# Weekly Lab Meeting

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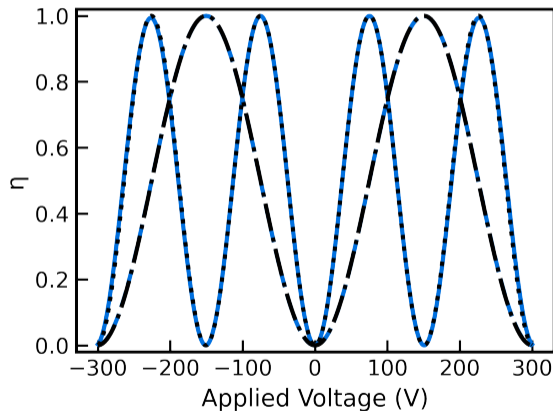
**KHU** NOPD LAB

# EO Bragg Modulator

# Revisions : PPLN vs PPKN

- **RCWT with thick hologram theory: PPLN vs PPKN**

  dashed line : PPLN, solid line : PPKN

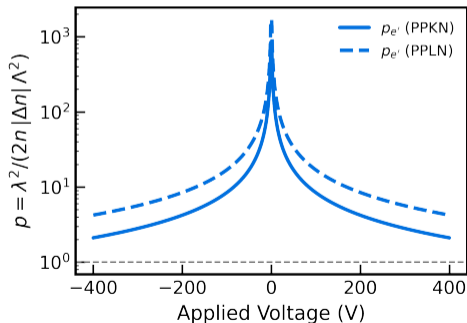|  | PPKN (KNbO$_3$) | PPLN (LiNbO$_3$) |
|---|---|---|
| *Common parameters* | | |
| Wavelength $\lambda$ | | 1064 nm |
| Poling period $\Lambda$ | | 20.13 μm |
| Crystal length $L$ | | 14.2 mm |
| Crystal thickness $t$ | | 780 μm |
| *z-polarized* | | |
| $n_3$ | 2.219 487 | 2.119 371 |
| $r_{33}$ (pm V$^{-1}$) | 64.0 | 30.8 |
| Beam walk-off $\rho$ (°) | 0 | 0 |
| Klein–Cook $Q$ | 223.5 | 219.7 |
| External angle $\theta$ (°) | 1.5 | 1.5 |
| Half-wave voltage $V_\pi$ (V) | 75.336 | 151.694 |

# Revisions : PPLN vs PPKN

- **Moharam-parameter**

    Trade off $\rightarrow$ Moharam parater and half-wave voltage

$$V_\pi = \frac{\pi \, \lambda \, t \cos \theta_B}{4L \, n_3^3 \, r_{33}}.$$
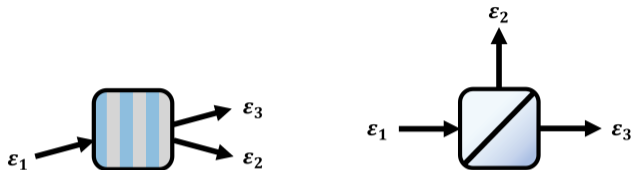
(1)

# EO Bragg Beam Splitter

# Another perspective of EO Bragg modulator

- **Tunable beam splitter : Classical Description**



$$|\varepsilon_1|^2 = |\varepsilon_2|^2 + |\varepsilon_3|^2 = |t\varepsilon_1|^2 + |r\varepsilon_1|^2 = (T + R)|\varepsilon_1|^2 \qquad (2)$$
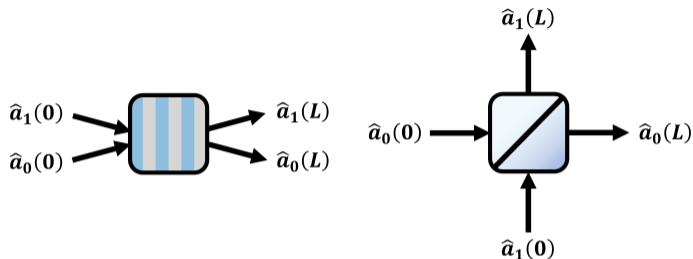
At $y = L$ under the perfect phase matching,

Zeroth-order diffraction efficiency and First-order diffraction efficiency:

$$T \equiv \eta_d(L) = \cos^2\left(\frac{\pi \Delta n L}{\lambda \cos(\theta_B - \rho)}\right), \quad R \equiv \eta_d(L) = \sin^2\left(\frac{\pi \Delta n L}{\lambda \cos(\theta_B - \rho)}\right) \qquad (3)$$

where $t = \cos(\cdot)$ and $r = \sin(\cdot)$.

