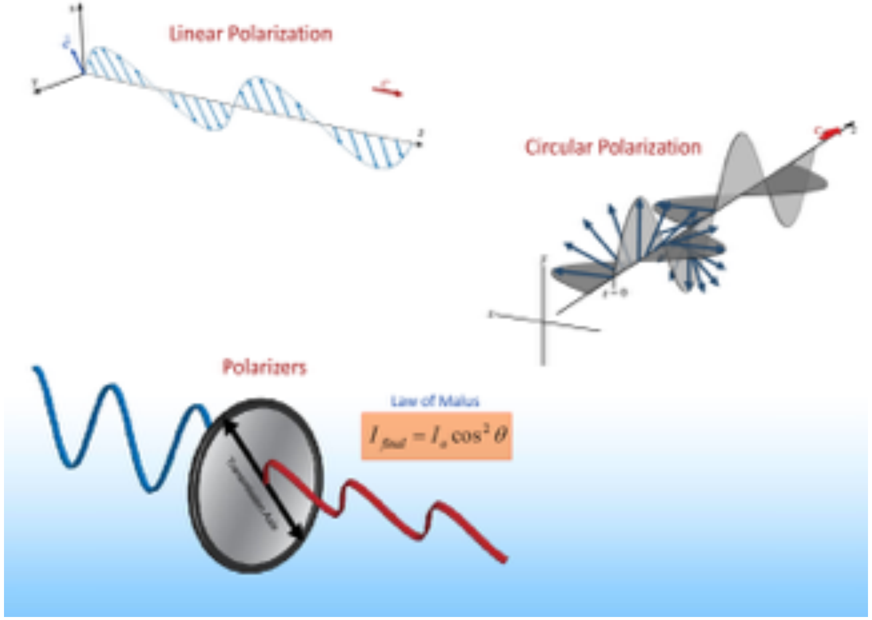
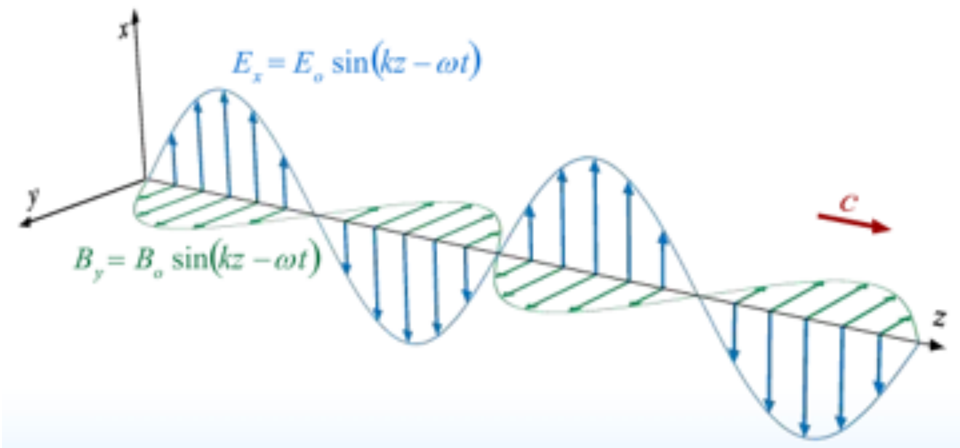
Physics 121
Lecture 24



So far we have considered plane waves that look like this:



$$\omega = kc$$

$$E_o = cB_o$$

$$c = \frac{1}{\sqrt{\mu_o \varepsilon_o}}$$

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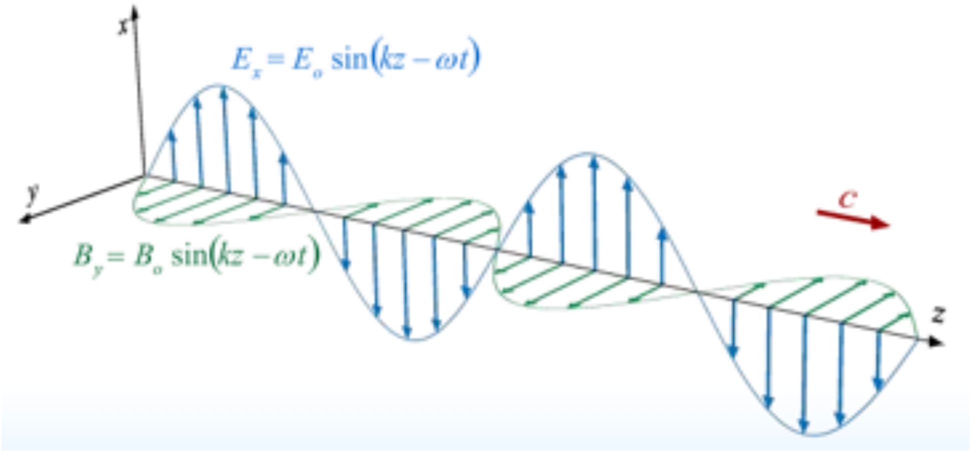

$$\omega = kc$$
$$E_o = cB_o$$
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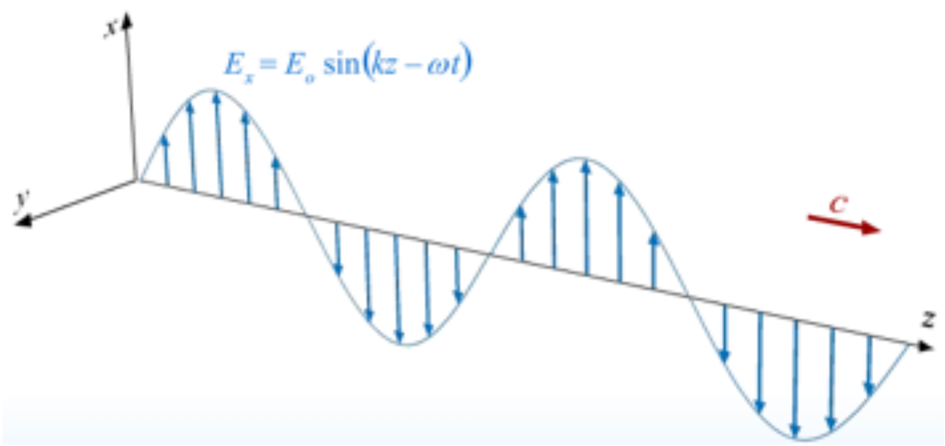
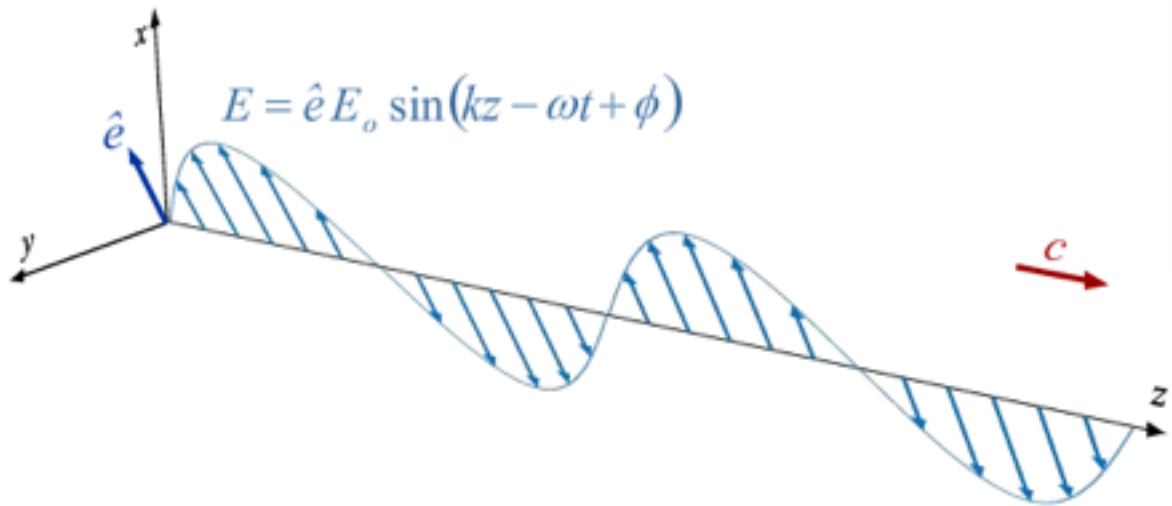
From now on just draw E and remember that B is still there:

$\vec{E}$ Field determines Polarization



Linear Polarization



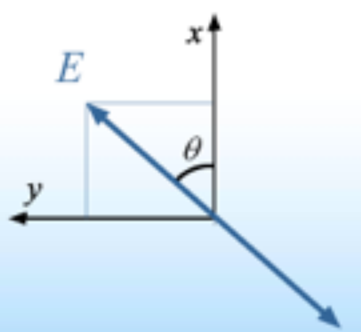
$$\omega = kc$$

$$E_o = cB_o$$

$$c = \frac{1}{\sqrt{\mu_o \varepsilon_o}}$$

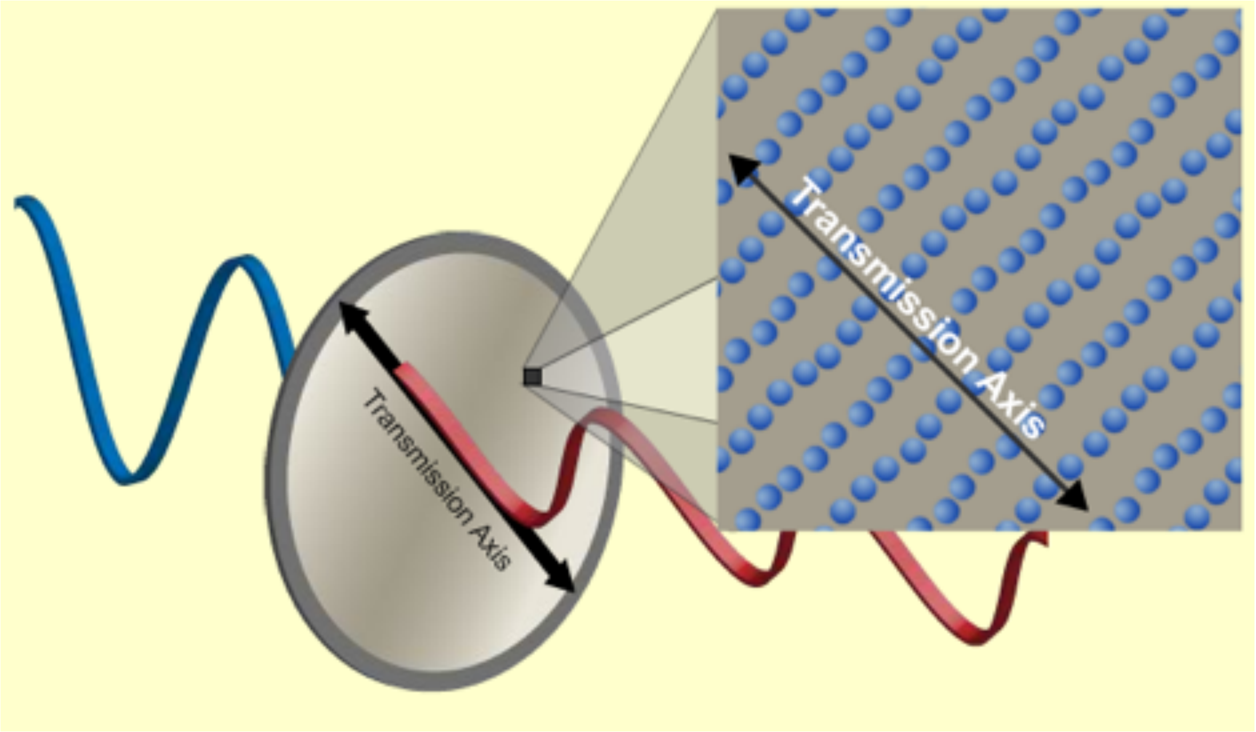
$$E_x = E_o \cos\theta \sin(kz - \omega t + \phi)$$

$$E_y = E_o \sin\theta \sin(kz - \omega t + \phi)$$



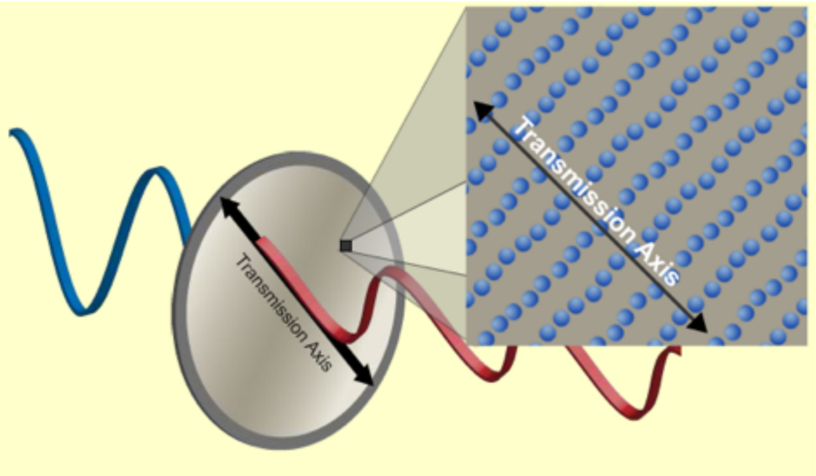
Wave Coming Out of the Screen

Polarizer



The molecular structure of a polarizer causes the component of the E field perpendicular to the Transmission Axis to be absorbed.

Clicker Question



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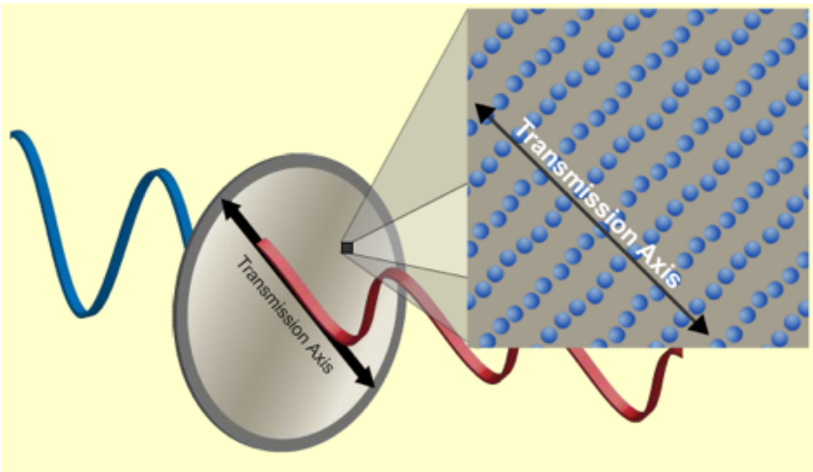

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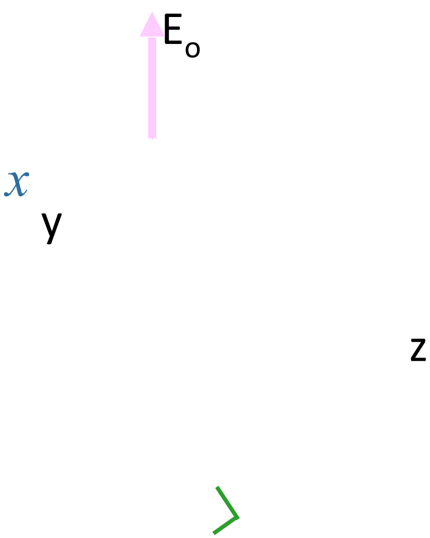
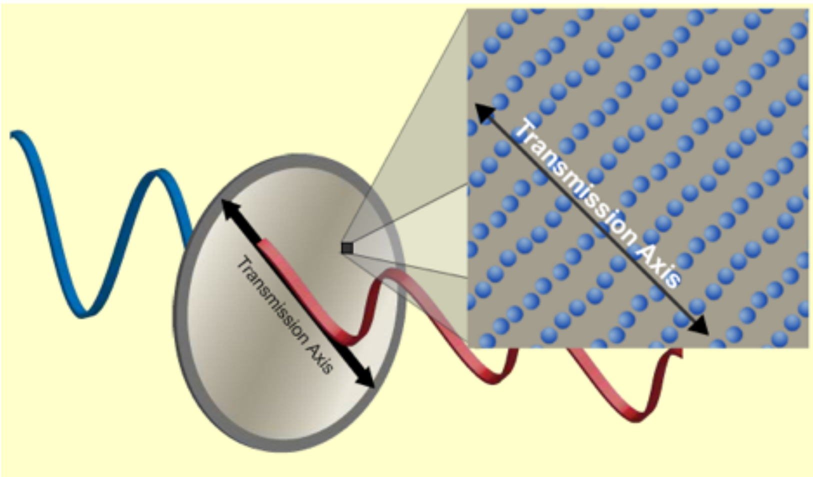


Suppose we have a beam traveling in the $+z$ – direction.

At $t = 0$ and $z = 0$, the electric field is aligned along the positive x – axis and has a magnitude equal to E_o

Clicker Question



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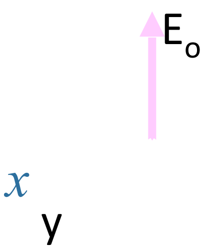
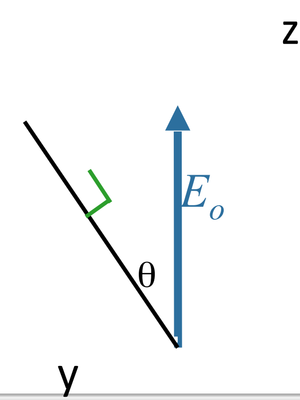


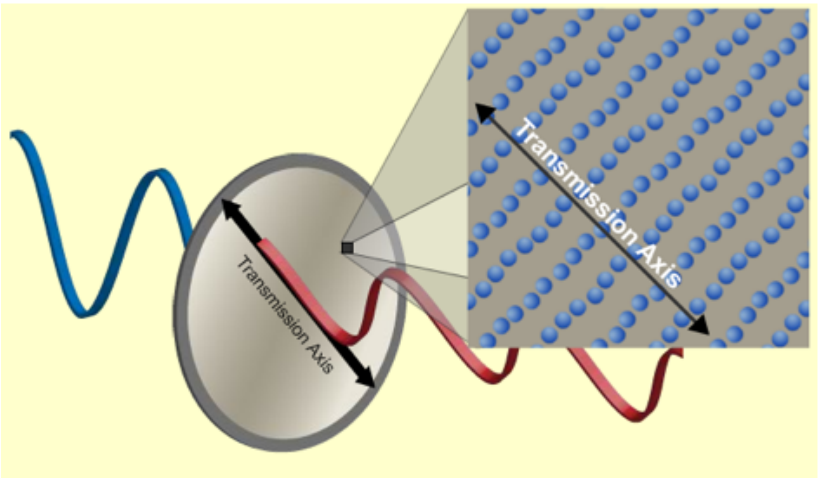
Suppose we have a beam traveling in the $+z$ – direction.
At $t = 0$ and $z = 0$, the electric field is aligned along the positive x – axis and has a magnitude equal to E_o

What is the component of E_o along a direction in the $x-y$ plane that makes an angle of θ with respect to the x – axis?

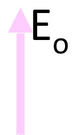


A) $E_o \sin\theta$ B) $E_o \cos\theta$ C) 0 D) $E_o / \sin\theta$ E) $E_o / \cos\theta$

Clicker Question



The molecular structure of a polarizer causes the component of the E field perpendicular to the Transmission Axis to be absorbed.



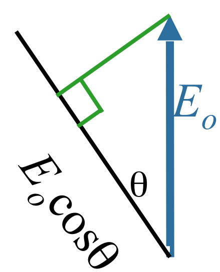
Suppose we have a beam traveling in the $+z$ – direction.
At $t = 0$ and $z = 0$, the electric field is aligned along the positive x – axis and has a magnitude equal to E_o

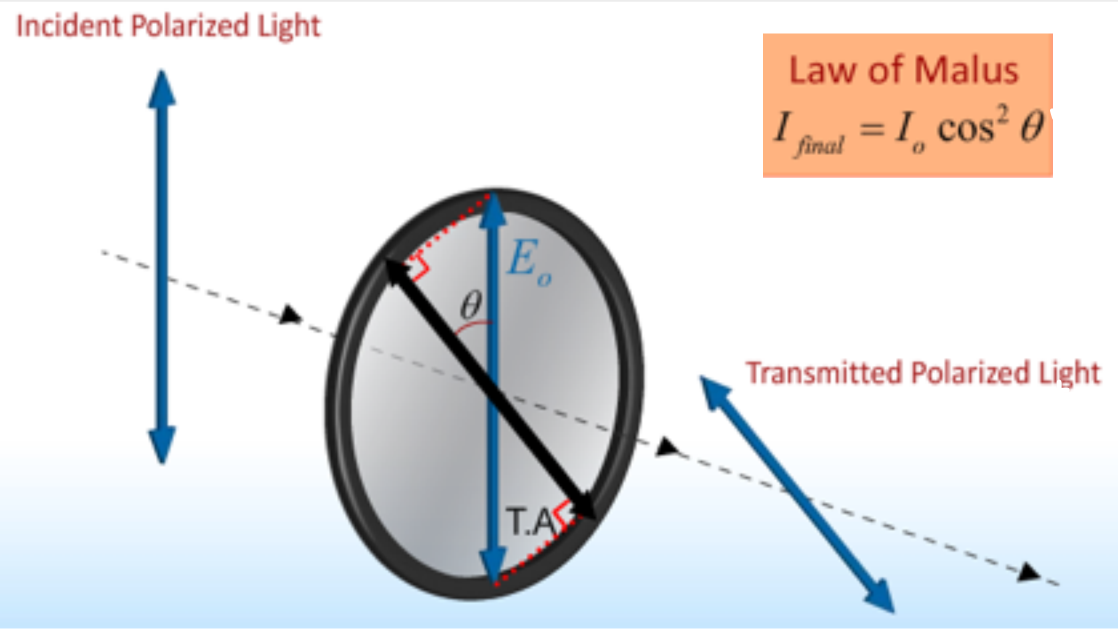
y

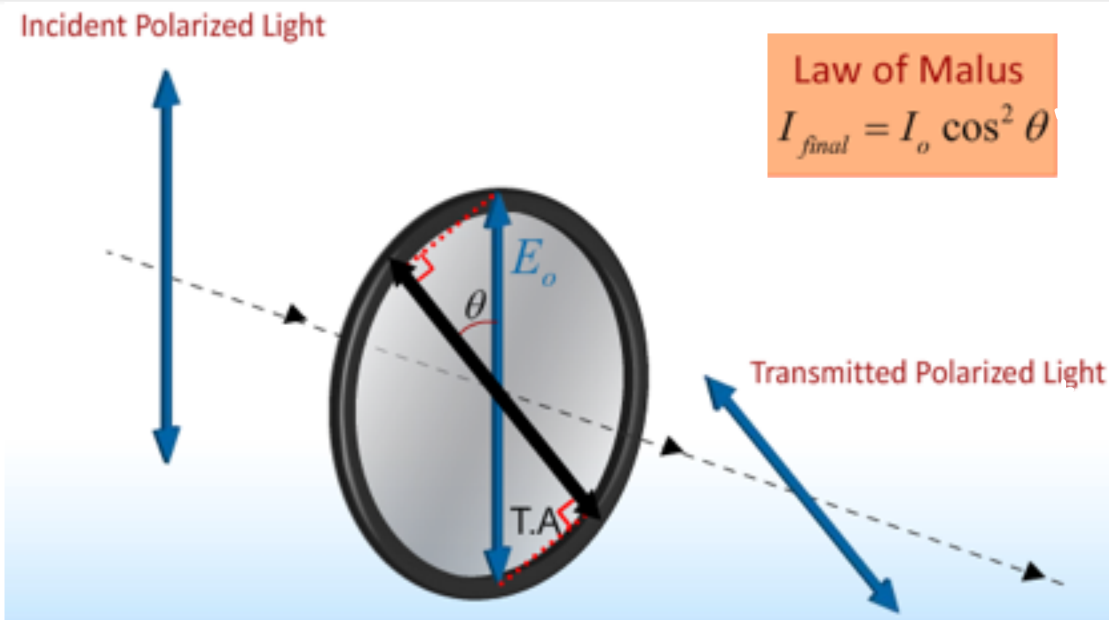
z

What is the component of E_o along a direction in the $x - y$ plane that makes an angle of θ with respect to the x – axis?

A) $E_o \sin\theta$ $\boxed{\text{B) } E_o \cos\theta}$ C) 0 D) $E_o / \sin\theta$ E) $E_o / \cos\theta$




Incident Polarized Light
Law of Malus
$I_{final} = I_o \cos^2 \theta$
E_o
θ
T.A
Transmitted Polarized Light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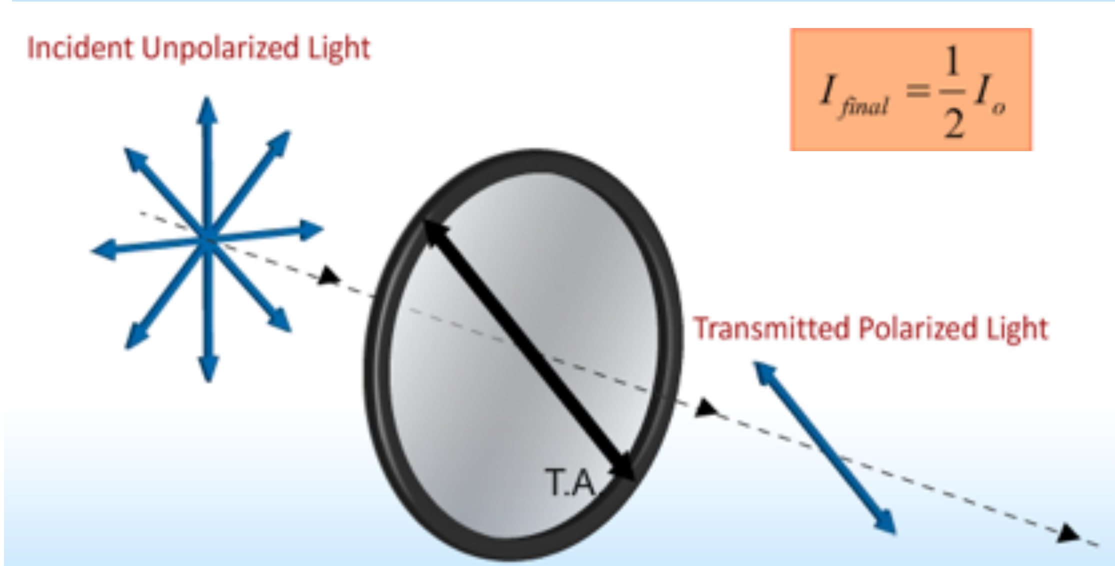
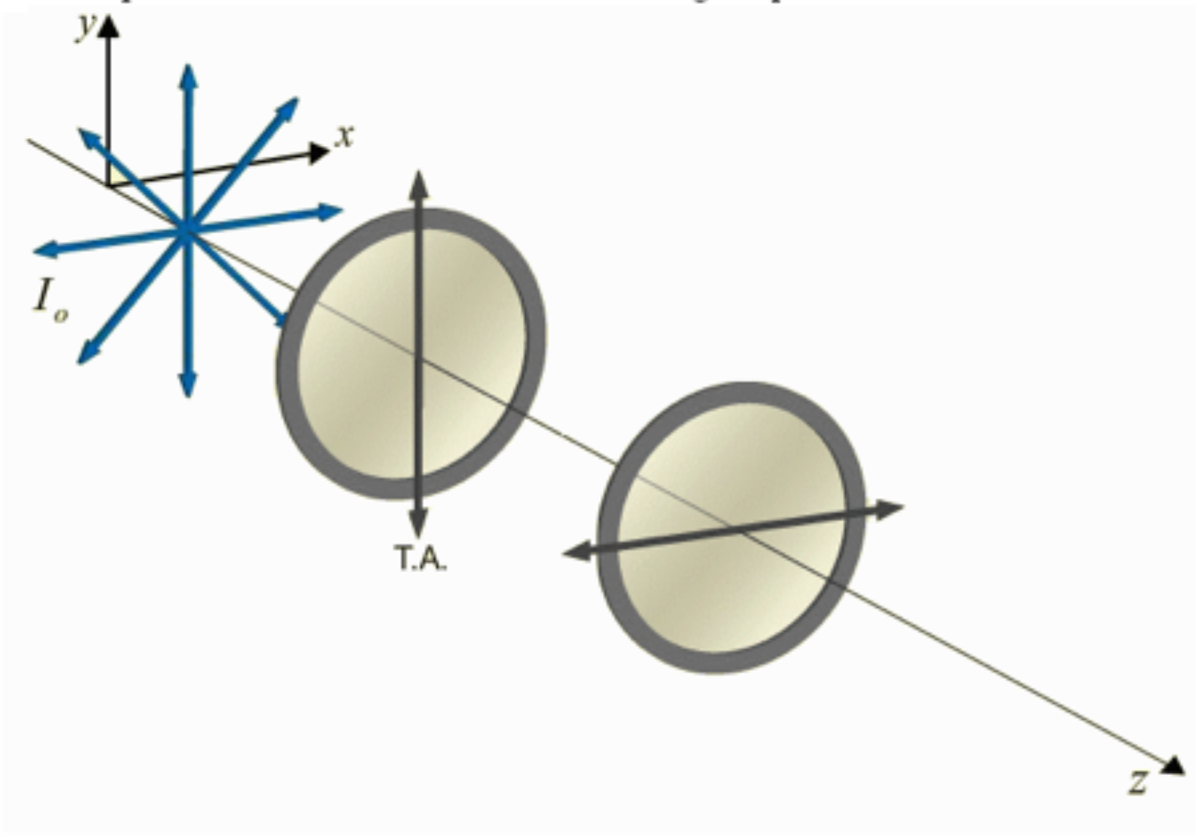

Incident Unpolarized Light
$I_{final} = \frac{1}{2} I_o$
T.A
Transmitted Polarized Light

CheckPoint 2

Two Polarizers

An unpolarized EM wave is incident on two orthogonal polarizers.



What percentage of the intensity gets through both polarizers?

- 50%
- 25%
- 0%

CheckPoint 2

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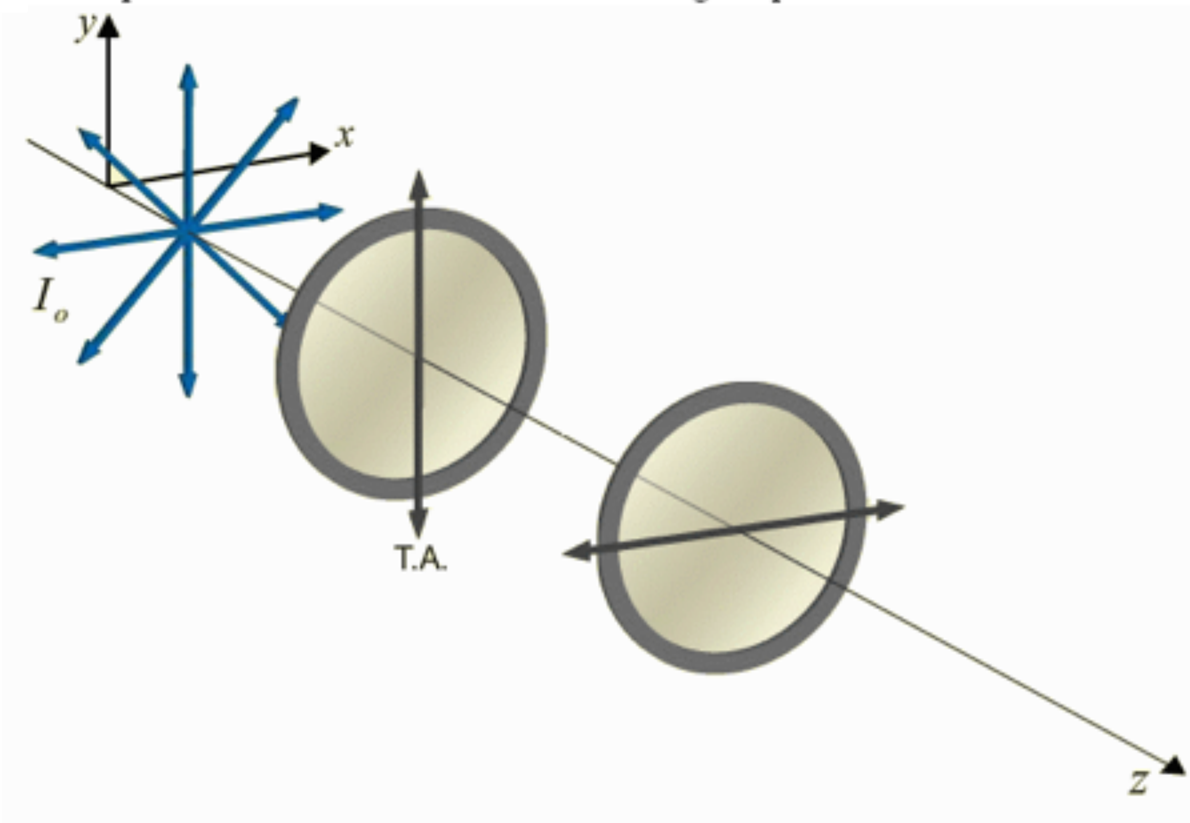

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The second polarizer is orthogonal to the first

No light will come through. $\cos(90^o) = 0$

CheckPoint 2

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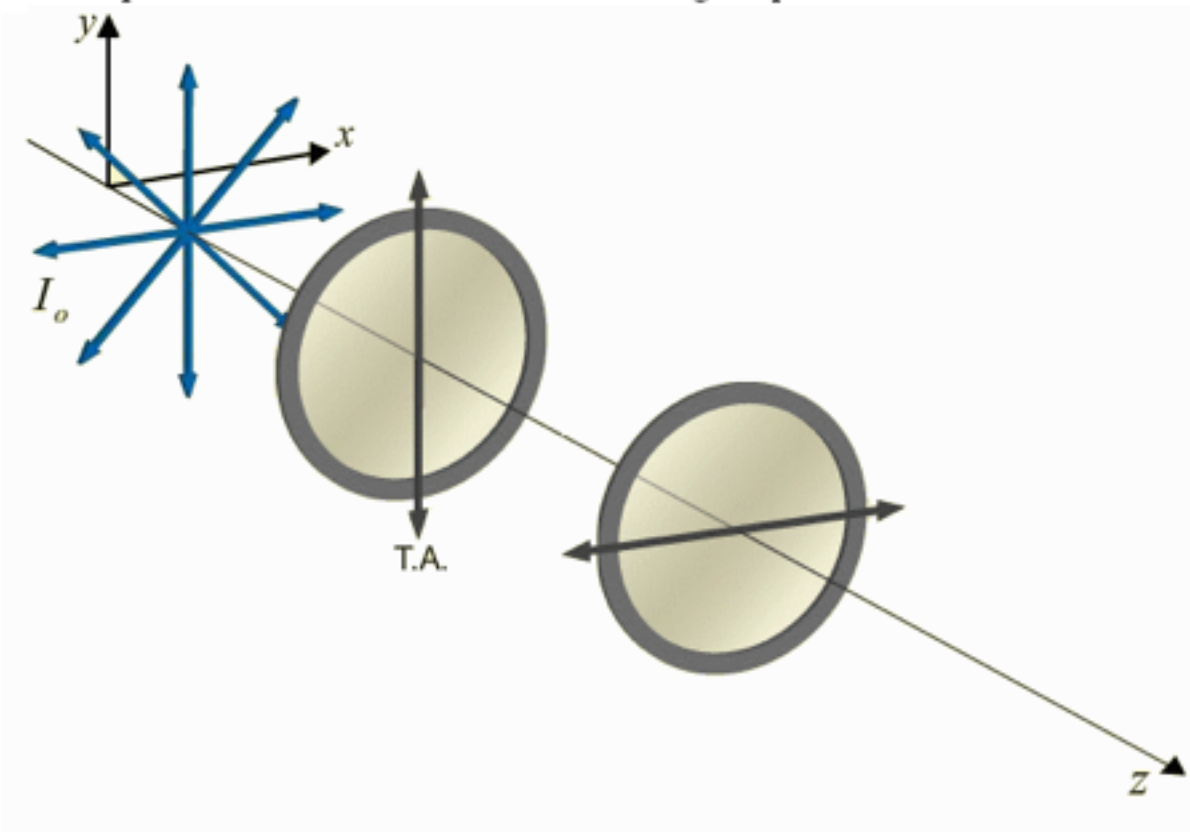

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CheckPoint 4

Two Polarizers

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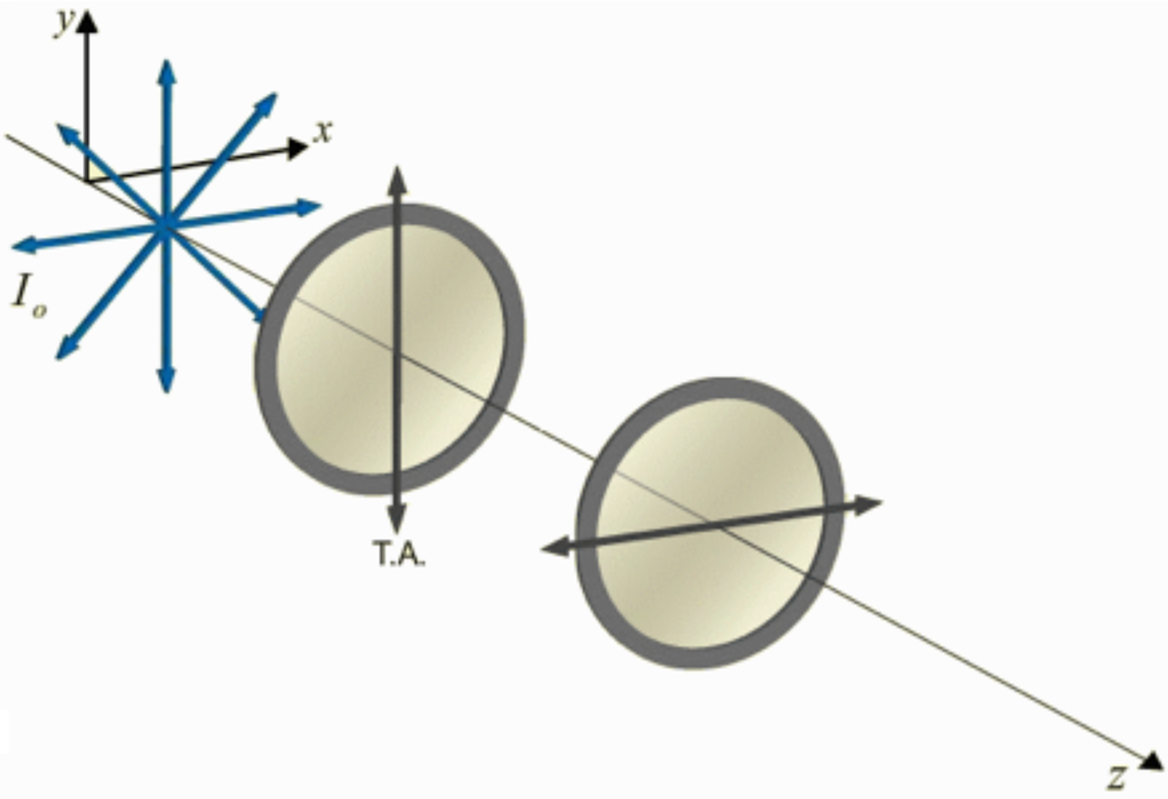

4) Is it possible to increase this percentage by inserting another polarizer between the original two?

