Electromagnetic Induction and Electromagnetic Waves

Topics:

- Electromagnetic induction
- Lenz's law
- Faraday's law
- The nature of electromagnetic waves
- The spectrum of electromagnetic waves

Sample question:

The ultraviolet view of the flowers on the right shows markings that cannot be seen in the visible region of the spectrum. Whose eyes are these markings intended for?

Reading Quiz

1. Which of the following will cause an induced current in a coil of wire?
   A. A magnet resting near the coil.
   B. The constant field of the earth passing through the coil.
   C. A magnet being moved into or out of the coil.
   D. A wire carrying a constant current near the coil.

Answer

1. Which of the following will cause an induced current in a coil of wire?

   C. A magnet being moved into or out of the coil.

Reading Quiz

2. The speed of electromagnetic waves in a vacuum
   A. depends upon the wavelength.
   B. depends on the photon energy.
   C. is the same as the speed of sound.
   D. is the same for all waves regardless of wavelength.

Answer

2. The speed of electromagnetic waves in a vacuum

D. is the same for all waves regardless of wavelength.

Reading Quiz

3. Comparing infrared and ultraviolet, we can say that

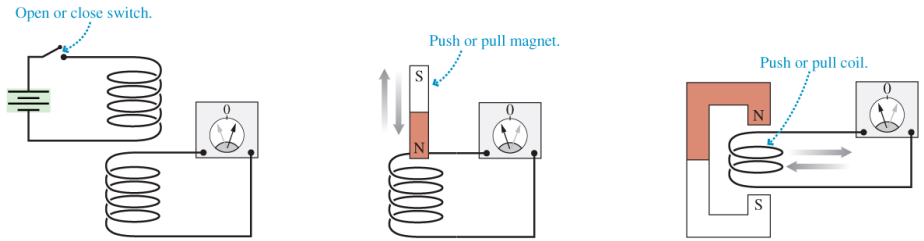
A. infrared has longer wavelength and higher photon energy.
B. infrared has longer wavelength and lower photon energy.
C. ultraviolet has longer wavelength and higher photon energy.
D. ultraviolet has longer wavelength and lower photon energy.

Answer

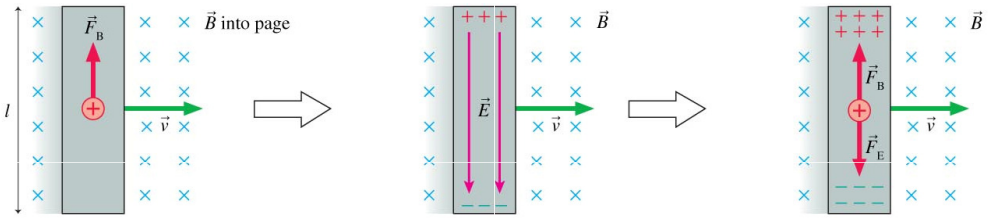
3. Comparing infrared and ultraviolet, we can say that

B. infrared has longer wavelength and lower photon energy.

Electromagnetic Induction

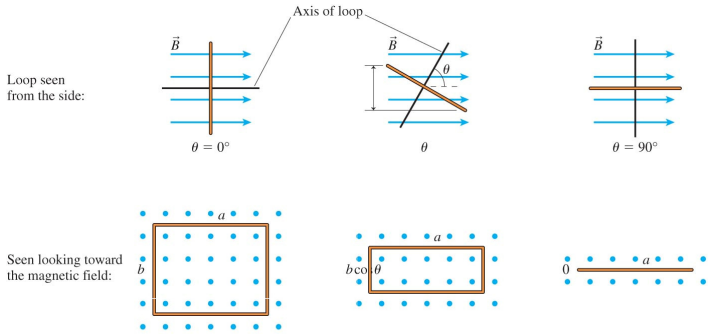


Motional emf



$$\mathcal{E} = vlB$$

Magnetic Flux



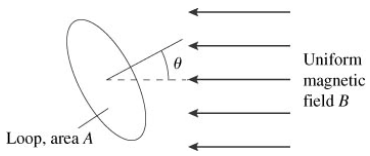
$$\Phi = A_{\text{eff}}B = AB\cos\theta$$

Magnetic flux through area A at angle θ to field B

Checking Understanding

A loop of wire of area A is tipped at an angle θ to a uniform magnetic field B. The maximum flux occurs for an angle $\theta = 0°$. What angle θ will give a flux that is ½ of this maximum value?

