\mathbf{k},\lambda} = \sqrt{\frac{\hbar}{2\omega}} (\hat{a}_{\mathbf{k},\lambda} + \hat{a}_{\mathbf{k},\lambda}^\dagger) \\
 \hat{a}_{\mathbf{k},\lambda}^\dagger &= \sqrt{\frac{1}{2\hbar\omega}} (\omega \hat{q}_{\mathbf{k},\lambda} - i \hat{p}_{\mathbf{k},\lambda}) \longrightarrow \hat{p}_{\mathbf{k},\lambda} = -i \sqrt{\frac{\hbar\omega}{2}} (\hat{a}_{\mathbf{k},\lambda} - \hat{a}_{\mathbf{k},\lambda}^\dagger)
 \end{aligned}$$

Ladder operator

Using these definition, the Hamiltonian yields:

$$\begin{aligned}
 \hat{H}_{\mathbf{k},\lambda} &= -\frac{1}{2} \frac{\hbar\omega}{2} (\hat{a}_{\mathbf{k},\lambda} - \hat{a}_{\mathbf{k},\lambda}^\dagger)(\hat{a}_{\mathbf{k},\lambda} - \hat{a}_{\mathbf{k},\lambda}^\dagger) + \frac{1}{2} \frac{\hbar\omega^2}{2\omega} (\hat{a}_{\mathbf{k},\lambda} + \hat{a}_{\mathbf{k},\lambda}^\dagger)(\hat{a}_{\mathbf{k},\lambda} + \hat{a}_{\mathbf{k},\lambda}^\dagger) \\
 &= \frac{\hbar\omega}{2} [\hat{a}_{\mathbf{k},\lambda}^\dagger \hat{a}_{\mathbf{k},\lambda} + \hat{a}_{\mathbf{k},\lambda} \hat{a}_{\mathbf{k},\lambda}^\dagger] = \hbar\omega \left[ \hat{a}_{\mathbf{k},\lambda}^\dagger \hat{a}_{\mathbf{k},\lambda} + \frac{1}{2} \right] = \hbar\omega \left[ n_{\mathbf{k},\lambda} + \frac{1}{2} \right].
 \end{aligned}$$

The time dependence of the ladder operator in Heisenberg equation is:

$$\frac{d\hat{a}_{\mathbf{k},\lambda}}{dt} = \frac{i}{\hbar} [\hat{H}_{\mathbf{k},\lambda}, \hat{a}_{\mathbf{k},\lambda}] = \frac{i}{\hbar} \left[ \hbar\omega \left( \hat{a}_{\mathbf{k},\lambda}^\dagger \hat{a}_{\mathbf{k},\lambda} + \frac{1}{2} \right), \hat{a}_{\mathbf{k},\lambda} \right] = -i\omega \hat{a}_{\mathbf{k},\lambda} \longrightarrow \begin{aligned} \hat{a}_{\mathbf{k},\lambda}(t) &= \hat{a}_{\mathbf{k},\lambda}(0) e^{-i\omega t} \\ \hat{a}_{\mathbf{k},\lambda}^\dagger(t) &= \hat{a}_{\mathbf{k},\lambda}^\dagger(0) e^{i\omega t} \end{aligned}$$

For example, we have the following applications:

$$\hat{a}_{\mathbf{k},\lambda} |0\rangle = |1\rangle_{\mathbf{k},\lambda}, \quad \hat{a}_{\mathbf{k},\lambda} |n\rangle_{\mathbf{k},\lambda} = \sqrt{n} |n-1\rangle_{\mathbf{k},\lambda}, \quad \hat{a}_{\mathbf{k},\lambda}^\dagger |n\rangle_{\mathbf{k},\lambda} = |n+1\rangle_{\mathbf{k},\lambda}, \quad \hat{a}_{\mathbf{k},\lambda} |n\rangle_{\mathbf{k},\lambda} |0\rangle_{\mathbf{k},\omega} = 0.$$

The operator product  $\hat{a}^\dagger \hat{a}$  has an important significance and is called the number operator  $\hat{n}$ , whose eigenequation is

$$\hat{n} |n\rangle = n |n\rangle.$$

The state  $|n\rangle$  is the energy eigenstate of the single mode field with energy eigenvalue  $E_n$ :

$$\hat{H} |n\rangle = \hbar\omega \left( \hat{a}^\dagger \hat{a} + \frac{1}{2} \right) |n\rangle = E_n |n\rangle$$

The relation between the number state and the raising operator  $\hat{a}^\dagger$  is:

$$|n\rangle = \frac{(\hat{a}^\dagger)^n}{\sqrt{n!}} |0\rangle.$$

### 1.2.3 Quantizing the multimode field

We now consider all the modes in the optical cavity:

$$\mathbf{E}(z, t) = \sum_{m,\lambda} \hat{\mathbf{e}}_\lambda \sqrt{\frac{2\omega_m^2}{\varepsilon_0 V}} \hat{q}_{m,\lambda}(t) \sin(k_m z) \quad (1.5)$$

$$\mathbf{B}(z, t) = \sum_{m,\lambda} (\hat{\mathbf{z}} \times \hat{\mathbf{e}}_\lambda) \frac{1}{k_m c^2} \sqrt{\frac{2\omega_m^2}{\varepsilon_0 V}} \dot{\hat{q}}_{m,\lambda}(t) \cos(k_m z). \quad (1.6)$$

where  $kL = m\pi$  and  $\hat{\mathbf{e}}_\lambda = \{\hat{\mathbf{x}}, \hat{\mathbf{y}}\}$ . The process is analogous; we compute the Hamiltonian:

$$\begin{aligned} H &= \int dV \left[ \frac{1}{2} \varepsilon_0 \mathbf{E}^2(z, t) + \frac{1}{2\mu_0} \mathbf{B}^2(z, t) \right] \\ &= \int dV \left[ \frac{1}{2} \varepsilon_0 \left\{ \sum_{m,\alpha} \hat{\mathbf{e}}_\alpha \sqrt{\frac{2\omega_m^2}{\varepsilon_0 V}} \hat{q}_{m,\alpha}(t) \sin(k_m z) \right\}^2 + \frac{1}{2\mu_0} \varepsilon_0 \left\{ \sum_{m,\alpha} (\hat{\mathbf{z}} \times \hat{\mathbf{e}}_\alpha) \frac{\mu_0}{\varepsilon_0} k_m \sqrt{\frac{2\omega_m^2}{\varepsilon_0 V}} \dot{\hat{q}}_{m,\alpha}(t) \cos(k_m z) \right\}^2 \right] \\ &\vdots \\ H &= \frac{1}{2} \sum_{m,\lambda} (\omega_m^2 \hat{q}_{m,\lambda}^2 + \dot{\hat{q}}_{m,\lambda}^2). \end{aligned}$$

That is,

Each mode of the EM field is an independent harmonic oscillator.

