Homework 6

1. If an electric field $E_0$ is applied in the [0,1,0] direction inside ADP, find the principal axes at $E_0=10^4$ V/m (Do not assume that if it is small it is equal to zero.). Use $\lambda=633\text{nm}$. What is the propagation direction for maximum birefringence and the value of the birefringence?

2. A bulk cube of KD*P is placed in one arm of a Mach-Zehnder interferometer to create a modulator. To couple light through the cube the width of the cube must be greater than 10mm. Use a wavelength of $\lambda=546\text{nm}$.
   a. Design a modulator using the KD*P cube to have the lowest voltage for 100% extinction. What is the required voltage?
   b. An integrated MZ modulator is fabricated from the same material. The length is still $L=10\text{mm}$ but the thickness is now $d=10\mu\text{m}$. Design the modulator and calculate the voltage for 100% extinction. (An integrated modulator has to operate with the voltage applied perpendicular to the propagation direction.)

3. A bulk modulator is designed to modulate a CO$_2$ laser, which has a wavelength of $\lambda=10.6\mu\text{m}$. The modulator is designed to use polarization filtering and uses a cube of material with dimension of 10mm. Design the modulator and determine the best cube orientation, and the required voltage range for entire extinction.
   a. What is the best material to use? You can only use materials from Table 9.2 that are listed for a wavelength of $\lambda=10.6\mu\text{m}$.
   b. What is the $V\pi$?

For problems 4-6 refer to the Avanex specification sheet and the reference article on lithium niobate modulators. An x-cut crystal means that the direction normal to the surface of the wafer is the x-direction of the crystal.

4. A modulator is fabricated using lithium niobate. Calculate the $V\pi$ of the modulator as a function of $d/L$, where $d$ is the electrode spacing and $L$ is the length of the modulator. Assume that the modulator is operated in a push-pull configuration. For the following cases
   a. y-propagating using an x-cut crystal
   b. x-propagating using a z-cut crystal

5. Why is the x-cut crystal used for the Avanex modulator?

6. Estimate the $d/L$ ratio for the Avanex modulator.

7. An amplitude modulator is configured in a polarization filter setup. The input polarization state is given by $\vec{E} = 4e^{i0.1\theta} + 2e^{i0.5\theta}$ and the output is passed through a linear polarizer oriented at 45 degrees. The modulator has a length $L$ and the two
indices of refraction are given by \( n_x = n_o - \frac{n_o^3}{2} r_{13} \frac{V}{d} \) and \( n_e = n_e - \frac{n_e^3}{2} r_{33} \frac{V}{d} \), where 

\[ n_o = 2.286, \quad n_e = 2.2, \quad r_{13} = 9.6 \text{ pm/V}, \quad r_{33} = 30.9 \text{ pm/V}, \quad \lambda = 1550 \text{ nm}, \quad \text{diff} = 1000, \quad \text{and} \quad L = 2 \text{ cm}. \]

a. Plot the relative optical power as a function of voltage.
b. What is the extinction ratio \( P_{\text{min}}/P_{\text{max}} \)?
1. If an electric field $E_0$ is applied in the $[0,1,0]$ direction inside ADP, find the principal axis. Is it dependent on the magnitude of the electric field $E_0$? If yes, find the principle axis at $E_0=10^4$ V/m. Use $\lambda=633$nm. What is the propagation direction for maximum birefringence and the value of the birefringence?

ADP is $4\eta m$

$$\Delta n = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \eta_{11} \\ 0 & \eta_{11} & 0 \\ 0 & 0 & \eta_{11} \end{bmatrix} \begin{bmatrix} E_0 \\ E_0 \\ E_0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \eta_{11} E_0 \\ \eta_{11} E_0 \\ 0 \end{bmatrix}$$

$n_0 = 1.5266$  $n_c = 1.808$

$$\frac{1}{n_0^2} x^2 + \frac{1}{n_e^2} y^2 + \frac{1}{n_c^2} z^2 + 2\eta_{11} E_0 xz = \frac{1}{n_0^2}$$

Need a coordinate rotation about the y-axis

$$\beta_1 = \beta$$

$$A_1 = A \cos^2 \theta + C \sin^2 \theta + D \sin \theta \cos \theta$$

$$C_1 = A \sin^2 \theta + C \cos^2 \theta - D \sin \theta \cos \theta$$

$$E_1 = -2A \sin \theta \cos \theta + 2C \cos \theta \sin \theta + D \left( \cos^2 \theta - \sin^2 \theta \right)$$