- yes
- no

CheckPoint 4

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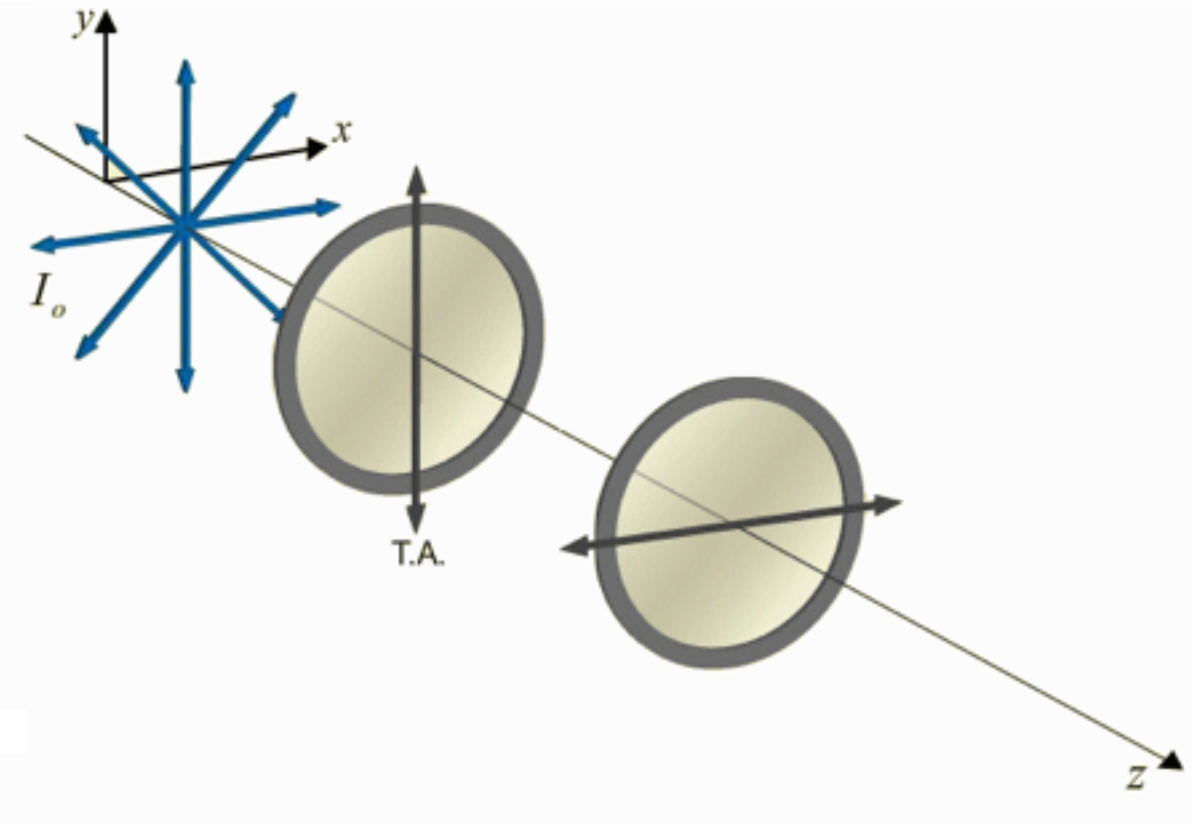


Two Polarizers

4) Is it possible to increase this percentage by inserting another polarizer between the original two?

- yes
- no

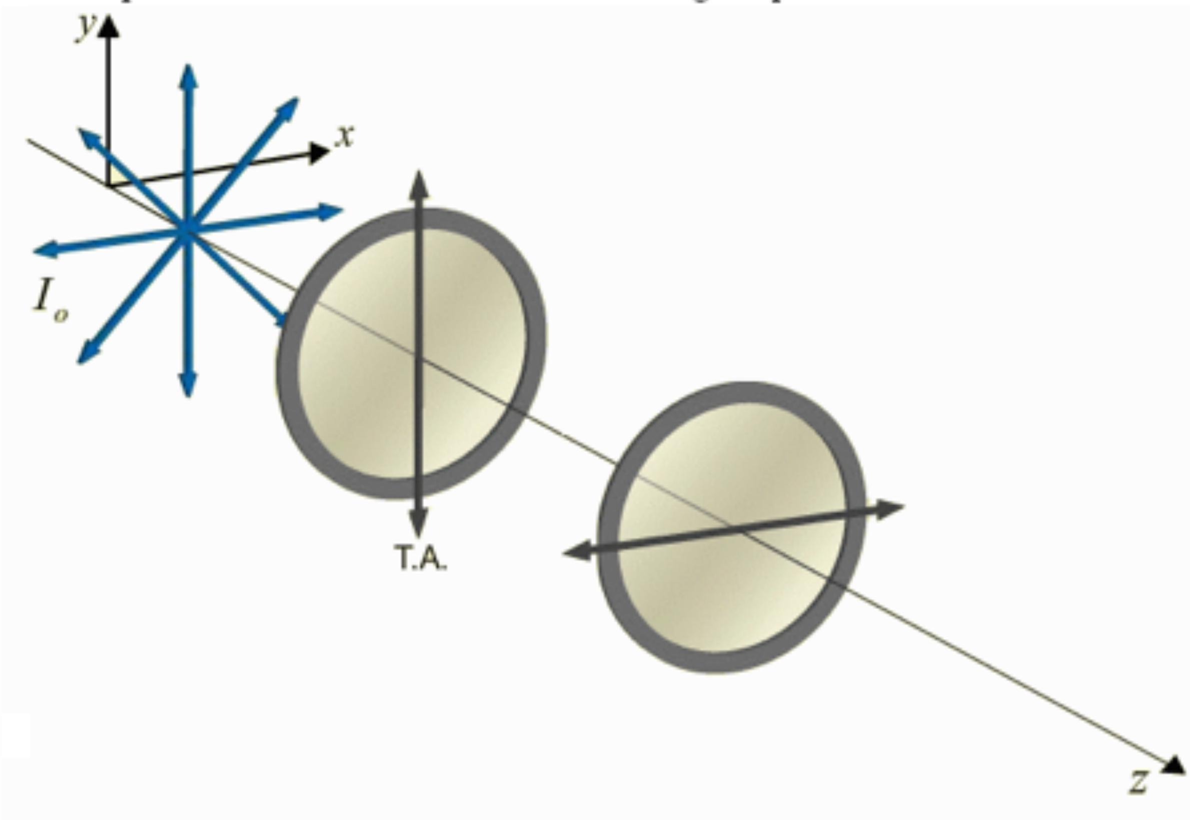
Any non-horizontal polarizer after the first polarizer will produce polarized light at that angle

Part of that light will make it through the horizontal polarizer

CheckPoint 4

Two Polarizers

An unpolarized EM wave is incident on two orthogonal polarizers.



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- ◯ yes
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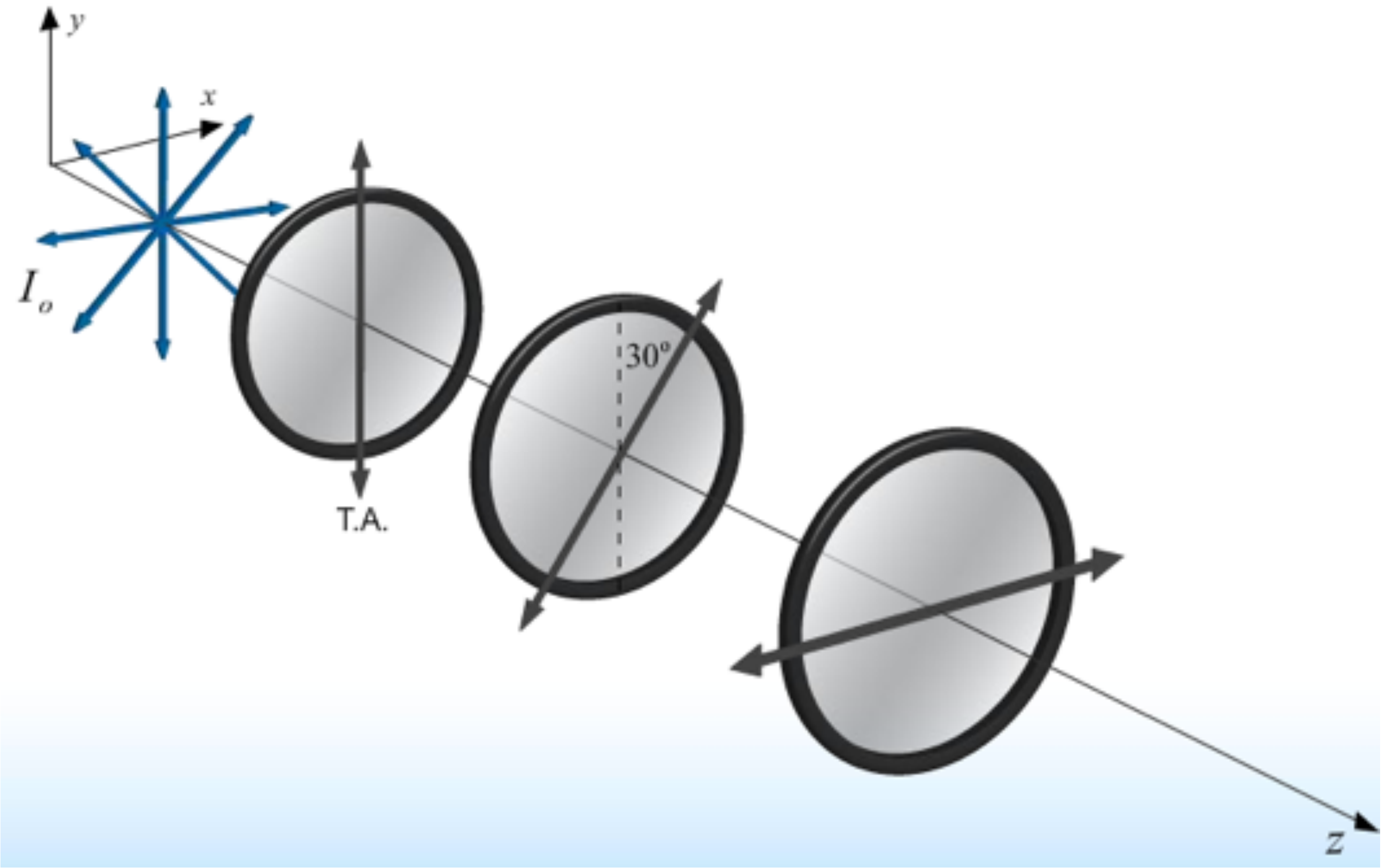
Demo



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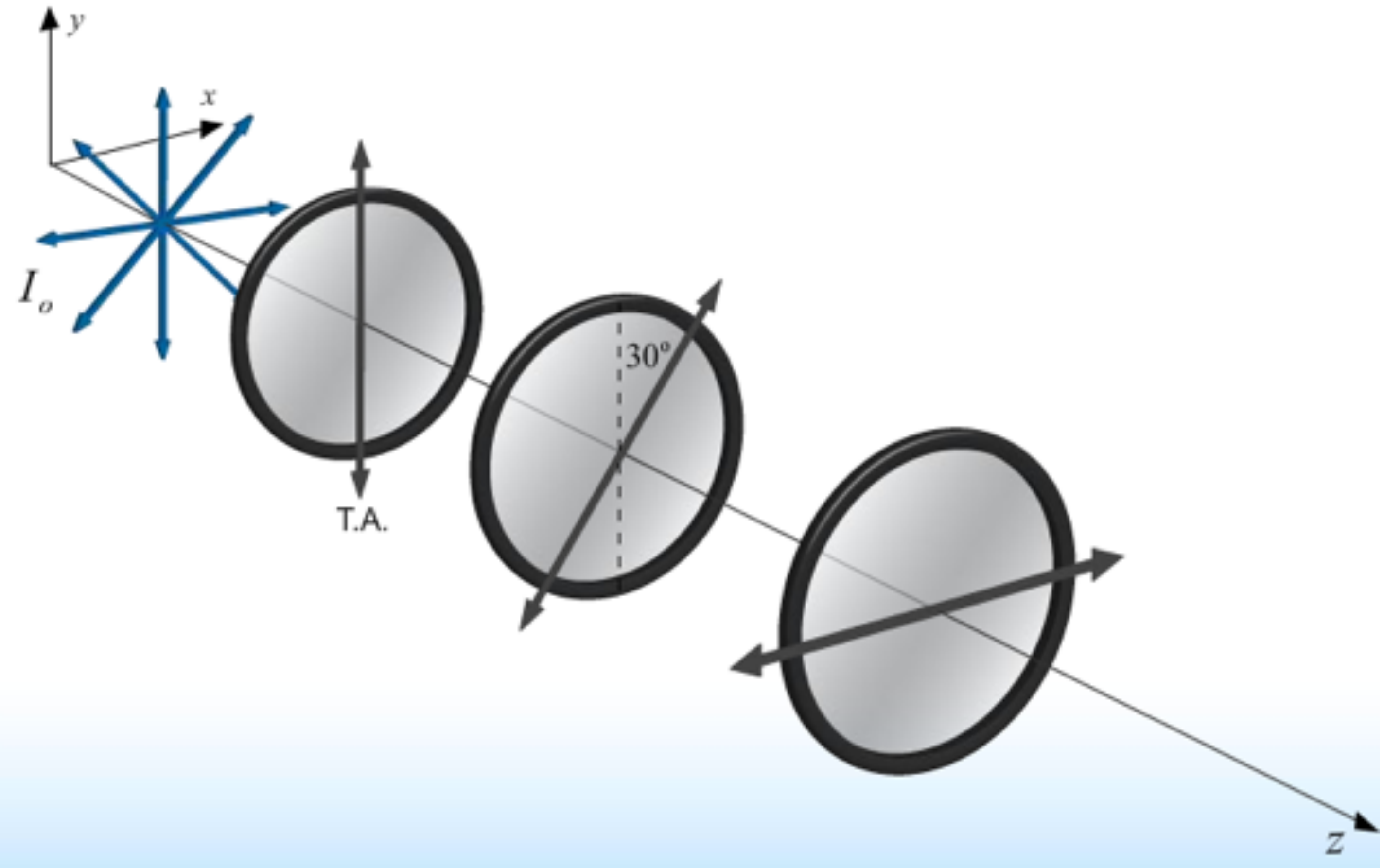
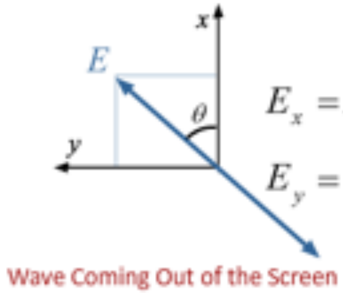


A third filter between the two crossed polarizzers allows some light through. The middle polarizer creates light with a component of E along the transmission axis of the third polarizer.

Circular Polarization

There is no reason that ϕ has to be the same for E_x and E_y:



$$\left.\begin{aligned} E_x &= E_o \cos\theta \sin(kz - \omega t + \phi_x) \\ E_y &= E_o \sin\theta \sin(kz - \omega t + \phi_y) \end{aligned}\right] \xrightarrow[\text{Wave Equation}]{\text{Satisfies}} \begin{aligned} \frac{\partial^2 E_x}{\partial z^2} &= \mu_o \varepsilon_o \frac{\partial^2 E_x}{\partial t^2} \\ \frac{\partial^2 E_y}{\partial z^2} &= \mu_o \varepsilon_o \frac{\partial^2 E_y}{\partial t^2} \end{aligned}$$

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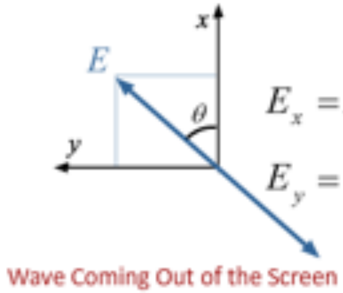

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Satisfies Wave Equation $\rightarrow$

$$\frac{\partial^2 E_x}{\partial z^2} = \mu_o \varepsilon_o \frac{\partial^2 E_x}{\partial t^2}$$
$$\frac{\partial^2 E_y}{\partial z^2} = \mu_o \varepsilon_o \frac{\partial^2 E_y}{\partial t^2}$$

Making ϕ_x different from ϕ_y causes circular or elliptical polarization:

Circular Polarization

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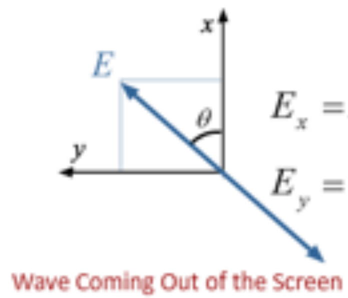

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Example:

$$\phi_x - \phi_y = 90^\circ = \frac{\pi}{2}$$

$$\theta = 45^\circ = \pi / 4$$

$$E_x = \frac{E_0}{\sqrt{2}} \cos(kz - \omega t)$$

$$E_x = \frac{E_0}{\sqrt{2}} \sin(kz - \omega t)$$

Circular Polarization

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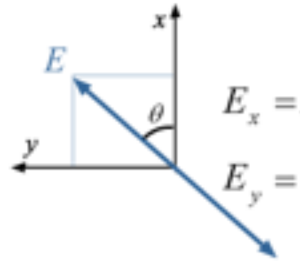

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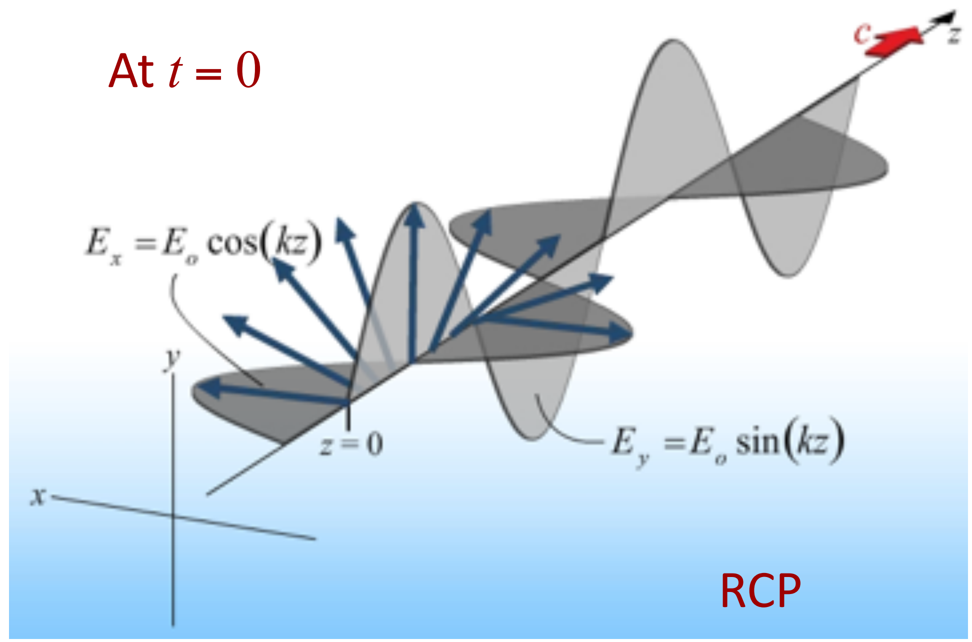
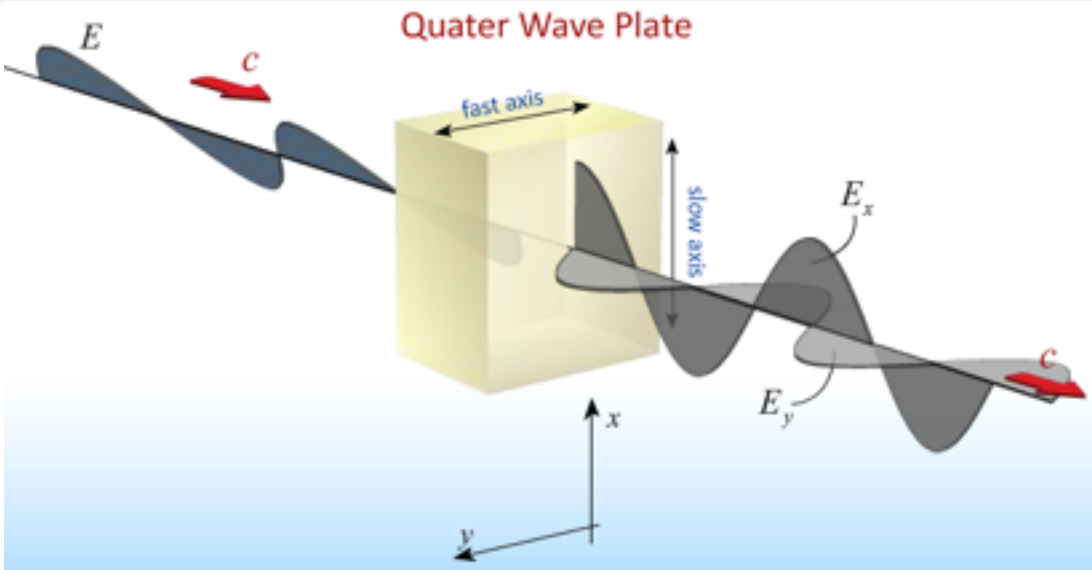


Q: How do we change the relative phase between E_x and E_y?

A: Birefringence



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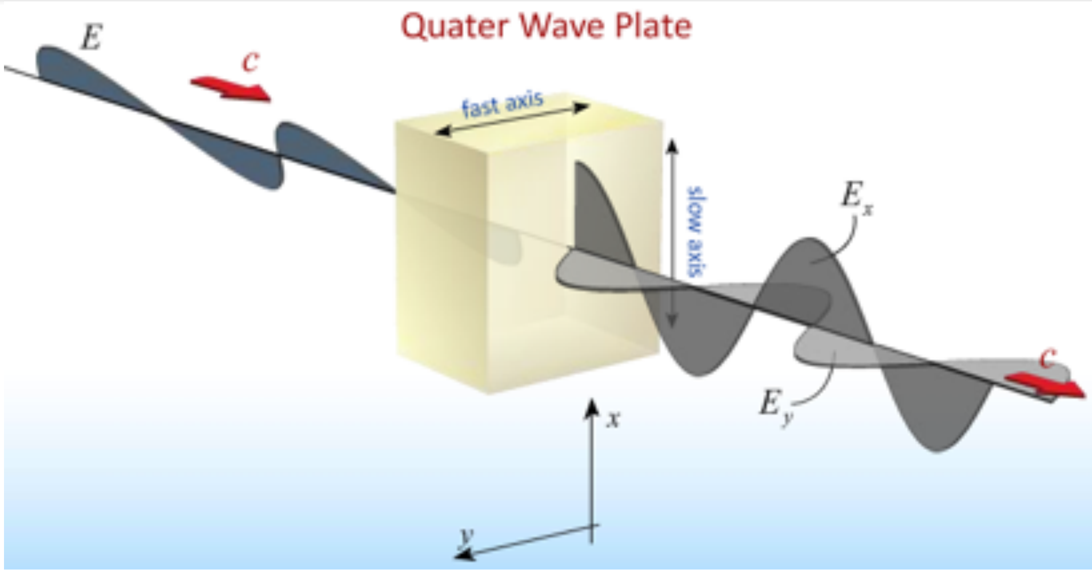

By picking the right thickness we can change the relative phase by exactly 90^o.

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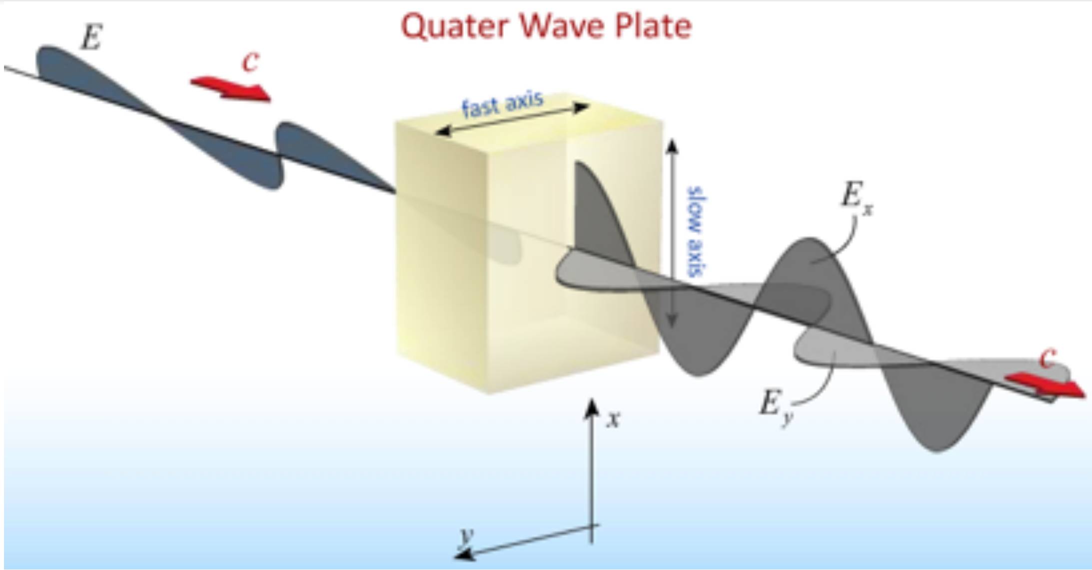

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This changes <u>linear</u> to <u>circular</u> polarization and is called a *quarter wave plate*

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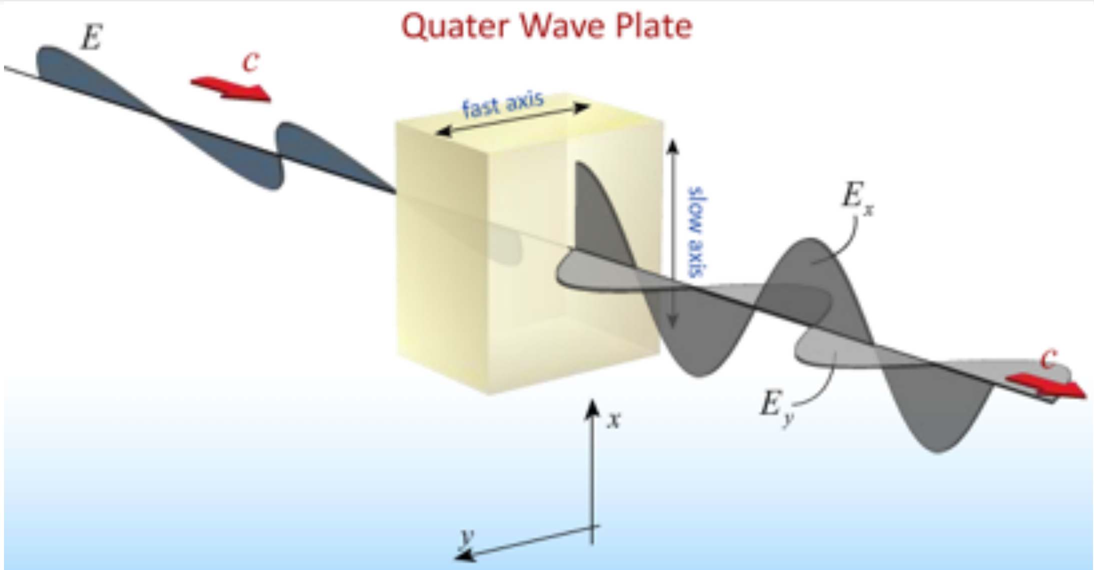

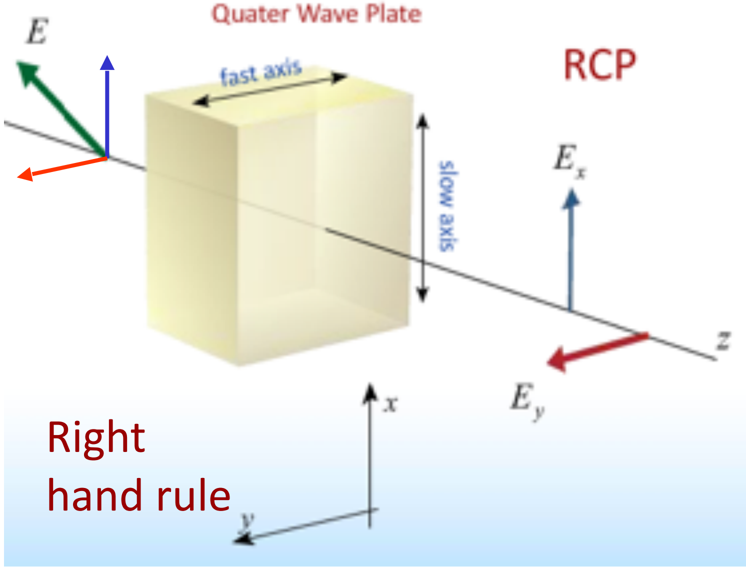

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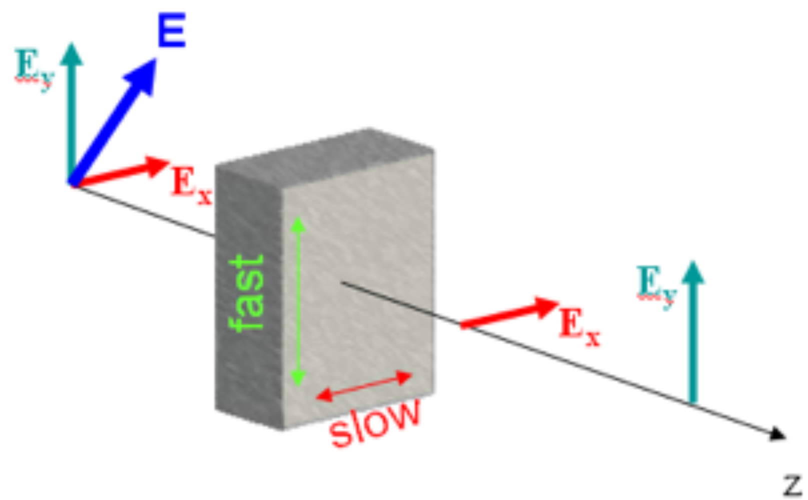
This changes linear to circular polarization and is called a *quarter wave plate*

Right or Left?

"red fox"
got it?



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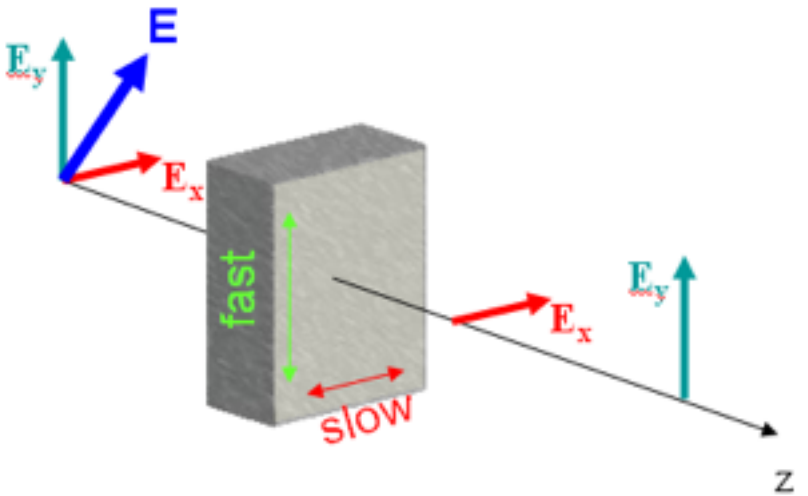
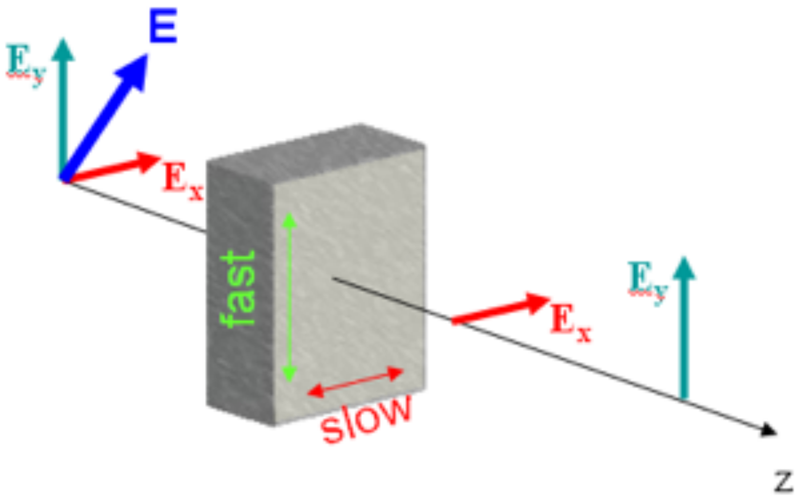


Right circularly polarized

Right or Left?

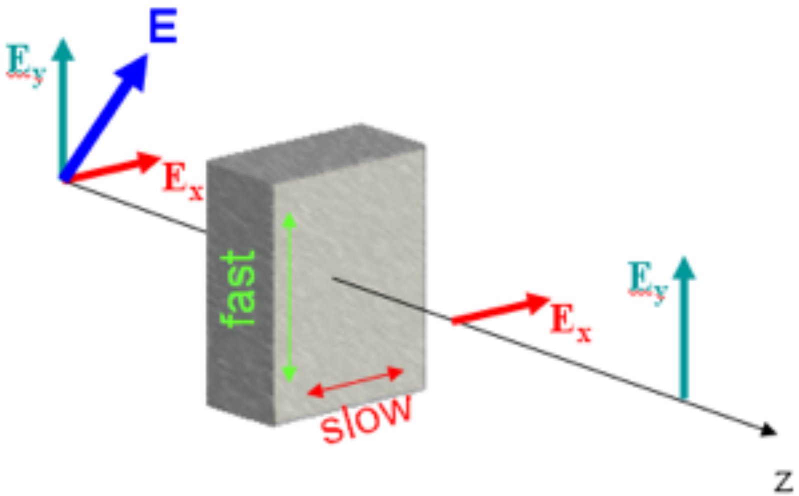
"red fox"
got it?



Right circularly polarized
Do right hand rule

Right or Left?