We can quantize the multimode EM field in a similar way as the single mode field to obtain the Hamiltonian:

$$\text{Hamiltonian multimode EM field} \quad \hat{H} = \sum_{m,\lambda} \hbar\omega_m \left[ \hat{a}_{m,\lambda}^\dagger \hat{a}_{m,\lambda} + \frac{1}{2} \right] = \sum_{m,\lambda} \hbar\omega_m \left[ \hat{n}_{m,\lambda} + \frac{1}{2} \right],$$

where  $\hat{n}_{m,\lambda}$  is the number of excitations in mode  $m, \lambda$ .

### 1.2.4 Quantizing EM field in free space

We define the scalar and vector potential

$$\mathbf{B} = \nabla \times \mathbf{A} \quad \text{and} \quad \mathbf{E} = -\partial_t \mathbf{A} - \nabla \phi.$$

Using these automatically satisfy the Gauss magnetic equation and Ampere law. In QO, we assume **Coulomb gauge**:  $\nabla \cdot \mathbf{A} = 0$ . With this, the E-field is

$$\mathbf{E} = -\partial_t \mathbf{A} - \nabla \phi = \mathbf{E}^\perp + \mathbf{E}^\parallel, \quad \text{where} \quad \begin{cases} \nabla \cdot \mathbf{E}^\perp = 0, & \mathbf{A} \text{ corresponds to radiation (all transverse)} \\ \mathbf{E}^\parallel = -\nabla \phi, & \mathbf{A} \text{ corresponds to the field of sources (all longitudinal)} \end{cases}.$$

In Coulomb gauge, in absence of charge  $\phi = 0$  such that the vector potential-wave equation is

$$\nabla^2 \mathbf{A} - \frac{1}{2} \partial_t^2 \mathbf{A} = 0.$$

It can be solved with the following plane wave

$$\mathbf{A}(\mathbf{r}, t) = \sum_{\mathbf{k}, \lambda} \hat{\mathbf{e}}_{\mathbf{k}, \lambda} \left[ A_{\mathbf{k}, \lambda} e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)} + A_{\mathbf{k}, \lambda}^* e^{-i(\mathbf{k} \cdot \mathbf{r} - \omega t)} \right], \quad \nabla \cdot \mathbf{A} = 0 \implies \mathbf{k} \cdot \hat{\mathbf{e}}_{\mathbf{k}, \lambda} = 0.$$

The vector potential in free space is expressed as a sueprposition of plane waves such that linear dispersion  $\omega = |\mathbf{k}|c$  is satisfied with  $\hat{\mathbf{e}}_{\mathbf{k}, \lambda} \cdot \hat{\mathbf{e}}_{\mathbf{k}, \lambda'} = \delta_{\lambda \lambda'}$ .

The quantization volume we quantize the field is considered to have finite volume of  $V$  and we impose periodic boundary such that each side is equal.

The E- and B-field are then:

$$\begin{aligned} \mathbf{E}(\mathbf{r}, t) &= -\partial_t \mathbf{A}(\mathbf{r}, t) = i \sum_{\mathbf{k}, \lambda} \hat{\mathbf{e}}_{\mathbf{k}, \lambda} \omega \left[ A_{\mathbf{k}, \lambda} e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)} + A_{\mathbf{k}, \lambda}^* e^{-i(\mathbf{k} \cdot \mathbf{r} - \omega t)} \right], \\ \mathbf{B}(\mathbf{r}, t) &= \nabla \times \mathbf{A}(\mathbf{r}, t) = i \sum_{\mathbf{k}, \lambda} \hat{\mathbf{e}}_{\mathbf{k}, \lambda} \left[ A_{\mathbf{k}, \lambda} e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)} + A_{\mathbf{k}, \lambda}^* e^{-i(\mathbf{k} \cdot \mathbf{r} - \omega t)} \right]. \end{aligned}$$

The energy (Hamiltonian) associated with the fields is:

$$\begin{aligned} H &= - \int dV \left[ \frac{1}{2} \varepsilon_0 \mathbf{E}^2(\mathbf{r}, t) + \frac{1}{2\mu_0} \mathbf{B}^2(\mathbf{r}, t) \right] \\ &\vdots \\ H &= 2\varepsilon_0 V \sum_{\mathbf{k}, \lambda} \omega^2 |A_{\mathbf{k}, \lambda}|^2. \end{aligned}$$

We have used the following relation:

$$\int dV e^{\pm i(\mathbf{k} - \mathbf{k}') \cdot \mathbf{r}} = \delta_{\mathbf{k} \mathbf{k}'} V.$$

Defining

$$A_{\mathbf{k}, \lambda} = \frac{1}{2\omega \sqrt{\varepsilon_0 V}} (\omega q_{\mathbf{k}, \lambda} + i p_{\mathbf{k}, \lambda}), \quad A_{\mathbf{k}, \lambda}^* = \frac{1}{2\omega \sqrt{\varepsilon_0 V}} (\omega q_{\mathbf{k}, \lambda} - i p_{\mathbf{k}, \lambda}).$$