Set $E_1 = 0$

$$0 = (-A+C) 2A \sin \theta \cos \theta + D \left( \cos^2 \theta - \sin^2 \theta \right)$$

$$(A-C) \sin \theta = D \cos \theta$$

$$\tan \theta = \frac{D}{A-C}$$

$$\tan 2\theta = \frac{2 \eta_{11} E_0}{n_0^2 - n_c^2} = \frac{1}{n_0^2} - \frac{1}{n_c^2}$$

$$\theta = \frac{1}{2} \tan^{-1} \left( \frac{2(23.41 \times 10^{-15}) \times (10^9)}{1.5266^2 - 1.808^2} \right)$$

$$\theta = -5.84^\circ \text{ degrees}$$

$$B_1 = \frac{1}{n_0^2}$$

$$A_1 = \frac{1}{n_e^2} - 2\eta_{11} E_0 (-8.685 \times 10^6)$$

$$C_1 = \frac{1}{n_c^2} + 2\eta_{11} E_0 (-8.685 \times 10^6)$$

May be birefringence when propagating in the $y$-direct.

$$n_x = n_0 + n_0 \eta_{11} E_0 \sin \theta \cos \theta$$

$$= 1.5266 - 7.23 \times 10^{-12}$$

$$n_y = n_e + n_e \eta_{11} E_0 \sin \theta \cos \theta = 1.808 + 6.64 \times 10^{-12}$$

$$\Delta n = (1.5266 - 7.23 \times 10^{-12}) - (1.808 + 6.64 \times 10^{-12})$$

$$\Delta n = 0.0458 - 1.38 \times 10^{-4}$$
2. A bulk cube of KD\(3^P\) is placed in one arm of a Mach-Zehnder interferometer to create a modulator. To couple light through the cube the width of the cube must be greater than 10mm. Use a wavelength of \(\lambda=546nm\).
   a. Design a modulator using the KD\(3^P\) cube to have the lowest voltage for 100% extinction. What is the required voltage?
   b. An integrated MZ modulator is fabricated from the same material. The length is still \(L=10mm\) but the thickness is now \(d=10\mu m\). Design the modulator and calculate the voltage for 100% extinction. (An integrated modulator has to operate with the voltage applied perpendicular to the propagation direction.)

\[
\begin{pmatrix}
  0 & 0 & 0 \\
  0 & 0 & 0 \\
  0 & 0 & 0 \\
  \tau_{51} & 0 & 0 \\
  0 & \tau_{41} & 0 \\
  0 & 0 & \tau_{65}
\end{pmatrix}
\]

\(\tau_{53}\) > \(\tau_{41}\)

From the previous problem, if \(E = E_0\) or \(E_0^2\) then \(\theta \approx 0\) and there is very little modulation so choose

\[
\bar{E} = E_0 \bar{z}
\]

\[
\frac{1}{A} x^2 + \frac{1}{B} y^2 + \frac{1}{C} z^2 + 2\tau_{63} E_0 xy = \frac{1}{D} = n^2
\]

rotate about the \(z\)-axis

\(y\) becomes \(x\)
\(z\) becomes \(y\)

\[
x = x_1 \Rightarrow z = z_1
\]
\[
y = y_1 \cos \theta - z_1 \sin \theta \Rightarrow x = x_1 \cos \theta - y_1 \sin \theta
\]
\[
z = y_1 \sin \theta + z_1 \cos \theta \Rightarrow y = x_1 \sin \theta + y_1 \cos \theta
\]

\[
A_1 = B \sin^2 \theta + A \cos^2 \theta - D \sin \theta \cos \theta
\]
\[
B_1 = B \cos^2 \theta + A \sin^2 \theta + D \sin \theta \cos \theta
\]
\[
C_1 = C
\]
\[
D_1 = -2B \sin \theta \cos \theta + 2A \sin \theta \cos \theta + D(\cos^2 \theta - \sin^2 \theta)
\]