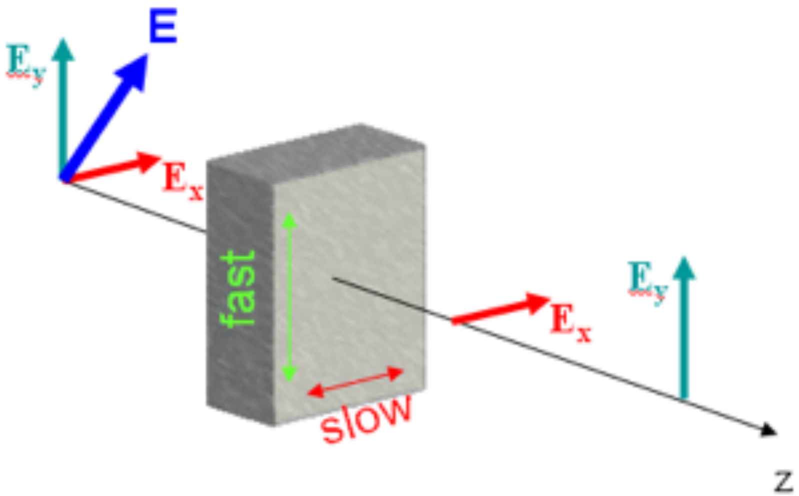
"red fox"
got it?



Right circularly polarized
Do right hand rule
Fingers along slow direction

Right or Left?

"red fox"
got it?



Right circularly polarized

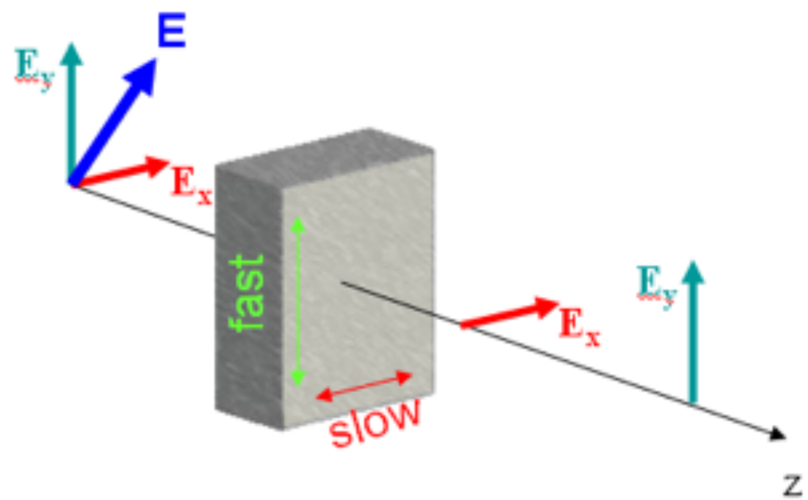
Do right hand rule

Fingers along slow direction

Cross into fast direction

Right or Left?

"red fox"
got it?



Right circularly polarized

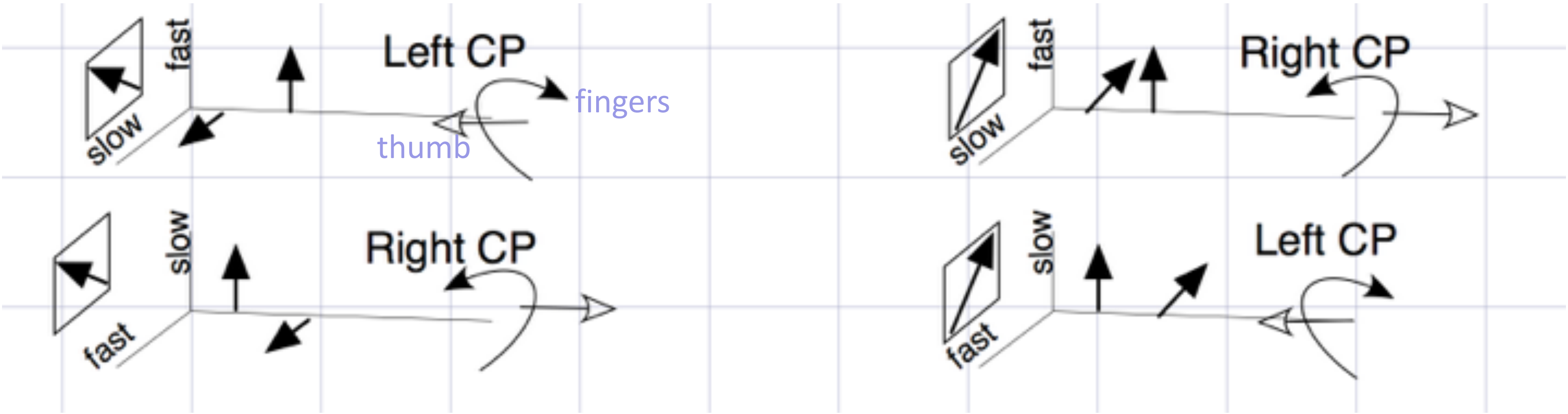
Do right hand rule

Fingers along slow direction

Cross into fast direction

If thumb points in direction of propagation: RCP

Identifying handedness of CP



Here are four different possibilities of incident linearly polarized light passing thru a qwp and the resulting circular polarization

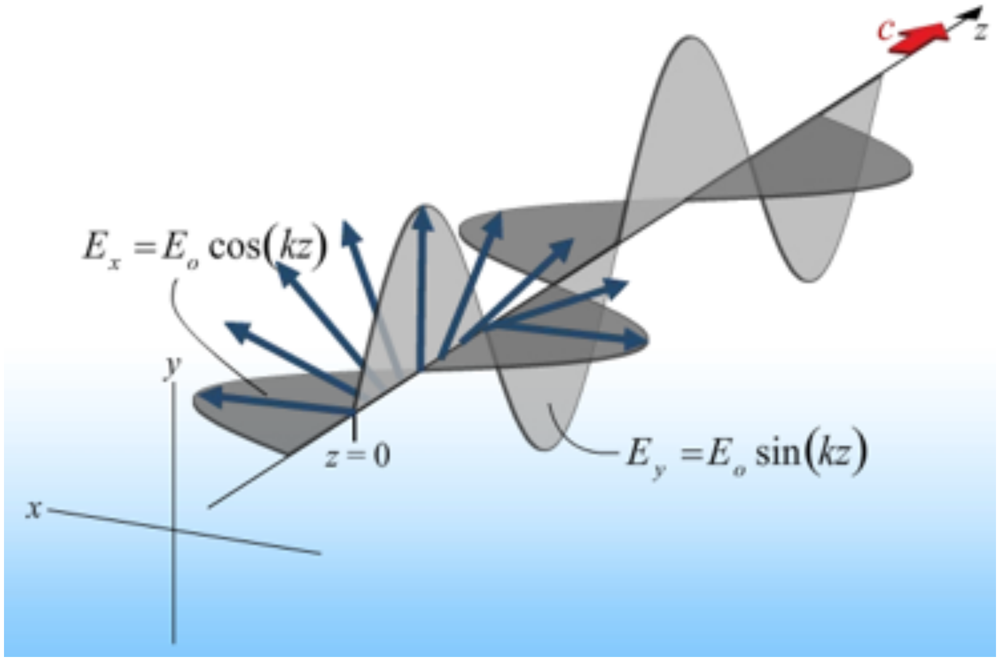
Circular Light on Linear Polarizer

Q: What happens when circularly polarized light is put through a polarizer along the y (or x) axis ?

A) $I = 0$

B) $I = \frac{1}{2} I_0$

C) $I = I_0$



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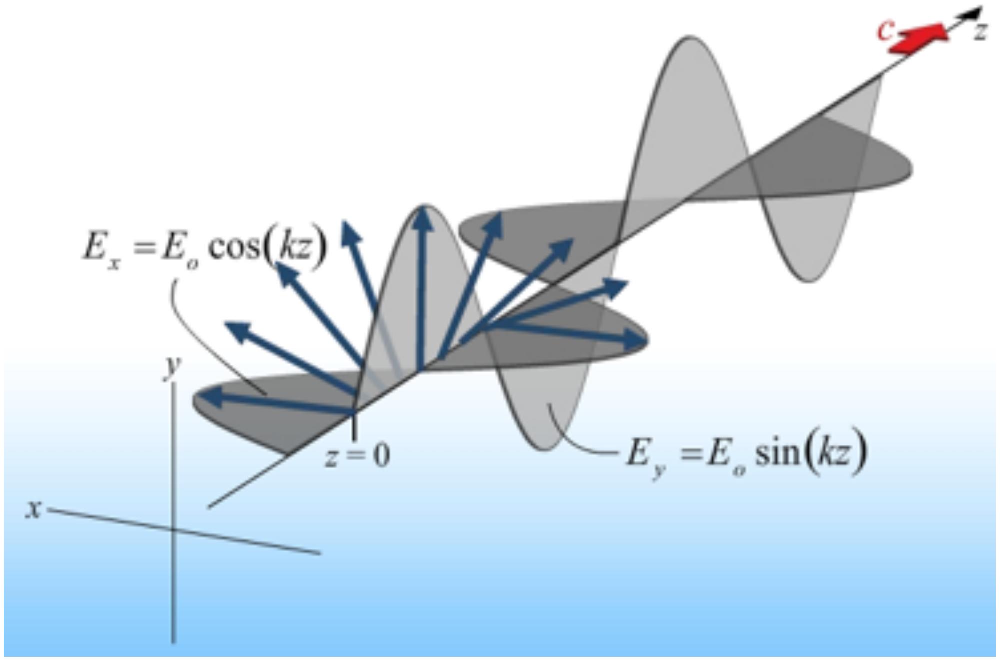
$$I = \varepsilon_0 c \langle E^2 \rangle$$



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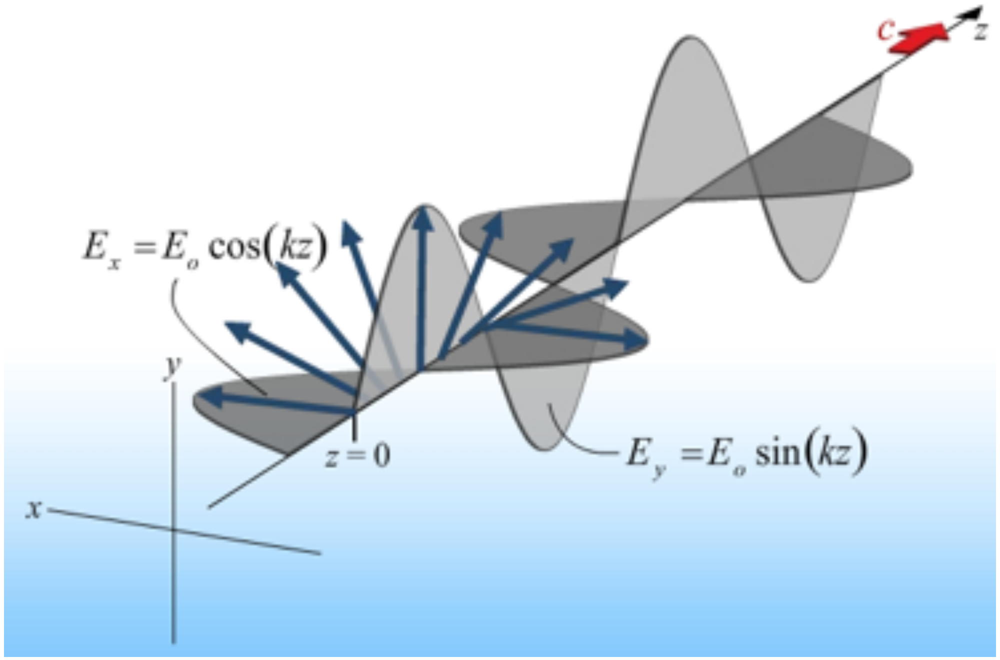
$$I = \varepsilon_0 c \left\langle E^2 \right\rangle$$

$$= \varepsilon_0 c \left\langle E_x^2 + E_y^2 \right\rangle$$



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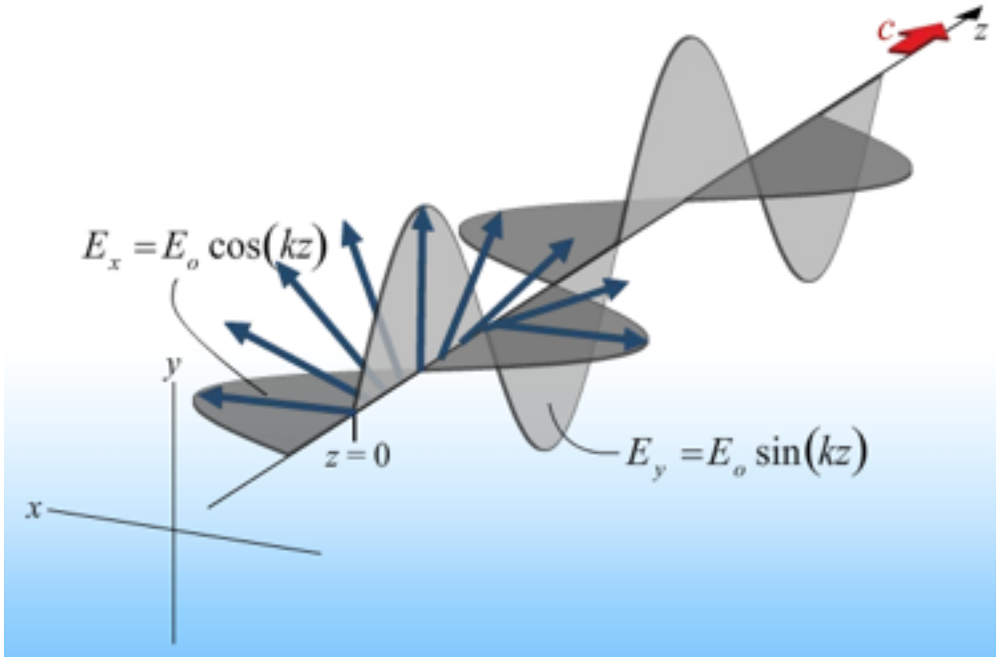
$$I = \varepsilon_0 c \langle E^2 \rangle$$

$$= \varepsilon_0 c \langle E_x^2 + \cancel{E_y^2} \rangle$$



Circular Light on Linear Polarizer

Q: What happens when circularly polarized light is put through a polarizer along the y (or x) axis ?

A) $I = 0$

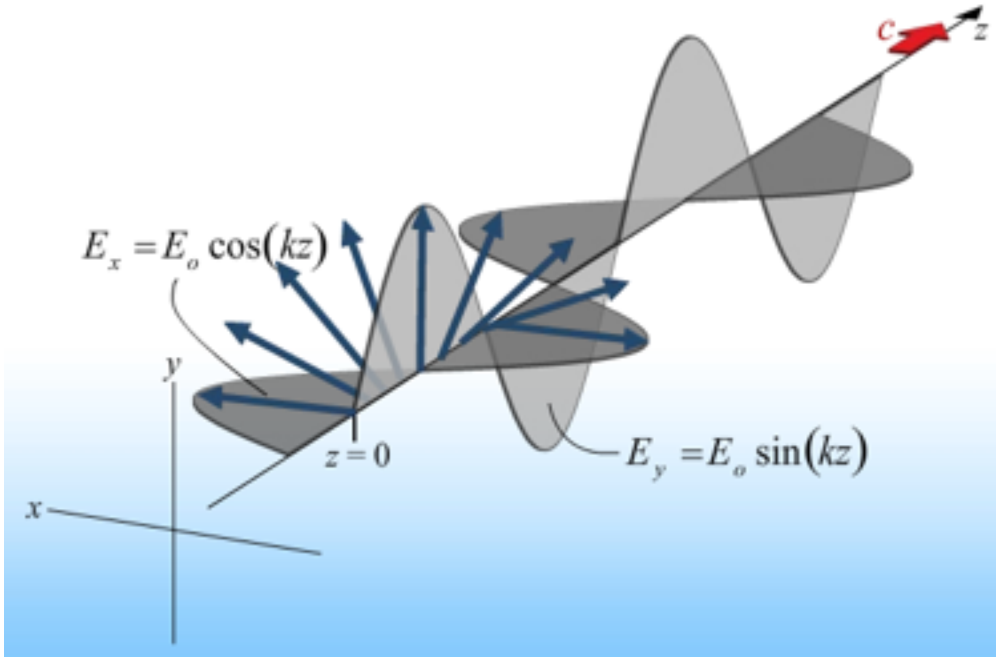
B) $I = ½\, I_0$

C) $I = I_0$

$$I = \varepsilon_0 c \langle E^2 \rangle$$

$$= \varepsilon_0 c \langle E_x^2 + \cancel{E_y^2} \rangle$$

$$= \varepsilon_0 c \frac{E_0^2}{2} \langle \cos^2(kz - \omega t) \rangle$$



Circular Light on Linear Polarizer

Q: What happens when circularly polarized light is put through a polarizer along the y (or x) axis ?

A) $I = 0$

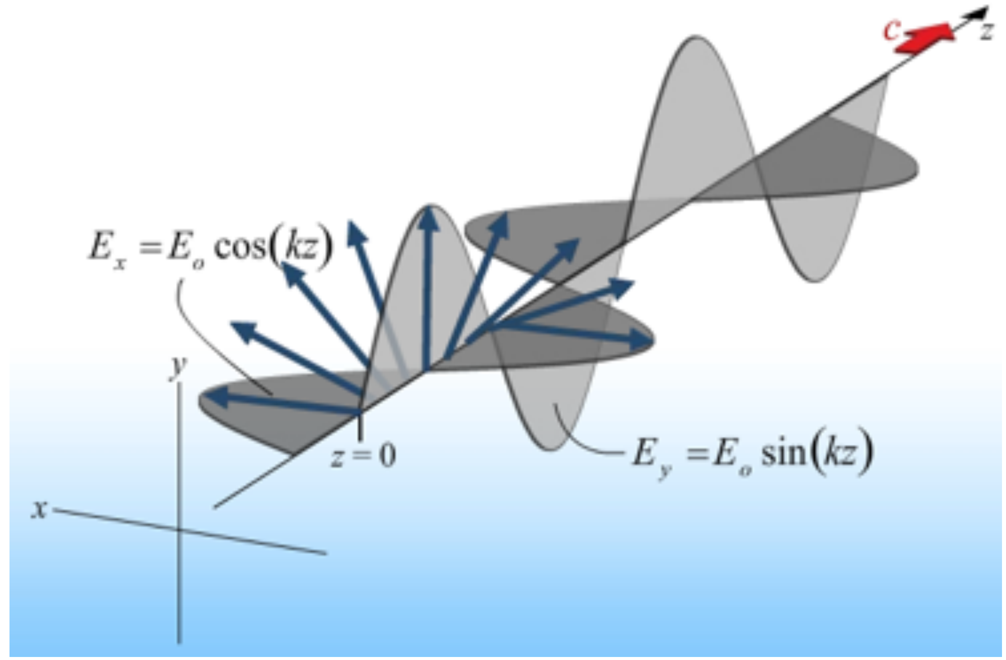
B) $I = \frac{1}{2} I_0$

C) $I = I_0$

$$I = \varepsilon_0 c \langle E^2 \rangle$$

$$= \varepsilon_0 c \langle E_x^2 + \cancel{E_y^2} \rangle$$

$$= \varepsilon_0 c \frac{E_0^2}{2} \underbrace{\langle \cos^2(kz - \omega t) \rangle}_{1/2}$$



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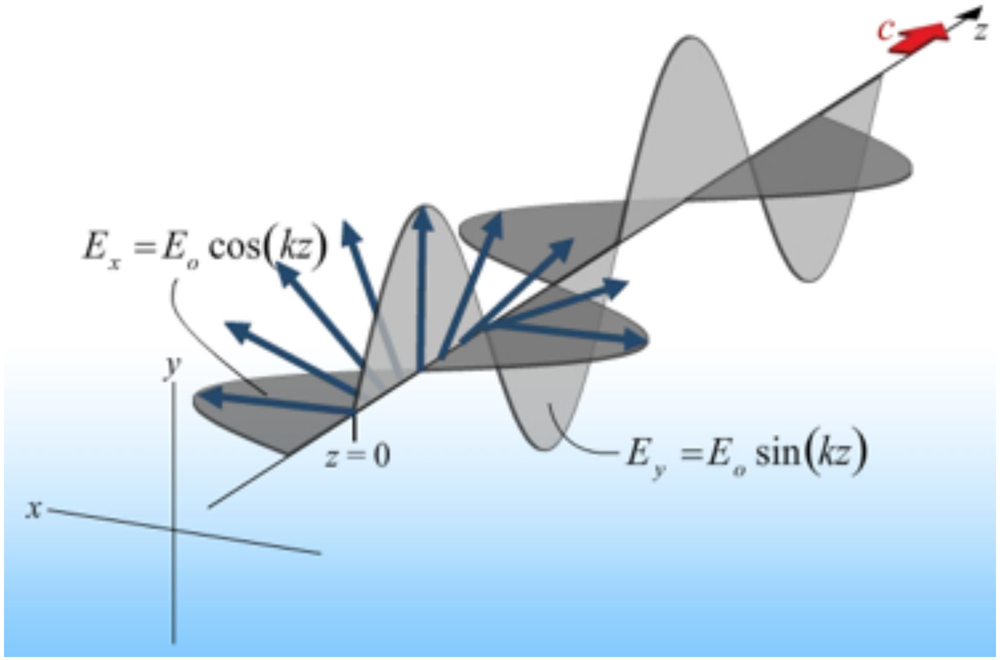

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$$= \frac{1}{2} \cdot \frac{1}{2} \varepsilon_0 c E_0^2$$

Half of before

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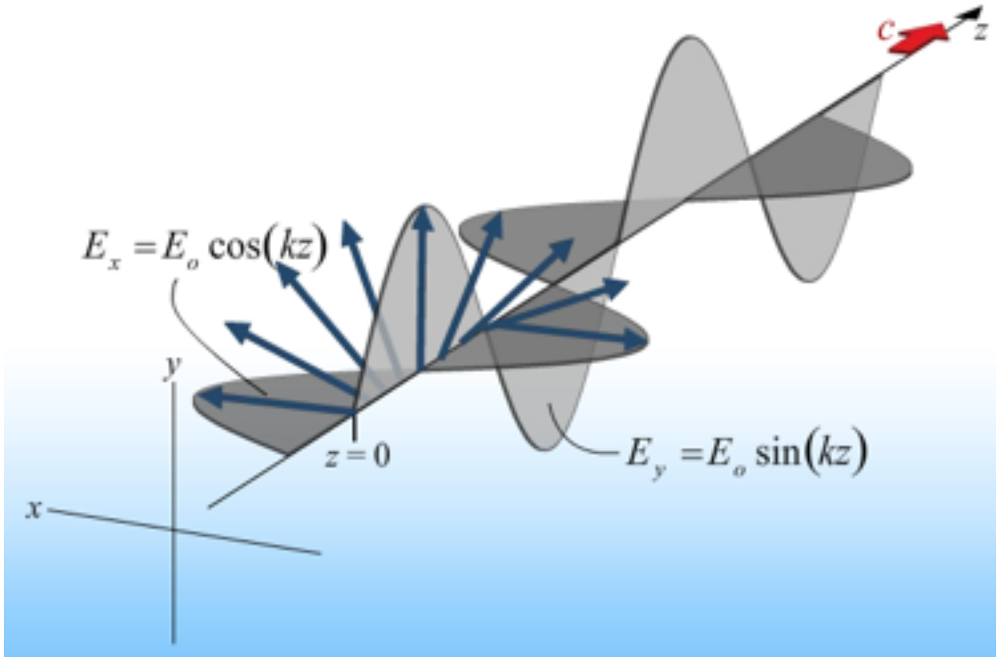
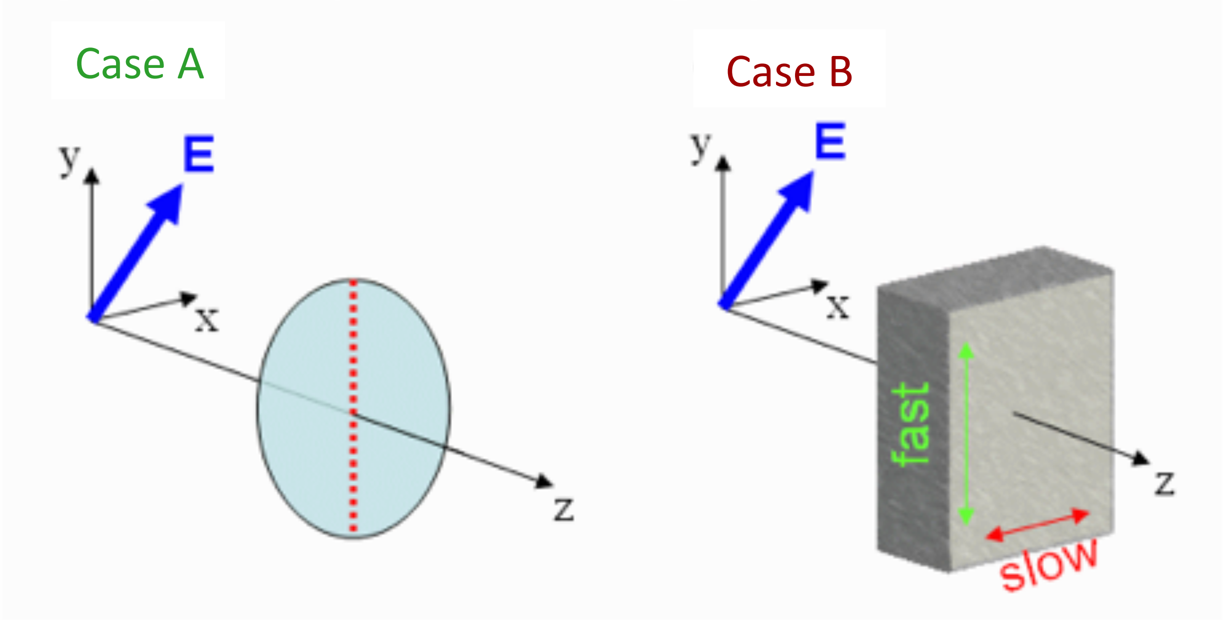


$$= \frac{1}{2} \cdot \frac{1}{2} \varepsilon_0 c E_0^2$$

Half of before

CheckPoint 6

Identical linearly polarized light at 45° from the y-axis and propagating along the z-axis is incident on two different objects. In cas[illegible] the light intercepts a linear polarizer with polarization along the y-axis. In case B the light intercepts a qu[illegible]er wave plate with fast axis along the y-axis

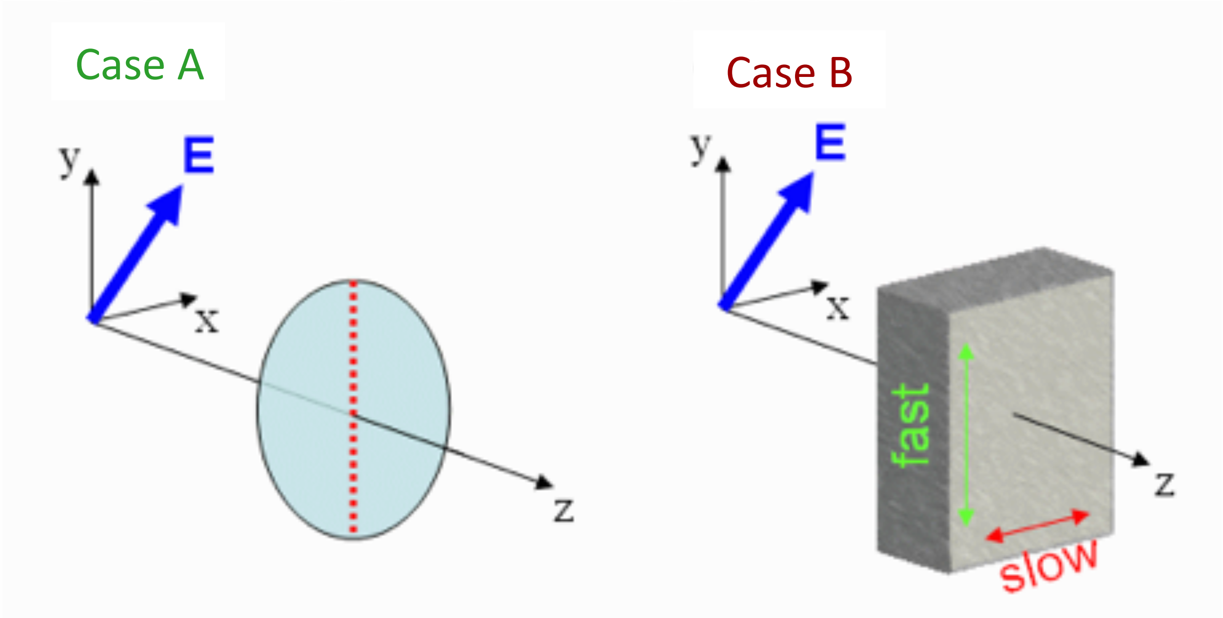


Compare the intensities of the light waves after transmission.

- ○ $I_A < I_B$
- ○ $I_A = I_B$
- ○ $I_A > I_B$

CheckPoint 6

Identical linearly polarized light at 45° from the y-axis and propagating along the z-axis is incident on two different objects. In cas the light intercepts a linear polarizer with polarization along the y-axis. In case B the light intercepts a qu... er wave plate with fast axis along the y-axis



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Case A:

E_x is absorbed

CheckPoint 6

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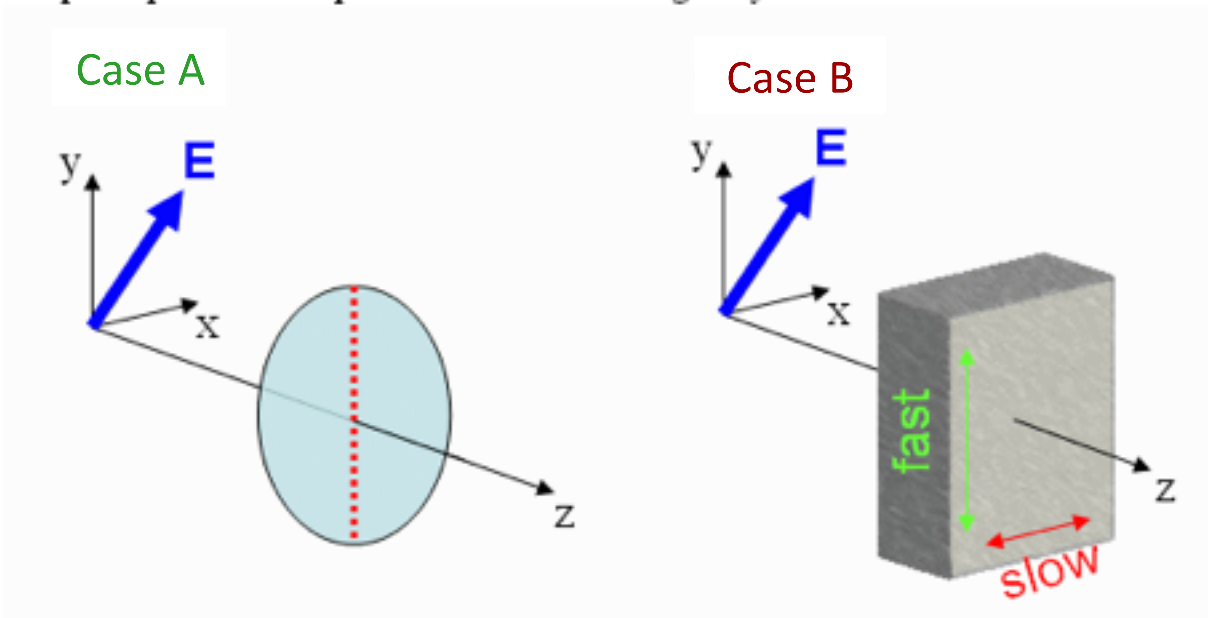

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$$I_A = I_0 \cos^2(45^o)$$

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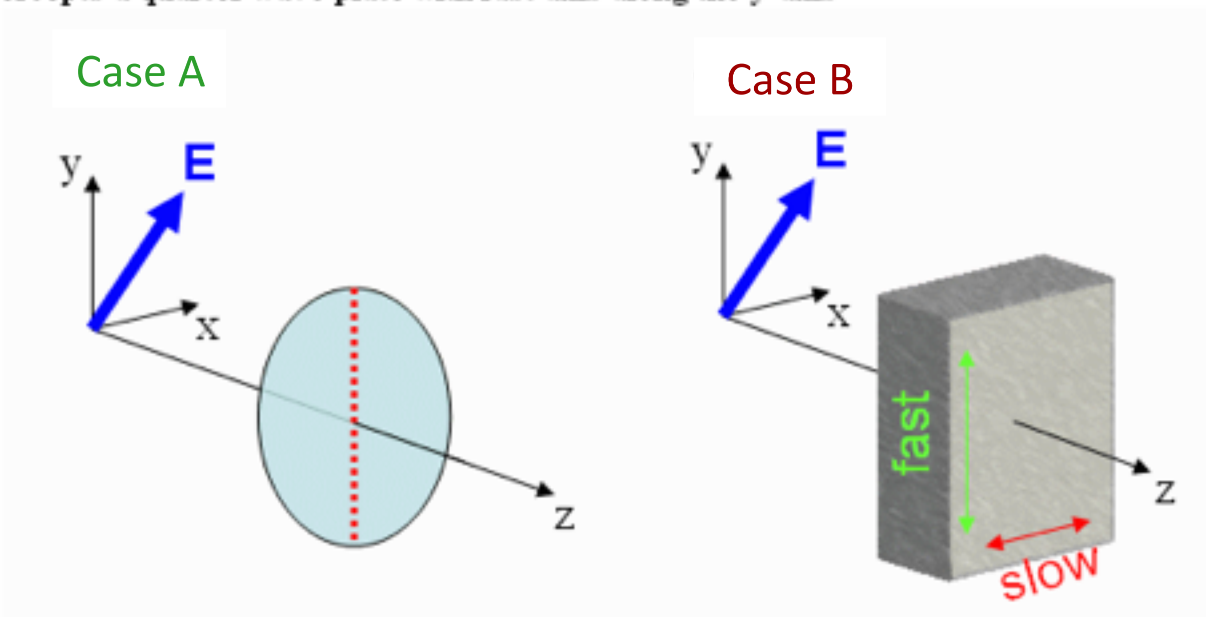

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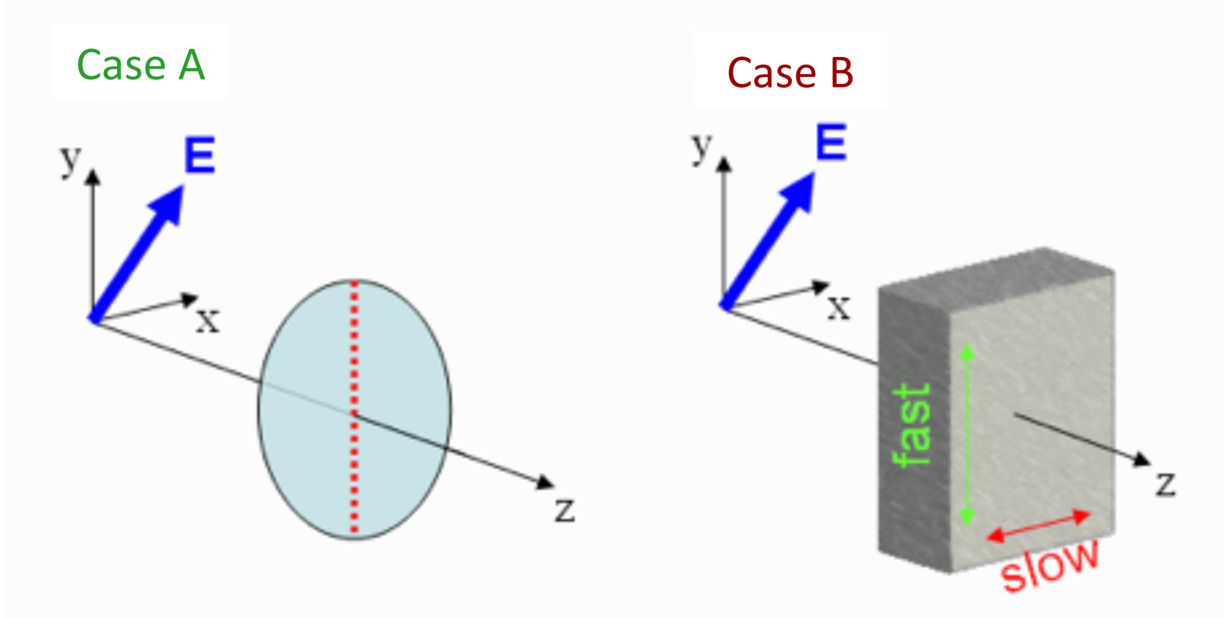

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$$I_A = \tfrac{1}{2} I_0$$

Case B:

(E_x, E_y) phase changed

CheckPoint 6

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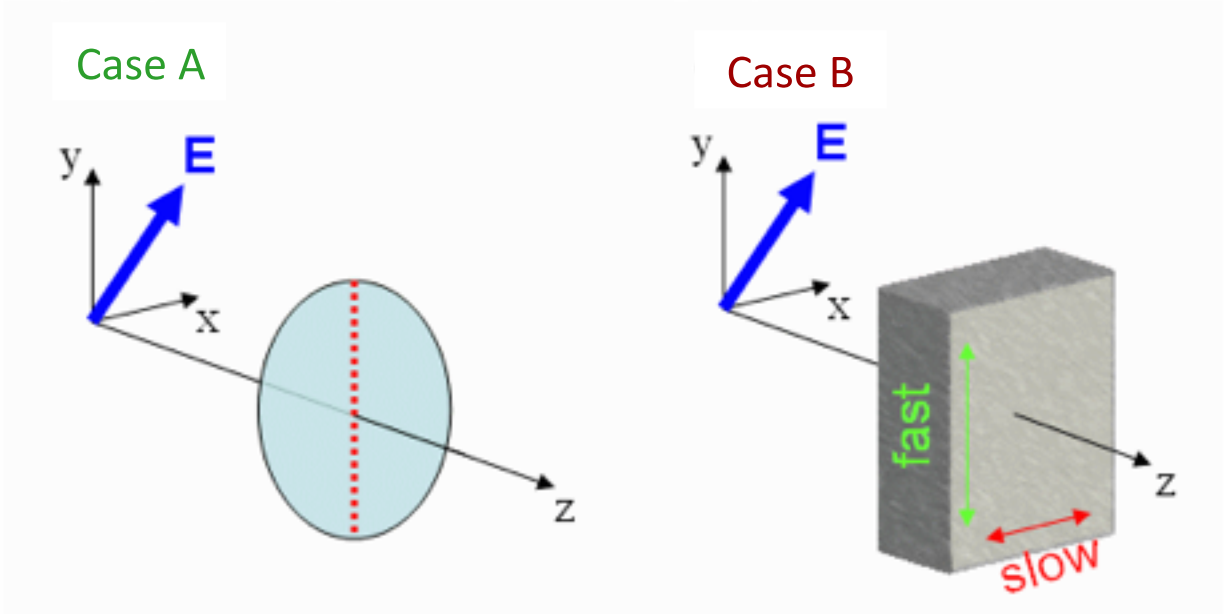

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(E_x, E_y) phase changed

$$I_B = I_0$$

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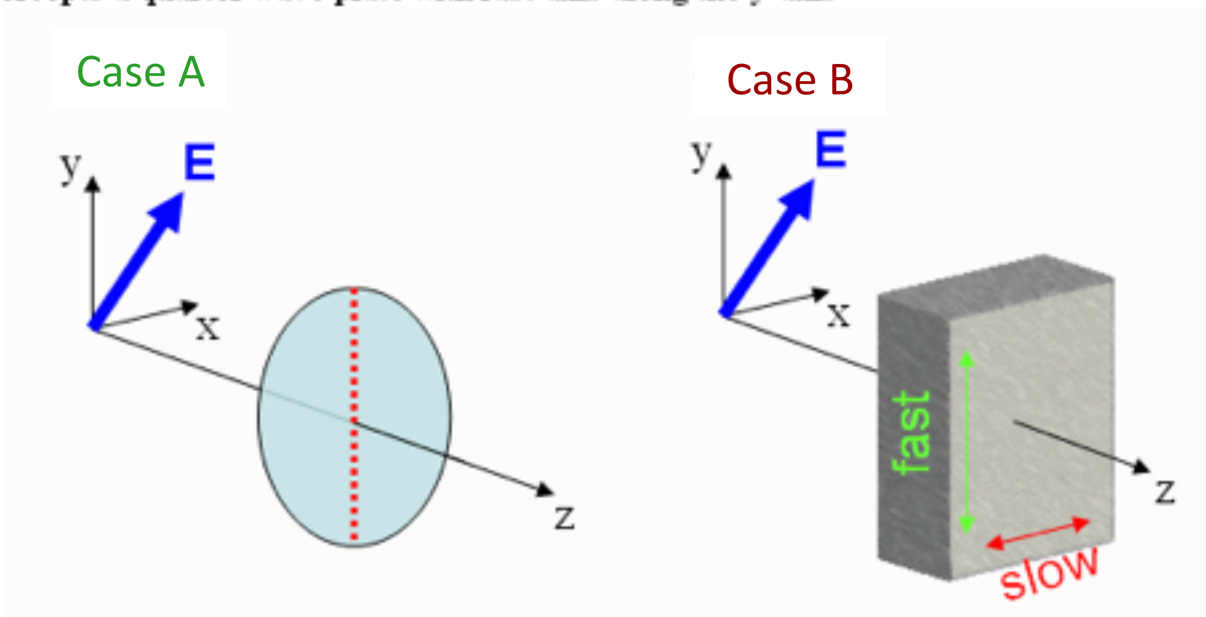

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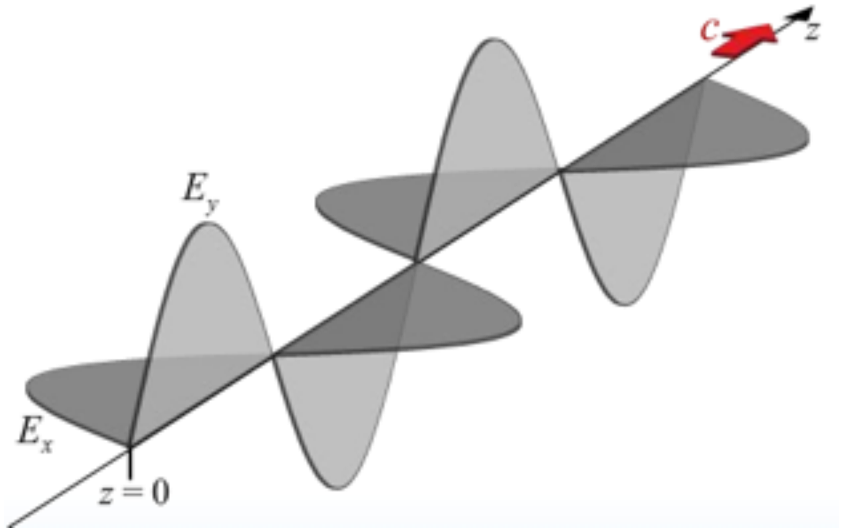
$$I_A = \tfrac{1}{2} I_0$$

Case B:

(E_x, E_y) phase changed

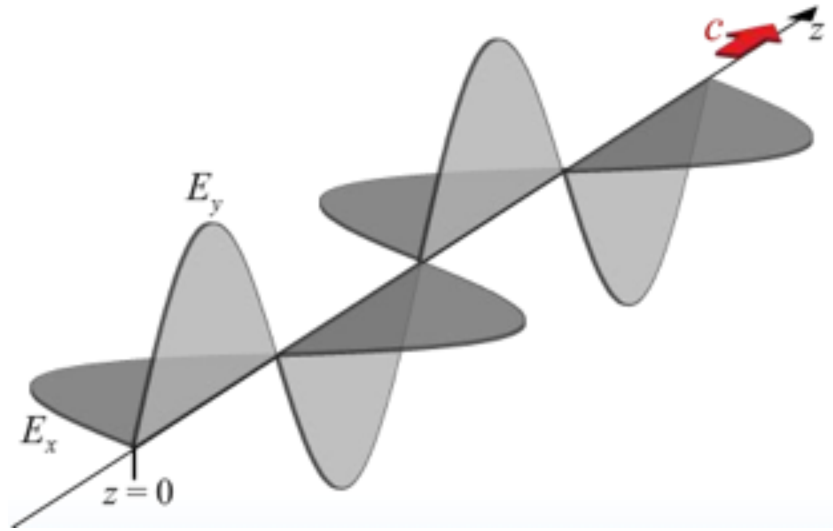
$$I_B = I_0$$

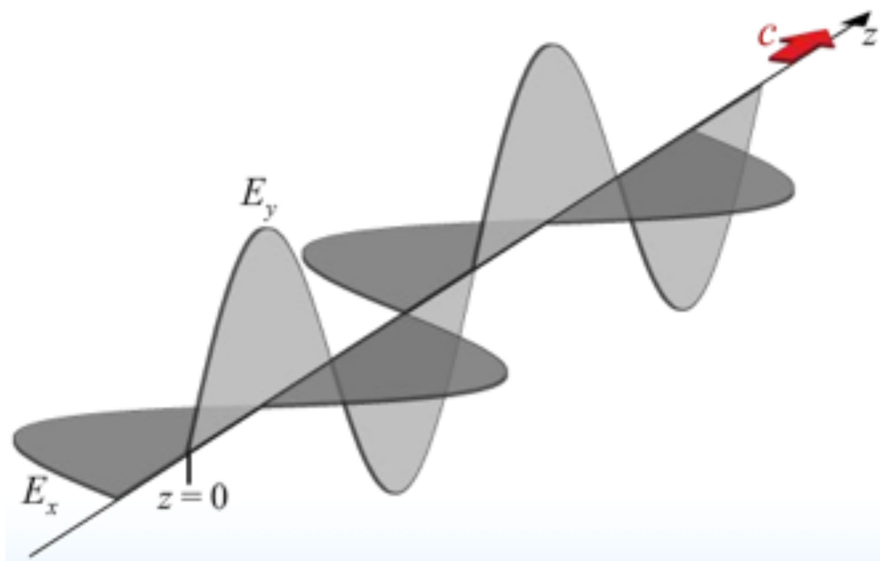

c
z
E_y
E_x
z = 0

PHASE

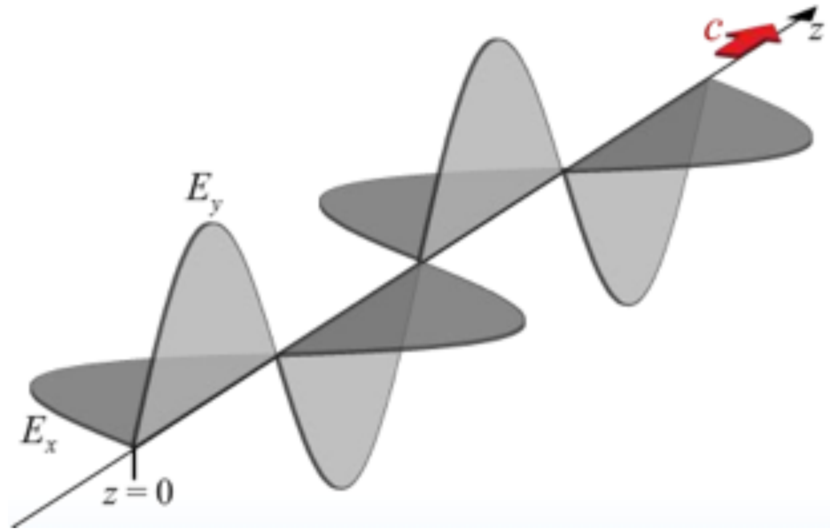
QW Plate

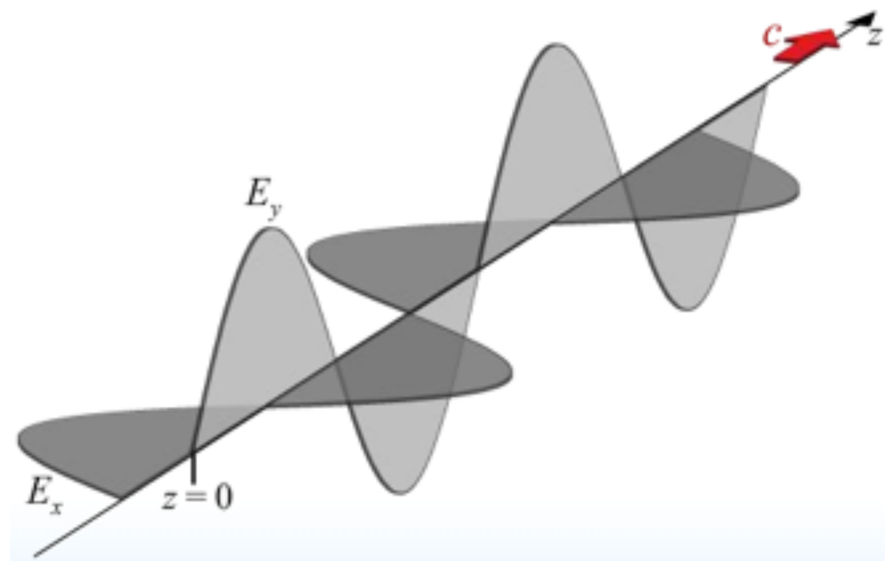
CHANGE





QW Plate





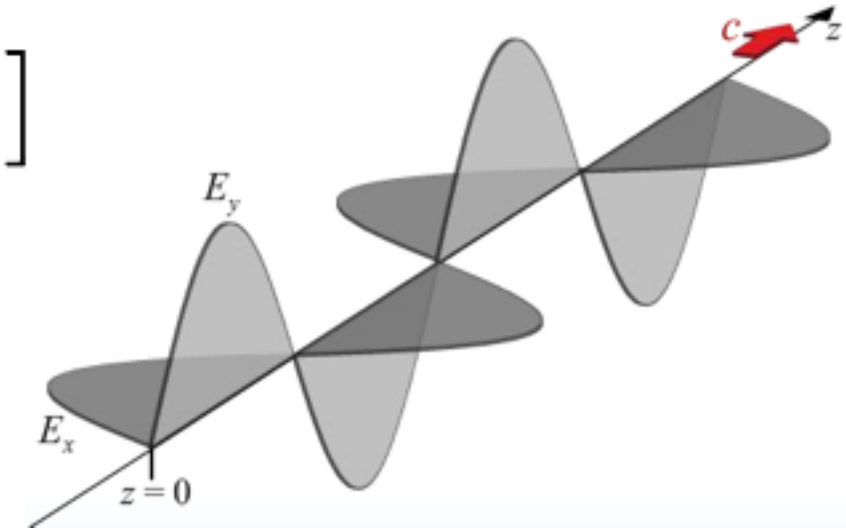
Both E_x and E_y
are still there, so
intensity is the same

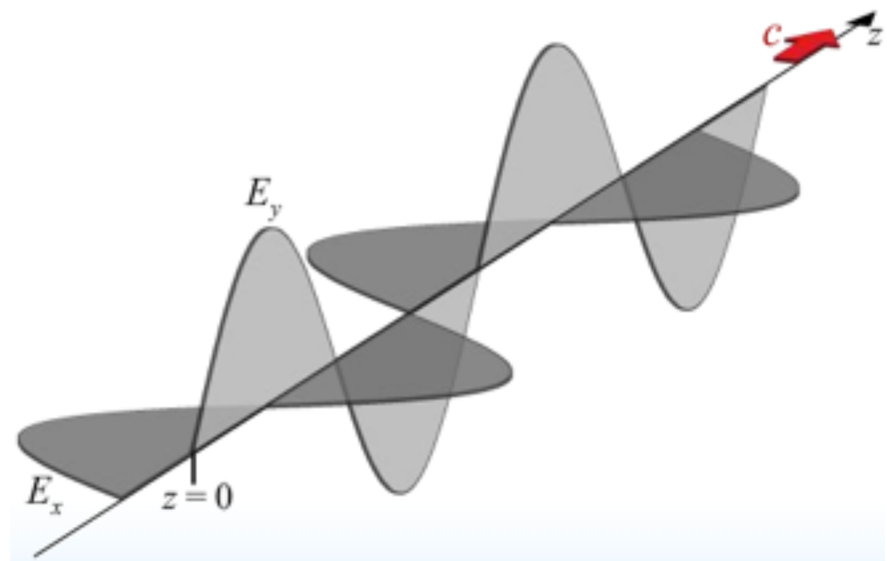
Intensity:

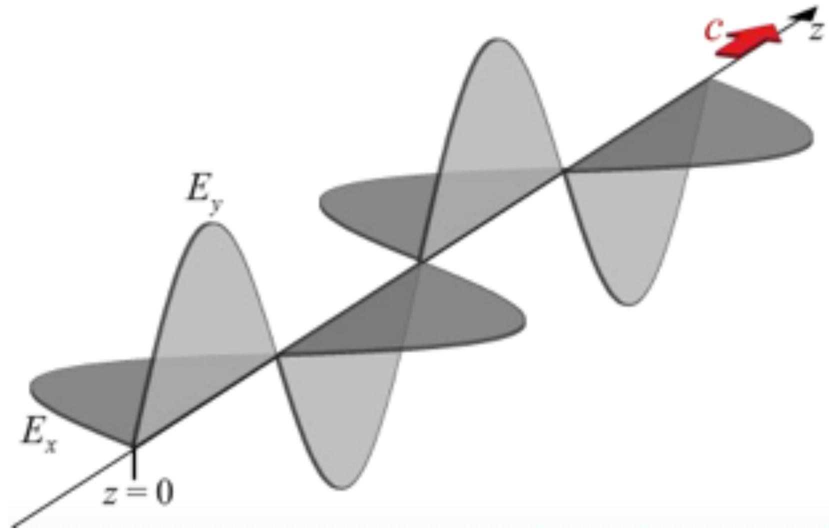
$$I = \epsilon_0 c \left[\langle E_x^2 \rangle + \langle E_y^2 \rangle \right]$$

QW Plate

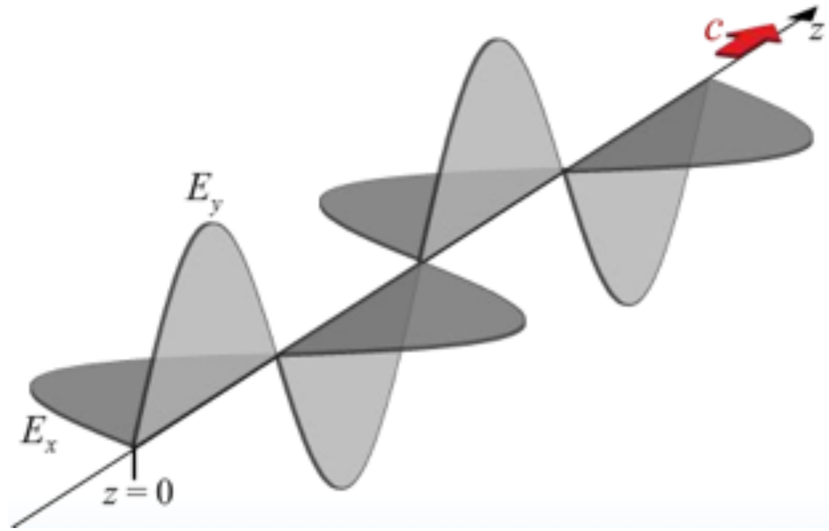
Both E_x and E_y are still there, so intensity is the same

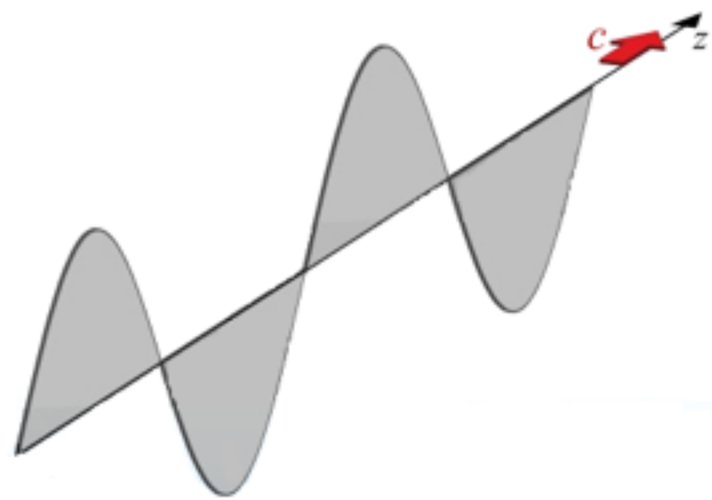





c
z
E_y
E_x
$z = 0$

Polarizer

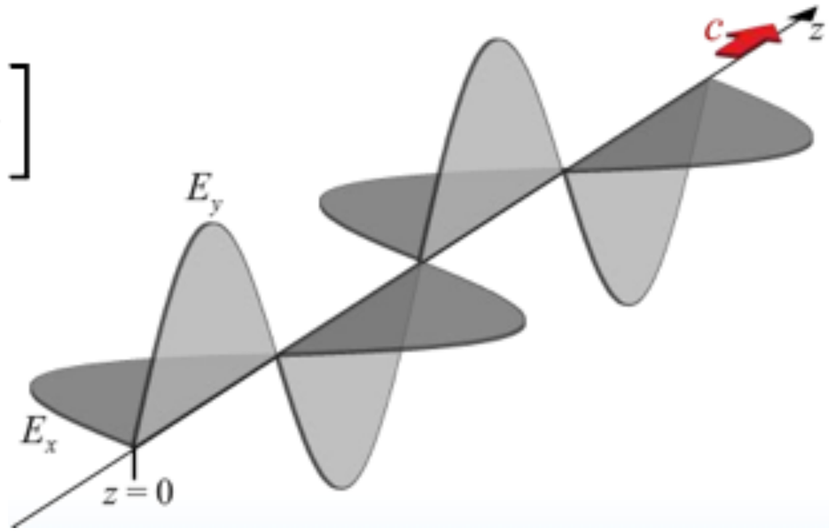


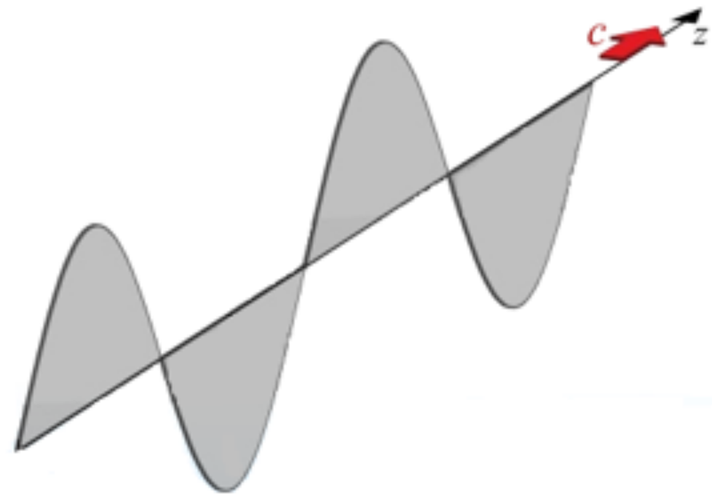


Intensity:

$$I = \epsilon_0 c \left[\langle E_x^2 \rangle + \langle E_y^2 \rangle \right]$$

Polarizer

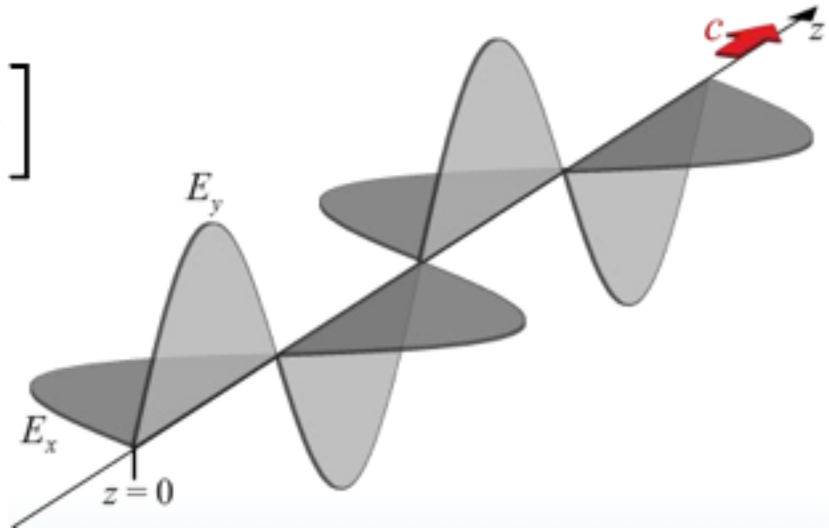


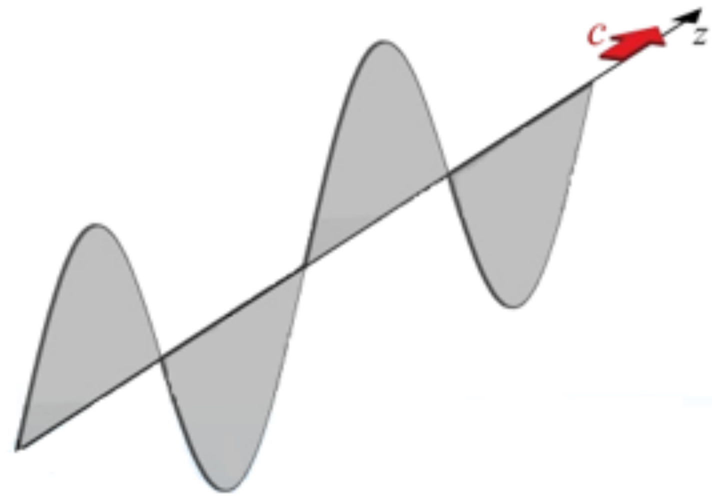


Intensity:

$$I = \epsilon_0 c \left[\cancel{\langle E_x^2 \rangle} + \langle E_y^2 \rangle \right]$$

Polarizer

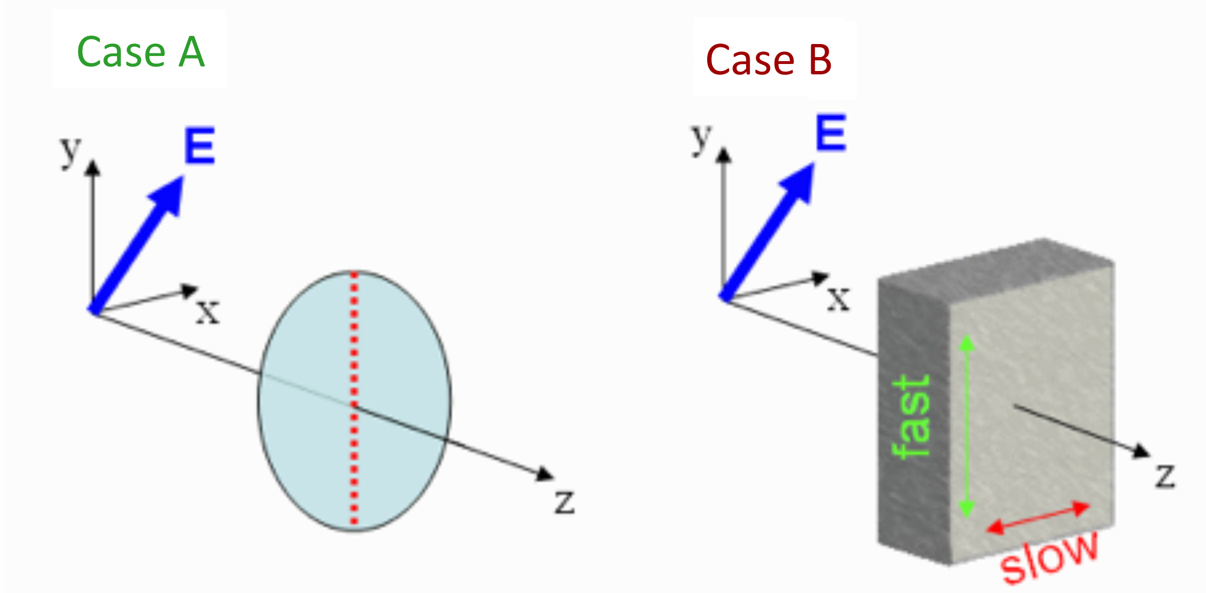




E_x is missing, so intensity is lower

CheckPoint 8

Identical linearly polarized light at 45° from the y-axis and propagating along the z-axis is incident on two different objects. In case A the light intercepts a linear polarizer with polarization along the y-axis. In case B the light intercepts a quarter wave plate with fast axis along the y-axis



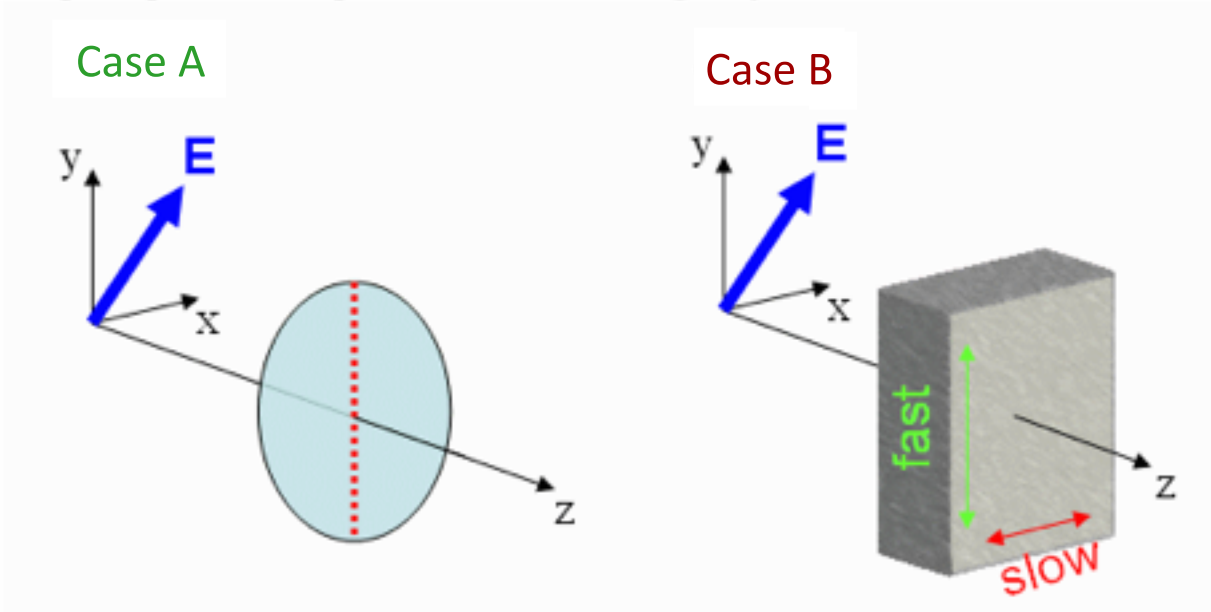
8) What is the polarization of the light wave in case B after it passed through the quarter wave plate?

ate?

- linearly polarized
- left circularly polarized
- right circularly polarized
- undefined

CheckPoint 8

Identical linearly polarized light at 45° from the y-axis and propagating along the z-axis is incident on two different objects. In case A the light intercepts a linear polarizer with polarization along the y-axis. In case B the light intercepts a quarter wave plate with fast axis along the y-axis



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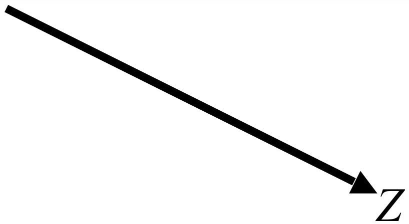

CheckPoint 8

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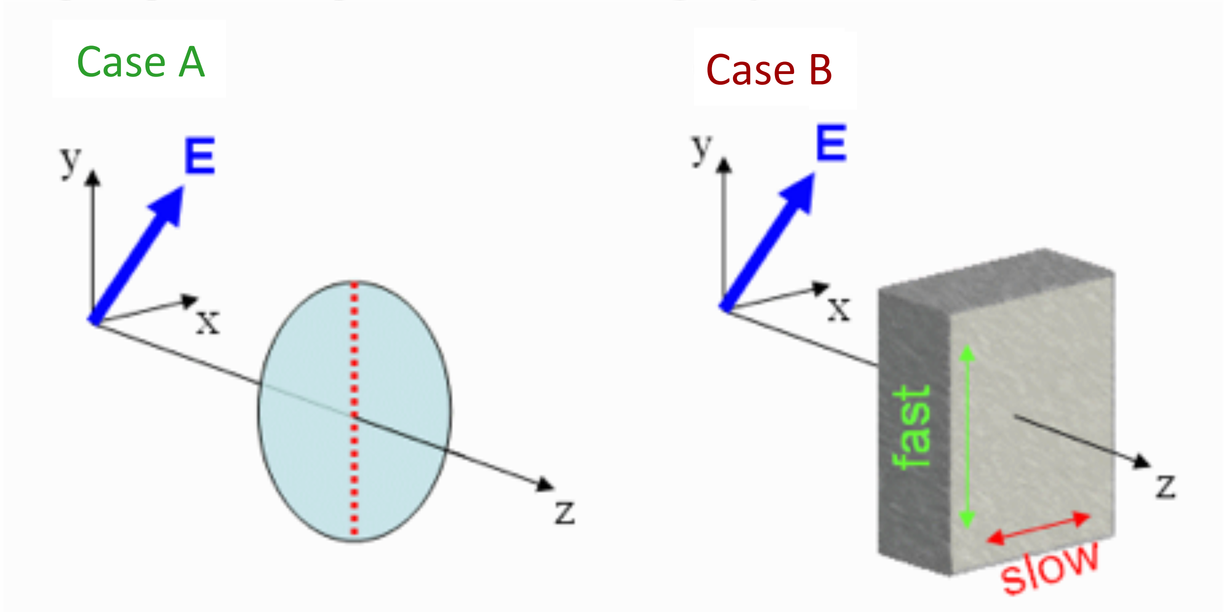

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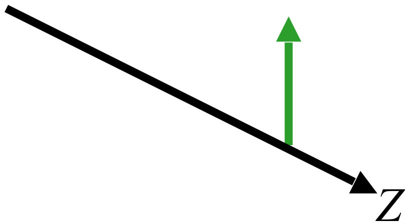

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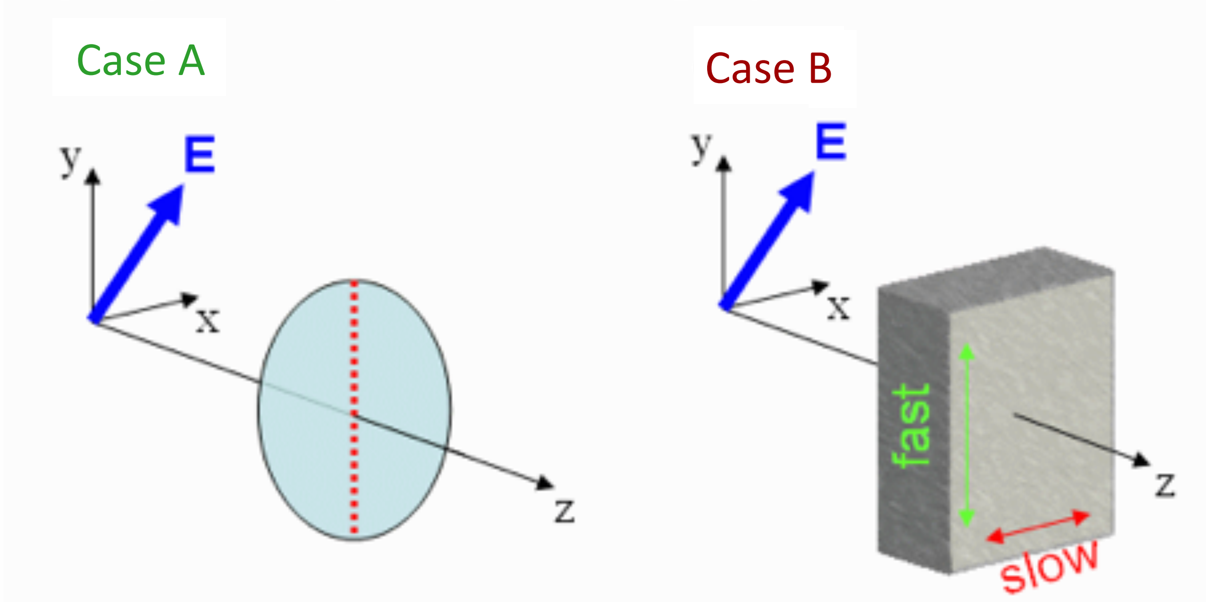
Identical linearly polarized light at 45° from the y-axis and propagating along the z-axis is incident on two different objects. In case A the light intercepts a linear polarizer with polarization along the y-axis. In case B the light intercepts a quarter wave plate with fast axis along the y-axis



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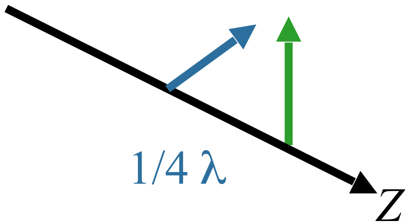
ate?