The Hamiltonian is:

$$H = \frac{1}{2} \sum_{\mathbf{k}, \lambda} (\omega^2 q_{\mathbf{k}, \lambda}^2 + p_{\mathbf{k}, \lambda}^2) \xrightarrow{\text{quantizing}} \hat{H} = \sum_{\mathbf{k}, \lambda} \hbar \omega \left( \hat{a}_{\mathbf{k}, \lambda}^\dagger \hat{a}_{\mathbf{k}, \lambda} + \frac{1}{2} \right),$$

where we have defined the ladder operators:

$$\hat{a} = \frac{1}{\sqrt{2\hbar\omega}}(\omega\hat{q} + i\hat{p}), \quad \hat{a}^\dagger = \frac{1}{\sqrt{2\hbar\omega}}(\omega\hat{q} - i\hat{p}). \quad (1.7)$$

So, the coefficients are expressed in term of the ladder:

$$A_{\mathbf{k}, \lambda} = \sqrt{\frac{\hbar}{2\omega\varepsilon_0 V}} \hat{a}_{\mathbf{k}, \lambda}, \quad A_{\mathbf{k}, \lambda}^* = \sqrt{\frac{\hbar}{2\omega\varepsilon_0 V}} \hat{a}_{\mathbf{k}, \lambda}^\dagger.$$

Thus the fields are:

$$\begin{aligned} \mathbf{A}(\mathbf{r}, t) &= \sum_{\mathbf{k}, \lambda} \sqrt{\frac{\hbar}{2\omega\varepsilon_0 V}} \hat{\mathbf{e}}_{\mathbf{k}, \lambda} \left[ \hat{a}_{\mathbf{k}, \lambda} e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)} + \hat{a}_{\mathbf{k}, \lambda}^\dagger e^{-i(\mathbf{k} \cdot \mathbf{r} - \omega t)} \right], \\ \mathbf{E}(\mathbf{r}, t) &= i \sum_{\mathbf{k}, \lambda} \sqrt{\frac{\hbar\omega}{2\varepsilon_0 V}} \hat{\mathbf{e}}_{\mathbf{k}, \lambda} \left[ \hat{a}_{\mathbf{k}, \lambda} e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)} + \hat{a}_{\mathbf{k}, \lambda}^\dagger e^{-i(\mathbf{k} \cdot \mathbf{r} - \omega t)} \right], \\ \mathbf{B}(\mathbf{r}, t) &= \frac{i}{c} \sum_{\mathbf{k}, \lambda} \sqrt{\frac{\hbar\omega}{2\varepsilon_0 V}} (\mathbf{k} \times \hat{\mathbf{e}}_{\mathbf{k}, \lambda}) \left[ \hat{a}_{\mathbf{k}, \lambda} e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)} + \hat{a}_{\mathbf{k}, \lambda}^\dagger e^{-i(\mathbf{k} \cdot \mathbf{r} - \omega t)} \right]. \end{aligned} \quad (1.8)$$

### 1.2.5 Electric field expectation and uncertainty

Lets consider one mode of the E-field in a number state:  $|n\rangle_{\mathbf{k}, \lambda}$ . Lets add the time dependence to the ladder operators:

$$\hat{a}_{\mathbf{k}, \lambda} e^{-i\omega t} \rightarrow \hat{a}_{\mathbf{k}, \lambda}(t), \quad \hat{a}_{\mathbf{k}, \lambda}^\dagger e^{i\omega t} \rightarrow \hat{a}_{\mathbf{k}, \lambda}^\dagger(t).$$

The E-field is:

$$\hat{\mathbf{E}}(\mathbf{r}, t) = i \sum_{\mathbf{k}, \lambda} e_{\mathbf{k}, \lambda} \sqrt{\frac{\hbar\omega}{2\varepsilon_0 V}} \left[ \hat{a}_{\mathbf{k}, \lambda}(t) e^{i\mathbf{k} \cdot \mathbf{r}} - \hat{a}_{\mathbf{k}, \lambda}^\dagger(t) e^{-i\mathbf{k} \cdot \mathbf{r}} \right].$$

Expectation value of the E-field is:

$$\begin{aligned} {}_{\mathbf{k}_0, \lambda_0} \langle n | \hat{\mathbf{E}}(\mathbf{r}, t) | n \rangle_{\mathbf{k}_0, \lambda_0} &= i {}_{\mathbf{k}, \lambda} \langle n | \hat{\mathbf{e}}_{\mathbf{k}, \lambda} \sqrt{\frac{\hbar\omega}{2\varepsilon_0 V}} \left[ \hat{a}_{\mathbf{k}, \lambda}(t) e^{i\mathbf{k} \cdot \mathbf{r}} - \hat{a}_{\mathbf{k}, \lambda}^\dagger(t) e^{-i\mathbf{k} \cdot \mathbf{r}} \right] | n \rangle_{\mathbf{k}_0, \lambda_0} \\ &= i {}_{\mathbf{k}_0, \lambda_0} \langle n | \hat{\mathbf{e}}_{\mathbf{k}_0, \lambda_0} \sqrt{\frac{\hbar\omega_0}{2\varepsilon_0 V}} \left[ \sqrt{n} |n-1\rangle_{\mathbf{k}_0, \lambda_0} e^{i\mathbf{k}_0 \cdot \mathbf{r}} - \sqrt{n+1} |n+1\rangle_{\mathbf{k}_0, \lambda_0} e^{-i\mathbf{k}_0 \cdot \mathbf{r}} \right] \\ &= 0. \end{aligned}$$

Thus, the average E-field is zero.

Lets consider the uncertainty of the E-field:

$$\begin{aligned} \langle \hat{\mathbf{E}} \rangle &= {}_{\mathbf{k}_0, \lambda_0} \langle n | \sum_{\mathbf{k}, \lambda} \sum_{\mathbf{k}', \lambda'} \sqrt{\frac{\hbar\omega}{2\varepsilon_0 V}} \sqrt{\frac{\hbar\omega'}{2\varepsilon_0 V}} \hat{\mathbf{e}}_{\mathbf{k}, \lambda} \cdot \hat{\mathbf{e}}_{\mathbf{k}', \lambda'} \left[ \hat{a}_{\mathbf{k}, \lambda} e^{i\mathbf{k} \cdot \mathbf{r}} - \hat{a}_{\mathbf{k}, \lambda}^\dagger e^{-i\mathbf{k} \cdot \mathbf{r}} \right] \left[ \hat{a}_{\mathbf{k}', \lambda'} e^{i\mathbf{k}' \cdot \mathbf{r}} - \hat{a}_{\mathbf{k}', \lambda'}^\dagger e^{-i\mathbf{k}' \cdot \mathbf{r}} \right] | n \rangle_{\mathbf{k}_0, \lambda_0} \\ &= \sum_{\mathbf{k}, \lambda} \sum_{\mathbf{k}', \lambda'} \sqrt{\frac{\hbar\omega}{2\varepsilon_0 V}} \sqrt{\frac{\hbar\omega'}{2\varepsilon_0 V}} \langle 1 | 1 \rangle_{\mathbf{k}', \lambda'} e^{i(\mathbf{k} - \mathbf{k}') \cdot \mathbf{r}} + \frac{\hbar\omega_0}{2\varepsilon_0 V} [{}_{\mathbf{k}_0, \lambda_0} \langle n+1 | \sqrt{n+1} + {}_{\mathbf{k}_0, \lambda_0} \langle n-1 | \sqrt{n}] [\sqrt{n+1} | n+1 \rangle_{\mathbf{k}_0, \lambda_0} + \dots] \\ &= \sum_{\{\mathbf{k}, \lambda\} \neq \{\mathbf{k}_0, \lambda_0\}} \frac{\hbar\omega}{2\varepsilon_0 V} + \frac{\hbar\omega_0}{2\varepsilon_0 V} (2n+1). \end{aligned}$$

So, the uncertainty is:

$$\text{E-field uncertainty} \quad \langle \Delta E^2 \rangle = \underbrace{\sum_{\{\mathbf{k}, \lambda\} \neq \{\mathbf{k}_0, \lambda_0\}} \frac{\hbar \omega}{2\varepsilon_0 V}}_{\text{All modes in vacuum state}} + \underbrace{\frac{\hbar \omega_0}{2\varepsilon_0 V} (2n + 1)}_{\text{Mode } (\mathbf{k}_0, \lambda_0)}.$$

## 1.3 Coherent states

The coherent state is defined as the eigenstate of the annihilator operator:

$$\hat{a} |\alpha\rangle = \alpha |\alpha\rangle, \quad \alpha \in \mathbb{C}.$$

The expected number of photons in the coherent state is:

$$\langle \alpha | \hat{n} | \alpha \rangle = \langle \alpha | \hat{a}^\dagger \hat{a} | \alpha \rangle = |\alpha|^2.$$

Coherent states are the most classical states of the quantized EM field.

It has the following results:

$$\langle \alpha | \hat{a}^2 | \alpha \rangle = \alpha^2, \quad \langle \alpha | \hat{a}^{\dagger 2} | \alpha \rangle = \alpha^{*2}, \quad \langle \alpha | \hat{a}^\dagger \hat{a} | \alpha \rangle = |\alpha|^2, \quad \langle \alpha | \hat{a} \hat{a}^\dagger | \alpha \rangle = |\alpha|^2 + 1.$$

For example, computing the expectation of the E-field (1.8) is:

$$\begin{aligned} \langle \mathbf{E} \rangle &= \langle \alpha | i \sum_{\mathbf{k}, \lambda} \sqrt{\frac{\hbar \omega}{2\varepsilon_0 V}} \hat{\mathbf{e}}_{\mathbf{k}, \lambda} [\hat{a}_{\mathbf{k}, \lambda} e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)} - \hat{a}_{\mathbf{k}, \lambda}^\dagger e^{-i(\mathbf{k} \cdot \mathbf{r} - \omega t)}] | \alpha \rangle \\ &= i \sqrt{\frac{\hbar \omega}{2\varepsilon_0 V}} \hat{\mathbf{e}}_{\mathbf{k}, \lambda} [\alpha e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)} - \alpha^* e^{-i(\mathbf{k} \cdot \mathbf{r} - \omega t)}] \\ \langle \mathbf{E} \rangle &= \mathcal{E} e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)} + \mathcal{E}^* e^{-i(\mathbf{k} \cdot \mathbf{r} - \omega t)} \longrightarrow \mathcal{E} = i \sqrt{\frac{\hbar \omega}{2\varepsilon_0 V}} \alpha \hat{\mathbf{e}}_{\mathbf{k}, \lambda}. \end{aligned}$$

The expectation value of the E-field for a coherent state corresponds to a classical E-field.

Let us now consider the uncertainty of the E-field for  $|\alpha\rangle$ :

$$\begin{aligned} \langle \Delta E^2 \rangle &= \langle \mathbf{E}^2 \rangle - \langle \mathbf{E} \rangle^2 \\ &= \langle \alpha | i \hat{\mathbf{e}}_{\mathbf{k}, \lambda} \sqrt{\frac{\hbar \omega}{2\varepsilon_0 V}} [\hat{a} e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)} - \hat{a}^\dagger e^{-i(\mathbf{k} \cdot \mathbf{r} - \omega t)}] \cdot i \hat{\mathbf{e}}_{\mathbf{k}, \lambda} \sqrt{\frac{\hbar \omega}{2\varepsilon_0 V}} [\hat{a} e^{i(\mathbf{k} \cdot \mathbf{r} - \omega t)} - \hat{a}^\dagger e^{-i(\mathbf{k} \cdot \mathbf{r} - \omega t)}] | \alpha \rangle - \langle \mathbf{E} \rangle^2 \\ &= -\frac{\hbar \omega}{2\varepsilon_0 V} [\alpha^2 e^{i2(\mathbf{k} \cdot \mathbf{r} - \omega t)} + \alpha^{*2} e^{-i2(\mathbf{k} \cdot \mathbf{r} - \omega t)} - |\alpha|^2 - (|\alpha|^2 + 1)] - \mathcal{E}^2 e^{i2(\mathbf{k} \cdot \mathbf{r} - \omega t)} - \mathcal{E}^{*2} e^{-i2(\mathbf{k} \cdot \mathbf{r} - \omega t)} - 2|\mathcal{E}|^2 \\ &= \mathcal{E}^2 e^{i2(\mathbf{k} \cdot \mathbf{r} - \omega t)} + \mathcal{E}^{*2} e^{-i2(\mathbf{k} \cdot \mathbf{r} - \omega t)} + 2|\mathcal{E}|^2 + \frac{\hbar \omega}{2\varepsilon_0 V} - \mathcal{E}^2 e^{i2(\mathbf{k} \cdot \mathbf{r} - \omega t)} - \mathcal{E}^{*2} e^{-i2(\mathbf{k} \cdot \mathbf{r} - \omega t)} - 2|\mathcal{E}|^2 \\ \langle \Delta E^2 \rangle &= \frac{\hbar \omega}{2\varepsilon_0 V}. \end{aligned}$$

This is the uncertainty in E-field limited by quantum noise.