Set \(D_1 = 0\)

\[
(B-A) 2 \sin \theta \cos \theta = D (\cos^2 \theta - \sin^2 \theta)
\]
\[
(B-A) \sin 2 \theta = D \cos 2 \theta
\]

\[
\tan \theta = \frac{D}{B-A} = \frac{2 \tau_{63} E_0}{\frac{1}{n_0^2} - \frac{1}{n_{ex}^2}} = \infty
\]

\[
\tan \theta = 90^\circ
\]

\[
\theta = 45^\circ
\]
\[ A_i = \frac{1}{2} B + \frac{1}{2} A - \frac{1}{2} D \]
\[ = \frac{1}{2} \frac{1}{n_{0z}^2} + \frac{1}{2} \frac{1}{n_{0x}^2} - \frac{1}{2} \left( 2r_{63} E_0 \right) = \frac{1}{n_{0z}^2} - r_{63} E_0 \]

\[ B_i = \frac{1}{2} (B + A + D) \]
\[ = \frac{1}{2} \frac{1}{n_{0z}^2} + \frac{1}{2} \frac{1}{n_{0x}^2} + r_{63} E_0 = \frac{1}{n_{0x}^2} + r_{63} E_0 \]

\[ C_i = \frac{1}{n_{0x}^2} \]

\[ D_i = 0 \]

\[ \frac{1}{n_{0x}^2} = \frac{1}{n_{0z}^2} - r_{63} E_0 \]

\[ n_x = \frac{1}{\left[ \frac{1}{n_{0x}^2} - r_{63} E_0 \right]}^{-1} \]

\[ n_x = n_0 \left( 1 - r_{63} n_{0z}^2 E_0 \right)^{-1} \]

\[ n_\gamma = n_0 + \frac{1}{2} r_{63} n_{0z}^2 E_0 \]

\[ n_z = n_0 - \frac{1}{2} r_{63} n_{0z}^2 E_0 \]

\[ n_2 = n_6 \]

We want the electric field in either the \( x \), or \( y \), direction.

2 options: (1) propagate in the \( z \) direction with field in \( y \), direction
(2) propagate in the \( y \), direction

For option 2, we are not normal to the surface so choose option 1

This requires either a ring electrode or a transparent electrode.
The field can be in either the $X_i$ or $X_j$ direction, which is 45° from the cube axes.

For a Mach Zehnder

$$\frac{I_{out}}{I_{in}} = \frac{1}{2} \left( 1 + \cos \Delta \phi \right)$$

$$\Delta \phi = \frac{2\pi}{\gamma} L \Delta \eta$$

$$= \frac{2\pi}{\gamma} \left( \frac{1}{2} \right) \left( 9 \times 10^5 \right) \left( 9 \times 10^5 \right) \sqrt{\frac{L}{d}}$$

$$V = \frac{\pi^2}{8} \left( 2 \times 8 \times 10^{-10} \right) \left( 1 \times 5 \times 10^{-3} \right) \sqrt{\frac{L}{d}}$$

$$V = 5.94 \times 10^{-3} \sqrt{\frac{L}{d}}$$

(b) Now \( \frac{d}{L} = \frac{10 \times 10^{-6}}{10 \times 10^{-3}} = 10^{-3} \)

$$V_{I} = 5.94 \times 10^{-3} \sqrt{\frac{L}{d}}$$

$$V_{II} = 5.94 \sqrt{d}$$
3. A bulk modulator is designed to modulate a CO₂ laser, which has a wavelength of \( \lambda = 10.6 \mu m \). The modulator is designed to use polarization filtering and uses a cube of material with dimension of 10mm. Design the modulator and determine the best cube orientation, and the required voltage range for entire extinction.

a. What is the best material to use? You can only use materials from Table 9.2 that are listed for a wavelength of \( \lambda = 10.6 \mu m \).

b. What is the \( V \pi \)?

\[
\lambda = 10.6 \mu m
\]

We need to use CdTe, GaAs, ZnSe, ZnTe. These are all 43m symmetry crystals and are initially isotropic materials.

\[
\gamma = \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
r_{44} & 0 & 0 \\
r_{44} & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
\end{bmatrix}
\]

\[
\frac{1}{n_0^2} x + \frac{1}{n_0^2} y + \frac{1}{n_0^2} z + 2r_{44} E_x y z = \frac{1}{n_0^2}
\]

rotates about the \( x \)-axis

\[
A_1 = A =
\]

\[
B_1 = B \cos \theta + C \sin \theta + D \cos \theta \sin \theta
\]

\[
C_1 = B \sin \theta + C \cos \theta - D \cos \theta \sin \theta
\]

\[
D_1 = -2B \sin \theta \cos \theta + Z C \sin \theta \cos \theta + D (\cos \theta - \sin \theta)
\]

