Homework 6

1. If an electric field Eo is applied in the [0,1,0] direction inside ADP, find the principal axes at Eo=10^4 V/m (Do not assume that if it is small it is equal to zero.). Use λ=633nm. 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 λ=546nm.
    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=10mm but the thickness is now d=10μm. 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 λ=10.6μm. 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 λ=10.6μm.
    b. What is the Vπ?

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 Vπ 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 $\vec{E} = 4e^{j0.1}\hat{x} + 2e^{j0.5}\hat{z}$ 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 $n_x = n_o - \frac{n_o^3}{2} r_{13} \frac{V}{d}$ and $n_z = n_e - \frac{n_e^3}{2} r_{33} \frac{V}{d}$, where n_o=2.286, n_e=2.2, r_{13}=9.6pm/V, r_{33}=30.9 pm/V, λ=1550nm, ~~d/L~~=1000, and L=2cm.

a. Plot the relative optical power as a function of voltage.
b. What is the extinction ratio (P_{min}/P_{max})?

1. If an electric field Eo is applied in the [0,1,0] direction inside ADP, find the principal axis. Is it dependent on the magnitude of the electric field Eo? If yes, find the principle axis at $E_o=10^4$ V/m. Use λ=633nm. What is the propagation direction for maximum birefringence and the value of the birefringence?

ADP is $\bar{4}2m$

$$\Delta\eta = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ r_{41} & 0 & 0 \\ 0 & r_{41} & 0 \\ 0 & 0 & r_{63} \end{bmatrix} \begin{bmatrix} 0 \\ E_o \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ r_{41} E_o \\ 0 \end{bmatrix}$$

$n_o = 1.5266 \quad n_e = 1.4808$

$$\frac{1}{n_o^2} x^2 + \frac{1}{n_o^2} y^2 + \frac{1}{n_e^2} z^2 + 2 r_{41} E_o \, xz = \frac{1}{n^2}$$

Need a coordinate rotation about the y-axis

$B_1 = B$

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

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

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

set $E_1 = 0$

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

$$(A-C)\sin 2\theta = D\cos 2\theta$$

$$\tan 2\theta = \frac{D}{A-C}$$

$$\tan 2\theta = \frac{2 r_{41} E_o}{\frac{1}{n_o^2} - \frac{1}{n_e^2}} =$$

$$\theta = \frac{1}{2}\tan^{-1}\left(\frac{2(23.41\times10^{-12})(10^4)}{\frac{1}{1.5266^2} - \frac{1}{1.4808^2}}\right)$$

$$\boxed{\theta = -5\times10^{-4} \text{ degrees}}$$

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

$A_1 = \frac{1}{n_o^2} - 2r_{41} E_o(-8.6859\times10^{-6})$

$C_1 = \frac{1}{n_e^2} + 2r_{41} E_o(-8.685\times10^{-6})$

Max birefringence when propagating in the y-direct

$n_x = n_o + n_o^3 r_{41} E_o \sin\theta\cos\theta$

$= 1.5266 - 7.23\times10^{-12}$

$n_y = n_e + n_e^3 r_{41} E_o \sin\theta\cos\theta = 1.4808 + 6.6\times10^{-12}$

$\Delta n = (1.5266 - 7.23\times10^{-12}) - (1.4808 + 6.6\times10^{-12})$

$$\boxed{\Delta n = 0.0458 - 1.38\times10^{-11}}$$

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 λ=546nm.
   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=10mm but the thickness is now d=10μm. 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.)

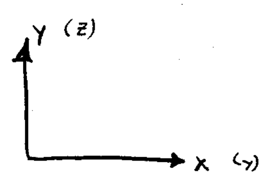
(a) KD*P is $\bar{4}2m$

$$r = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ r_{41} & 0 & 0 \\ 0 & r_{41} & 0 \\ 0 & 0 & r_{63} \end{bmatrix} \qquad r_{63} > r_{41}$$

From the previous problem, if $\bar{E} = E_o \hat{x}$ or $E_o \hat{y}$ then $\theta \approx 0$ and there is very little modulation so choose

$$\bar{E} = E_o \hat{z}$$

$$\underbrace{\frac{1}{n_o^2}}_{A} x^2 + \underbrace{\frac{1}{n_o^2}}_{B} y^2 + \underbrace{\frac{1}{n_E^2}}_{C} z^2 + \underbrace{2 r_{63} E_o}_{D}\, xy = \frac{1}{n^2}$$