A. $\theta = 30°$
B. $\theta = 45°$
C. $\theta = 60°$
D. $\theta = 90°$



Answer

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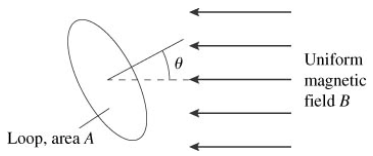
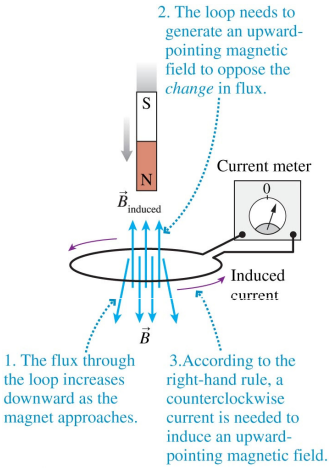
C. $\theta = 60°$



Lenz's Law



Lenz's law There is an induced current in a closed, conducting loop if and only if the magnetic flux through the loop is changing. The direction of the induced current is such that the induced magnetic field opposes the *change* in the flux.

Using Lenz's Law

TACTICS BOX 25.1 Using Lenz's law Exercises 5–9

1. Determine the direction of the applied magnetic field. The field must pass through the loop.
2. Determine how the flux is changing. Is it increasing, decreasing, or staying the same?
3. Determine the direction of an induced magnetic field that will oppose the *change* in the flux:
   - Increasing flux: The induced magnetic field points opposite the applied magnetic field.
   - Decreasing flux: The induced magnetic field points in the same direction as the applied magnetic field.
   - Steady flux: There is no induced magnetic field.
4. Determine the direction of the induced current. Use the right-hand rule to determine the current direction in the loop that generates the induced magnetic field you found in step 3.

Faraday's Law

Faraday's law An emf $\mathcal{E}$ is induced in a conducting loop if the magnetic flux through the loop changes. If the flux changes by $\Delta\Phi$ during time interval Δt, the magnitude of the emf is

$$\mathcal{E} = \left|\frac{\Delta\Phi}{\Delta t}\right| \qquad (25.11)$$

and the direction of the emf is such as to drive an induced current in the direction given by Lenz's law.

PROBLEM-SOLVING STRATEGY 25.1 Electromagnetic induction

PREPARE Make simplifying assumptions about wires and magnetic fields. Draw a picture or a circuit diagram. Use Lenz's law to determine the direction of the induced current.

SOLVE The mathematical representation is based on Faraday's law

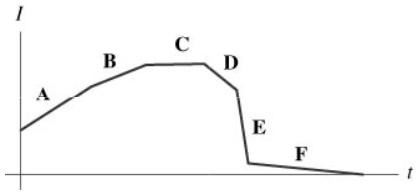
$$\mathcal{E} = \left|\frac{\Delta\Phi}{\Delta t}\right|$$

For an N-turn coil, multiply by N. The size of the induced current is $I = \mathcal{E}/R$.

ASSESS Check that your result has the correct units, is reasonable, and answers the question.

Checking Understanding

A long conductor carrying a current runs next to a loop of wire. The current in the wire varies as in the graph. Which segment of the graph corresponds to the largest induced current in the loop?



Answer

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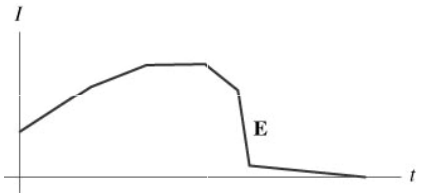
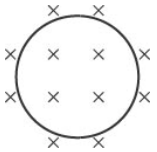


Checking Understanding

A magnetic field goes through a loop of wire, as below. If the magnitude of the magnetic field is increasing, what can we say about the current in the loop?

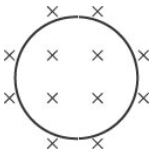
A. The loop has a clockwise current.
B. The loop has a counterclockwise current.
C. The loop has no current.