CheckPoint 8

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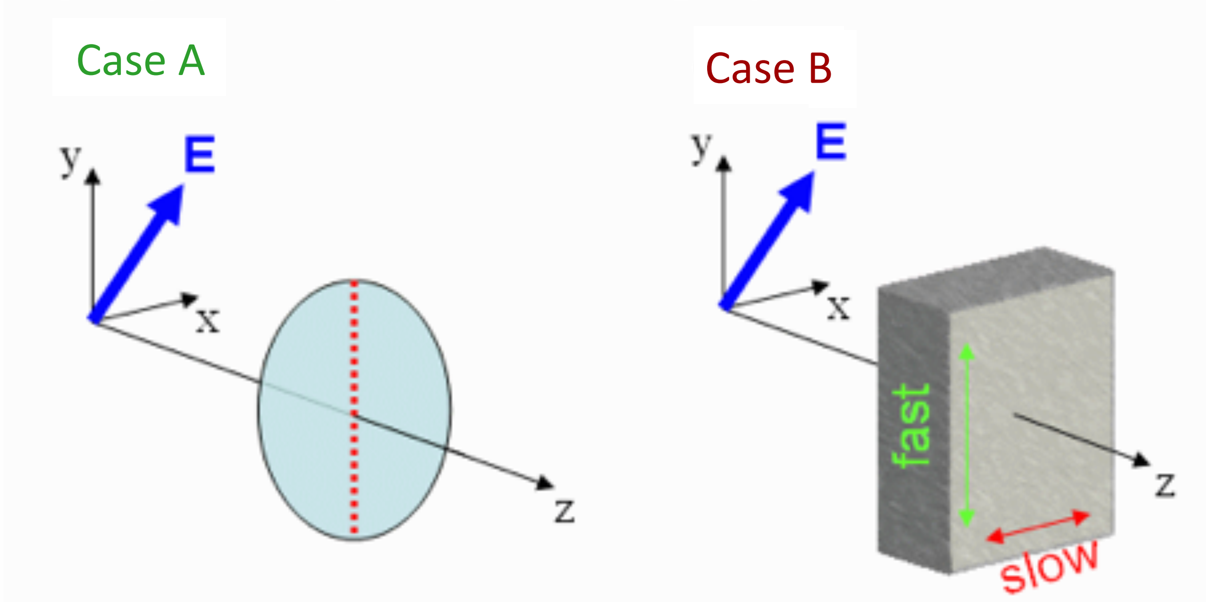

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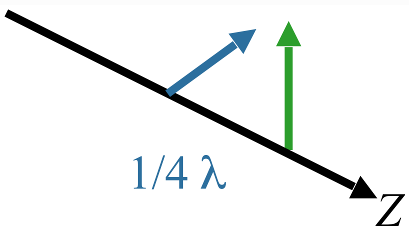

RCP

CheckPoint 8

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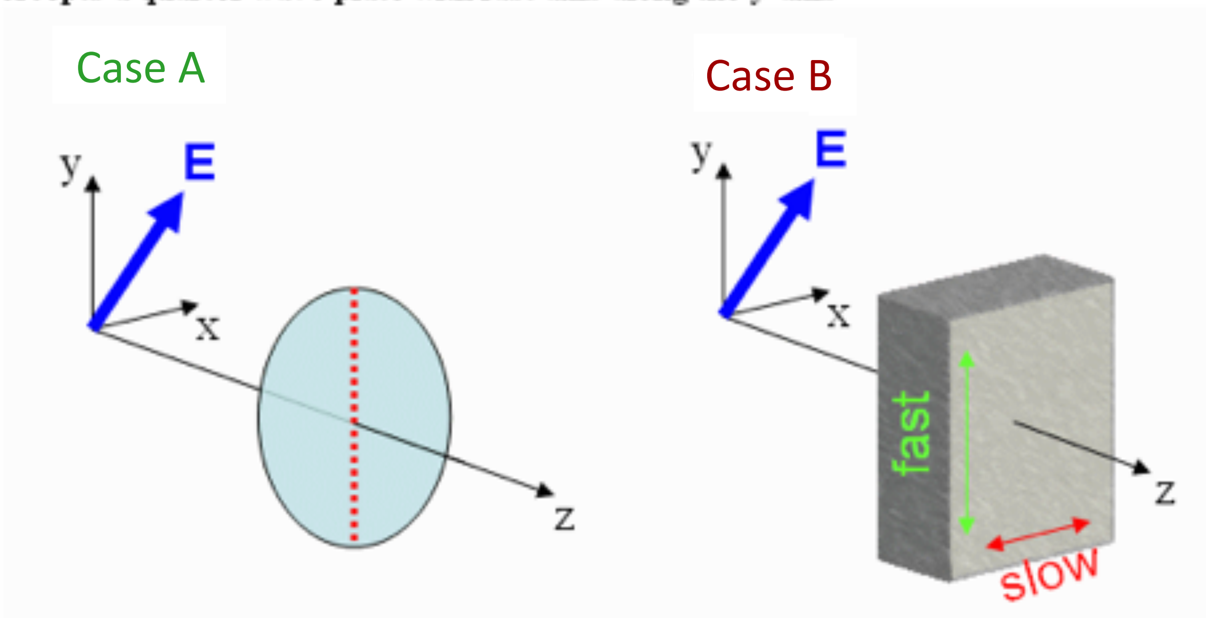

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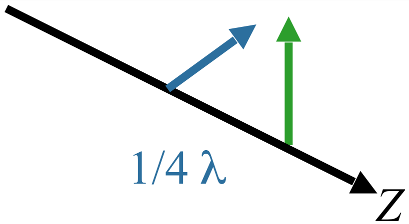
- ○ right circularly polarized
- ○ undefined



RCP

CheckPoint 10

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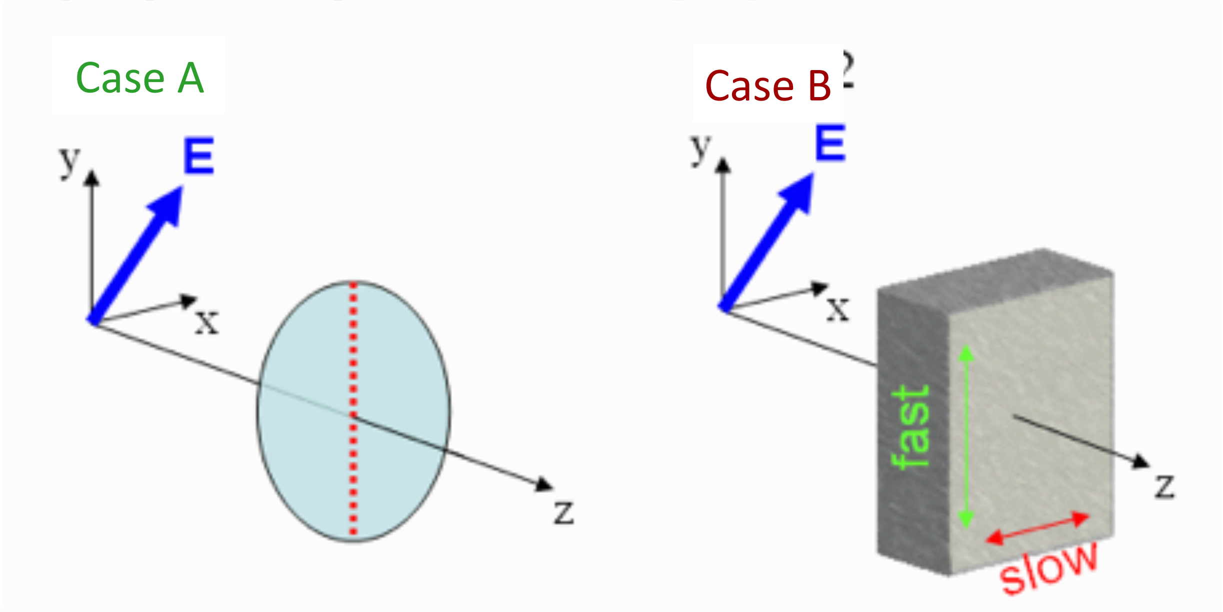
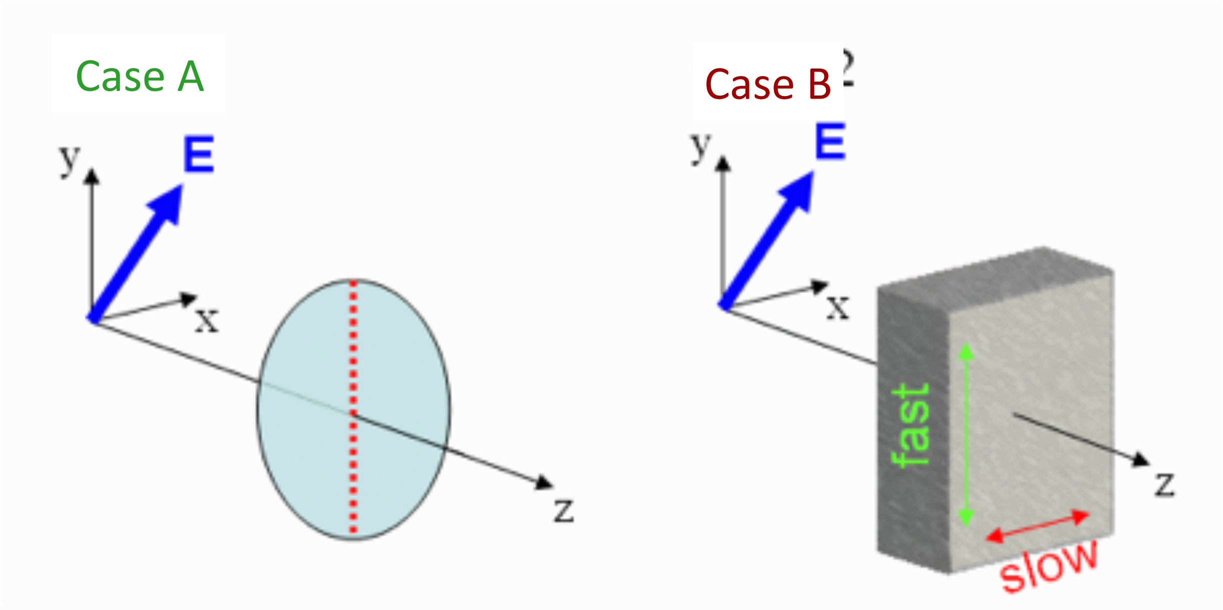


10) If the thickness of the quater-wave plate in case B is doubled, what is the polarization state of the light wave after passing through the wave plate?

- linearly polarized
- right or left circularly polarized
- undefined

CheckPoint 10

Identical linearly polarized light at 45° from the y-axis and propagating along the z-axis is incident on two different objects. In case A the light intercepts a linear polarizer with polarization along the y-axis. In case B the light intercepts a quarter wave plate with fast axis along the y-axis



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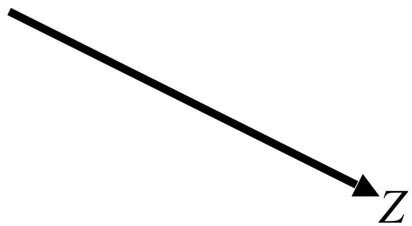

CheckPoint 10

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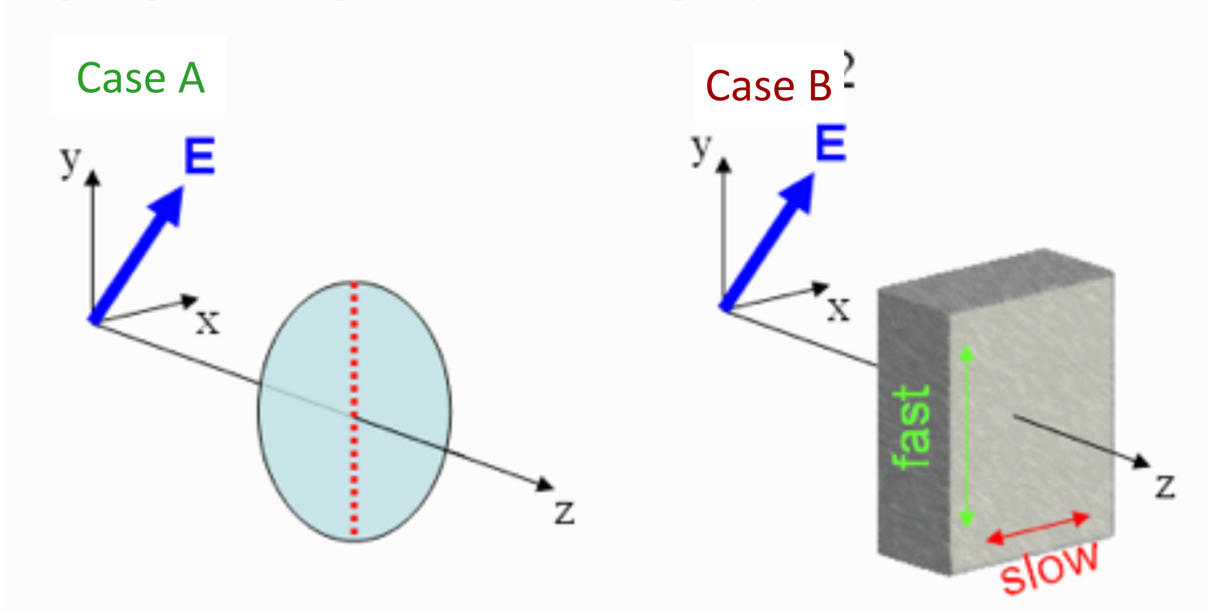

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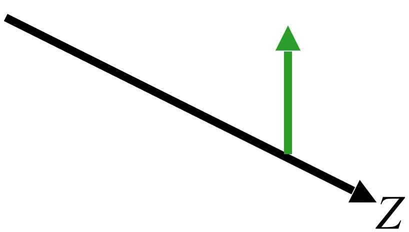

CheckPoint 10

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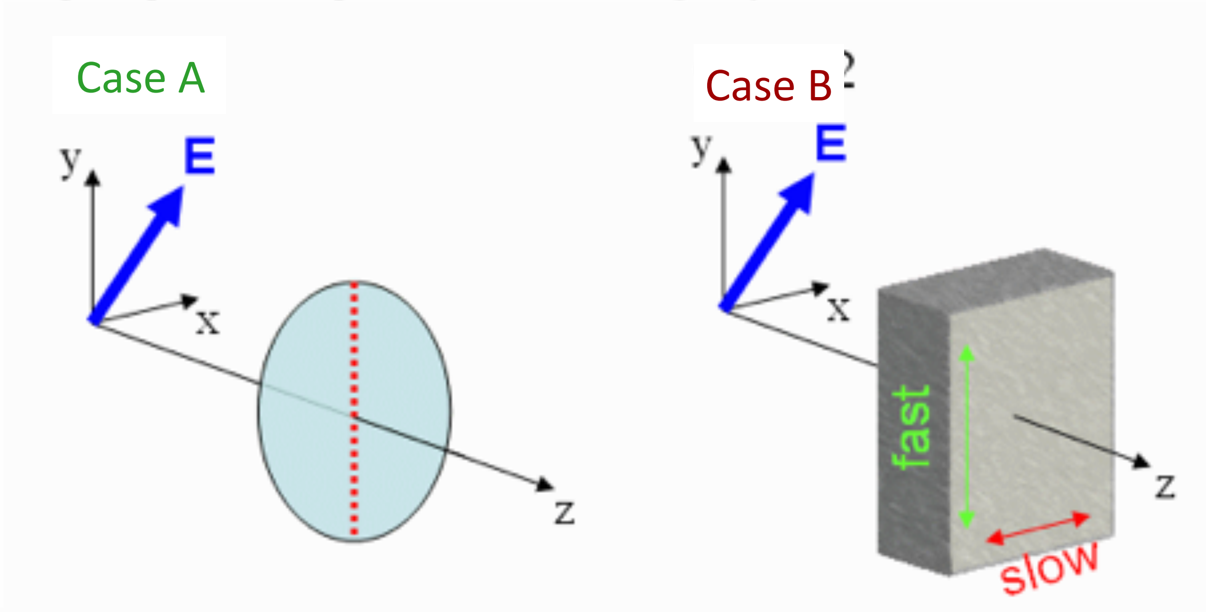

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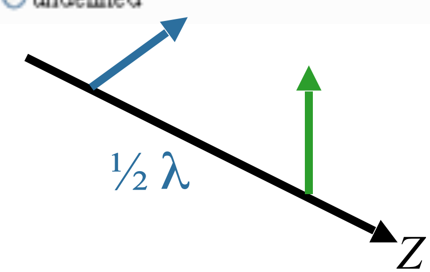
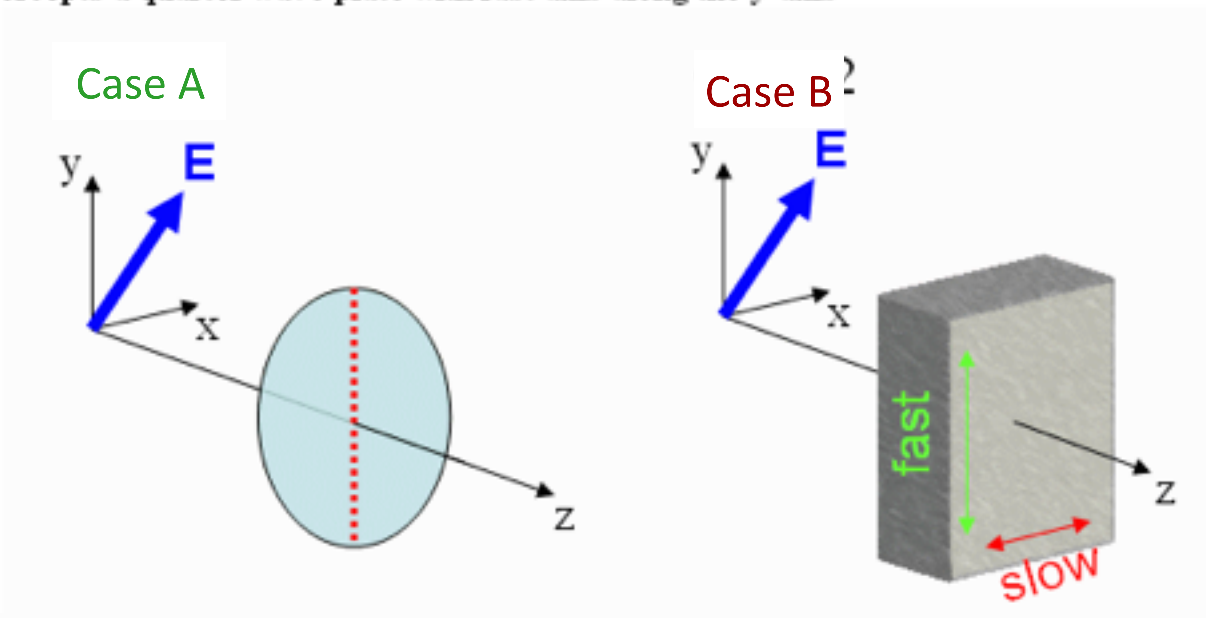


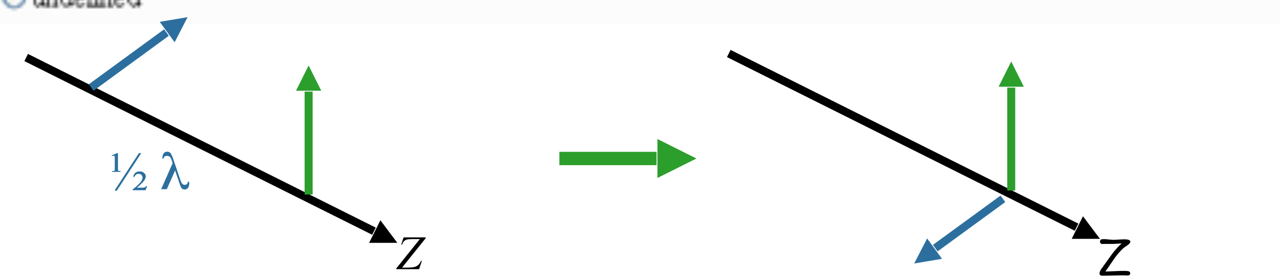
CheckPoint 10

Identical linearly polarized light at 45° from the y-axis and propagating along the z-axis is incident on two different objects. In case A the light intercepts a linear polarizer with polarization along the y-axis. In case B the light intercepts a quarter wave plate with fast axis along the y-axis



10) If the thickness of the quater-wave plate in case B is doubled, what is the polarization state of the light wave after passing through the wave plate?

- ○ linearly polarized
- ○ right or left circularly polarized
- ○ undefined



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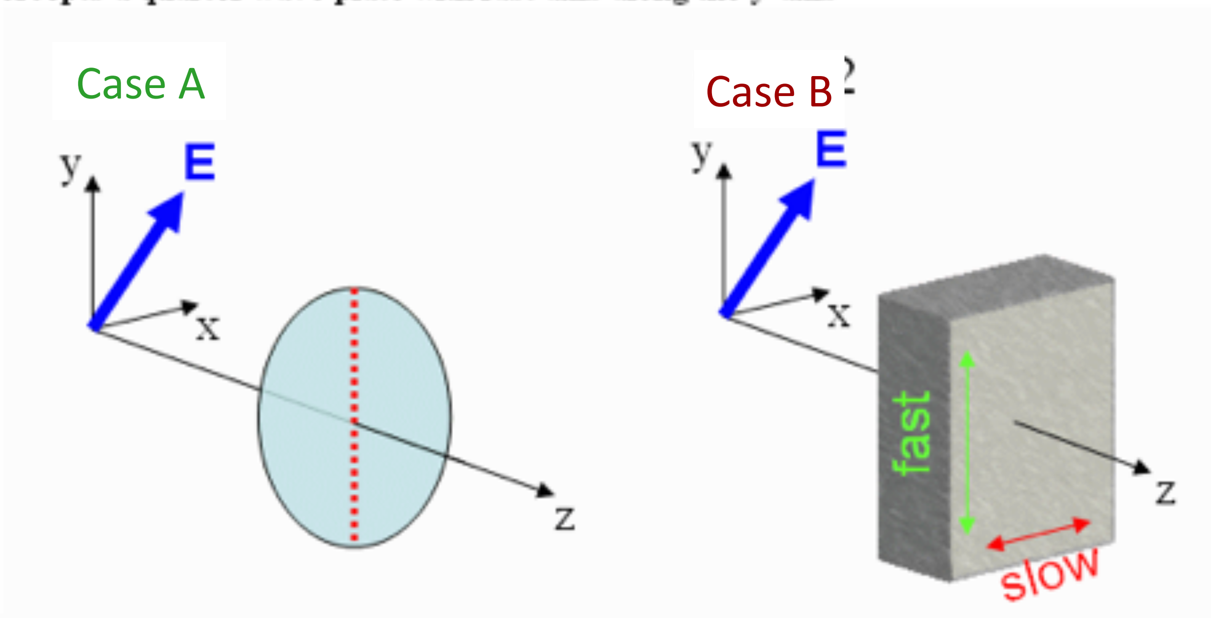
Identical linearly polarized light at 45° from the y-axis and propagating along the z-axis is incident on two different objects. In case A the light intercepts a linear polarizer with polarization along the y-axis. In case B the light intercepts a quarter wave plate with fast axis along the y-axis



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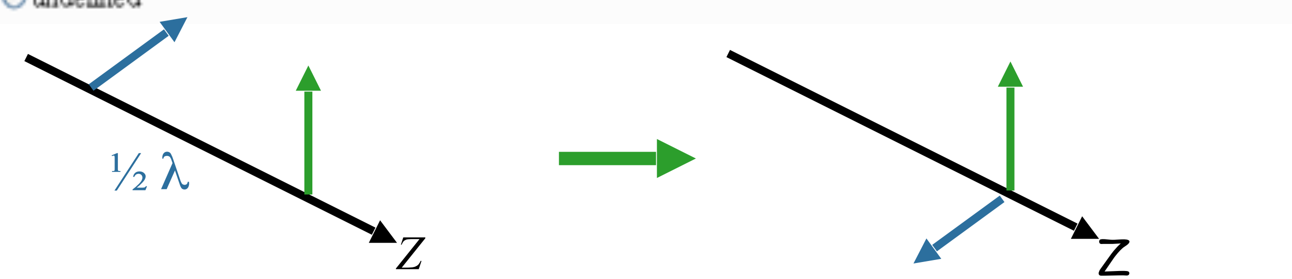


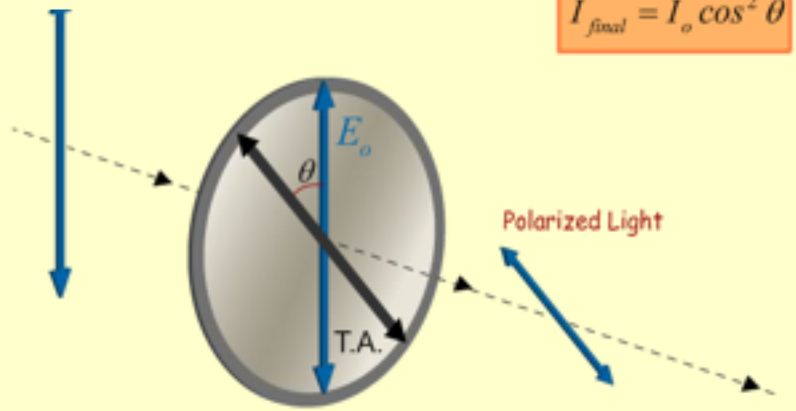
Executive Summary:

Polarizers & QW Plates:

Polarized Light

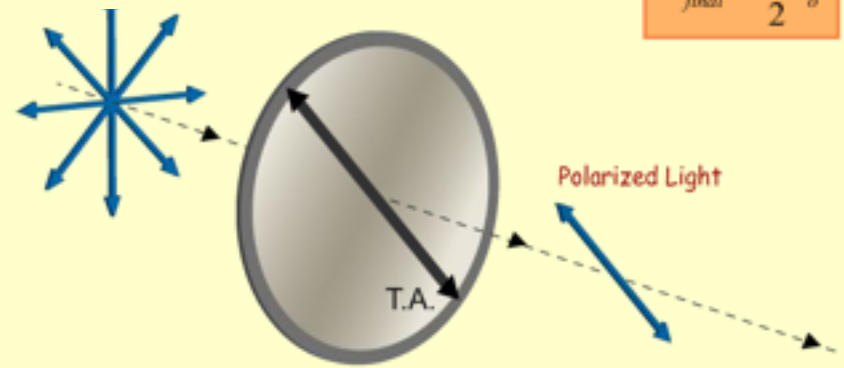
Law of Malus

$$I_{final} = I_o \cos^2\theta$$

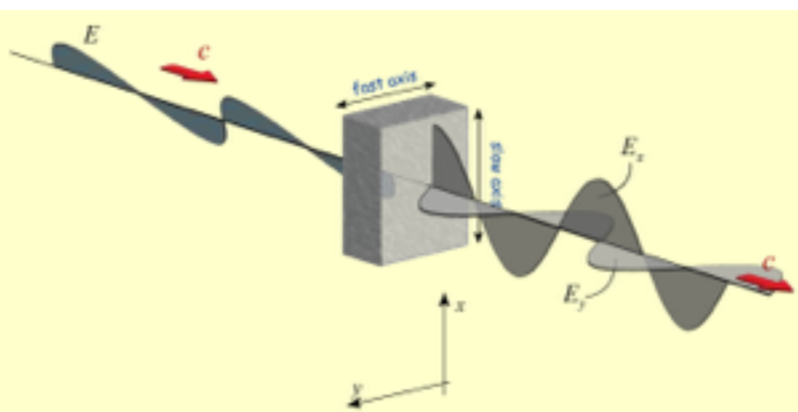


Circularly or Un-polarized Light

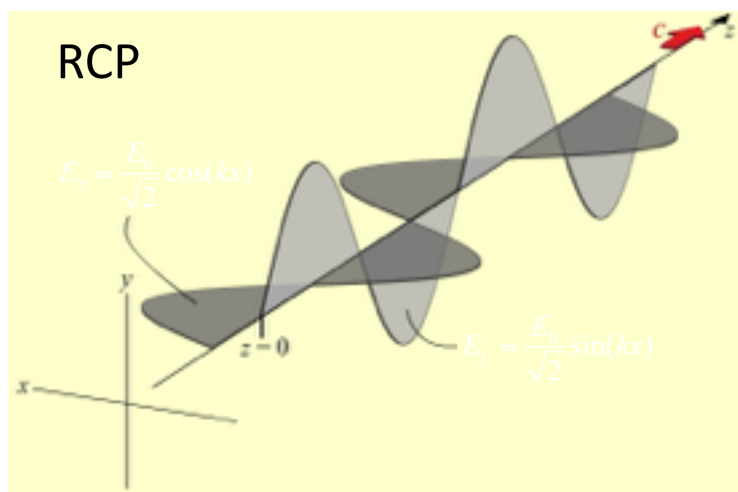
$$I_{final} = \frac{1}{2} I_o$$



Birefringence



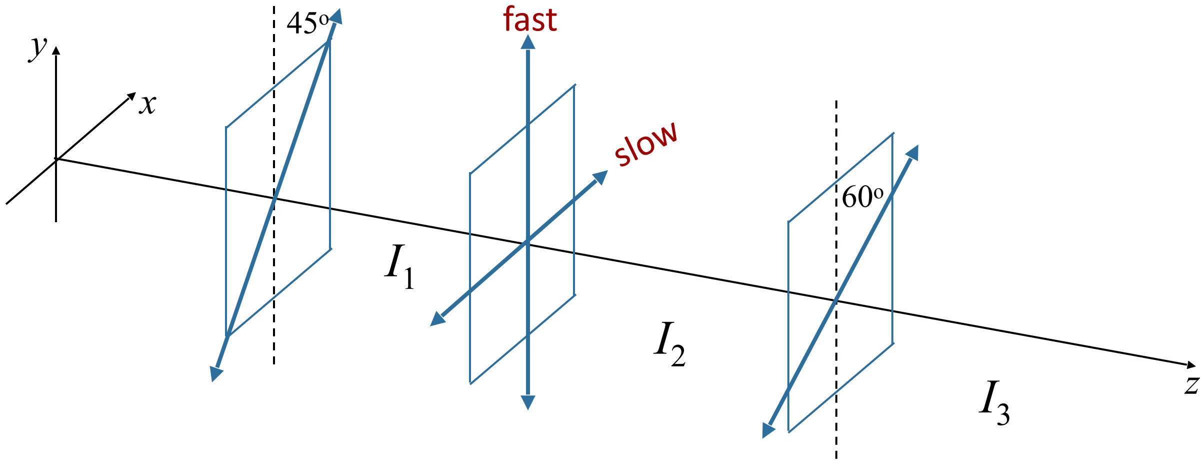
RCP



Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.

What is the intensity I_3 in terms of I_1?



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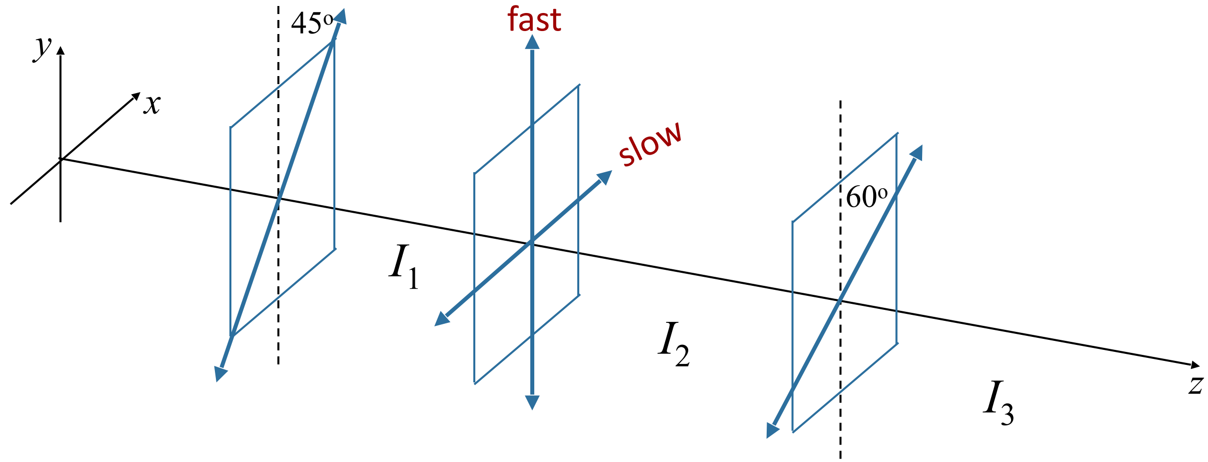
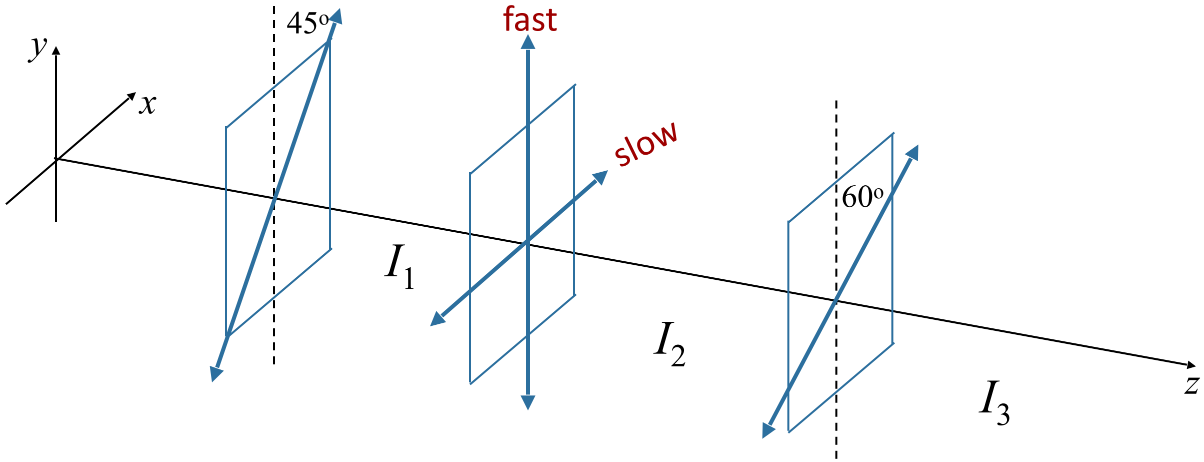


Conceptual Analysis

Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.

What is the intensity I_3 in terms of I_1?



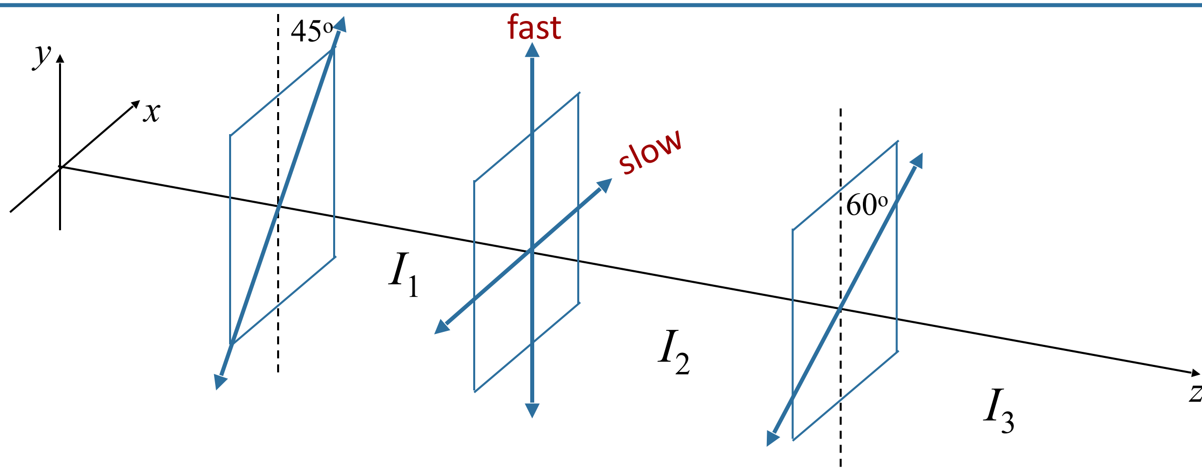
Conceptual Analysis

Linear Polarizers: absorbs E field component perpendicular to TA

Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.

What is the intensity I_3 in terms of I_1?