rotate about the z-axis
Y becomes x
z becomes y

$$x = x_1 \Rightarrow \qquad z = z_1$$
$$y = y_1 \cos\theta - z_1 \sin\theta \Rightarrow \qquad x = x_1 \cos\theta - y_1 \sin\theta$$
$$z = y_1 \sin\theta + z_1 \cos\theta \Rightarrow \qquad y = x_1 \sin\theta + y_1 \cos\theta$$

$$A_1 = B \sin^2\theta + A \cos^2\theta - D \sin\theta \cos\theta$$
$$B_1 = B \cos^2\theta + A \sin^2\theta + D \sin\theta \cos\theta$$
$$C_1 = C$$
$$D_1 = -2B \sin\theta \cos\theta + 2A \sin\theta \cos\theta + D(\cos^2\theta - \sin^2\theta)$$
set $D_1 = 0$

$$(B-A)\, 2\sin\theta \cos\theta = D(\cos^2\theta - \sin^2\theta)$$
$$(B-A) \sin 2\theta = D \cos 2\theta$$

$$\tan 2\theta = \frac{D}{B-A} = \frac{2 r_{63} E_o}{\frac{1}{n_o^2} - \frac{1}{n_o^2}} = \infty$$

$$\tan 2\theta = 90^\circ$$

$$\theta = 45^\circ$$

$$A_1 = \tfrac{1}{2}B + \tfrac{1}{2}A - \tfrac{1}{2}D$$

$$= \frac{1}{2}\frac{1}{n_o^2} + \frac{1}{2}\frac{1}{n_o^2} - \frac{1}{2}(2r_{63}E_o) = \frac{1}{n_o^2} - r_{63}E_o$$

$$B_1 = \tfrac{1}{2}(B + A + D)$$

$$= \frac{1}{2n_o^2} + \frac{1}{2n_o^2} + r_{63}E_o = \frac{1}{n_o^2} + r_{63}E_o$$

$$C_1 = \frac{1}{n_E^2}$$

$$D_1 = 0$$

$$\frac{1}{n_x^2} = \frac{1}{n_o^2} - r_{63}E_o$$

$$n_x = \left[\frac{1}{n_o^2} - r_{63}E_o\right]^{-1/2}$$

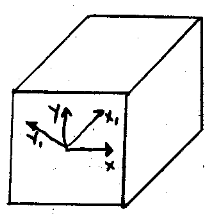
$$n_x = n_o\left(1 - r_{63}n_o^2E_o\right)^{-1/2}$$

$$n_x = n_o + \tfrac{1}{2}r_{63}n_o^3E_o$$

$$n_y = n_o - \tfrac{1}{2}r_{63}n_o^3E_o$$

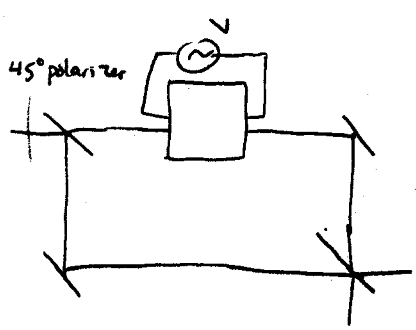
$$n_z = n_E$$

We want the electric field in either the x_1 or y_1 direction



2 options: (1) propagate in the $\hat{z}$ direction with field in y_1 direction
(2) propagate in the $\hat{x}_1$ direction

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

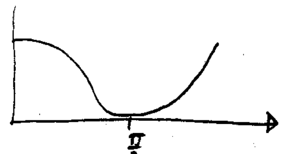


this requires either a ring electrode or a transparent electrode

The field can be in either the x_1 or y_1 direction, which is $45°$ from the cube axes.

for a Mach Zehnder

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



$$\Delta\phi = \frac{2\pi}{\lambda} L \,\Delta n$$

$$= \frac{2\pi}{\lambda}\left(\frac{1}{2}\right)\left(r_{63}\right) n_0^3 \; V \frac{L}{d}$$

$$\pi = \frac{\pi}{546\times10^{-9}}\left(26.8\times10^{-12}\right)\left(1.5079^3\right) V$$

$$V_\pi = \frac{\left(546\times10^{-9}\right)}{\left(26.8\times10^{-12}\right)\left(1.5079^3\right)}$$

$$\boxed{V_\pi = 5942 \text{ V}}$$

(b) Now $\frac{d}{L} = \frac{10\times10^{-6}}{10\times10^{-3}} = 10^{-3}$

$$V_\pi = 5942 \times 10^{-3}$$

$$\boxed{V_\pi = 5.94 \text{ V}}$$

3. A bulk modulator is designed to modulate a CO_2 laser, which has a wavelength of λ=10.6μm. 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 λ=10.6μm.
    b. What is the $V\pi$?