Also, we know that the eigenstates of  $|\alpha\rangle$  do not form an orthonormal basis. However, we know that the number state  $|n\rangle$  form an orthonormal basis and we can expand the coherent state in terms of the number states, as follows,

$$|\alpha\rangle = e^{-|\alpha|^2/2} \sum_n \frac{\alpha^n}{\sqrt{n!}} |n\rangle.$$

The probability of finding  $n$  photons in a coherent state is:

$$P_n = |\langle n|\alpha\rangle|^2 = \left| \langle n|e^{-|\alpha|^2/2} \sum_m \frac{\alpha^m}{\sqrt{m!}} |m\rangle \right|^2 = \left| e^{-|\alpha|^2/2} \frac{\alpha^n}{\sqrt{n!}} \right|^2 = e^{-|\alpha|^2} \frac{|\alpha|^{2n}}{n!}.$$

Recalling that  $\langle \hat{n} \rangle = |\alpha|^2 = \bar{n}$ :

Probability of finding  $n$  photons in a coherent state

$$P_n = \frac{e^{-\bar{n}} \bar{n}^n}{n!}.$$

## 1.4 Quadrature operators

Recall the E-field operator for a singel mode is:

$$\begin{aligned} \hat{\mathbf{E}}(\mathbf{r}, t) &= i\sqrt{\frac{\hbar\omega}{2\varepsilon_0 V}} \hat{\mathbf{e}}_{\mathbf{k},\lambda} [\hat{a}e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)} - \hat{a}^\dagger e^{-i(\mathbf{k}\cdot\mathbf{r}-\omega t)}] \\ &= i\sqrt{\frac{\hbar\omega}{2\varepsilon_0 V}} \hat{\mathbf{e}}_{\mathbf{k},\lambda} [\hat{a}e^{-i\omega t}e^{i\mathbf{k}\cdot\mathbf{r}} - \hat{a}^\dagger e^{i\omega t}e^{-i\mathbf{k}\cdot\mathbf{r}}] \\ &= i\sqrt{\frac{\hbar\omega}{2\varepsilon_0 V}} \hat{\mathbf{e}}_{\mathbf{k},\lambda} [\hat{a}(t)e^{i\mathbf{k}\cdot\mathbf{r}} - \hat{a}^\dagger(t)e^{-i\mathbf{k}\cdot\mathbf{r}}] \\ \hat{\mathbf{E}}(\mathbf{r}, t) &= i\sqrt{\frac{\hbar\omega}{2\varepsilon_0 V}} \hat{\mathbf{e}}_{\mathbf{k},\lambda} [\hat{a}(t) \cos(\mathbf{k} \cdot \mathbf{r}) + i\hat{a}(t) \sin(\mathbf{k} \cdot \mathbf{r}) - \hat{a}^\dagger(t) \cos(\mathbf{k} \cdot \mathbf{r}) + i\hat{a}^\dagger(t) \sin(\mathbf{k} \cdot \mathbf{r})]. \end{aligned}$$

Lets define the quadrature operators:

$$\begin{aligned} \text{Quadrature operators} \quad \hat{X}_1 &= \frac{1}{2}(\hat{a} + i\hat{a}^\dagger) \\ \hat{X}_2 &= \frac{1}{2i}(\hat{a} - \hat{a}^\dagger) \end{aligned} \quad (1.9)$$

where  $[\hat{X}_1, \hat{X}_2] = \frac{i}{2}$ . In the E-field, if we collect the cosine and sine, we get

$$\hat{\mathbf{E}}(\mathbf{r}, t) = -\sqrt{\frac{2\hbar\omega}{\varepsilon_0 V}} \hat{\mathbf{e}}_{\mathbf{k},\lambda} [\hat{X}_1(t) \sin(\mathbf{k} \cdot \mathbf{r}) + \hat{X}_2(t) \cos(\mathbf{k} \cdot \mathbf{r})].$$

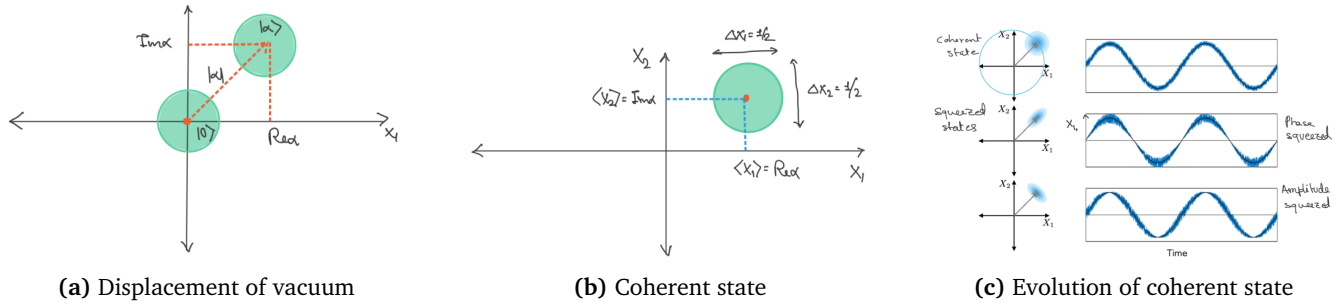
The expectation value of these operators is:

$$\begin{aligned} \langle \alpha | \hat{X}_1(0) | \alpha \rangle &= \langle \alpha | \frac{\hat{a} + \hat{a}^\dagger}{2} | \alpha \rangle = \text{Re}(\alpha), \quad \langle \alpha | \hat{X}_2(0) | \alpha \rangle = \langle \alpha | \frac{\hat{a} - \hat{a}^\dagger}{2i} | \alpha \rangle = \text{Im}(\alpha), \\ \langle \Delta \hat{X}_1^2 \rangle &= \langle \alpha | \frac{1}{4}(\hat{a} + \hat{a}^\dagger)^2 | \alpha \rangle - \frac{1}{4}(\alpha + \alpha^*)^2 = \frac{1}{4}, \quad \langle \Delta \hat{X}_2^2 \rangle = \frac{1}{4}. \end{aligned}$$