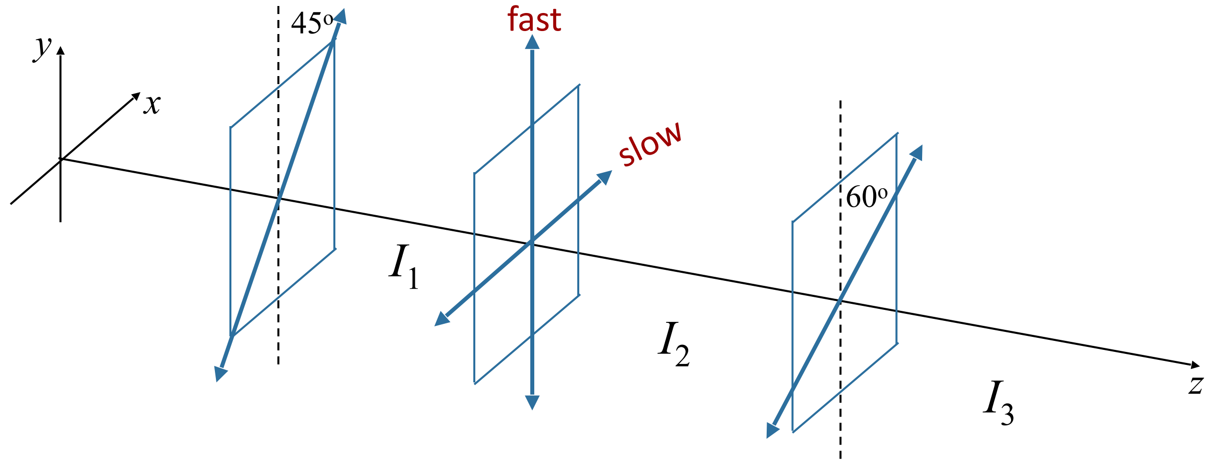
Conceptual Analysis

Linear Polarizers: absorbs E field component perpendicular to TA

Quarter Wave Plates: Shifts phase of E field components in fast-slow directions

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.

What is the intensity I_3 in terms of I_1?



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Linear Polarizers: absorbs E field component perpendicular to TA

Quarter Wave Plates: Shifts phase of E field components in fast-slow directions

Strategic Analysis

Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.

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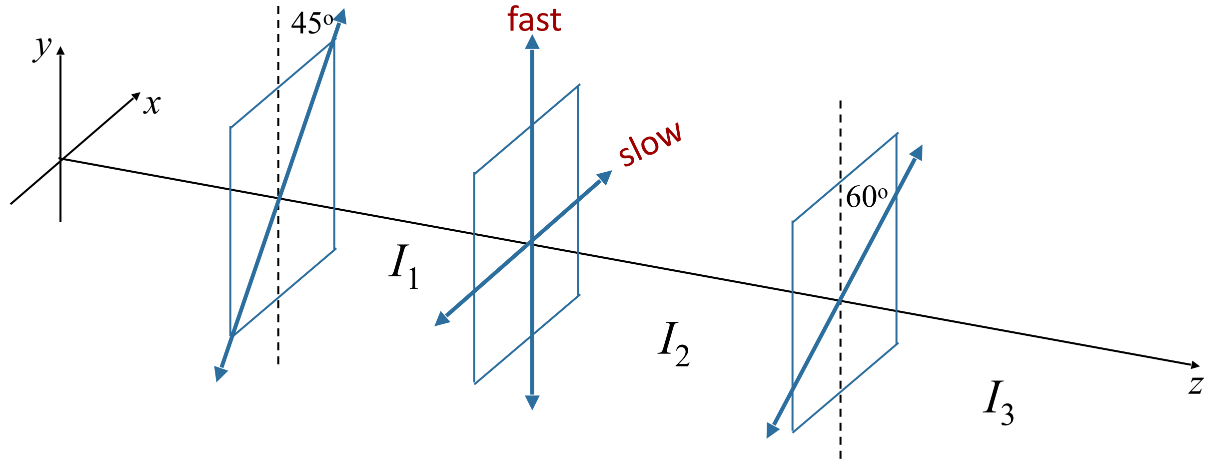


Conceptual Analysis

Linear Polarizers: absorbs E field component perpendicular to TA

Quarter Wave Plates: Shifts phase of E field components in fast-slow directions

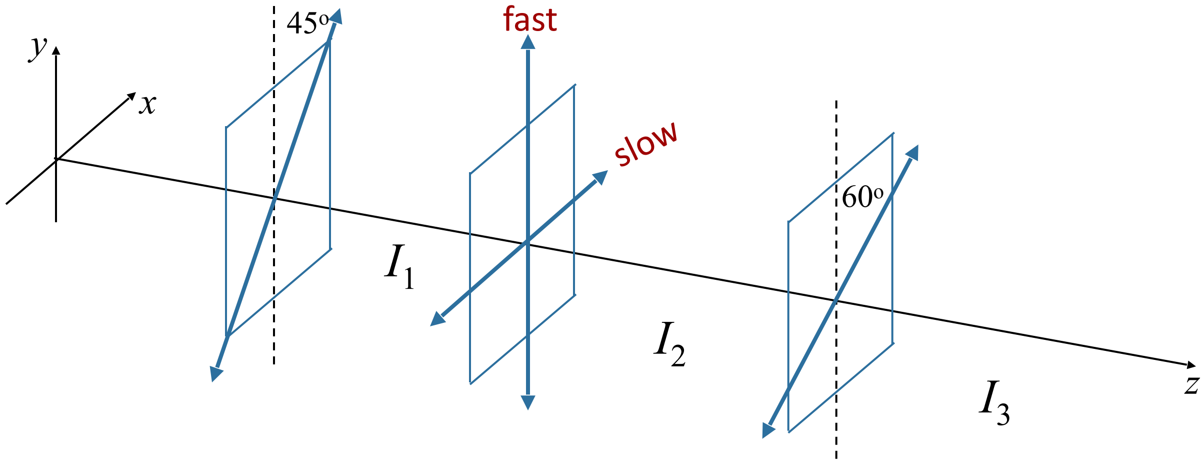
Strategic Analysis

Determine state of polarization and intensity reduction after each object

Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.

What is the intensity I_3 in terms of I_1?



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Determine state of polarization and intensity reduction after each object

Multiply individual intensity reductions to get final reduction.

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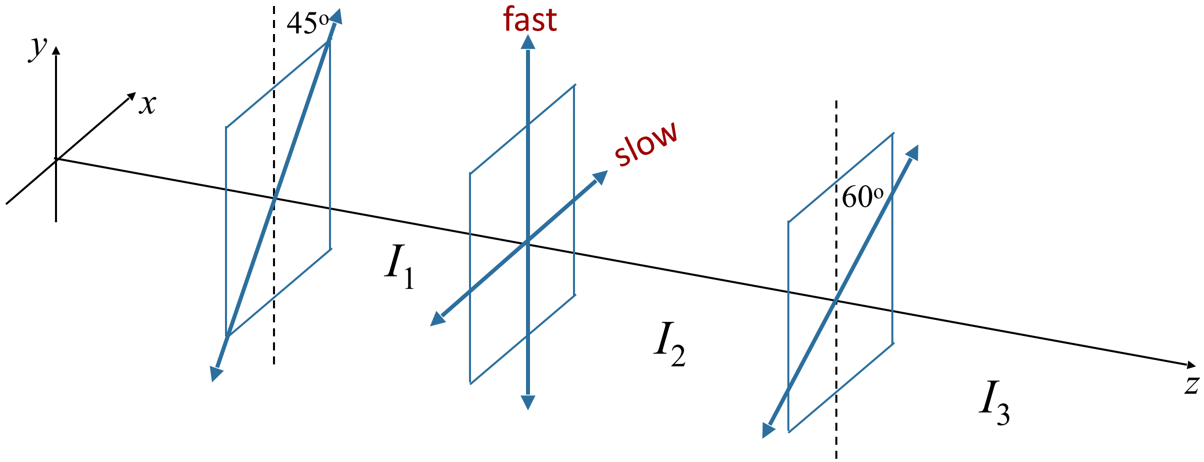

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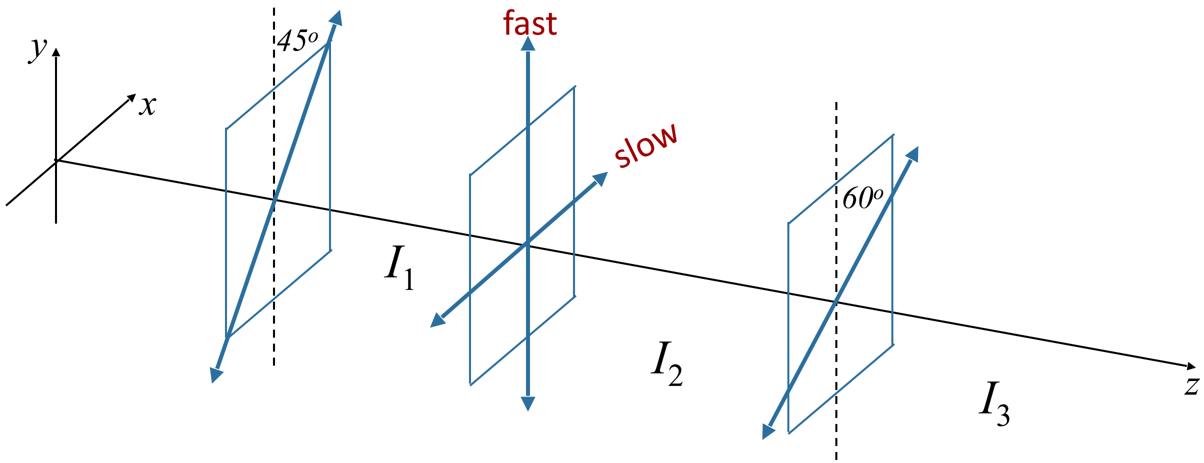
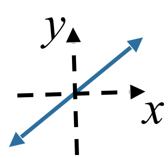
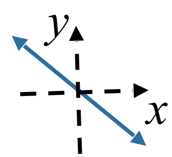


What is the polarization of the light after the QWP?

A) LCP

B) RCP

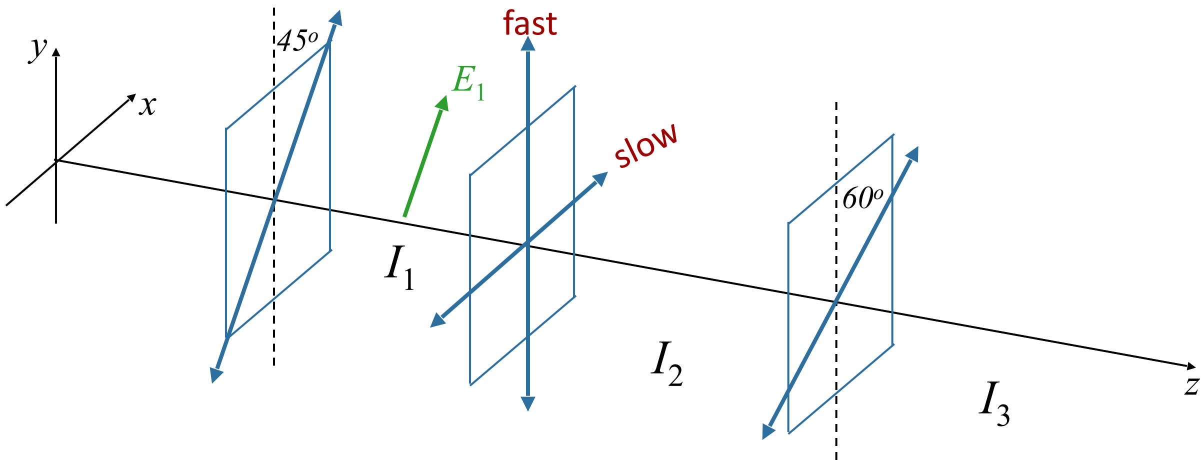
C) 

D) 

E) un-polarized

Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.



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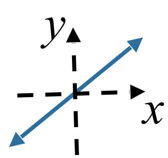
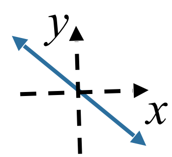
C) 

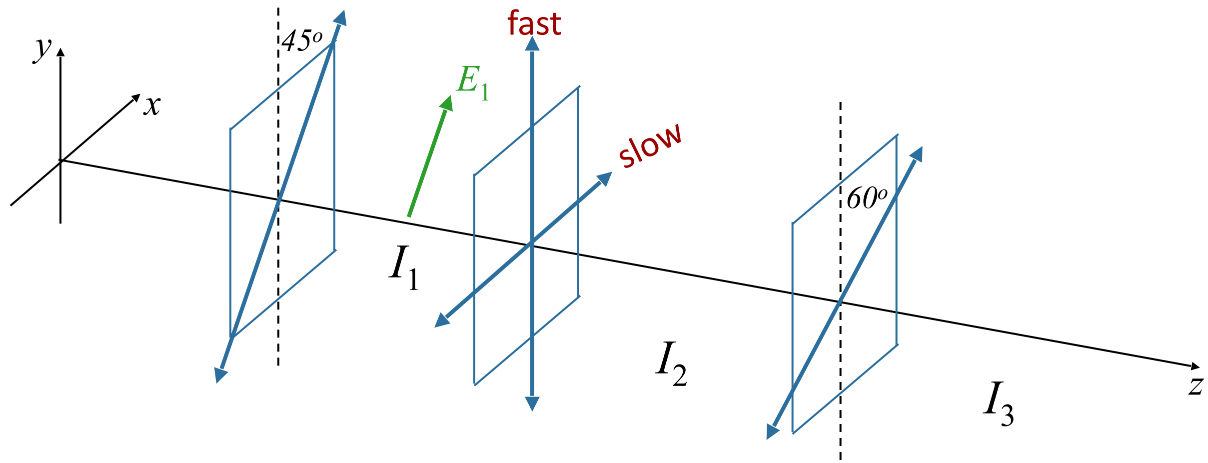
D) 

E) un-polarized

Light incident on QWP is linearly polarized at 45° to fast axis

Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.



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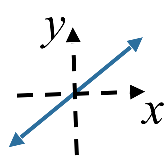
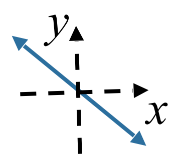
C) 

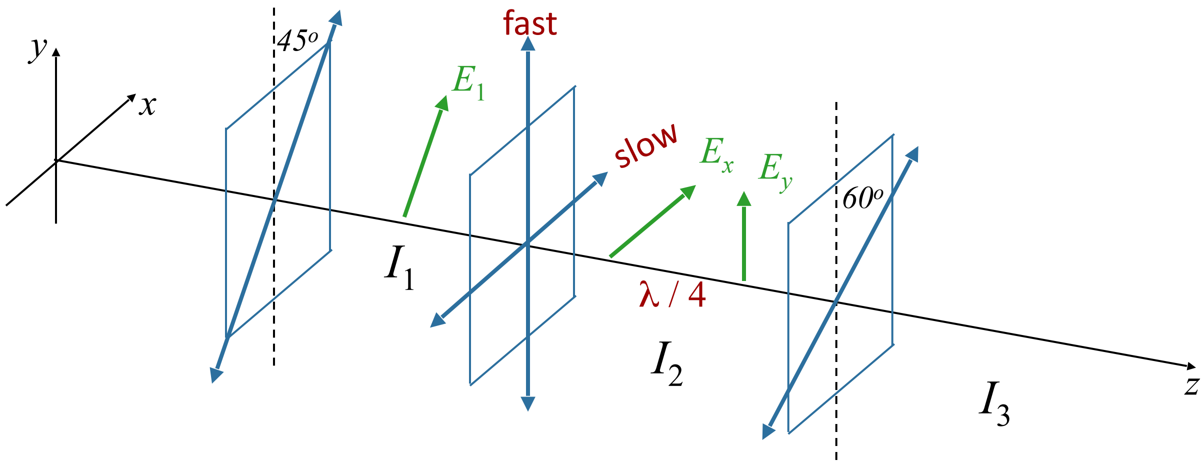
D) 

E) un-polarized

Light incident on QWP is linearly polarized at 45° to fast axis → Light will be circularly polarized after QWP

Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.



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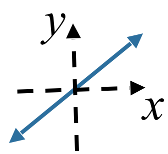
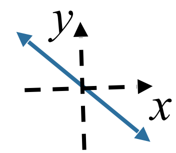
C) 

D) 

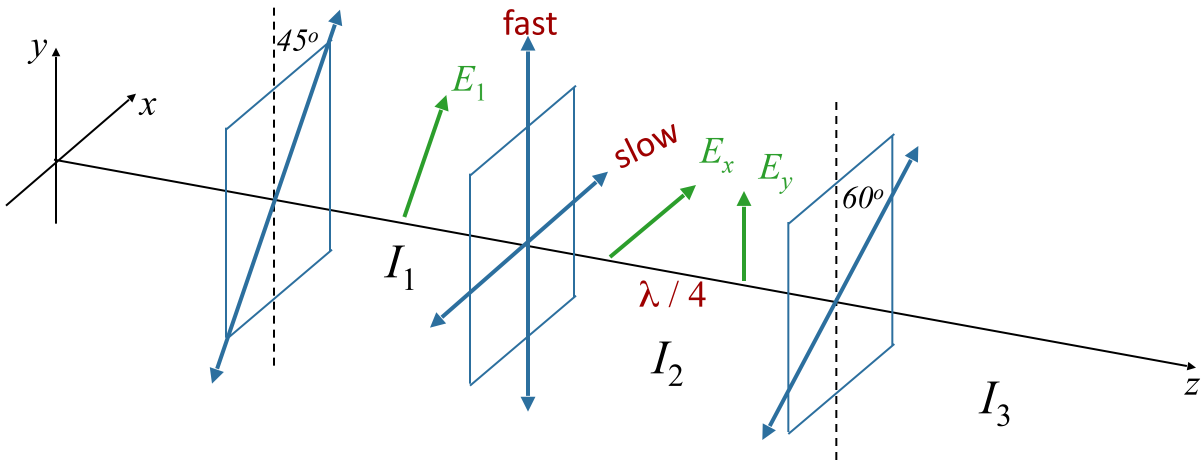
E) un-polarized

Light incident on QWP is linearly polarized at 45^o to fast axis → Light will be circularly polarized after QWP

LCP or RCP? Easiest way: Right Hand Rule:

Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.



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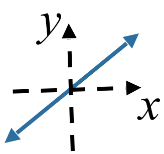
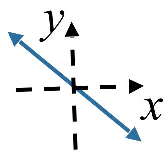


D)



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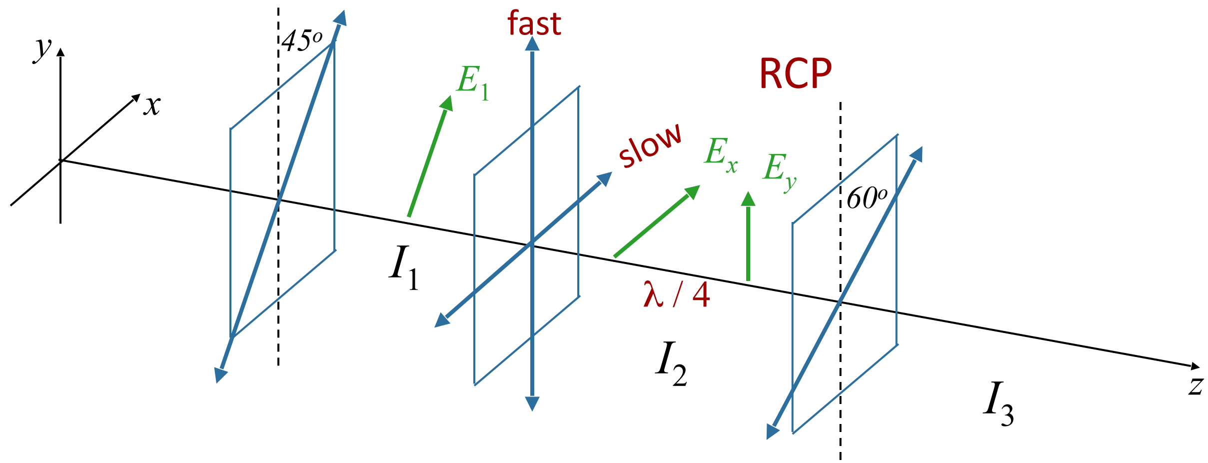
Light incident on QWP is linearly polarized at 45° to fast axis → Light will be circularly polarized after QWP

LCP or RCP? Easiest way: Right Hand Rule:

Curl fingers of RH back to front
Thumb points in dir of propagation
if right hand polarized.

Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.



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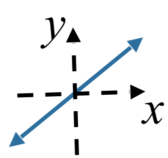
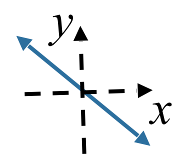
A) LCP B) RCP C) 

D) 

E) un-polarized

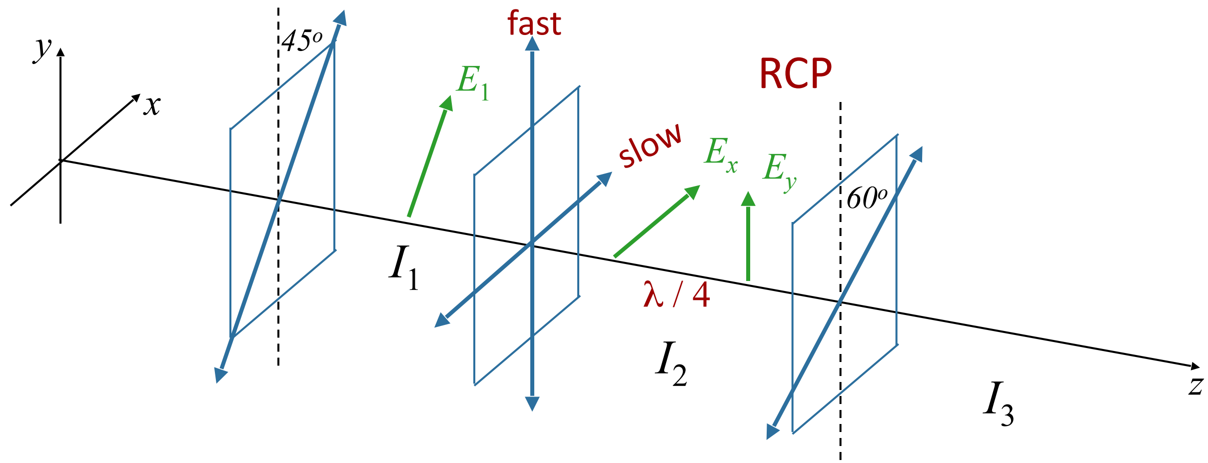
Light incident on QWP is linearly polarized at 45° to fast axis → Light will be circularly polarized after QWP

LCP or RCP? Easiest way: Right Hand Rule:

Curl fingers of RH back to front
Thumb points in dir of propagation
if right hand polarized. → RCP

Calculation

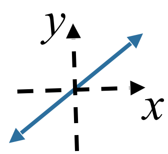
Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.

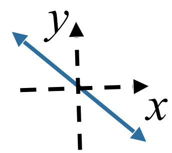


What is the polarization of the light after the QWP?

A) LCP

$\boxed{\text{B) RCP}}$

C) 

D) 

E) un-polarized

Light incident on QWP is linearly polarized at 45° to fast axis → Light will be circularly polarized after QWP

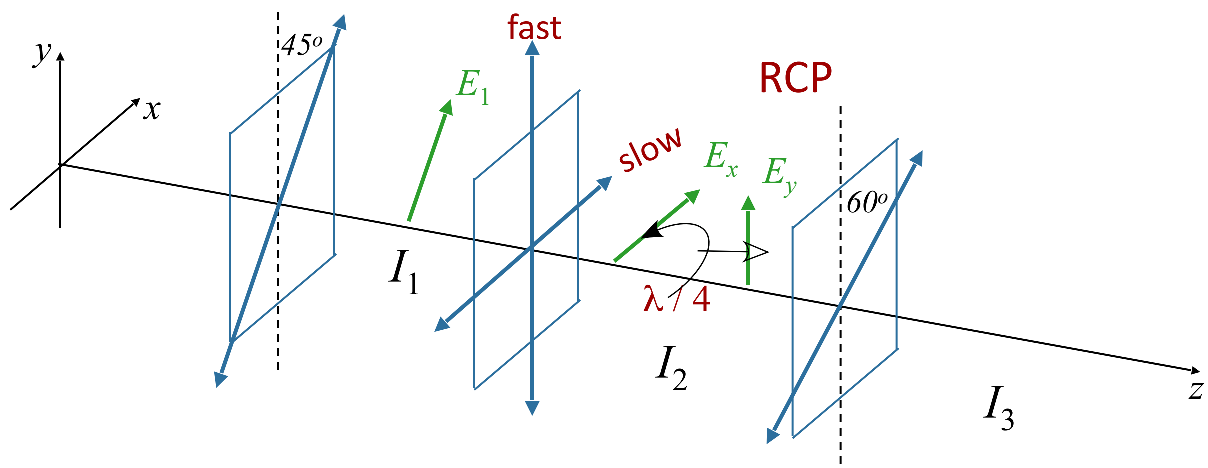
LCP or RCP? Easiest way: Right Hand Rule:

Curl fingers of RH back to front
Thumb points in dir of propagation
if right hand polarized.

RCP

Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.

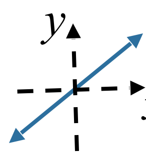


What is the polarization of the light after the QWP?

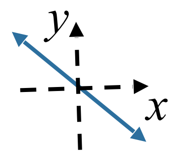
A) LCP

B) RCP

C)



D)



E) un-polarized

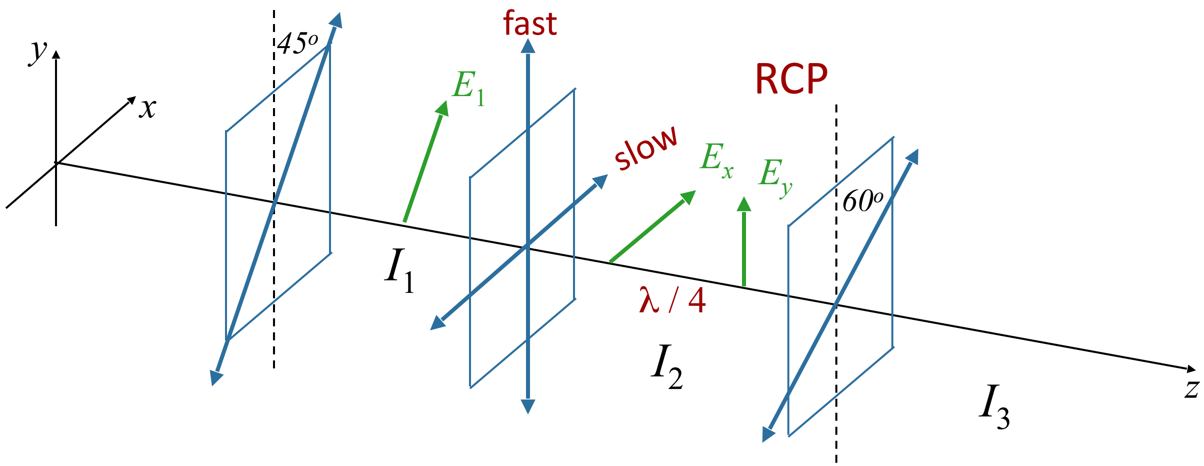
Light incident on QWP is linearly polarized at 45° to fast axis → Light will be circularly polarized after QWP

LCP or RCP? Easiest way: Right Hand Rule:

Curl fingers of RH back to front
Thumb points in dir of propagation
if right hand polarized. → RCP

Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.



What is the intensity I_2 of the light after the QWP?

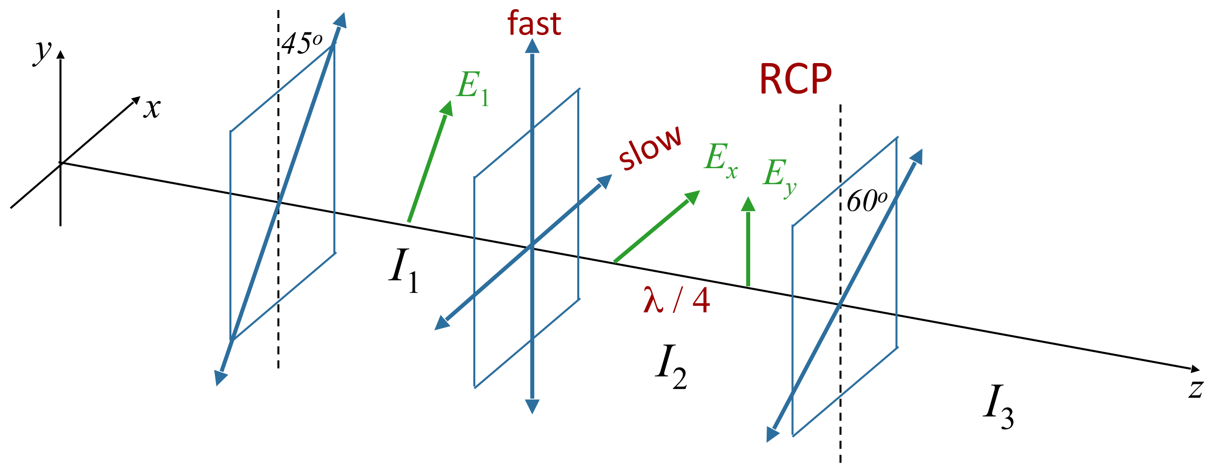
A) $I_2 = I_1$

B) $I_2 = \frac{1}{2} I_1$

C) $I_2 = \frac{1}{4} I_1$

Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.



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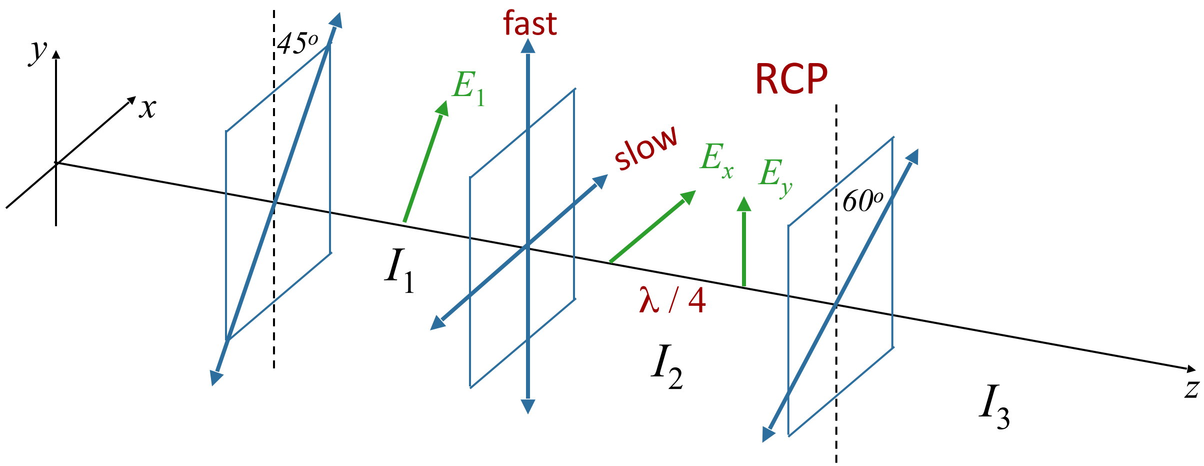
A) $I_2 = I_1$ B) $I_2 = \frac{1}{2} I_1$ C) $I_2 = \frac{1}{4} I_1$

No absorption: Just a phase change!

Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.



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A) $I_2 = I_1$ B) $I_2 = \frac{1}{2} I_1$ C) $I_2 = \frac{1}{4} I_1$

Before:

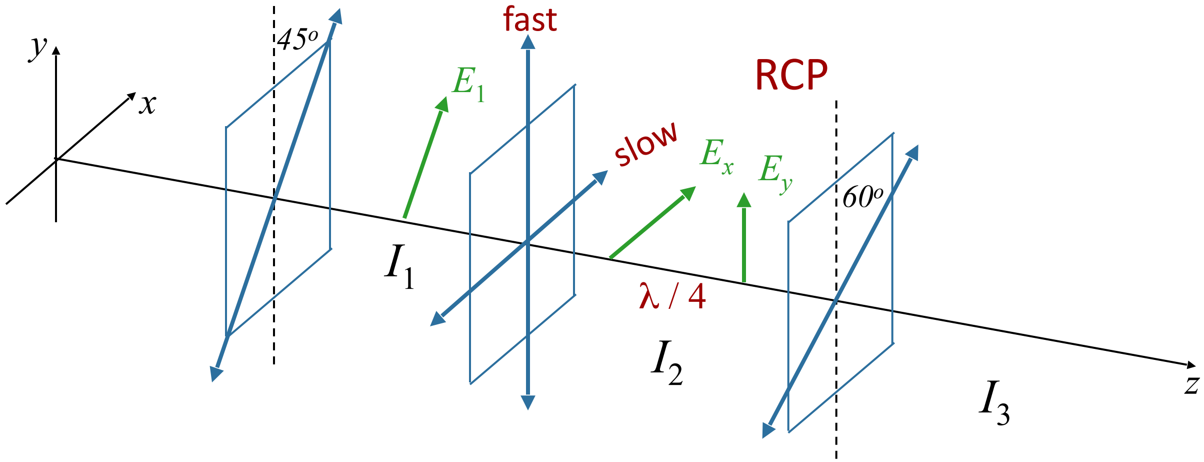
No absorption: Just a phase change!

$$E_x = \frac{E_1}{\sqrt{2}} \sin(kz - \omega t)$$

$$E_y = \frac{E_1}{\sqrt{2}} \sin(kz - \omega t)$$

Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.



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No absorption: Just a phase change!

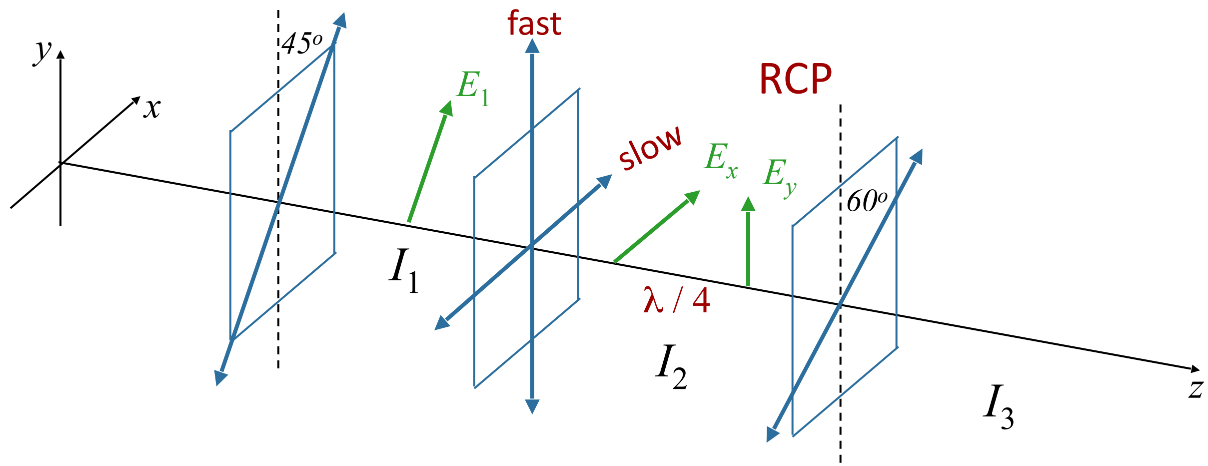
After:

$$E_x = \frac{E_1}{\sqrt{2}}\cos(kz - \omega t)$$

$$E_y = \frac{E_1}{\sqrt{2}}\cos(kz - \omega t)$$

Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.



What is the intensity I_2 of the light after the QWP?

A) $I_2 = I_1$ B) $I_2 = ½ I_1$ C) $I_2 = ¼ I_1$

Before:

$$E_x = \frac{E_1}{\sqrt{2}} \sin(kz - \omega t)$$

$$E_y = \frac{E_1}{\sqrt{2}} \sin(kz - \omega t)$$

No absorption: Just a phase change!

$$I = \epsilon_0 c \left[\langle E_x^2 \rangle + \langle E_y^2 \rangle \right]$$

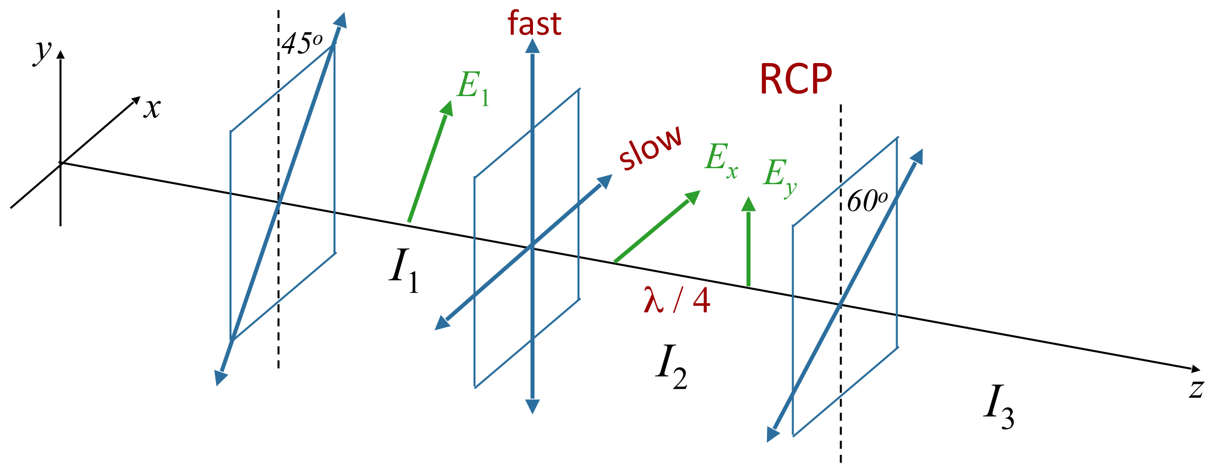
After:

$$E_x = \frac{E_1}{\sqrt{2}} \cos(kz - \omega t)$$

$$E_y = \frac{E_1}{\sqrt{2}} \cos(kz - \omega t)$$

Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.