$\lambda = 10.6\,\mu m$

We need to use CdTe, GaAs, ZnSe, ZnTe. These are all $\bar{4}3m$ symmetry crystals and are initially isotropic materials

$$r = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ r_{41} & 0 & 0 \\ 0 & r_{41} & 0 \\ 0 & 0 & r_{41} \end{bmatrix}$$

$$\frac{1}{n_o^2}x + \frac{1}{n_o^2}y + \frac{1}{n_o^2}z + 2r_{41}E_x\,yz = \frac{1}{n^2}$$

rotate about the x-axis

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

$D_1 = 0 = (C-B)\,2\sin\theta\cos\theta + D(\cos^2\theta - \sin^2\theta)$
$B-C\ \sin 2\theta = D\cos 2\theta$

$$\tan 2\theta = \frac{D}{B-C} = \frac{2r_{41}E_x}{\frac{1}{n_o^2} - \frac{1}{n_o^2}} = \infty$$

$2\theta = 90°$
$\theta = 45°$

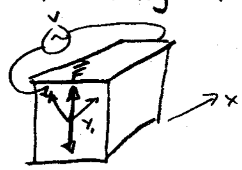
$A_1 = A = \frac{1}{n_o^2}$

$B_1 = B\cos^2(45) + C\sin^2(45) + D\cos(45)\sin(45)$
$= \frac{1}{n_o^2} + 2r_{41}E_x\left(\frac{1}{2}\right) = \frac{1}{n_o^2} + r_{41}E_x$

$C_1 = \frac{1}{n_o^2} - r_{41}E_x$

$D_1 = 0$
$n_{y_1} = n_o - \frac{1}{2}r_{41}n_o^3E_x$
$n_{z_1} = n_o + \frac{1}{2}r_{41}n_o^3E_x$

For polarization filtering we want to propagate in the $\hat{x}$-direction.



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

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

$$\Gamma = \phi_2 - \phi_1$$

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

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

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

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

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

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

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

choose CdTe

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

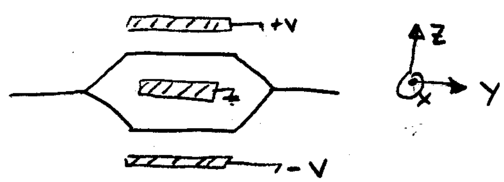
$$\boxed{V_\pi = 44 \text{ KV}}$$

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 Vπ 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

(a)



$$\hat{E} = E_z \hat{z}$$

$$r = \begin{bmatrix} 0 & -r_{22} & r_{13} \\ 0 & r_{22} & r_{13} \\ 0 & 0 & r_{33} \\ 0 & r_{51} & 0 \\ r_{51} & 0 & 0 \\ -r_{22} & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ E_z \end{bmatrix}$$

$$\left(\frac{1}{n_o^2} + r_{13} E_z\right)x + \left(\frac{1}{n_o^2} + r_{13} E_z\right)y + \left(\frac{1}{n_e^2} + r_{33} E_z\right) z = \frac{1}{n^2}$$

$$n_x = n_o - \tfrac{1}{2} n_o^3 r_{13} E_z$$

$$n_y = n_o - \tfrac{1}{2} n_o^3 r_{13} E_z$$

$$n_z = n_e - \tfrac{1}{2} n_e^3 r_{33} E_z$$

The best field direction is $\hat{z}$ because $r_{33} n_e^3 > r_{13} n_o^3$

$$\phi_1 = \frac{2\pi}{\lambda} n_e L - \frac{2\pi}{\lambda}\left(\tfrac{1}{2}\right) n_e^3 r_{33} V \frac{L}{d}$$

$$\phi_2 = \frac{2\pi}{\lambda} n_e L + \frac{2\pi}{\lambda}\left(\tfrac{1}{2}\right) n_e^3 r_{33} V \frac{L}{d}$$

$$\Delta\phi = \phi_2 - \phi_1 = \frac{2\pi}{\lambda} n_e^3 r_{33} V \frac{L}{d}$$

$$\frac{I_{out}}{I_{in}} = \frac{1}{2}\left(1 + \cos\left(\frac{2\pi}{\lambda} n_e^3 r_{33} V \frac{L}{d}\right)\right)$$

$$\frac{2\pi}{\lambda} n_e^3 r_{33} V_\pi \frac{L}{d} = \pi$$

$$V_\pi = \frac{\lambda}{2} \frac{1}{n_e^3 r_{33}} \frac{d}{L}$$

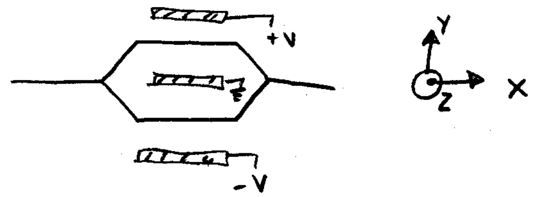
for $\lambda = 1.55\,\mu m$ use the $\lambda = 3.39\,\mu m$ value in the table