Answer

A magnetic field goes through a loop of wire, as below. If the magnitude of the magnetic field is increasing, what can we say about the current in the loop?

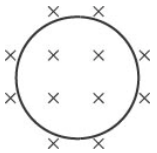
B. The loop has a counterclockwise current.



Checking Understanding

A magnetic field goes through a loop of wire, as below. If the magnitude of the magnetic field is decreasing, what can we say about the current in the loop?

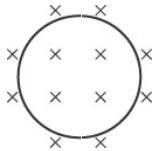
A. The loop has a clockwise current.
B. The loop has a counterclockwise current.
C. The loop has no current.



Answer

A magnetic field goes through a loop of wire, as below. If the magnitude of the magnetic field is decreasing, what can we say about the current in the loop?

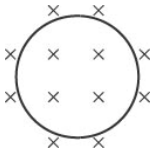
A. The loop has a clockwise current.



Checking Understanding

A magnetic field goes through a loop of wire, as below. If the magnitude of the magnetic field is constant, what can we say about the current in the loop?

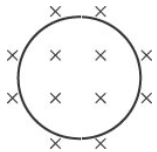
A. The loop has a clockwise current.
B. The loop has a counterclockwise current.
C. The loop has no current.



Answer

A magnetic field goes through a loop of wire, as below. If the magnitude of the magnetic field is constant, what can we say about the current in the loop?

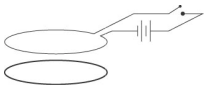
C. The loop has no current.



Checking Understanding

A battery, a loop of wire, and a switch make a circuit below. A second loop of wire sits directly below the first. Just before the switch is closed, what can we say about the current in the lower loop?

A. The loop has a clockwise current.
B. The loop has a counterclockwise current.
C. The loop has no current.



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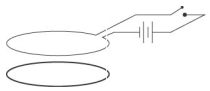
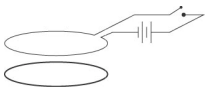


Checking Understanding

A battery, a loop of wire, and a switch make a circuit below. A second loop of wire sits directly below the first. Immediately after the switch is closed, what can we say about the current in the lower loop?

A. The loop has a clockwise current.
B. The loop has a counterclockwise current.
C. The loop has no current.



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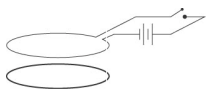
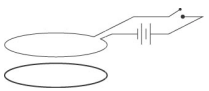


Checking Understanding

A battery, a loop of wire, and a switch make a circuit below. A second loop of wire sits directly below the first. Long after the switch is closed, what can we say about the current in the lower loop?

A. The loop has a clockwise current.
B. The loop has a counterclockwise current.
C. The loop has no current.



Answer

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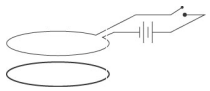
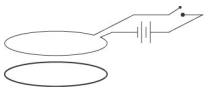
C. The loop has no current.



Checking Understanding

A battery, a loop of wire, and a switch make a circuit below. A second loop of wire sits directly below the first. Immediately after the switch is reopened, what can we say about the current in the lower loop?

A. The loop has a clockwise current.
B. The loop has a counterclockwise current.
C. The loop has no current.



Answer

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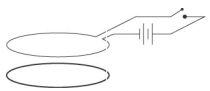
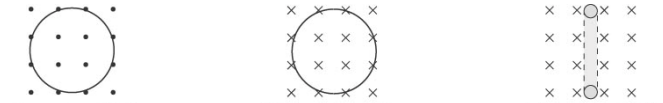
B. The loop has a counterclockwise current.