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A) $I_2 = I_1$ B) $I_2 = \frac{1}{2} I_1$ C) $I_2 = \frac{1}{4} I_1$

Before:

$$E_x = \frac{E_1}{\sqrt{2}}\sin(kz - \omega t)$$

$$E_y = \frac{E_1}{\sqrt{2}}\sin(kz - \omega t)$$

No absorption: Just a phase change!

$$I = \epsilon_0 c\left[\langle E_x^2\rangle + \langle E_y^2\rangle\right]$$

Same before & after!

After:

$$E_x = \frac{E_1}{\sqrt{2}}\cos(kz - \omega t)$$

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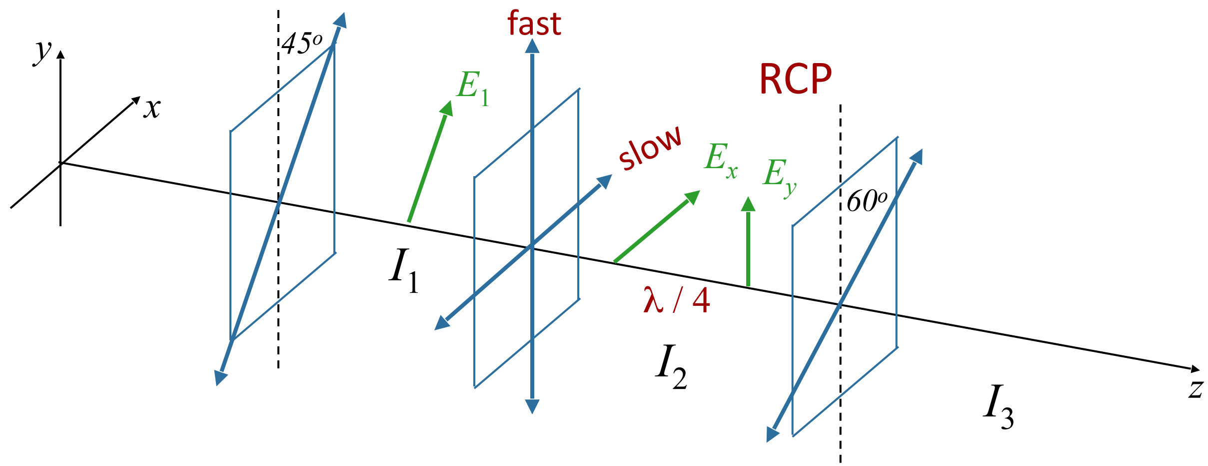
Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.



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No absorption: Just a phase change!

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Same before & after!

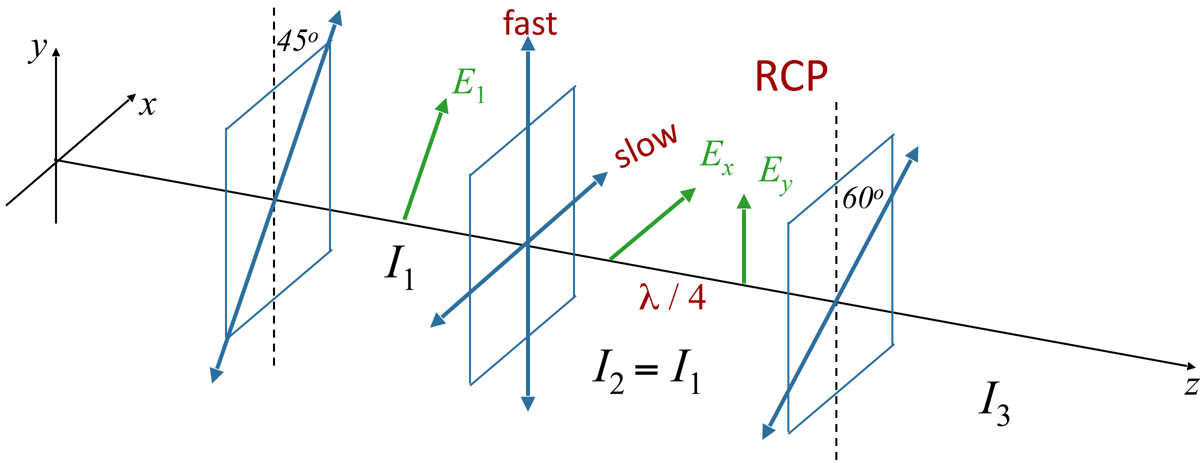
After:

$$E_x = \frac{E_1}{\sqrt{2}} \cos(kz - \omega t)$$

$$E_y = \frac{E_1}{\sqrt{2}} \cos(kz - \omega t)$$

Calculation

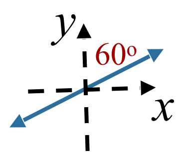
Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.

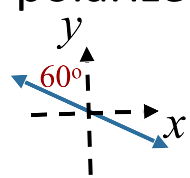


What is the polarization of the light after the 60^{o} polarizer?

A) LCP

B) RCP

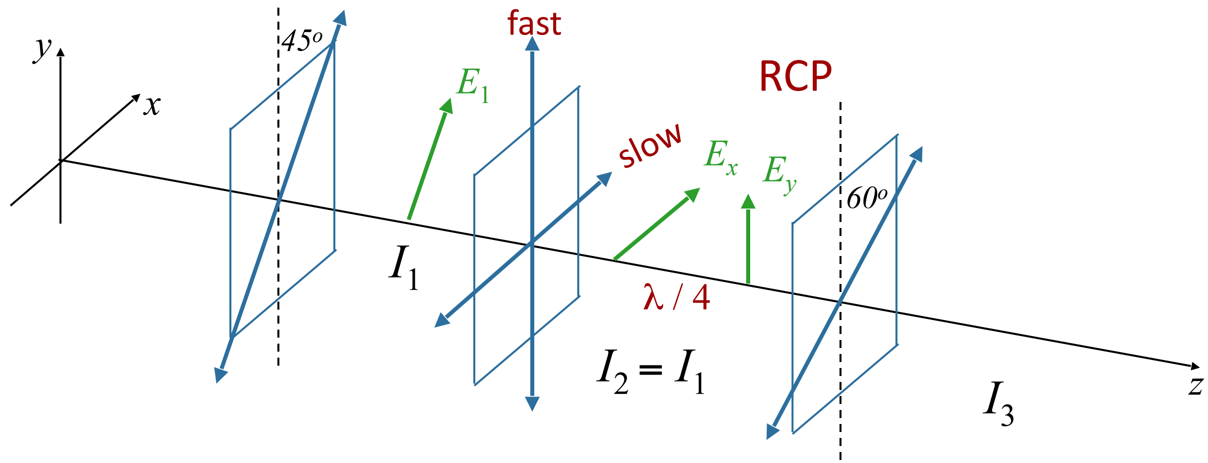
C) 

D) 

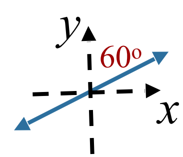
E) un-polarized

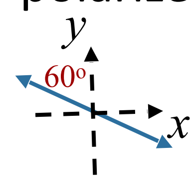
Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.



What is the polarization of the light after the 60° polarizer?

A) LCP B) RCP C) 

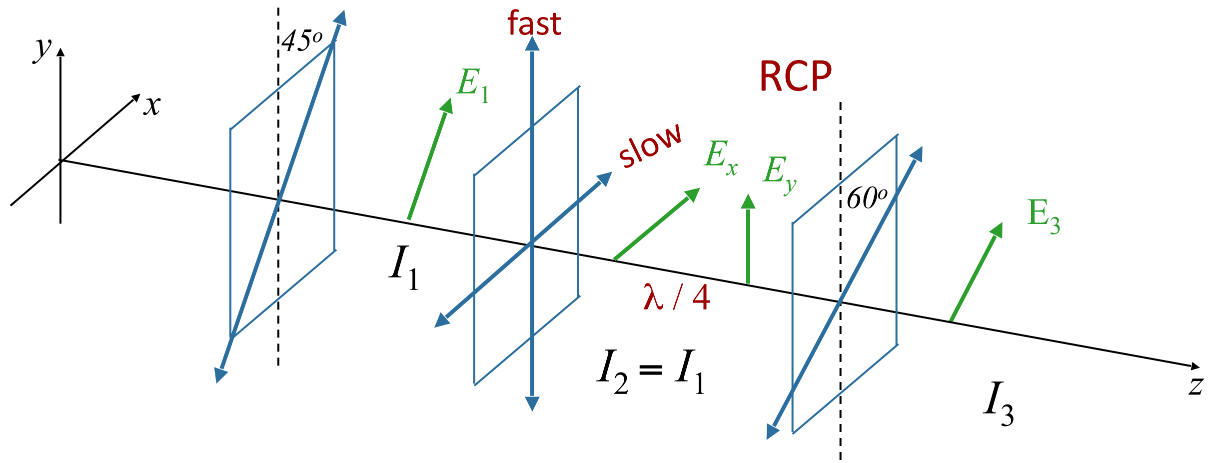
D) 

E) un-polarized

Absorption: only passes components of E parallel to TA $(\theta = 60^o)$

Calculation

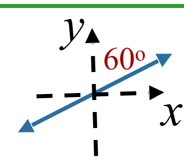
Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.

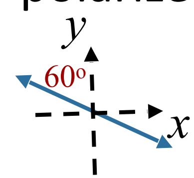


What is the polarization of the light after the 60° polarizer?

A) LCP

B) RCP

C) 

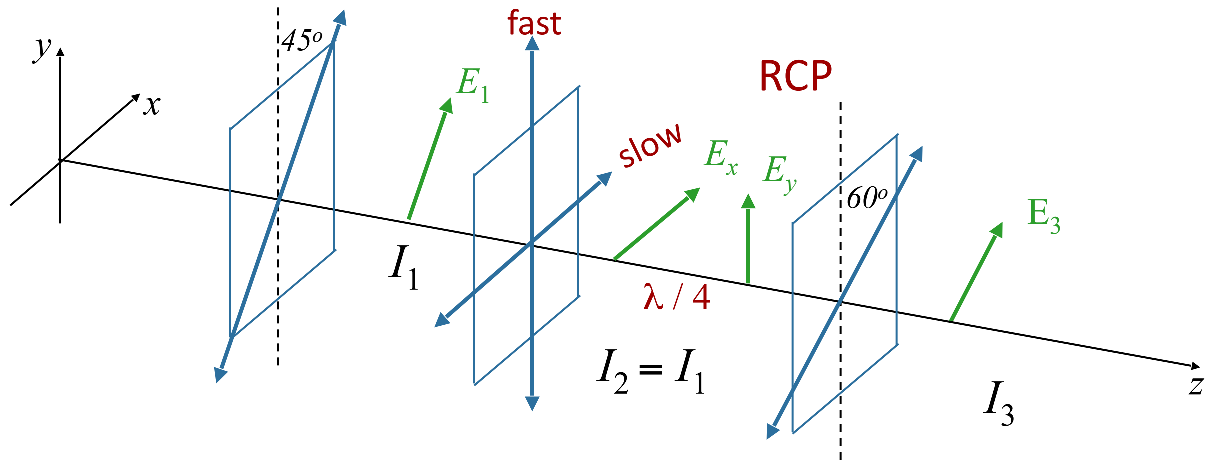
D) 

E) un-polarized

Absorption: only passes components of E parallel to TA ($\theta = 60°$)

Calculation

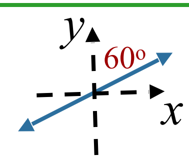
Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.

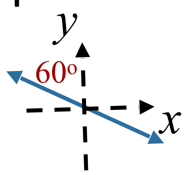


What is the polarization of the light after the 60° polarizer?

A) LCP

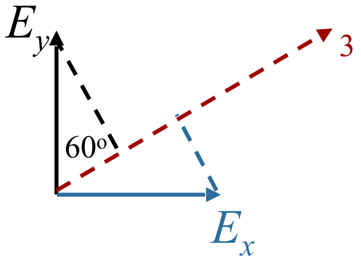
B) RCP

C) 

D) 

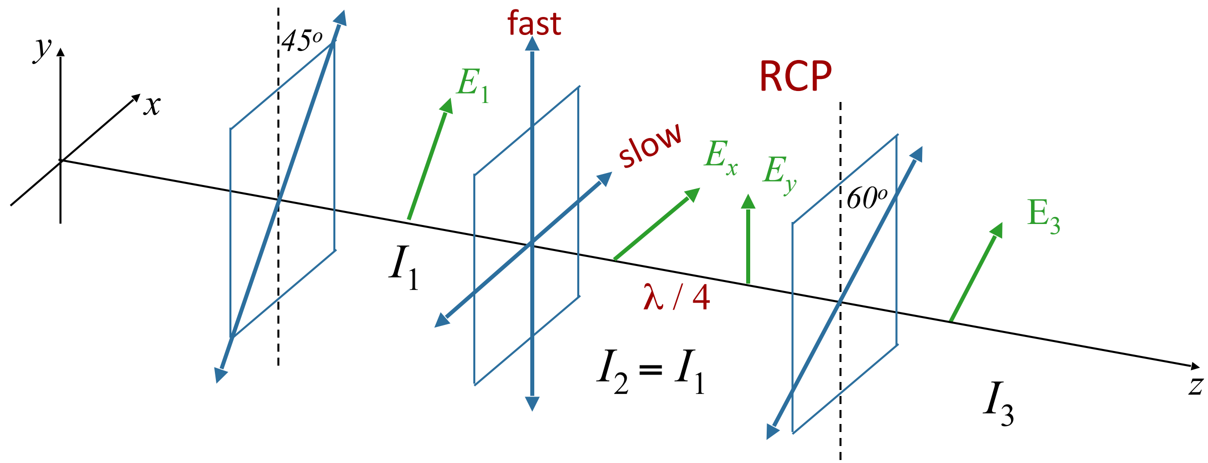
E) un-polarized

Absorption: only passes components of E parallel to TA $(\theta = 60^o)$



Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.

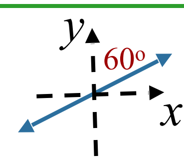


What is the polarization of the light after the 60^o polarizer?

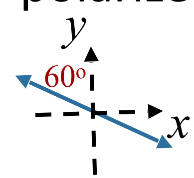
A) LCP

B) RCP

C)

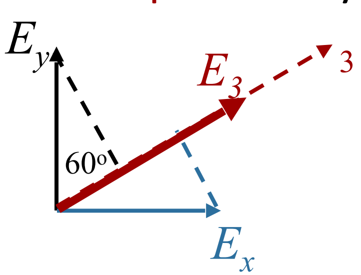


D)



E) un-polarized

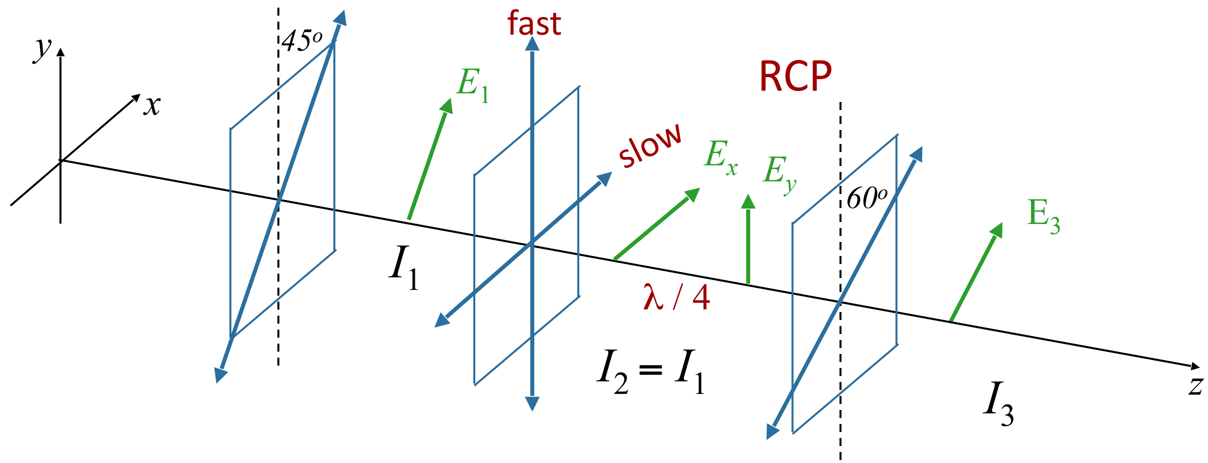
Absorption: only passes components of E parallel to TA $(\theta = 60^o)$



$$E_3 = E_x \sin\theta + E_y \cos\theta$$

Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.



What is the polarization of the light after the 60^o polarizer?

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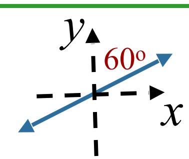
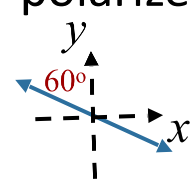
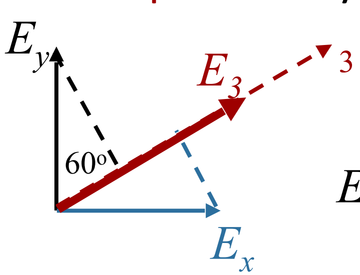
C) 

D) 

E) un-polarized

Absorption: only passes components of E parallel to TA $(\theta = 60^o)$

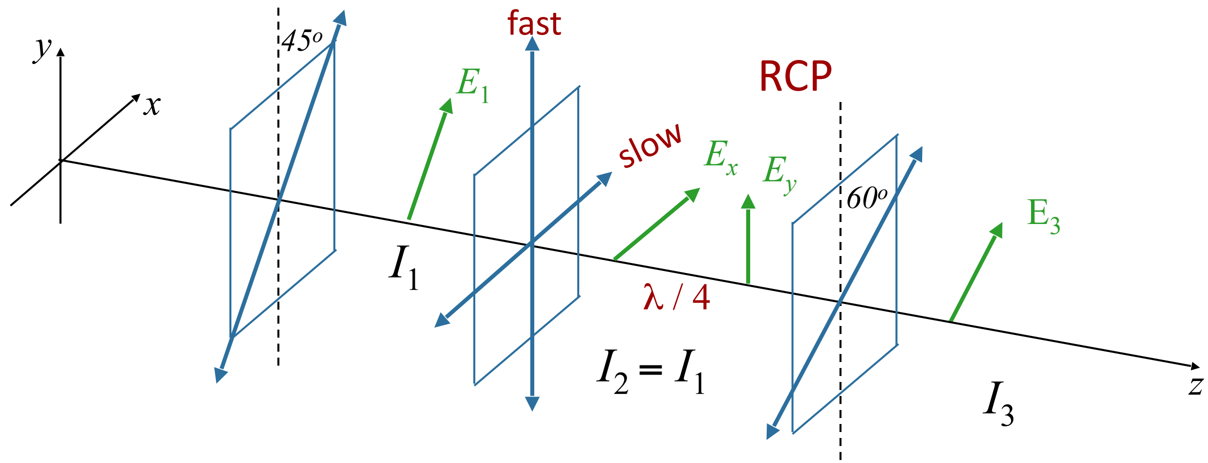


$$E_3 = E_x \sin\theta + E_y \cos\theta$$

$$E_3 = \frac{E_1}{\sqrt{2}}\left(\cos(kz - \omega t)\sin\theta + \sin(kz - \omega t)\cos\theta\right)$$

Calculation

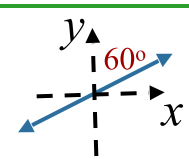
Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.

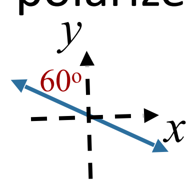


What is the polarization of the light after the 60° polarizer?

A) LCP

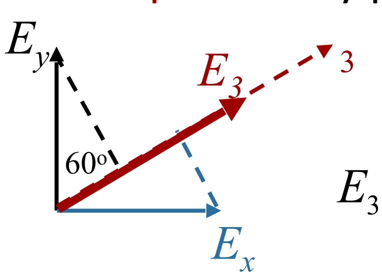
B) RCP

C) 

D) 

E) un-polarized

Absorption: only passes components of E parallel to TA $(\theta = 60^o)$



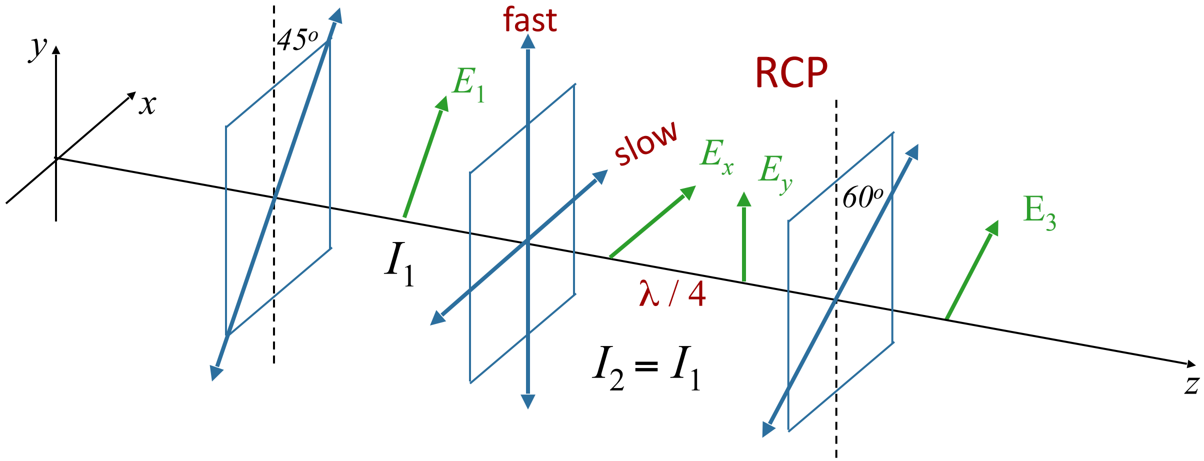
$$E_3 = E_x \sin\theta + E_y \cos\theta$$

$$E_3 = \frac{E_1}{\sqrt{2}}\left(\cos(kz - \omega t)\sin\theta + \sin(kz - \omega t)\cos\theta\right)$$

$$E_3 = \frac{E_1}{\sqrt{2}}\left(\sin(kz - \omega t + \theta)\right)$$

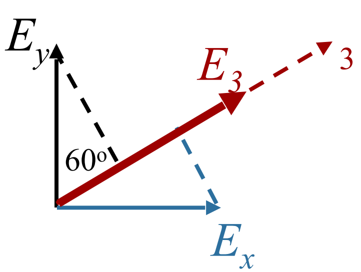
Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.



What is the intensity I_3 of the light after the 60° polarizer?

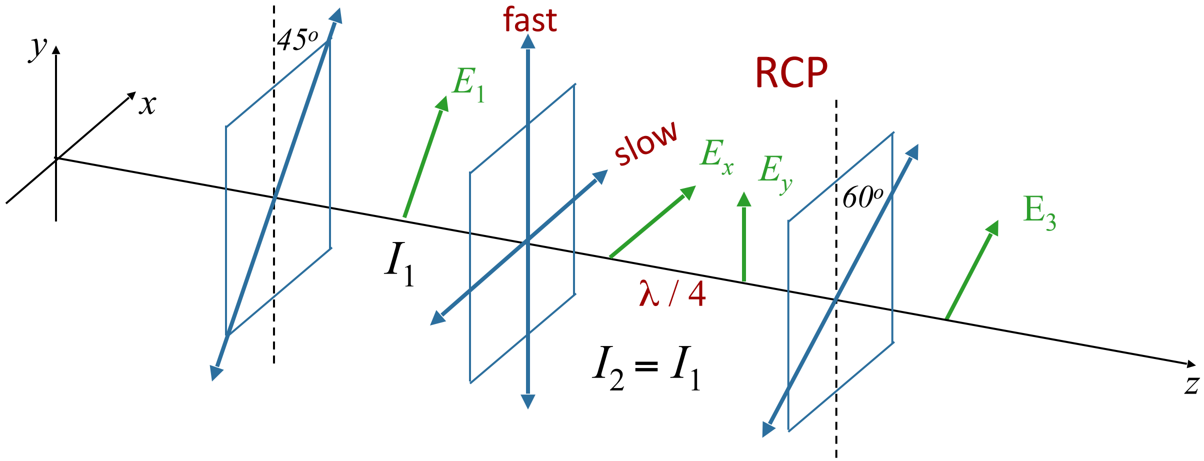
A) $I_3 = I_1$ B) $I_3 = ½ I_1$ C) $I_3 = ¼ I_1$



$$E_3 = \frac{E_1}{\sqrt{2}}$$

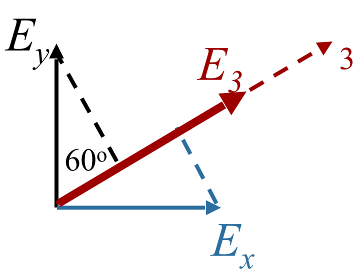
Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.



What is the intensity I_3 of the light after the 60° polarizer?

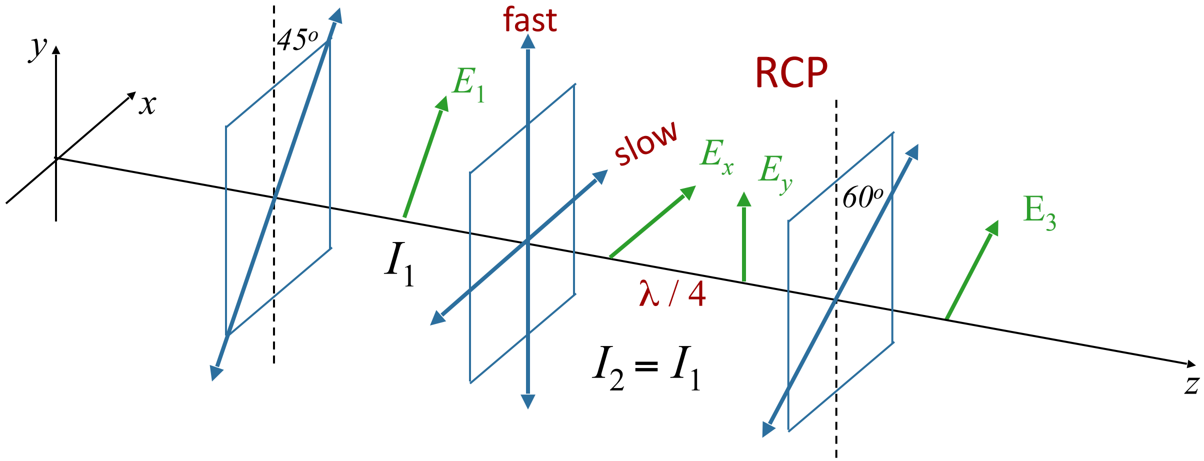
A) $I_3 = I_1$ B) $I_3 = \frac{1}{2} I_1$ C) $I_3 = \frac{1}{4} I_1$



$$E_3 = \frac{E_1}{\sqrt{2}} \qquad I \propto E^2$$

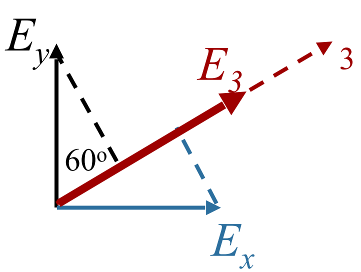
Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.



What is the intensity I_3 of the light after the 60^o polarizer?

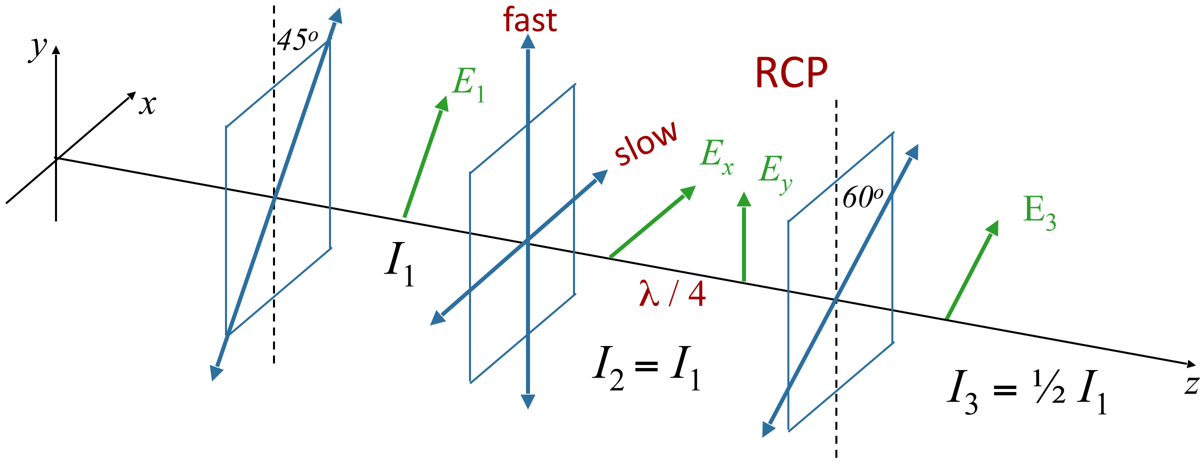
A) $I_3 = I_1$ B) $I_3 = ½\, I_1$ C) $I_3 = ¼\, I_1$



$$E_3 = \frac{E_1}{\sqrt{2}} \qquad I \propto E^2 \quad \Rightarrow \quad I_3 = \frac{1}{2} I_1$$

Calculation

Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.

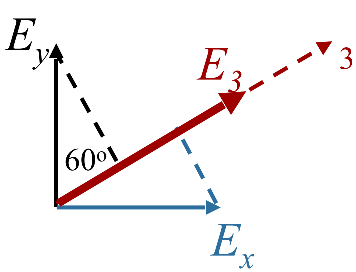


What is the intensity I_3 of the light after the 60^o polarizer?

A) $I_3 = I_1$

B) $\boxed{I_3 = \frac{1}{2} I_1}$

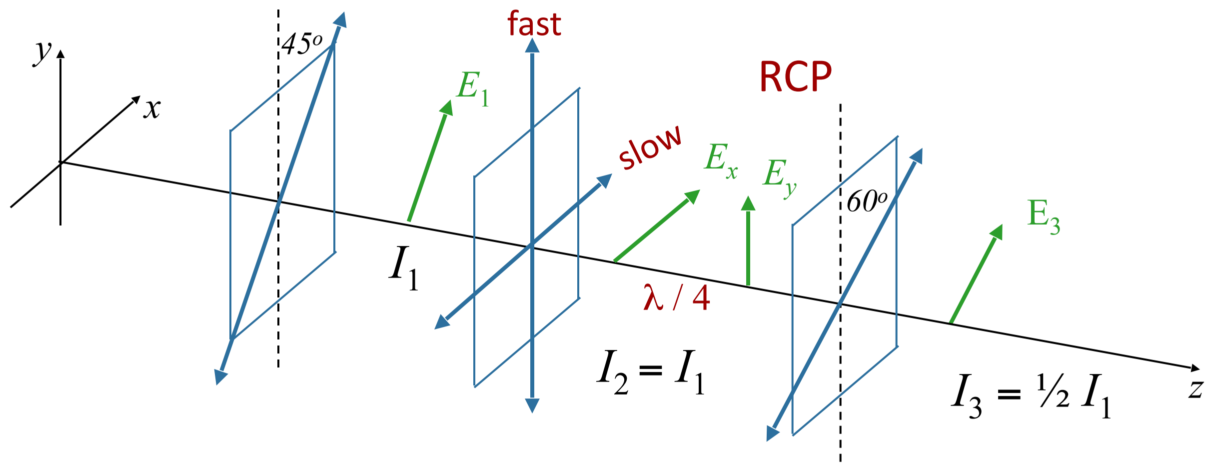
C) $I_3 = \frac{1}{4} I_1$



$$E_3 = \frac{E_1}{\sqrt{2}} \qquad I \propto E^2 \quad \Rightarrow \quad I_3 = \frac{1}{2} I_1$$

Calculation

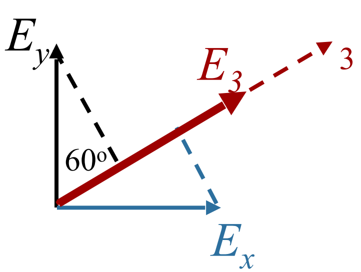
Light is incident on two linear polarizers and a quarter wave plate (QWP) as shown.



What is the intensity I_3 of the light after the 60° polarizer?

A) $I_3 = I_1$ $\qquad$ $\boxed{\text{B) } I_3 = \tfrac{1}{2} I_1}$ $\qquad$ C) $I_3 = \tfrac{1}{4} I_1$

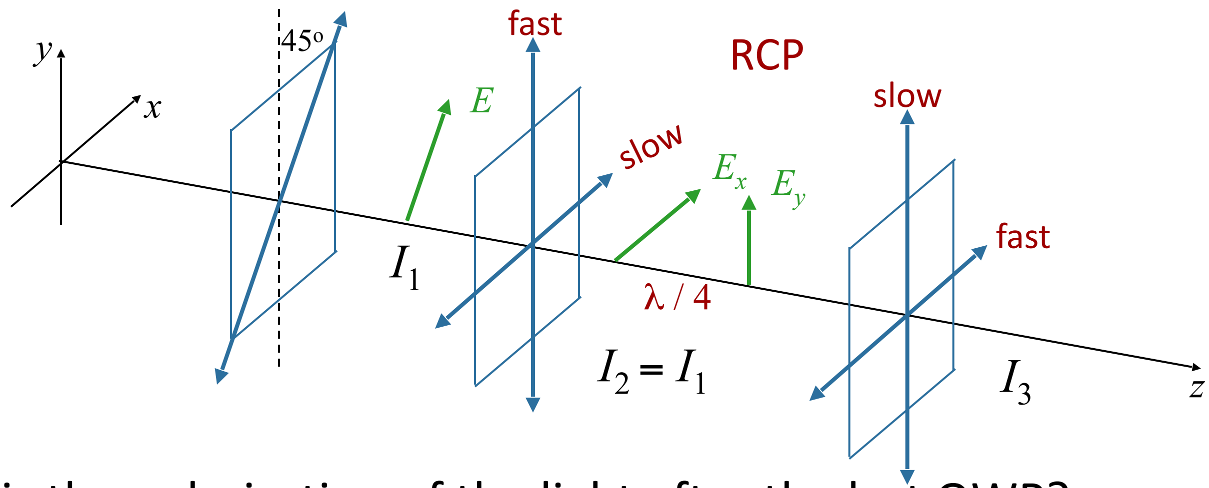
$$E_3 = \frac{E_1}{\sqrt{2}} \qquad I \propto E^2 \quad \Rightarrow \quad I_3 = \frac{1}{2} I_1$$



NOTE: This does not depend on θ !

Follow-Up 1

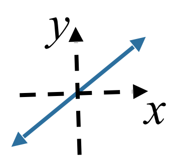
Replace the 60^o polarizer with another QWP as shown.

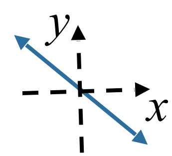


What is the polarization of the light after the last QWP?

A) LCP

B) RCP

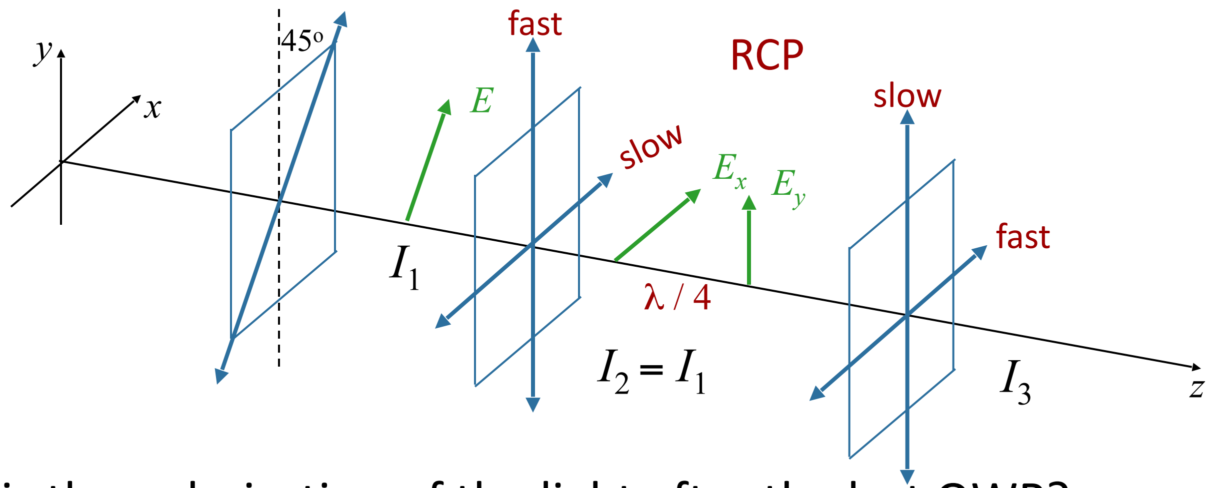
C) 

D) 

E) un-polarized

Follow-Up 1

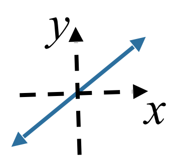
Replace the 60^o polarizer with another QWP as shown.