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

$$V_\pi = \frac{(1.55\times10^{-6})}{2}\ \frac{1}{(2.073^3)(28\times10^{-12})}\ \frac{d}{L}$$

$$\boxed{V_\pi = 3108\ \frac{d}{L}}$$

(b)



$\vec{E} = E_Y\,\hat{y}$

$$\left(\frac{1}{n_o^2} - r_{22}E_Y\right)x + \left(\frac{1}{n_o^2} + r_{22}E_Y\right)y + \frac{1}{n_e^2}z + 2r_{51}E_Y\,yz = \frac{1}{n^2}$$

$A_1 = A$

$B_1 = B\cos^2\theta + C\sin^2\theta + D\sin\theta\cos\theta$

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

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

$$D_1 = 0 = (C-B)\,2\sin\theta\cos\theta + D(\cos^2\theta - \sin^2\theta)$$

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

$$\tan 2\theta = \frac{D}{B-C} = \frac{2r_{51}E_Y}{\frac{1}{n_o^2} + r_{22}E_Y - \frac{1}{n_e^2}}$$

$$\theta = \tan^{-1}\frac{2r_{51}E_Y}{\frac{1}{n_o^2} - \frac{1}{n_e^2} + r_{22}E_Y}$$

$$\theta \approx 0$$

$A_1 = A = \frac{1}{n_o^2} - r_{22}E_Y$

$B_1 \approx B = \frac{1}{n_o^2} + r_{22}E_Y$

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

$D_1 = 0$

the optical field is in either the $\hat{y}$ or $\hat{z}$ direction. The best case is the $\hat{y}$ direction

$n_y = n_o - \frac{1}{2}n_o^3 r_{22}E_Y$

$\Delta\Phi = 2\left(\frac{2\pi}{\lambda}\right)\left(\frac{1}{2}\right)n_o^3 r_{22}E_Y L = \frac{2\pi}{\lambda}n_o^3 r_{22}E_Y L$

$\frac{I_{out}}{I_{in}} = \frac{1}{2}\left(1 + \cos\left(\frac{2\pi}{\lambda}n_o^3 r_{22}E_Y L\right)\right)$

$$\pi = \frac{2\pi}{\lambda}n_o^3 r_{22}V_\pi\frac{L}{d}$$

$$V_\pi = \frac{\lambda}{2n_o^3 r_{22}}\frac{d}{L} = \frac{1.55\times10^{-6}}{(4)(2.136^3)(3.1\times10^{-12})}\frac{d}{L} = \boxed{25652\ \frac{d}{L}}$$

(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 piezo electric effect, which can cause charge build up which Varies the bais of the modulator

(6) For the Avanex modulator
$\vec{E} = E_z \hat{z}$, y- propagating, push-pull

$V_\pi = 3108 \frac{d}{L}$

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

$\frac{d}{L} = \frac{5}{3108}$

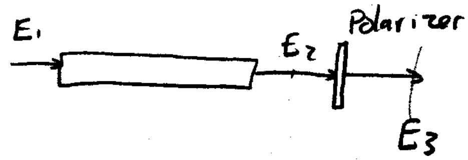
$\boxed{\frac{d}{L} = 0.0016}$

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 $n_x = n_o - \frac{n_o^3}{2} r_{13} \frac{V}{d}$ and $n_z = n_e - \frac{n_e^3}{2} r_{33} \frac{V}{d}$, where n_o=2.286, n_e=2.2, r_{13}=9.6pm/V, r_{33}=30.9 pm/V, λ=1550nm, ~~d/t~~=1000, and L=2cm.

   a. Plot the relative optical power as a function of voltage.
   b. What is the extinction ratio (P_{min}/P_{max})?

$$\vec{E} = 4e^{j0.1}\hat{x} + 2e^{j0.5}\hat{z}$$

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



$$n_x = n_o - \tfrac{1}{2} n_o^3 r_{13} \frac{V}{d}$$

$$\phi_x = \frac{2\pi}{\lambda} n_o L - \frac{\pi}{\lambda} n_o^3 r_{13} \frac{V}{d} L$$

$$= \left(\frac{2\pi}{1.55\times10^{-6}}\right)(2.286)(.02) - \left(\frac{\pi}{1.55\times10^{-6}}\right)(2.286^3)(9.6\times10^{-12})\,V\,(10^3)$$

$$\phi_y = \left(\frac{2\pi}{1.55\times10^{-6}}\right)(2.2)(0.02) - \left(\frac{\pi}{1.55\times10^{-6}}\right)(2.2^3)(30.9\times10^{-12})(10^3)$$

$$E_2 = \begin{bmatrix} 4e^{j0.1} e^{j\phi_x} \\ 2e^{j0.5} e^{j\phi_y} \end{bmatrix}$$

