Derivation of the equations

1 Ch.1

$$m = 0$$

$$\mathcal{E} = h\nu = \frac{hc}{\lambda}$$

$$p = \frac{h\nu}{c} = \frac{h}{\lambda}$$

$$\Phi = \frac{AI}{h\nu_0} = \frac{P}{h\nu_0}$$

2 Ch.2

2.1 2.1 Quantization of field

$$\vec{\nabla} \cdot \vec{A} = 0 \tag{1}$$

$$\nabla^2 \vec{A} - \frac{1}{c^2}\frac{\partial^2 \vec{A}}{\partial t^2} \tag{2}$$

$$\vec{E} = -\frac{\partial \vec{A}}{\partial t}, \vec{B} = \vec{\nabla} \times \vec{A} \tag{3}$$

fourier series expansion of A:

$$\vec{A}(\vec{r},t) = \sum_k (\vec{A_k}(t)e^{i\vec{k}\cdot\vec{r}} + \vec{A_k}^*(t)e^{-i\vec{k}\cdot\vec{r}}) \tag{4}$$

$$k_x = \frac{2\pi n_x}{L}, k_y = \frac{2\pi n_y}{L}, k_z = \frac{2\pi n_z}{L} \tag{5}$$

$$\vec{k} \cdot \vec{A_k} = \vec{k} \cdot \vec{A_k}^* = 0 \tag{6}$$

substitute eq(2.4) with (2.2)

$$\nabla^2 = (\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2})$$

$$\sum_k (\vec{A_k}(t)(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2})e^{i(k_x x + k_y y + k_z z)} + c.c)$$

$$\sum_k (-k^2 \vec{A}_k(t)e^{i\vec{k}\cdot\vec{r}} + -k^2 \vec{A}_k^{\,*}(t)e^{-i\vec{k}\cdot\vec{r}})$$

for single k,

$$k^2 \vec{A}_k(t) + \frac{1}{c^2}\frac{\partial^2 \vec{A}_k(t)}{\partial t^2} = 0 \tag{7}$$

$$\vec{A}_k = \vec{A}_k e^{-i\omega_k t}, \omega_k = ck \tag{8}$$

$$\vec{A}(\vec{r},t) = \sum_k (\vec{A}_k e^{-i\omega_k t + i\vec{k}\cdot\vec{r}} + \vec{A}_k^{\,*} e^{-i\vec{k}\cdot\vec{r} + i\omega_k t}) \tag{9}$$

$$\vec{E}_k(\vec{r},t) = \sum_k \vec{E}_k = i\sum_k \omega_k (\vec{A}_k e^{-i\omega_k t + i\vec{k}\cdot\vec{r}} + \vec{A}_k^{\,*} e^{-i\vec{k}\cdot\vec{r} + i\omega_k t}) \tag{10}$$

$$\vec{B}_k(\vec{r},t) = \sum_k \vec{B}_k = i\sum_k \vec{k} \times (\vec{A}_k e^{-i\omega_k t + i\vec{k}\cdot\vec{r}} + \vec{A}_k^{\,*} e^{-i\vec{k}\cdot\vec{r} + i\omega_k t}) \tag{11}$$

calculation process for eq(11):

$$\nabla \times \vec{A} = \nabla \times (\vec{A}_k e^{-i\omega_k t + i\vec{k}\cdot\vec{r}} + \vec{A}_k^{\,*} e^{-i\vec{k}\cdot\vec{r} + i\omega_k t})$$

$$(\frac{\partial}{\partial y}A_{k_z}e^{i\omega_k t + i\vec{k}\cdot\vec{r}} - \frac{\partial}{\partial z}A_{k_y}e^{i\omega_k t + i\vec{k}\cdot\vec{r}})\hat{i}$$

$$+(\frac{\partial}{\partial z}A_{k_x}e^{i\omega_k t + i\vec{k}\cdot\vec{r}} - \frac{\partial}{\partial x}A_{k_z}e^{i\omega_k t + i\vec{k}\cdot\vec{r}})\hat{j}$$

$$+(\frac{\partial}{\partial x}A_{k_y}e^{i\omega_k t + i\vec{k}\cdot\vec{r}} - \frac{\partial}{\partial y}A_{k_x}e^{i\omega_k t + i\vec{k}\cdot\vec{r}})\hat{z}$$

$$\overline{\mathscr{E}_k} = \frac{1}{2}\int (\epsilon_0 \overline{E_k^2} + \frac{\overline{B_k^2}}{\mu_0})dV \tag{12}$$

$$\overline{\vec{E}_k^2} = \frac{1}{T}\int_0^T dt E_k^2 = 2\omega_k^2 \left|\vec{A}_k\right|^2 \tag{13}$$

$$\overline{\vec{B}_k^2} = \frac{1}{T}\int_0^T dt E_k^2 = 2k_k^2 \left|\vec{A}_k\right|^2 \tag{14}$$