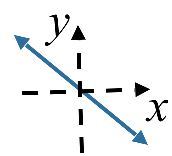


What is the polarization of the light after the last QWP?

A) LCP

B) RCP

C) 

D) 

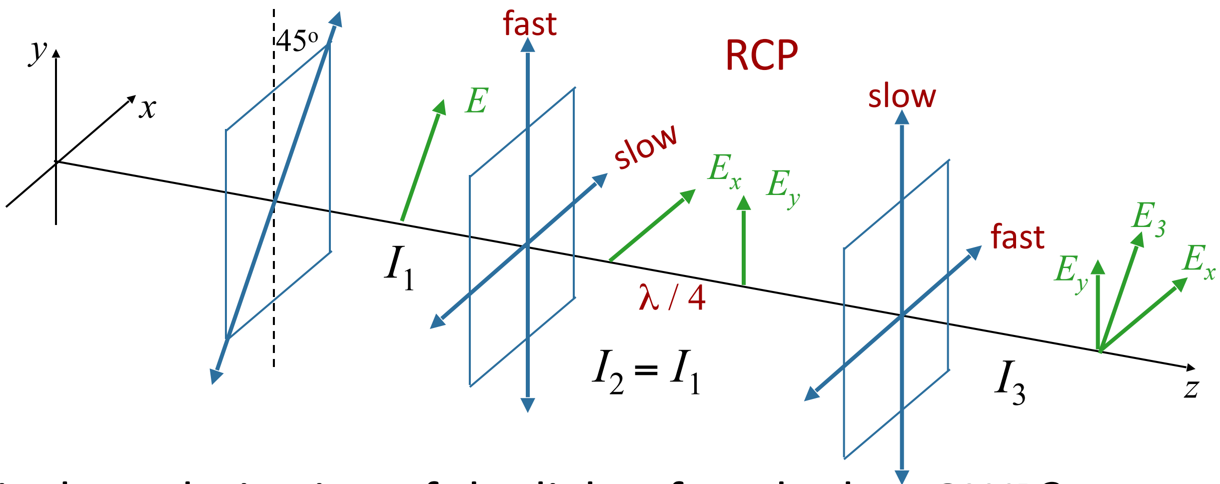
E) un-polarized

Easiest way:

E_{fast} is $\lambda / 4$ ahead of E_{slow}

Follow-Up 1

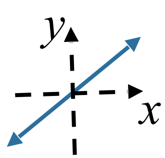
Replace the 60^{o} polarizer with another QWP as shown.

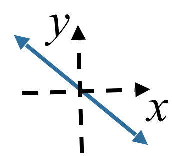


What is the polarization of the light after the last QWP?

A) LCP

B) RCP

C) 

D) 

E) un-polarized

Easiest way:

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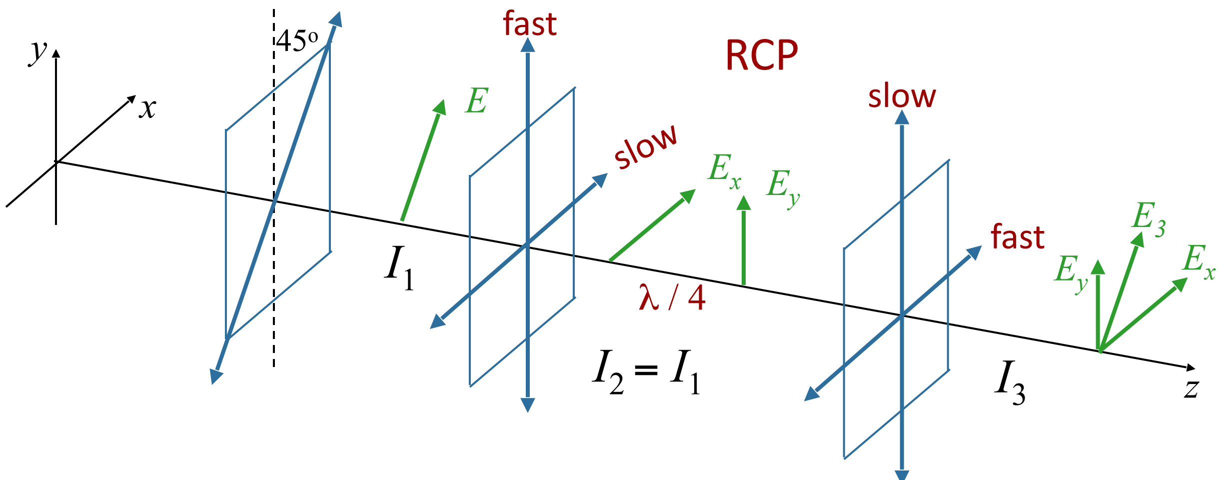
Follow-Up 1

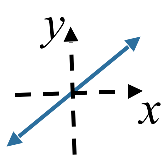
Replace the 60^{o} polarizer with another QWP as shown.

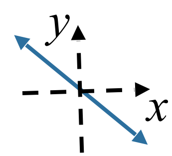


What is the polarization of the light after the last QWP?

A) LCP

B) RCP

C) 

D) 

E) un-polarized

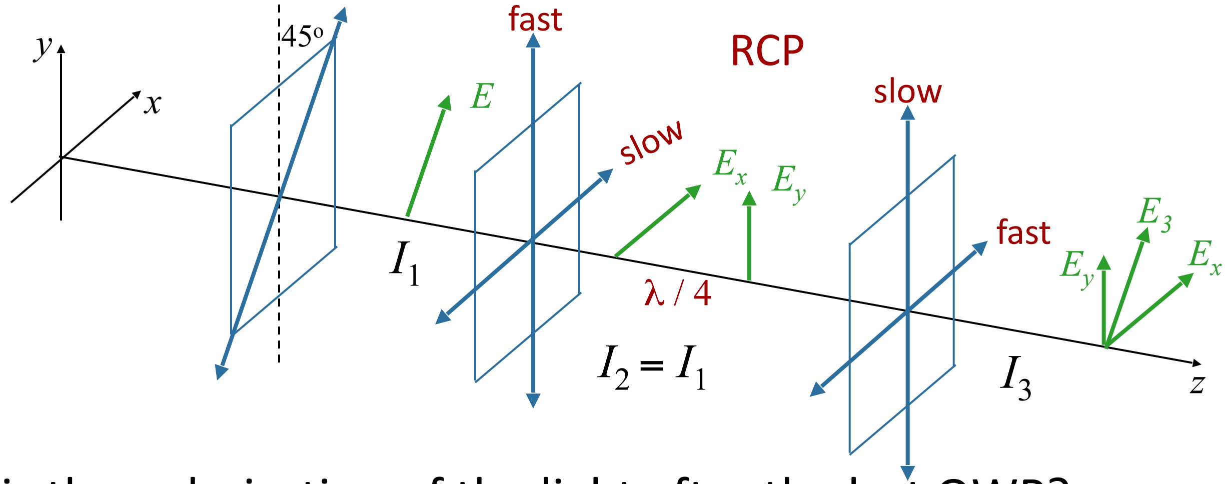
Easiest way:

E_{fast} is λ / 4 ahead of E_{slow}

Brings E_x and E_y back in phase!

Follow-Up 1

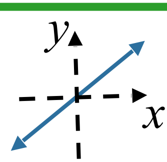
Replace the 60° polarizer with another QWP as shown.

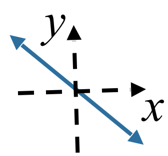


What is the polarization of the light after the last QWP?

A) LCP

B) RCP

C) 

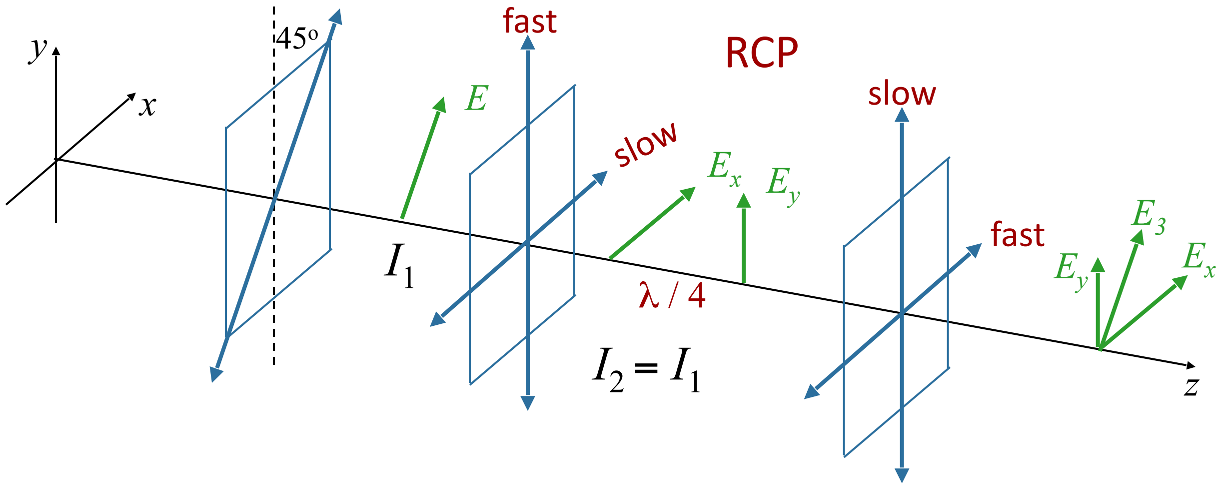
D) 

E) un-polarized

Easiest way:
E_{fast} is $\lambda / 4$ ahead of E_{slow} → Brings E_x and E_y back in phase!

Follow-Up 2

Replace the 60^{o} polarizer with another QWP as shown.

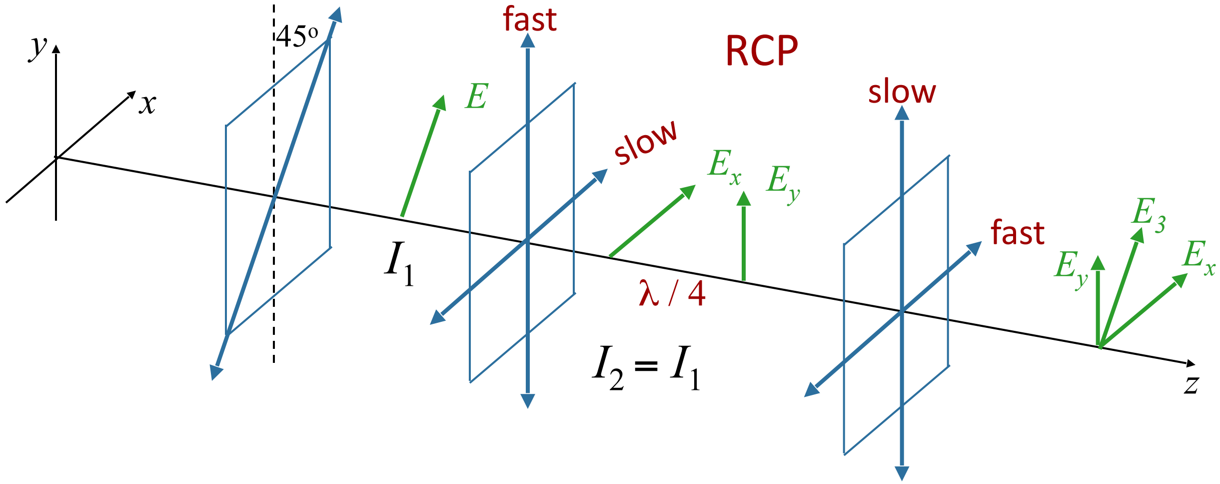


What is the intensity I_3 of the light after the last QWP?

A) I_1 B) $\frac{1}{2} I_1$ C) $\frac{1}{4} I_1$

Follow-Up 2

Replace the 60^o polarizer with another QWP as shown.



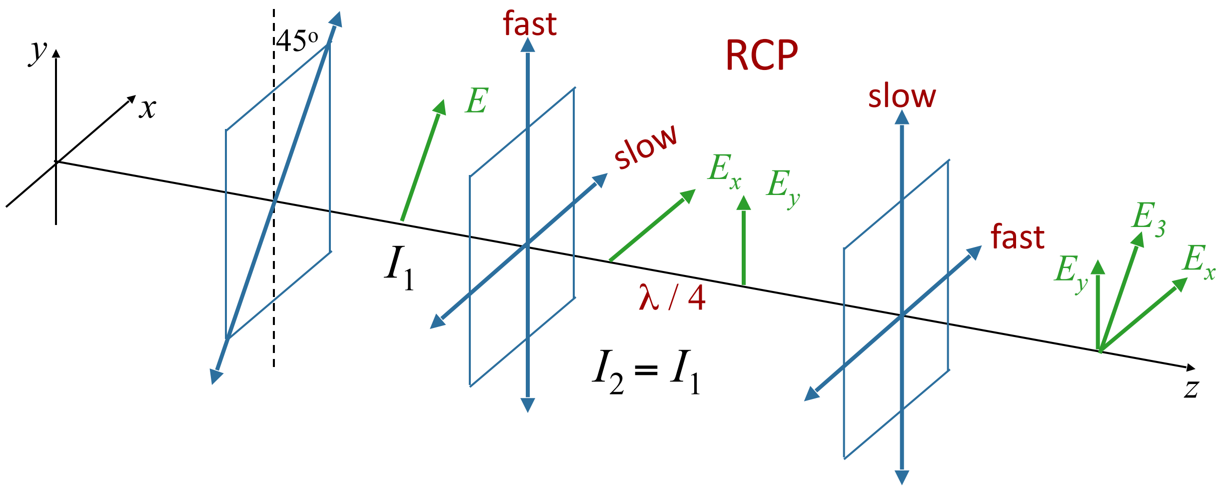
What is the intensity I_3 of the light after the last QWP?

A) I_1 B) $\frac{1}{2} I_1$ C) $\frac{1}{4} I_1$

No absorption: Just a phase change!

Follow-Up 2

Replace the 60° polarizer with another QWP as shown.



What is the intensity I_3 of the light after the last QWP?

A) I_1 B) $\frac{1}{2} I_1$ C) $\frac{1}{4} I_1$

Before:

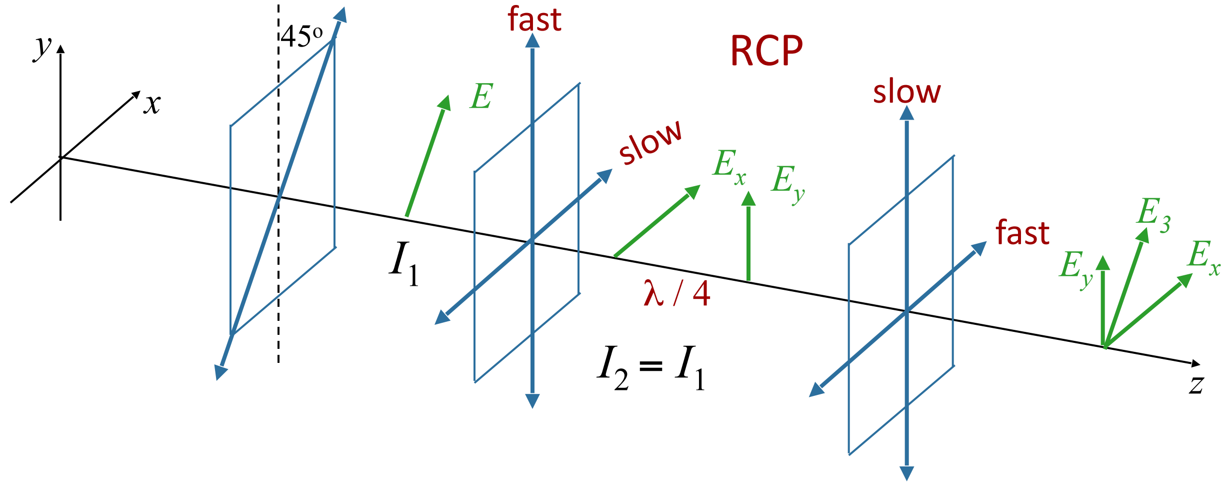
No absorption: Just a phase change!

$$E_x = \frac{E_1}{\sqrt{2}} \cos(kz - \omega t)$$

$$E_y = \frac{E_1}{\sqrt{2}} \sin(kz - \omega t)$$

Follow-Up 2

Replace the 60° polarizer with another QWP as shown.



What is the intensity I_3 of the light after the last QWP?

A) I_1

B) $\frac{1}{2}\, I_1$

C) $\frac{1}{4}\, I_1$

No absorption: Just a phase change!

Before:

$$E_x = \frac{E_1}{\sqrt{2}}\cos(kz - \omega t)$$

$$E_y = \frac{E_1}{\sqrt{2}}\sin(kz - \omega t)$$

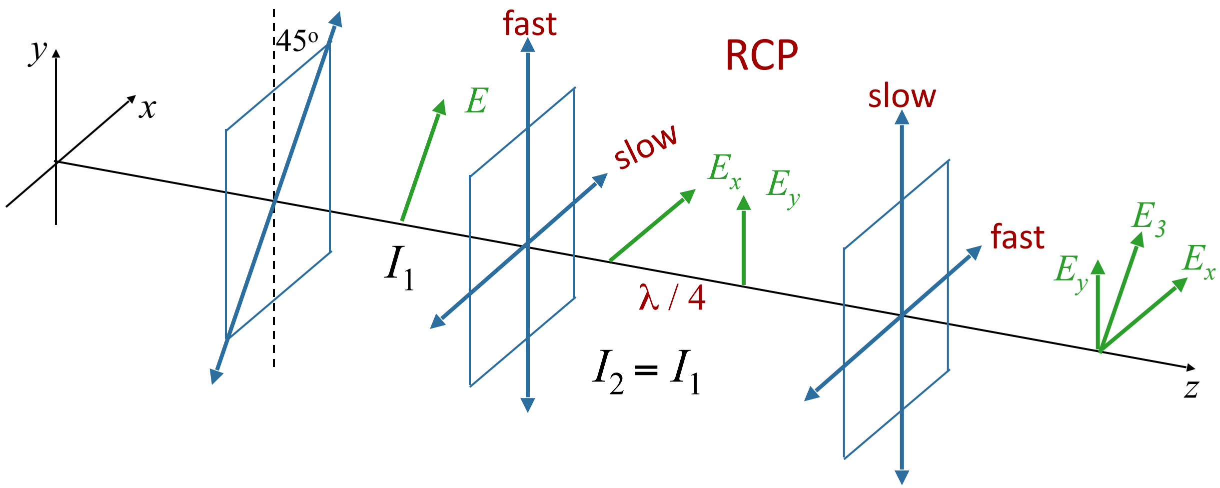
After:

$$E_x = \frac{E_1}{\sqrt{2}}\cos(kz - \omega t)$$

$$E_y = \frac{E_1}{\sqrt{2}}\cos(kz - \omega t)$$

Follow-Up 2

Replace the 60^o polarizer with another QWP as shown.



What is the intensity I_3 of the light after the last QWP?

A) I_1 B) $\frac{1}{2} I_1$ C) $\frac{1}{4} I_1$

Before:

$$E_x = \frac{E_1}{\sqrt{2}} \cos(kz - \omega t)$$

$$E_y = \frac{E_1}{\sqrt{2}} \sin(kz - \omega t)$$

No absorption: Just a phase change!

Intensity $= \langle E^2 \rangle$

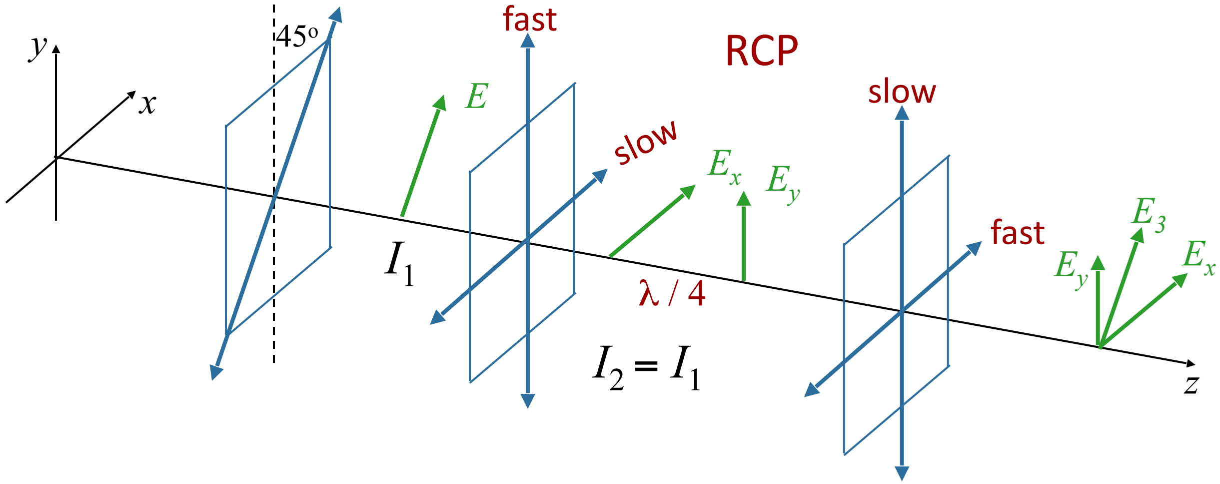
After:

$$E_x = \frac{E_1}{\sqrt{2}} \cos(kz - \omega t)$$

$$E_y = \frac{E_1}{\sqrt{2}} \cos(kz - \omega t)$$

Follow-Up 2

Replace the 60° polarizer with another QWP as shown.



What is the intensity I_3 of the light after the last QWP?

A) I_1 B) ½ I_1 C) ¼ I_1

Before:

No absorption: Just a phase change!

After:

$$E_x = \frac{E_1}{\sqrt{2}}\cos(kz - \omega t)$$

Intensity $= \langle E^2 \rangle$

$$E_x = \frac{E_1}{\sqrt{2}}\cos(kz - \omega t)$$

$$E_y = \frac{E_1}{\sqrt{2}}\sin(kz - \omega t)$$

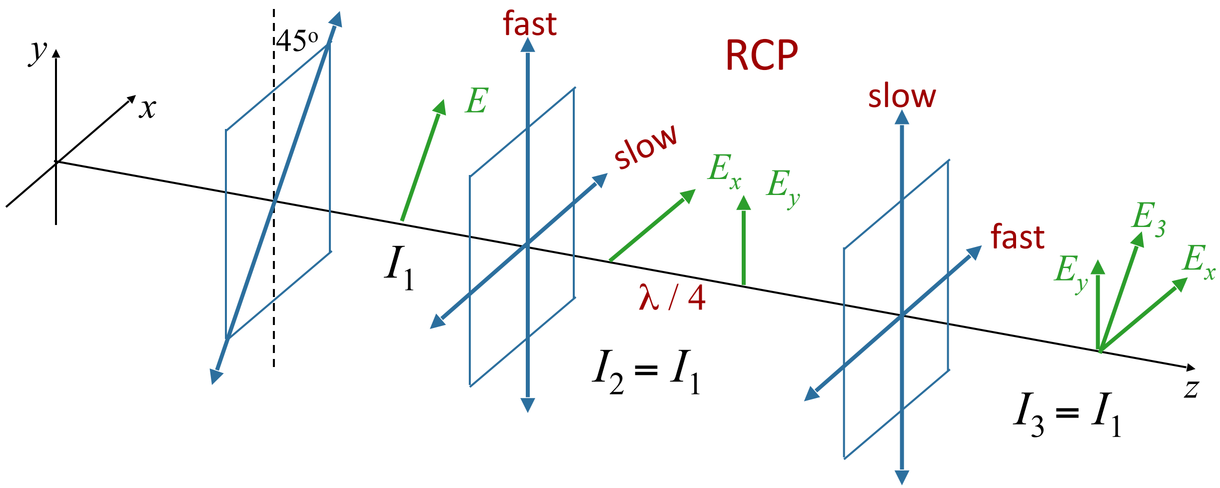
$$I_{before} = \frac{E_1^2}{2}$$

$$I_{after} = \frac{E_1^2}{2}$$

$$E_y = \frac{E_1}{\sqrt{2}}\cos(kz - \omega t)$$

Follow-Up 2

Replace the 60º polarizer with another QWP as shown.



What is the intensity I_3 of the light after the last QWP?

$\boxed{\text{A) } I_1}$ B) ½ I_1 C) ¼ I_1

Before:

$$E_x = \frac{E_1}{\sqrt{2}}\cos(kz - \omega t)$$

$$E_y = \frac{E_1}{\sqrt{2}}\sin(kz - \omega t)$$

No absorption: Just a phase change!

Intensity $= \langle E^2 \rangle$

$$I_{before} = \frac{E_1^2}{2} \quad \longleftrightarrow \quad I_{after} = \frac{E_1^2}{2}$$

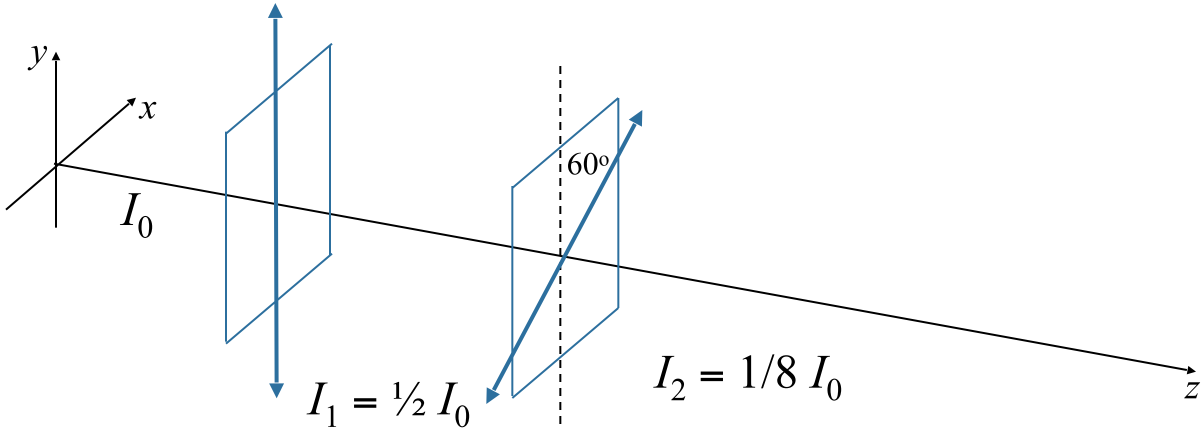
After:

$$E_x = \frac{E_1}{\sqrt{2}}\cos(kz - \omega t)$$

$$E_y = \frac{E_1}{\sqrt{2}}\cos(kz - \omega t)$$

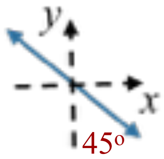
Follow-Up 3

Consider light incident on two linear polarizers as shown. Suppose $I_2 = 1/8\ I_0$



What is the possible polarization of the input light?

A) LCP

B) 

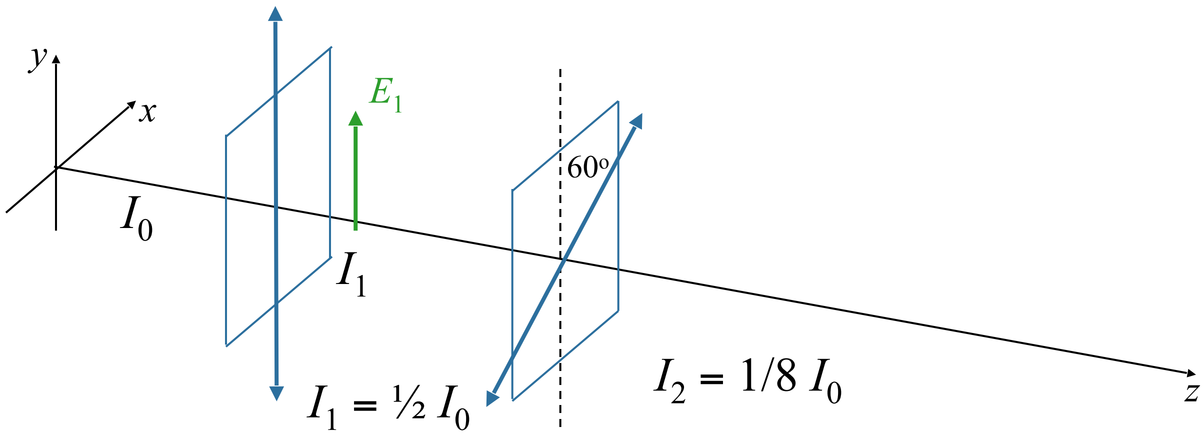
C) un-polarized $I_2 = 1/8\ I_0 \;\Rightarrow\; I_1 = ½\ I_0$

D) all of above

E) none of above

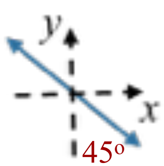
Follow-Up 3

Consider light incident on two linear polarizers as shown. Suppose $I_2 = 1/8\ I_0$



What is the possible polarization of the input light?

A) LCP

B) 

C) un-polarized

D) all of above

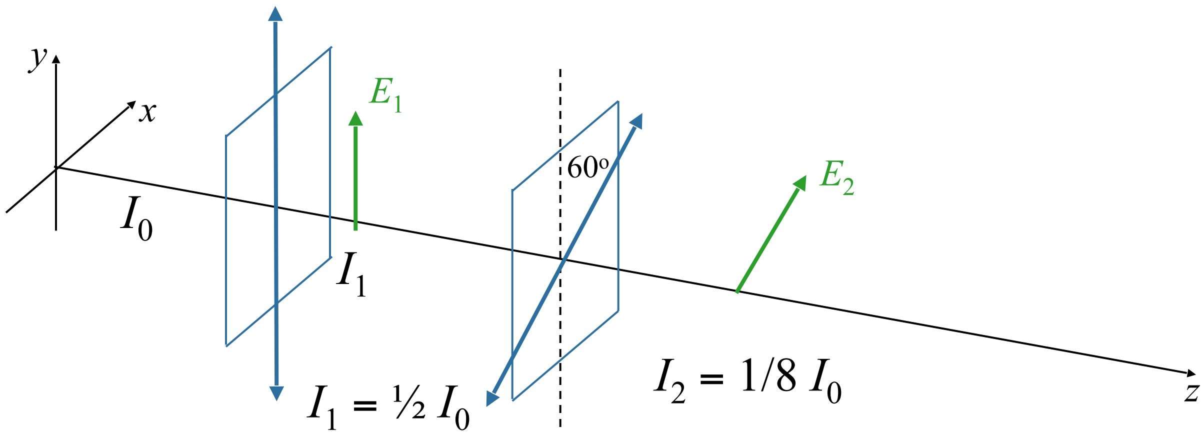
E) none of above

After first polarizer: LP along y–axis with intensity I_1

$I_2 = 1/8\ I_0 \Rightarrow I_1 = ½\ I_0$

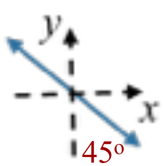
Follow-Up 3

Consider light incident on two linear polarizers as shown. Suppose $I_2 = 1/8\ I_0$



What is the possible polarization of the input light?

A) LCP

B) 

C) un-polarized

D) all of above

E) none of above

After first polarizer: LP along y–axis with intensity I_1

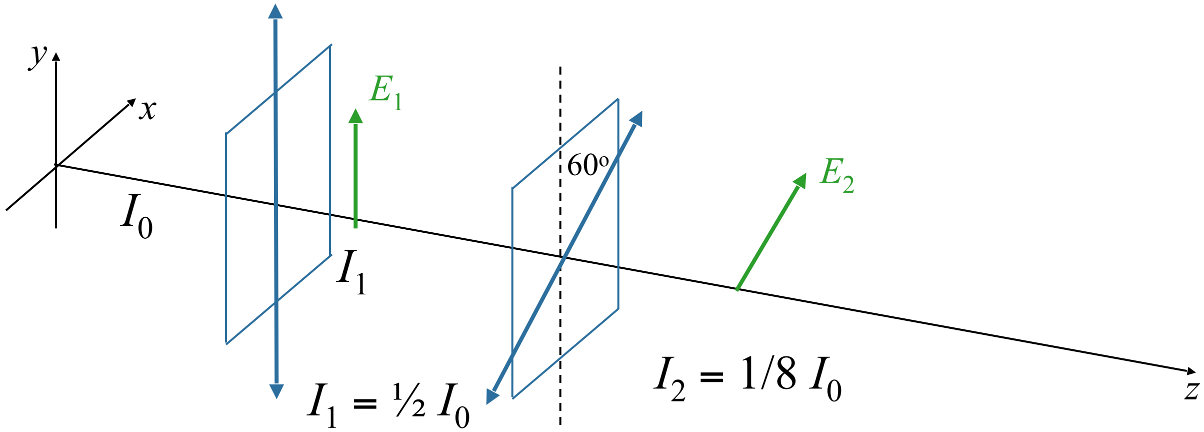
After second polarizer: LP at 60° wrt y–axis

Intensity: $I_2 = I_1\cos^2(60°) = ¼\ I_1$

$I_2 = 1/8\ I_0 \Rightarrow I_1 = ½\ I_0$

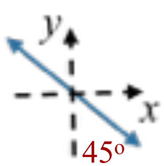
Follow-Up 3

Consider light incident on two linear polarizers as shown. Suppose $I_2 = 1/8\ I_0$



What is the possible polarization of the input light?

A) LCP

B) 

C) un-polarized

D) all of above

E) none of above

After first polarizer: LP along y–axis with intensity I_1

After second polarizer: LP at 60° wrt y–axis

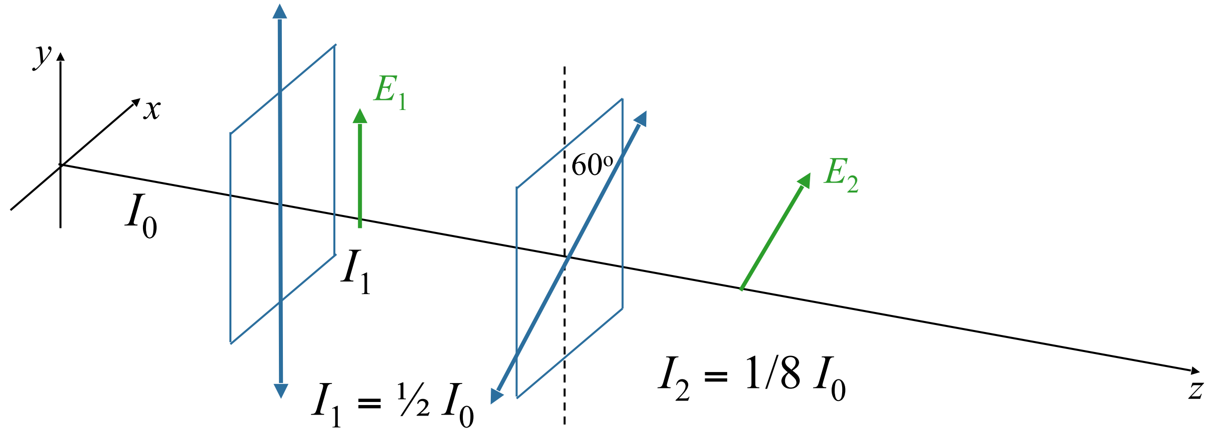
Intensity: $I_2 = I_1 \cos^2(60^o) = ¼\ I_1$

$I_2 = 1/8\ I_0$ ➽ $I_1 = ½\ I_0$

Question is: What kind of light loses ½ of its intensity after passing through vertical polarizer?

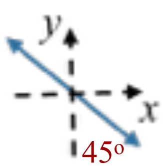
Follow-Up 3

Consider light incident on two linear polarizers as shown. Suppose $I_2 = 1/8\ I_0$



What is the possible polarization of the input light?

A) LCP

B) 

C) un-polarized

D) all of above

E) none of above

After first polarizer: LP along y–axis with intensity I_1

After second polarizer: LP at 60° wrt y–axis

Intensity: $I_2 = I_1\cos^2(60°) = ¼\ I_1$

$I_2 = 1/8\ I_0 \Rightarrow I_1 = ½\ I_0$

Question is: What kind of light loses ½ of its intensity after passing through vertical polarizer?

Answer: Everything except LP at θ other than 45°