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

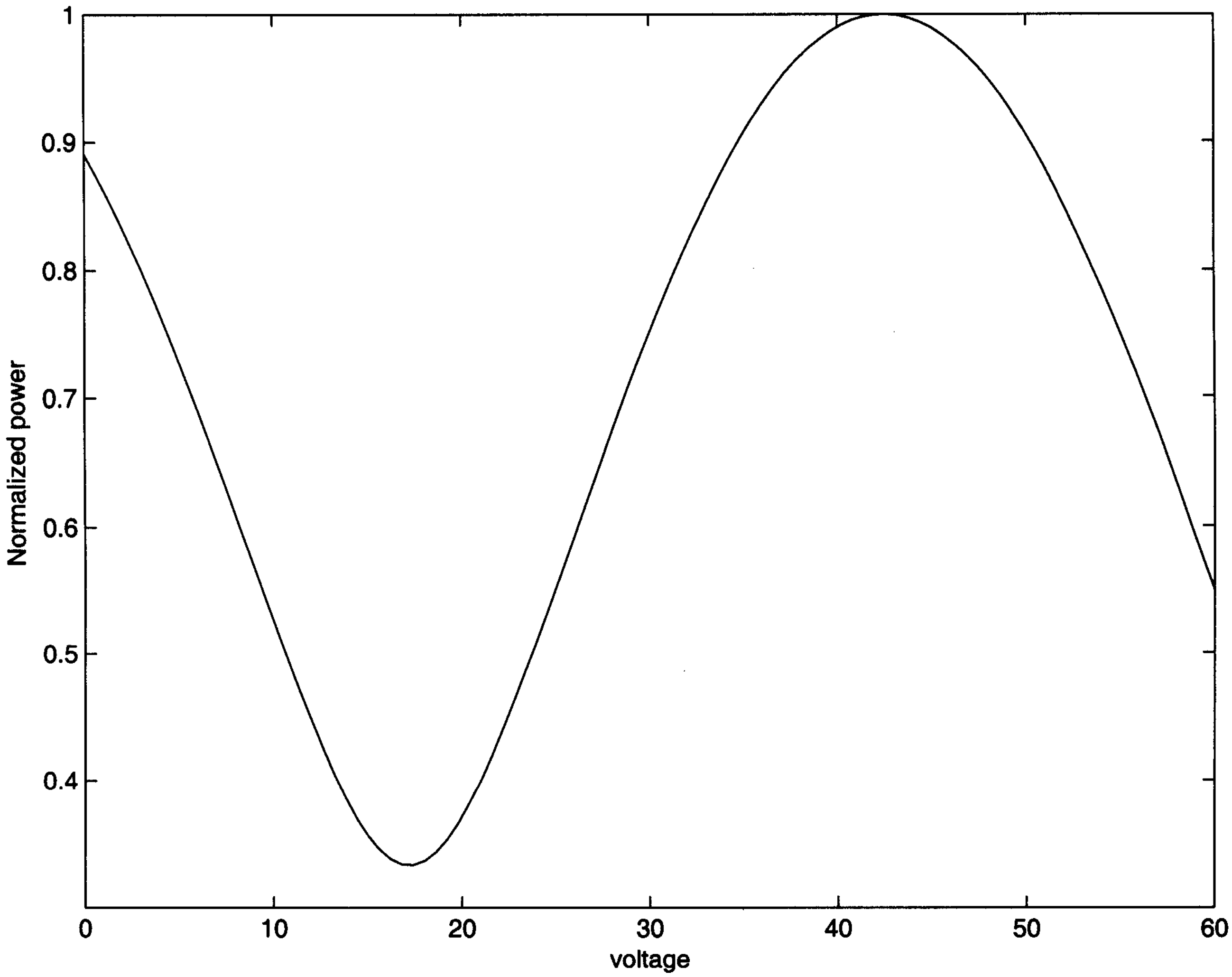
$$\frac{P_{min}}{P_{max}} = 0.33$$

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%EO modulation using polarization filtering
%with unbalanced polarizations.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
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')
```



1
0.9
0.8
0.7
0.6
0.5
0.4
Normalized power
0
10
20
30
40
50
60
voltage