That is, there is a minimum uncertainty that a state can possibly have in the two quadrature  $\hat{X}_1, \hat{X}_2$ , such a state is referred to as *minimum uncertainty state*. When  $\alpha = 0$  we have the vacuum state and therefore  $\langle \hat{X}_1(0) \rangle = \langle \hat{X}_2(0) \rangle = 0$ ,  $\langle \hat{X}_1^2(0) \rangle = \langle \hat{X}_2^2(0) \rangle = 1/4$ . Coherent states are also referred to as displaced vacuum states. Specifically,

$$|\alpha\rangle = \hat{D}(\alpha)|0\rangle, \quad \hat{D}(\alpha) = e^{\alpha\hat{a}^\dagger - \alpha^*\hat{a}}.$$



If we include the time dependence:

$$\langle \alpha | \hat{X}_1(t) | \alpha \rangle = \frac{\alpha e^{-i\omega t} + \alpha^* e^{i\omega t}}{2} = \text{Re}(\alpha e^{-i\omega t}), \quad \langle \alpha | \hat{X}_2(t) | \alpha \rangle = \frac{\alpha e^{-i\omega t} - \alpha^* e^{i\omega t}}{2i} = \text{Im}(\alpha e^{-i\omega t}).$$

The phase space representation of states allows one to access information about the noise/variance associated with any state when a specific E-field quadrature is measured.

### 1.4.1 Taking the continuum limit

In free space the sum over all  $\mathbf{k}$  becomes an integral:

$$\sum_{\mathbf{k}} \rightarrow N \int d^3\mathbf{k} = N \int_0^\infty dk k^2 \int_0^\pi d\theta \sin\theta \int_0^{2\pi} d\phi,$$

where  $N$  is the normalization equal to volume/mode. We consider a volume of quantization that is the region in free space where we are quantizing the field  $V = L_x L_y L_z$ . Allowed  $\mathbf{k}$  vectors are  $k_x = (2\pi/L_x)m_x$ ,  $k_y = (2\pi/L_y)m_y$  and  $k_z = (2\pi/L_z)m_z$ , that is, we ensure that the lengths fit an integer number of wavelengths.

The number of modes in between  $\mathbf{k}$  and  $\mathbf{k} + \Delta\mathbf{k}$  is:

$$\Delta m_x \Delta m_y \Delta m_z = \frac{L_x L_y L_z}{(2\pi)^3} \Delta k_x \Delta k_y \Delta k_z = \frac{V}{(2\pi)^3} \Delta k_x \Delta k_y \Delta k_z.$$

Using the above normalization:

$$\sum_{\mathbf{k}, \lambda} \rightarrow \sum_{\lambda} \int d^3\mathbf{k} \int_0^\pi d\theta \sin\theta \int_0^{2\pi} d\phi \frac{V}{8\pi^2}.$$

Thus, any continuum limit involves

$$\text{Continuum limit} \quad \sum_{\mathbf{k}} \rightarrow \frac{V}{8\pi^2} \int d^3\mathbf{k}.$$

## 1.5 Squeezed states

Lets define the squeeze operator

$$\text{Squeezing operator} \quad |\xi, 0\rangle = \hat{S}(\xi) |0\rangle, \quad \text{with} \quad \hat{S}(\xi) = e^{\frac{1}{2}(\xi^* \hat{a}^2 - \xi \hat{a}^{\dagger 2})}, \quad \xi \in \mathbb{C}.$$

Lets use it to compute the expectation value for the quadrature operators.

$$\langle \xi, 0 | \hat{X}_1 | \xi, 0 \rangle = \langle 0 | \hat{S}^\dagger(\xi) \left( \frac{\hat{a} + \hat{a}^\dagger}{2} \right) \hat{S}(\xi) | 0 \rangle = \frac{1}{2} \langle 0 | (\hat{S}^\dagger \hat{a} \hat{S} + \hat{S}^\dagger \hat{a}^\dagger \hat{S}) | 0 \rangle.$$

We define displaced ladder operators as

$$\text{Squeezing ladder operators} \quad \tilde{a} = \hat{S}^\dagger(\xi) \hat{a} \hat{S}(\xi), \quad \xi = r e^{i\phi}.$$

Using the BCH formula

$$e^L A e^{-L} = A + [L, A] + \frac{1}{2!} [L, [L, A]] + \dots$$

and  $A = \hat{a}$  with  $L = -\frac{1}{2}(\xi^* \hat{a}^2 - \xi \hat{a}^{\dagger 2})$  allow us to express the squeezing ladder operator

$$\begin{aligned} \tilde{a} &= \hat{S}^\dagger(\xi) \hat{a} \hat{S}(\xi) = \hat{a} \cosh(r) - \hat{a}^\dagger e^{i\phi} \sinh(r) \\ \tilde{a}^\dagger &= \hat{S}(\xi)^\dagger \hat{a}^\dagger \hat{S}(\xi) = \hat{a}^\dagger \cosh(r) - \hat{a} e^{i\phi} \sinh(r). \end{aligned}$$

We have used several orders. Its derivative wrt  $r$  is:

$$\frac{d\tilde{a}}{dr} = \hat{a} \sinh(r) - \hat{a}^\dagger e^{i\phi} \cosh(r) = -e^{i\phi} \tilde{a}^\dagger, \quad \frac{d\tilde{a}^\dagger}{dr} = -e^{-i\phi} \tilde{a}.$$