\[
D_1 = 0 = (C-B) \frac{2 \sin \theta \cos \theta}{B-C} = \frac{2r_{44} E_x}{B-C} = 0
\]

\[
\tan \theta = \frac{D}{B-C} = \frac{2r_{44} E_x}{n_0^2 - \frac{1}{n_0^2}} = \infty
\]

\[
2\theta = 90^o
\]

\[
\theta = 45^o
\]

\[
A_1 = A = \frac{1}{n_0^2}
\]

\[
B_1 = B \cos^2(45) + C \sin^2(45) + D \cos(45) \sin(45)
\]

\[
= \frac{1}{n_0^2} + 2r_{44} E_x (\frac{1}{2}) = \frac{1}{n_0^2} + r_{44} E_x
\]

\[
C_1 = \frac{1}{n_0^2} - r_{44} E_x
\]

\[
D_1 = 0
\]

\[
r_{44} = n_0 - \frac{1}{2} r_{44} n_0^3 E_x
\]

\[
r_2 = n_0 + \frac{1}{2} r_{44} n_0^3 E_x
\]
For polarization filtering we want to propagate in the $x$- direction.

\[ \phi_1 = \frac{2 \pi}{\lambda} L n - \left( \frac{2 \pi}{\lambda} \right) \frac{1}{2} r_{41} n^3 \frac{V}{d} \]

\[ \phi_2 = \frac{2 \pi}{\lambda} L n + \left( \frac{2 \pi}{\lambda} \right) \frac{1}{2} r_{41} n^3 \frac{V}{d} \]

\[ R = \phi_2 - \phi_1 \]

\[ \frac{I_{out}}{I_{in}} = \sin^2 \left( \frac{\phi_2 - \phi_1}{2} \right) = \sin^2 \left( \frac{\pi}{2} \frac{V}{V_n} \right) \]

\[ \left( \frac{\pi}{2} \right) \left( \frac{V}{V_n} \right) = \frac{\lambda}{2} \left[ \frac{\pi}{\lambda} r_{41} n^3 \frac{V}{d} + \frac{\pi}{\lambda} r_{41} n^3 \frac{L}{d} \right] \]

\[ \left( \frac{\pi}{2} \right) \left( \frac{1}{V_n} \right) = \frac{\pi}{\lambda} r_{41} n^3 \frac{L}{d} \]

\[ V_{\pi} = \left( \frac{\pi}{2} \right) \left( \frac{\pi}{\lambda} \right) \left( \frac{1}{r_{41} n^3} \right) \frac{d}{L} \]

\[ V_{\pi} = \frac{\lambda}{2} r_{41} n^3 \]

From the table choose the largest $r_{41} n^3$

CdTe : 120
GaAs : 54
ZnSe : 35
ZnTe : 77

Choose CdTe

\[ V_{\pi} = \frac{10.6 \times 10^{-6}}{(2)(120 \times 10^{-12})} \]

\[ V_{\pi} \approx 44 \text{ KV} \]
For problems 4-6 refer to the Avanex specification sheet and the reference article on lithium niobate modulators. An x-cut crystal means that the direction normal to the surface of the wafer is the x-direction of the crystal.

4. A modulator is fabricated using lithium niobate. Calculate the \( V_\pi \) of the modulator as a function of \( d/L \), where \( d \) is the electrode spacing and \( L \) is the length of the modulator. Assume that the modulator is operated in a push-pull configuration. For the following cases

a. y-propagating using an x-cut crystal
b. x-propagating using a z-cut crystal

for both cases, assume lateral applied electric field

\[
\begin{align*}
E &= E_2 \hat{z} \\
\mathbf{r} &= \begin{bmatrix} 0 & -r_{22} & r_{13} \\ 0 & r_{22} & r_{13} \\ 0 & 0 & r_{33} \\ r_{51} & 0 & 0 \\ -r_{22} & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ E_2 \end{bmatrix} \\
\left( \frac{1}{n_0^2} + r_{13} E_2 \right) x + \left( \frac{1}{n_0^2} + r_{15} E_2 \right) y + \left( \frac{1}{n_e^2} + r_{33} E_2 \right) z &= \frac{1}{\eta^2} \\
n_x &= n_0 - \frac{1}{2} n_0^3 r_{13} E_2 \\
n_y &= n_0 - \frac{1}{2} n_0^3 r_{15} E_2 \\
n_z &= n_e - \frac{1}{2} n_e^3 r_{33} E_2 \\
\end{align*}
\]