$$\overline{\mathscr{E}_k} = (\epsilon_0\omega_k^2\left|\vec{A}_k\right|^2 + \frac{k_k^2}{\mu_0}\left|\vec{A}_k\right|^2) = 2\epsilon_0\omega_k^2 V\left|\vec{A}_k\right|^2 \tag{15}$$

$$\vec{A}_k = \frac{\vec{\epsilon_k}}{\sqrt{4\epsilon_0 V \omega_k^2}}(\omega_k q_k + ip_k) \tag{16}$$

$$\overline{\mathscr{E}_k} = \frac{1}{2}(\omega_k^2 q_k^2 + p_k^2) \tag{17}$$

$$\overline{\mathscr{E}} = \sum_k \overline{\mathscr{E}_k} = 2\epsilon_0 V \sum_k \omega_k^2 \left|\vec{A}_k\right|^2 = \frac{1}{2}\sum_k (\omega_k^2 q_k^2 + p_k^2) \tag{18}$$

$$\hat{H} = \frac{1}{2}\sum_k (\omega_k^2 \hat{q}_k^2 + \hat{p}_k^2) \tag{19}$$

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since

$$[\hat{q}_k, \hat{p}_k] = i\hbar$$

$$\hat{a}_k = \frac{1}{\sqrt{2\hbar\omega_k}}(\omega_k\hat{q}_k + i\hat{p}_k) \tag{20}$$

$$\hat{a^\dagger}_k = \frac{1}{\sqrt{2\hbar\omega_k}}(\omega_k\hat{q}_k - i\hat{p}_k) \tag{21}$$

$$[\hat{a}_k, \hat{a^\dagger}_k] = \hat{a}_k\hat{a^\dagger}_k - \hat{a^\dagger}_k\hat{a}_k$$

$$\hat{a}_k\hat{a^\dagger}_k = \frac{1}{2\hbar\omega_k}(\omega_k\hat{q}_k + i\hat{p}_k)(\omega_k\hat{q}_k - i\hat{p}_k)$$

$$= \frac{1}{2\hbar\omega_k}(\omega_k^2\hat{q}_k^2 + \hat{p}_k^2 - i\omega_k\hat{q}\hat{p} + i\omega_k\hat{p}\hat{q})$$

$$= \frac{1}{2\hbar\omega_k}(\omega_k^2\hat{q}_k^2 + \hat{p}_k^2 - i\omega_k[\hat{q}_k, \hat{p}_k])$$

$$\hat{a^\dagger}_k\hat{a}_k = \frac{1}{2\hbar\omega_k}(\omega_k^2\hat{q}_k^2 + \hat{p}_k^2 + i\omega_k[\hat{q}_k, \hat{p}_k])$$

$$[\hat{a}_k, \hat{a^\dagger}_k] = \frac{1}{2\hbar\omega_k}(-2i\omega_k[\hat{q}_k, \hat{p}_k]) = -\frac{i}{\hbar}[\hat{q}_k, \hat{p}_k] = -\frac{i}{\hbar}i\hbar = 1$$

$$[\hat{a}_k, \hat{a^\dagger}_k] = \delta_{kk^*} \tag{22}$$

$$\hat{\vec{A}}_k = \vec{\epsilon_k}\sqrt{\frac{\hbar}{2\epsilon_0\omega_k V}}\hat{A}_k \tag{23}$$

$$\vec{A}(\vec{r}, t) = \sum_k \vec{\epsilon_k}\sqrt{\frac{\hbar}{2\epsilon_0\omega_k V}}(\hat{a}_k e^{-i\omega_k t + i\vec{k}\cdot\vec{r}} + \hat{a}_k^\dagger e^{-i\vec{k}\cdot\vec{r} + i\omega_k t}) \tag{24}$$

$$\vec{E}(\vec{r}, t) = i\sum_k \vec{\epsilon_k}\sqrt{\frac{\hbar\omega_k}{2\epsilon_0 V}}(\hat{a}_k e^{-i\omega_k t + i\vec{k}\cdot\vec{r}} + \hat{a}_k^\dagger e^{-i\vec{k}\cdot\vec{r} + i\omega_k t}) \tag{25}$$

$$\vec{B}(\vec{r}, t) = i\sum_k \vec{k}\times\vec{\epsilon_k}\sqrt{\frac{\hbar}{2\epsilon_0\omega_k V}}(\hat{a}_k e^{-i\omega_k t + i\vec{k}\cdot\vec{r}} + \hat{a}_k^\dagger e^{-i\vec{k}\cdot\vec{r} + i\omega_k t}) \tag{26}$$