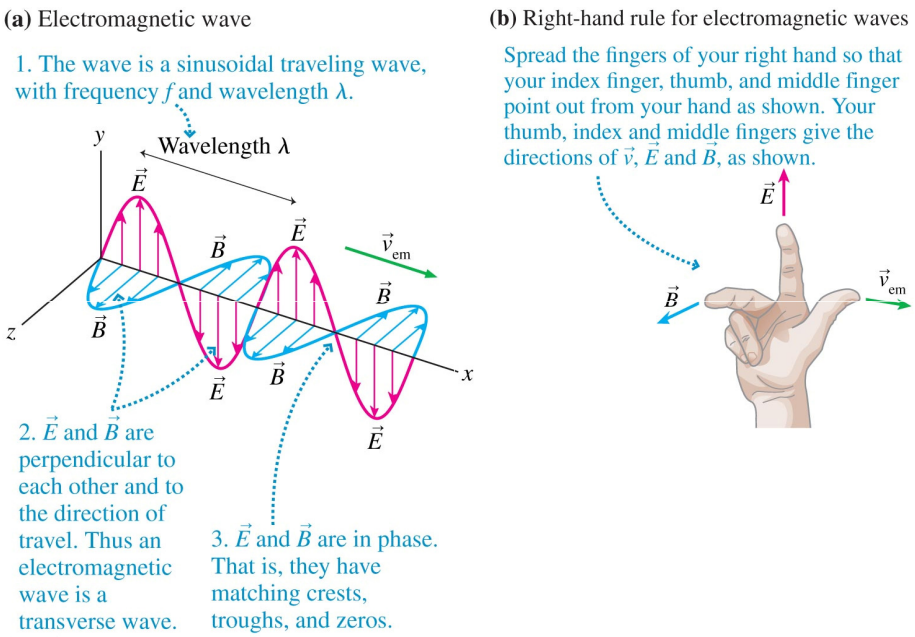
The figure shows a 10-cm-diameter loop in three different magnetic fields. The loop's resistance is 0.1 Ω. For each situation, determine the strength and direction of the induced current.



a) Increasing at 0.5 T/s b) Decreasing at 0.5 T/s c) Decreasing at 0.5 T/s

A coil used to produce changing magnetic fields in a TMS (transcranial magnetic field stimulation) device is connected to a high-current power supply. As the current ramps to hundreds or even thousands of amps, the magnetic field increases. In a typical pulsed-field machine, the current near the coil will go from 0 T to 2.5 T in a time of 200 μs. Suppose a technician holds his hand near the device, and this increasing field is directed along the axis of his hand—meaning the flux goes through his gold wedding band, which is 2.0 cm in diameter. What emf is induced in the ring?

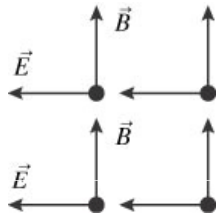
Electromagnetic Waves



Checking Understanding

A plane electromagnetic wave has electric and magnetic fields at all points in the plane as noted below. With the fields oriented as shown, the wave is moving

A. into the plane of the paper.
B. out of the plane of the paper.
C. to the left.
D. to the right.
E. toward the top of the paper.
F. toward the bottom of the paper.



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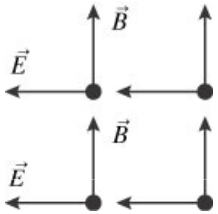
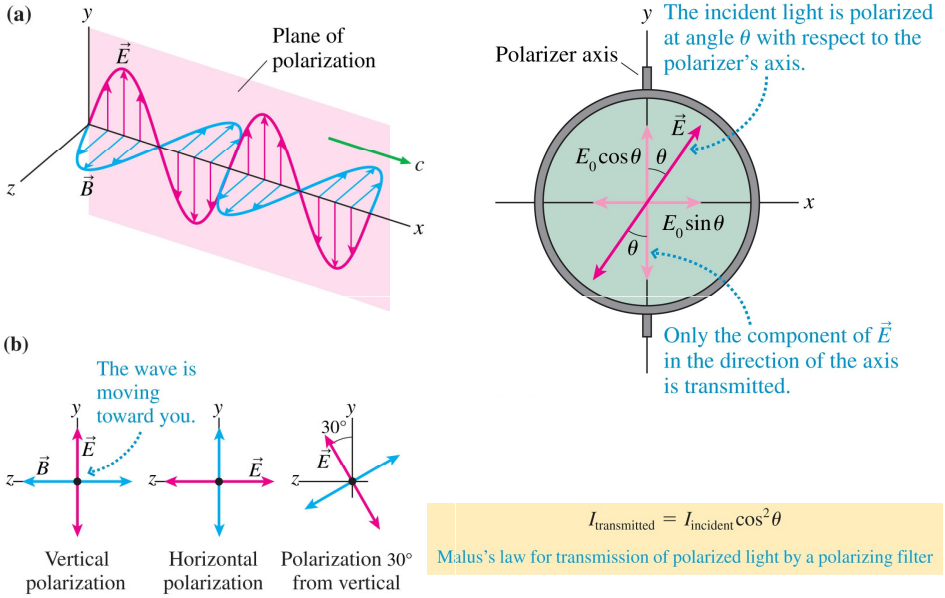