Taking another derivative yields:

$$\frac{d^2 \tilde{a}}{dr^2} = \tilde{a}.$$

Now we can continue the expectation of the quadrature:

$$\begin{aligned} \langle \hat{X}_1 \rangle &= \frac{1}{2} \langle 0 | (\hat{S}^\dagger \hat{a} \hat{S} + \hat{S}^\dagger \hat{a}^\dagger \hat{S}) | 0 \rangle = \frac{1}{2} \langle 0 | [\tilde{a} + \tilde{a}^\dagger] | 0 \rangle \\ &= \frac{1}{2} \langle 0 | [\hat{a} \cosh(r) - e^{i\phi} \hat{a}^\dagger \sinh(r) + \hat{a}^\dagger \cosh(r) - e^{-i\phi} \hat{a} \sinh(r)] | 0 \rangle = 0. \\ \langle \hat{X}_2 \rangle &= \text{similarly} = 0. \end{aligned}$$

We can do the same for the operator square:

$$\begin{aligned} \langle \hat{X}_1^2 \rangle &= \frac{1}{4} \langle 0 | \hat{S}^\dagger(\xi) [(\hat{a} + \hat{a}^\dagger)(\hat{a} + \hat{a}^\dagger)] \hat{S}(\xi) | 0 \rangle = \frac{1}{4} \langle 0 | \hat{S}^\dagger(\hat{a} + \hat{a}^\dagger) \hat{S} \hat{S}^\dagger(\hat{a} + \hat{a}^\dagger) \hat{S} | 0 \rangle \\ &= \frac{1}{4} \langle 0 | (\tilde{a} + \tilde{a}^\dagger)(\tilde{a} + \tilde{a}^\dagger) | 0 \rangle = \frac{1}{4} \langle 0 | e^{-2r} (\hat{a} + \hat{a}^\dagger)^2 | 0 \rangle = \frac{e^{-2r}}{4}. \end{aligned}$$

Similarly we can obtain the respective quantities for  $\hat{X}_2$  and the uncertainties are:

$$\langle \hat{X}_1 \rangle = \langle \hat{X}_2 \rangle = 0 \implies \Delta \hat{X}_1 = \frac{e^{-r}}{2}, \quad \Delta \hat{X}_2 = \frac{e^r}{2}.$$

### 1.5.1 Displaced squeezing state

Now,

$$\text{Displaced squeezing state} \quad |\xi, \alpha\rangle = \hat{D}(\alpha)\hat{S}(\xi)|0\rangle.$$

Now, the operators are:

$$\begin{aligned}\tilde{a} &= \hat{S}^\dagger(\xi)\hat{D}^\dagger(\alpha)\hat{a}\hat{D}(\alpha)\hat{S}(\xi) = \cosh(r)\hat{a} - e^{i\phi}\sinh(r)\hat{a}^\dagger + \alpha, \\ \tilde{a}^\dagger &= \hat{S}^\dagger(\xi)\hat{D}^\dagger(\alpha)\hat{a}^\dagger\hat{D}(\alpha)\hat{S}(\xi) = \cosh(r)\hat{a}^\dagger - e^{-i\phi}\sinh(r)\hat{a} + \alpha^*.\end{aligned}$$

The expected number of photons in a displaced squeezed state is:

$$\langle 0|\tilde{a}^\dagger\tilde{a}|0\rangle = \langle 0|[\cosh(r)\hat{a}^\dagger - e^{-i\phi}\sinh(r)\hat{a} + \alpha^*][\cosh(r)\hat{a} - e^{i\phi}\sinh(r)\hat{a}^\dagger + \alpha]|0\rangle = \sinh^2|\xi| + |\alpha|^2.$$

The expected value in the quadrature value is:

$$\begin{aligned}\langle \xi, \alpha|\hat{X}_1|\xi, \alpha\rangle &= \langle 0|\hat{S}^\dagger\hat{D}^\dagger\hat{X}_1\hat{D}\hat{S}|0\rangle = \langle 0|\hat{S}^\dagger\hat{D}^\dagger\left(\frac{\hat{a} + \hat{a}^\dagger}{2}\right)\hat{D}\hat{S}|0\rangle = \frac{1}{2}\langle 0|(\tilde{a} + \tilde{a}^\dagger)|0\rangle \\ &= \frac{1}{2}\langle 0|[\cosh(r)\hat{a} - e^{i\phi}\sinh(r)\hat{a}^\dagger + \alpha + \cosh(r)\hat{a}^\dagger - e^{-i\phi}\sinh(r)\hat{a} + \alpha^*]|0\rangle = \text{Re}(\alpha). \\ \langle \xi, \alpha|\hat{X}_2|\xi, \alpha\rangle &= \text{Im}(\alpha).\end{aligned}$$

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## Chapter 2

# Optical devices

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## 2.1 Beam splitter

Let us consider the action of a beam splitter (BS) on two input modes of same frequency and polarization. Classically, the output E-field can be defined in terms of the input E-fields:

$$\begin{bmatrix} E'_1 \\ E'_2 \end{bmatrix} = \begin{bmatrix} t' & r \\ r' & t \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \end{bmatrix}.$$

$\{r, t\}$  and  $\{r', t'\}$  are reflection/transmission coefficient associated with the two interfaces of the BS. From energy conservation, we must have

$$\text{Energy conservation in the BS} \quad |E_1|^2 + |E_2|^2 = |E'_1|^2 + |E'_2|^2.$$

If we assume  $E_2 = 0$ , then

$$|E_1|^2 = |t'E_1|^2 + |r'E_1|^2 \longrightarrow |r'|^2 + |t'|^2 = 1. \quad (2.1)$$

Similarly, setting  $E_1 = 0$  yields

$$|E_2|^2 = |rE_2|^2 + |tE_2|^2 \longrightarrow |r|^2 + |t|^2 = 1. \quad (2.2)$$

In general,

$$\begin{aligned} |E_1|^2 + |E_2|^2 &= |E'_1|^2 + |E'_2|^2 \\ &= (t'E_1 + rE_2)(t'^*E_1^* + r^*E_2^*) + (r'E_1 + tE_2)(r'^*E_1^* + t^*E_2^*) \\ &= |t'|^2|E_1|^2 + |r|^2|E_2|^2 + |r'|^2|E_1|^2 + |t|^2|E_2|^2 + r't'^*E_1^*E_2 + t'r^*E_1E_2^* + r't'^*E_1E_2^* + r'^*tE_1^*E_2 \\ |E_1|^2 + |E_2|^2 &= |E_1|^2(|r'|^2 + |t'|^2) + |E_2|^2(|r|^2 + |t|^2) + E_1^*E_2(rt'^* + r'^*t) + E_1E_2^*(r't^* + r^*t') \\ 0 &= E_1^*E_2(rt'^* + r'^*t) + c.c. \end{aligned}$$