2.2   2.2 Quantized single mode field

single mode, wave vector k, angular frequency $\omega = ck$

$$\hat{H} = \frac{1}{2}(\omega^2\hat{q}^2 + \hat{p}^2) \tag{27}$$

$\hat{q}$: position operator , $\hat{p}$: momentum operator

$$\hat{q} = \sqrt{\frac{\hbar}{2\omega}}(\hat{a} + \hat{a}^\dagger) \tag{28}$$

$$\hat{p} = i\sqrt{\frac{\hbar\omega}{2}}(\hat{a}^\dagger - \hat{a}) \tag{29}$$

$$\hat{H} = \frac{\hbar\omega}{2}(\hat{a}^\dagger\hat{a} + \hat{a}\hat{a}^\dagger + \frac{1}{2}) \tag{30}$$

$$\hat{H}\ket{n} = \hbar\omega(\hat{a}^\dagger\hat{a} + \frac{1}{2})\ket{n} = \mathscr{E}_n\ket{n} \tag{31}$$

$$\hbar\omega\hat{a}^\dagger\hat{a}a^\dagger\hat{a} + \frac{1}{2}\hat{a}^\dagger\ket{n} = \hbar\omega(\hat{a}^\dagger\hat{a} - \frac{1}{2})\ket{n} \tag{32}$$

$$= \mathscr{E}_n\hat{a}^\dagger\ket{n}$$

$$\hat{H}\hat{a}^\dagger\ket{n} = \hbar\omega(\hat{a}^\dagger\hat{a} + \frac{1}{2})\hat{a}^\dagger\ket{n} = (\mathscr{E}_n + \hbar\omega)\hat{a}^\dagger\ket{n} \tag{33}$$

$$\hat{H}\hat{a}\ket{n} = (\mathscr{E}_n - \hbar\omega)(\hat{a}\ket{n}) \tag{34}$$

$$\hat{a}^\dagger\ket{n} \propto \ket{n+1}, \mathscr{E}_{n+1} = \mathscr{E}_n + \hbar\omega \tag{35}$$

$$\hat{a}\ket{n} \propto \ket{n-1}, \mathscr{E}_{n-1} = \mathscr{E}_n - \hbar\omega \tag{36}$$

$$\hat{H}\hat{a}\ket{0} = (\mathscr{E}_0 - \hbar\omega)(\hat{a}\ket{0}) \tag{37}$$

$$\hat{a}\ket{0} = 0 \tag{38}$$

$$\hat{H}\ket{0} = \frac{1}{2}\hbar\omega\ket{0} = \mathscr{E}\ket{0} \tag{39}$$

$$\hat{a}^\dagger\hat{a}\ket{n} = n\ket{n} \tag{40}$$

$$\hat{a}^\dagger = c_n\ket{n+1}\hat{a}^\dagger = \sqrt{n+1}\ket{n+1} \tag{41}$$

$$\hat{a} = d_n\ket{n-1} \tag{42}$$

$$\hat{a}^\dagger = \sqrt{n+1}\ket{n1} \tag{43}$$

$$\hat{a} = \sqrt{n}\ket{n-1} \tag{44}$$

$$\ket{n} = \frac{1}{\sqrt{n!}}(\hat{a}^\dagger)^n\ket{0} \tag{45}$$

2.3 2.3 quantized multi mode radiation field

$$\hat{H} = \sum_k \hbar\omega_k(\hat{a}^\dagger\hat{a} + \frac{1}{2}) \tag{46}$$

$$\mathscr{E}_{k_1} + \mathscr{E}_{k_2} + \mathscr{E}_{k_3} + ... + \mathscr{E}_{k_n} = \sum_{i=1}^N (n_{k_1} + \frac{1}{2})\hbar\omega_k$$

$$\hat{H}\ket{n_k} = (\sum_k \hbar\omega_k(\hat{a}^\dagger\hat{a} + \frac{1}{2}))\ket{n_k} = (\sum_k \hbar\omega_k(n_k + \frac{1}{2}))\ket{n_k} \tag{47}$$

2.4   2.4 General states of the quantized radiation field

If single mode light is in a pure state, Generally we can describe its state as linear superposition.

$$|\phi\rangle = \sum_n a_n |n\rangle \tag{48}$$

Probability, Expectation value, Uncertainty:

$$P_n = |a_n|^2, <n> = \sum_n n P_n = \sum_n n|a_n|^2$$

$$\Delta n = \sqrt{(n-<n>)^2} = \sqrt{(<n^2> - <n>^2)} = \sqrt{\sum_n n^2 P_n - (\sum_n n P_n)^2}$$
$$\tag{49}$$

$$a_n = e^{-\frac{|\alpha^2|}{2}} \frac{\alpha^n}{\sqrt{n!}} \tag{50}$$

If single mode light is in a mixed state, than we can describe its state by using density operator, $\hat{\rho} = \sum_\phi P_\phi |\phi\rangle \langle\phi|$

$$\hat{\rho} = \sum_n P_n |n\rangle \langle n| \tag{51}$$

Expectation value of number of the photon n is:

$$<n> = <\hat{a}^\dagger \hat{a}> = Tr$$