# Another perspective of EO Bragg modulator

- **Tunable beam splitter : Quantum Description**



(1) Classical complex field amplitudes $\rightarrow$ annihilation operators

$$\varepsilon_1(L) = r\varepsilon_0(0), \quad \varepsilon_0(L) = t\varepsilon_0(0) \ \rightarrow \ \hat{a}_1(L) = r\hat{a}_1(0), \quad \hat{a}_0(0) = t\hat{a}_0(0) \tag{4}$$

(2) Coupling coefficient $g$ given by classical two coupled wave theory

$$g = \frac{\pi \Delta n}{\lambda \cos(\theta_B - \rho)} \tag{5}$$

# Hamiltonian of EO Bragg Beam Splitter

- **For a system of two coupled bosonic modes**

  In the spatial Heisenberg picture, the mode operators evolve along the $y$ direction,

  $$\frac{\mathrm{d}\hat{a}_j}{\mathrm{d}y} = \frac{i}{\hbar}[\hat{H}, \hat{a}_j]. \tag{6}$$

  Beamsplitter Hamiltonian

  $$\hat{H} = \hbar\beta\left(\hat{a}_0^\dagger\hat{a}_0 + \hat{a}_1^\dagger\hat{a}_1\right) + \hbar g\left(\hat{a}_1^\dagger\hat{a}_0 + \hat{a}_0^\dagger\hat{a}_1\right) \tag{7}$$

  where propagation constant $\beta = \mathbf{k}_B^{(0)} \cdot \hat{y} = \mathbf{k}_B^{(1)} \cdot \hat{y} = \frac{2n\pi}{\lambda}\cos\theta_B$

  The coupled bosonic modes equation

  $$\frac{\mathrm{d}}{\mathrm{d}y}\begin{pmatrix}\hat{a}_0(0)\\\hat{a}_1(0)\end{pmatrix} = i\begin{pmatrix}\beta & g\\g & \beta\end{pmatrix}\begin{pmatrix}\hat{a}_0(0)\\\hat{a}_1(0)\end{pmatrix} = i\left(\beta\mathrm{I} + g\mathrm{X}\right)\begin{pmatrix}\hat{a}_0(0)\\\hat{a}_1(0)\end{pmatrix}, \tag{8}$$

# Hamiltonian of EO Bragg Beam Splitter

- **Solving coupled bosonic modes equation**

  The formal solution is

  $$\begin{pmatrix} \hat{a}_0(y) \\ \hat{a}_1(y) \end{pmatrix} = e^{i\beta y} e^{igXy} \begin{pmatrix} \hat{a}_0(0) \\ \hat{a}_1(0) \end{pmatrix}. \tag{9}$$

  in the SU(2) form

  $$\hat{U}(y) \equiv e^{igXy} = I\cos(gy) + iX\sin(gy). \tag{10}$$

  The creation and annihilation operators after propagating $y$

  $$\hat{a}_0(y) = e^{i\beta y}\left[\cos(gy)\hat{a}_0(0) + i\sin(gy)\hat{a}_1(0)\right] \tag{11}$$

  $$\hat{a}_1(y) = e^{i\beta y}\left[i\sin(gy)\hat{a}_0(0) + \cos(gy)\hat{a}_1(0)\right] \tag{12}$$

# Exercise : Photon number state on EO Bragg Beam Splitter

- **Photon number state** $|n_0, n_1\rangle \equiv |n_0\rangle \otimes |n_1\rangle$

  A single photon impinging from the incident port with vacuum

  $$|\psi(0)\rangle = |1, 0\rangle = \hat{a}_0^\dagger(0) |0, 0\rangle \tag{13}$$

  Evolution along the propagation with $\hat{U}(y) = \exp\left(-\frac{i}{\hbar}\hat{H}\,y\right)$

  $$|\psi(y)\rangle = \hat{U}(y) |\psi(0)\rangle = \hat{a}_0^\dagger(y) |0, 0\rangle. \tag{14}$$

  The propagated state $|\psi(y)\rangle$

  $$|\psi(y)\rangle = e^{-i\beta y} \left[\cos(\Omega y) |1, 0\rangle - i\sin(\Omega y) |0, 1\rangle\right]. \tag{15}$$

## Exercise : Photon number state on EO Bragg Beam Splitter

- **Photon number state** $|n_0, n_1\rangle \equiv |n_0\rangle \otimes |n_1\rangle$

  The first–order mode probability

  $$R = \left|\langle 0, 1|\psi(L)\rangle\right|^2 = \sin^2(gL). \tag{16}$$

  The zeroth–order probability

  $$T = \left|\langle 1, 0|\psi(L)\rangle\right|^2 = \cos^2(gL). \tag{17}$$