The best field direction is \( \hat{z} \) because \( r_{33} n_e^3 > r_{13} n_0^3 \)

\[
\phi_1 = \frac{2\pi}{
\Lambda}
\Lambda
n_e L - \frac{2\pi}{
\Lambda}
\Lambda
\left( \frac{1}{2} \right) n_e^3 r_{33} \sqrt{\frac{L}{d}} \\
\phi_2 = \frac{2\pi}{
\Lambda}
\Lambda
n_e L + \frac{2\pi}{
\Lambda}
\Lambda
\left( \frac{1}{2} \right) n_e^3 r_{33} \sqrt{\frac{L}{d}} \\
\Delta \phi = \phi_2 - \phi_1 = \frac{2\pi}{
\Lambda}
\Lambda
n_e^3 r_{33} \sqrt{\frac{L}{d}} \\

\begin{align*}
\text{I}_{\text{out}} &\sim \frac{1}{2} \left( 1 + \cos \left( \frac{2\pi}{
\Lambda}
\Lambda
n_e^3 r_{33} \sqrt{\frac{L}{d}} \right) \right) \\
\frac{2\pi}{
\Lambda}
\Lambda
n_e^3 r_{33} \sqrt{\frac{L}{d}} &= \frac{\n\pi}{
\Lambda}
\Lambda
 \frac{1}{2} \\
\eta_\pi &= \frac{1}{2} \frac{1}{n_e^3 r_{33}} \frac{d}{L} \\
\end{align*}
\]
for $\lambda = 1.55 \mu m$ use the $\lambda = 3.39 \mu m$ value in the table

$r_{33} = 28 \text{ pm/V}, \quad n_e = 2.073$

$$V_{\Pi} = \frac{(1.55 \times 10^{-6})}{(2.073^2)(28 \times 10^{-11})} \frac{d}{L}$$

$$V_{\Pi} = 3.10 \frac{d}{L}$$

(b)

$$E = E_y \hat{y}$$

$$\left(\frac{1}{n_0^2} - (r_{22} E_y) \right) x + (\frac{1}{n_0^2} + (r_{22} E_y)) y + \frac{1}{n_e^2} z + 2 (r_{51} E_y) z = \frac{1}{n_2^2}$$

$$A_1 = A$$

$$B_1 = B \cos \phi + C \sin \phi + D \sin \phi \cos \phi$$

$$C_1 = B \sin \phi + C \cos \phi - D \sin \phi \cos \phi$$

$$D_1 = -2 B \sin \phi \cos \phi + 2 C \sin \phi \cos \phi + D (\cos \phi - \sin \phi)$$

$$D_1 = 0 = (C - B) 2 \sin \phi \cos \phi + D (\cos \phi - \sin \phi)$$

$$(B - C) \sin 2 \phi = D \cos 2 \phi$$

$$\tan 2 \phi = \frac{D}{B - C} = \frac{2 \sqrt{r_{51} E_y}}{\frac{1}{n_0^2} + r_{22} E_y - \frac{1}{n_e^2}}$$

$$\phi = \tan^{-1} \frac{2 \sqrt{r_{51} E_y}}{\frac{1}{n_0^2} - \frac{1}{n_e^2} + r_{22} E_y}$$

$$\phi \approx 0$$

$$A_1 = A = \frac{1}{n_0^2} - r_{22} E_y$$

$$B_1 \approx B = \frac{1}{n_0^2} + r_{22} E_y$$

$$C_1 \approx C = \frac{1}{n_e^2}$$

$$D_1 = 0$$

the optical field is in either the $y$ or $z$ direction. The best case is the $y$ direction

$$n_y = n_0 - \frac{1}{2} n_0^2 r_{22} E_y$$

$$\Delta \phi = 2 \left( \frac{2\pi}{\lambda} \right) \frac{n_0^2 r_{22} E_y L}{2} = \frac{2\pi}{\lambda} n_0^2 r_{22} E_y L$$

$$\sin \phi = \frac{1}{2} \left( 1 + \cos \left( \frac{2\pi}{\lambda} n_0^2 r_{22} E_y L \right) \right)$$

$$\phi = \frac{2\pi}{\lambda} n_0^2 r_{22} V_{\Pi} \frac{d}{L}$$

$$V_{\Pi} = \lambda \frac{d}{2 n_0^2 r_{22} \frac{d}{L}} = \frac{1.55 \times 10^{-6}}{(4)(2.136^2)(3.1 \times 10^{-12})} \frac{d}{L} = 2.56 \frac{d}{L}$$
(5) X-cut crystal is easier to create side by side electrodes the produce a field in the z-direction.