Thus,

$$rt'^* + r'^*t = 0. \quad (2.3)$$

For a 50 : 50 BS which as  $r' = 1/\sqrt{2}$ ,  $t' = 1/\sqrt{2}$ , and  $r = 1/\sqrt{2}$ , (2.1), (2.2) and (2.3) implies that  $t = -1/\sqrt{2}$ . Similarly, the quantum description of the BS is

$$\begin{bmatrix} \hat{a}'_1 \\ \hat{a}'_2 \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \hat{a}_1 \\ \hat{a}_2 \end{bmatrix}. \quad (2.4)$$

Now, the ladder operators are equal to the E-fields. This equation implies that

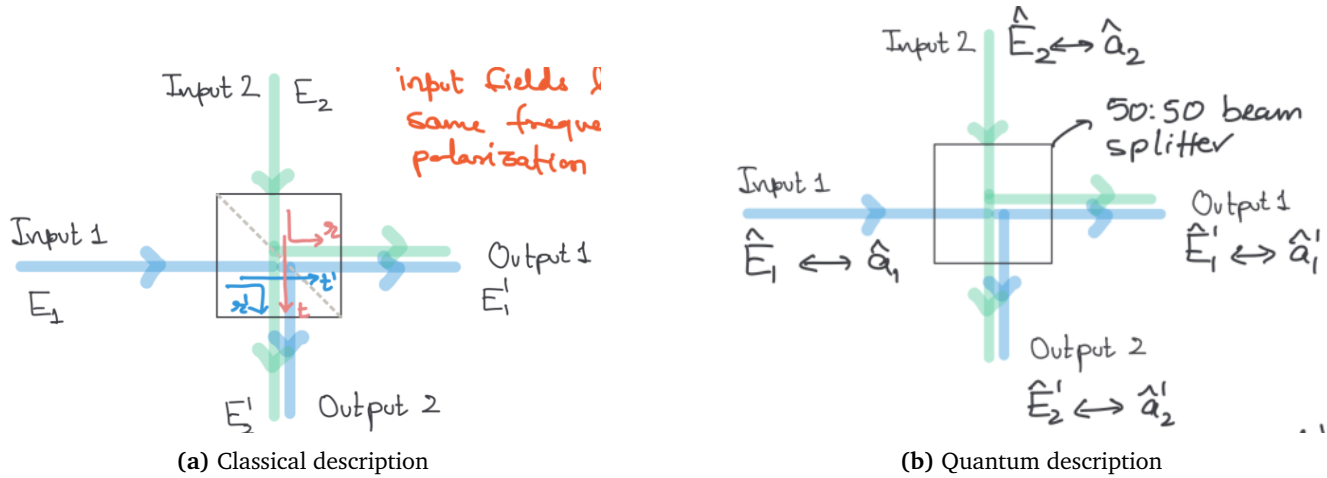
$$\hat{a}'_1 = \frac{1}{\sqrt{2}}(\hat{a}_1 + \hat{a}_2), \quad \text{and} \quad \hat{a}'_2 = \frac{1}{\sqrt{2}}(\hat{a}_1 - \hat{a}_2).$$

### Ejemplo 2.1

### Single photon incident in one input

The input is:

$$\text{Input} = |1\rangle_1 |0\rangle_2 = (\hat{a}_1^\dagger |0\rangle_1) |0\rangle_2 = |1\rangle_1 |0\rangle_2.$$



**Figure 2.1** Description of a beamsplitter (BS).

Note that

$$\hat{a}_1 = \frac{1}{\sqrt{2}}(\hat{a}'_1 + \hat{a}'_2) \quad \text{and} \quad \hat{a}_1^\dagger = \frac{1}{\sqrt{2}}(\hat{a}'_1^\dagger + \hat{a}'_2^\dagger).$$

The output is then

$$\text{Output} = \frac{1}{\sqrt{2}}(\hat{a}'_1^\dagger + \hat{a}'_2^\dagger) |0\rangle_{1'} |0\rangle_{2'} = \frac{1}{\sqrt{2}}[|1\rangle_{1'} |0\rangle_{2'} + |0\rangle_{1'} |1\rangle_{2'}].$$

Thus, there is a 50 : 50 probability of detecting the photon in one of the output ports.

## Ejemplo 2.2

## Both input with photons

The input is:

$$\text{Input} = |1\rangle_1 |1\rangle_2 = \hat{a}_1^\dagger |0\rangle_1 \hat{a}_2^\dagger |0\rangle_2.$$

The output is:

$$\begin{aligned} \text{Output} &= \frac{1}{2}[\hat{a}_1'^\dagger + \hat{a}_2'^\dagger][\hat{a}_1'^\dagger - \hat{a}_2'^\dagger] |0\rangle_{1'} |0\rangle_{2'} \\ &= \frac{1}{2}[\hat{a}_1'^\dagger \hat{a}_1'^\dagger - \hat{a}_2'^\dagger \hat{a}_2'^\dagger + \hat{a}_1'^\dagger \hat{a}_2'^\dagger - \hat{a}_2'^\dagger \hat{a}_1'^\dagger] |0\rangle_{1'} |0\rangle_{2'} \\ &= \frac{1}{2}[\sqrt{2}|2\rangle_{1'} |0\rangle_{2'} - \sqrt{2}|0\rangle_{1'} |2\rangle_{2'}] \\ \text{Output} &= \frac{1}{\sqrt{2}}[|2\rangle_{1'} |0\rangle_{2'} - |0\rangle_{1'} |2\rangle_{2'}]. \end{aligned}$$

Thus, when two photons are simultaneously incident on each input, both either go into output 1 or output 2 but never in both at the same time.

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