X-cut crystal also has a reduced piezoelectric effect, which can cause charge build up which varies the bias of the modulator.

(6) For the Avonex modulator

\[ E = E_x \varepsilon, \ \text{y-propagating, push-pull} \]

\[ V_\pi = 3108 \frac{d}{L} \]

\[ V_\pi = 5V = 3108 \frac{d}{L} \]

\[ \frac{d}{L} = \frac{5}{3108} \]

\[ \frac{d}{L} = 0.0016 \]
7. An amplitude modulator is configured in a polarization filter setup. The input polarization state is given by \( \vec{E} = 4e^{j0.1 \hat{x}} + 2e^{j0.5 \hat{z}} \) and the output is passed through a linear polarizer oriented at 45 degrees. The modulator has a length \( L \) and the two indices of refraction are given by \( n_x = n_o - \frac{n_o^3}{2} \frac{r_{13}}{d} V \) and \( n_z = n_o - \frac{n_o^3}{2} \frac{r_{33}}{d} V \), where \( n_o = 2.286, n_e = 2.2, r_{13} = 9.6 \text{pm/V}, r_{33} = 30.9 \text{pm/V}, \lambda = 1550 \text{nm}, d = 1000, \) and \( L = 2 \text{cm} \).

a. Plot the relative optical power as a function of voltage.

b. What is the extinction ratio \( (P_{\text{min}}/P_{\text{max}}) \)?

\[
\vec{E} = \begin{bmatrix} 4e^{j0.1} \\ 2e^{j0.5} \end{bmatrix} \hat{x} + \begin{bmatrix} 2 \\ 4 \end{bmatrix} e^{j0.5} \hat{z}
\]

\[
E_1 = \begin{bmatrix} 4e^{j0.1} \\ 2e^{j0.5} \end{bmatrix}
\]

\[
t_n = n_o - \frac{1}{2} n_o^3 \frac{r_{13}}{d} V
\]

\[
\phi_n = \frac{2\pi}{n} n_o L - \frac{2\pi}{n} n_o^3 r_{13} \frac{V}{d} L
\]

\[
= \left( \frac{2\pi}{1.55 \times 10^4} \right) (2.286)(0.02) - \left( \frac{2\pi}{1.55 \times 10^4} \right) (7.276^3)(9.6 \times 10^{-12}) \sqrt{10^3}
\]

\[
\phi_y = \left( \frac{2\pi}{1.55 \times 10^4} \right) (2, 0.02) - \left( \frac{2\pi}{1.55 \times 10^4} \right) (2.3^3)(30.9 \times 10^{-12}) \sqrt{10^3}
\]

\[
E_2 = \begin{bmatrix} 4e^{j0.1} e^{j\phi_n} \\ 2e^{j0.5} e^{j\phi_n} \end{bmatrix}
\]

\[
E_3 = \begin{bmatrix} E_2 \end{bmatrix} \frac{1}{2} \begin{bmatrix} 1 \\ 1 \end{bmatrix}
\]

\[
\frac{P_{\text{min}}}{P_{\text{max}}} = 0.33
\]
% EO modulation using polarization filtering
% with unbalanced polarizations.

\begin{verbatim}
lambda=1.55e-6;
no=2.286;
ne=1.2;
r13=9.6e-12;
r33=30.9e-12;
L=2e-2;
d=1e-3*L;

E1=[4*exp(j*0.1);2*exp(j*0.5)]
pol=1/2*[1,1;1,1];
VV=linspace(0,60,101);
for lp=1:length(VV)
    V=VV(lp);
    phix=2*pi/lambda*no*L-pi/lambda*no^3*r13*V*L/d;
    phiz=2*pi/lambda*ne*L-pi/lambda*ne^3*r33*V*L/d;

    E2=E1.*[exp(j*phix);exp(j*phiz)];
    E3=pol*E2;
    P(lp)=norm(E3);
end

plot(VV,P./max(P))
xlabel('voltage')
ylabel('Normalized power')
\end{verbatim}