Electromagnetic Waves Carry Energy

1) Inside the cavity of a microwave oven, the 2.4 GHz electromagnetic waves have an intensity of 5.0 kW/m^2. What is the strength of the electric field? The magnetic field?
2) A digital cell phone emits a 1.9 GHz electromagnetic wave with total power 0.60 W. At a cell phone tower 2.0 km away, what is the intensity of the wave? (Assume that the wave spreads out uniformly in all directions.) What are the electric and magnetic field strengths at this distance?

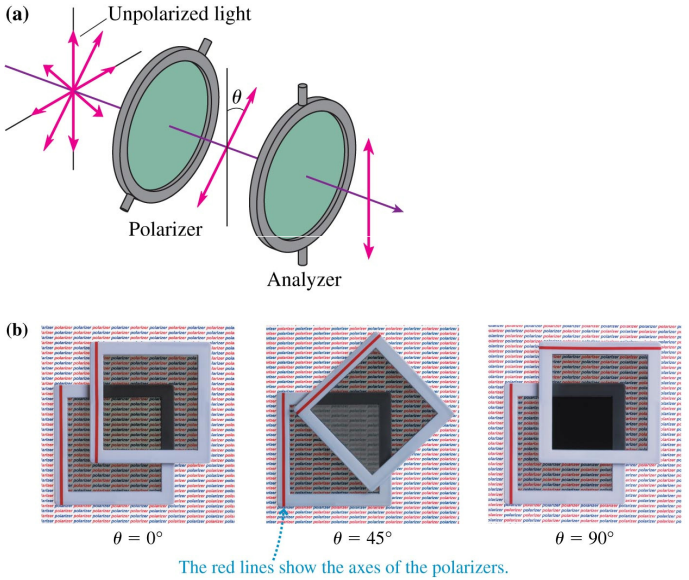
Polarization



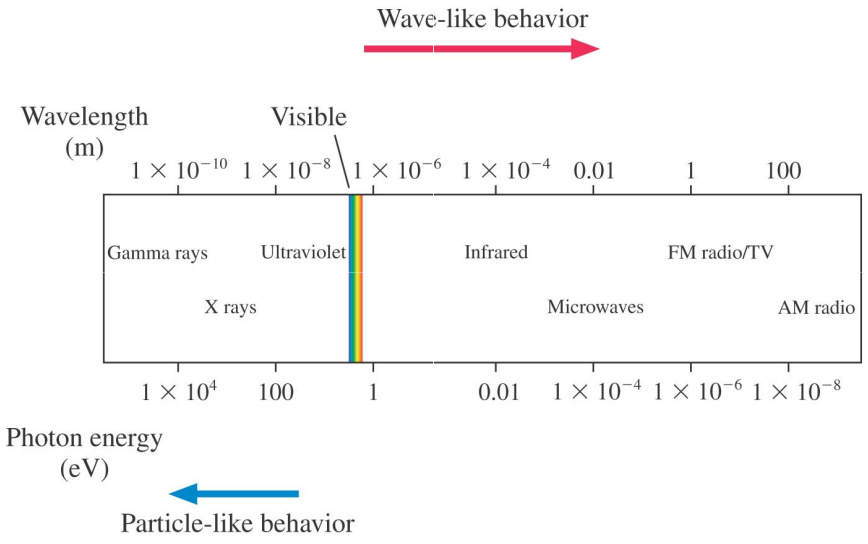
$$I_{\text{transmitted}} = I_{\text{incident}} \cos^2\theta$$

Malus's law for transmission of polarized light by a polarizing filter

Light passed through a polarizing filter has an intensity of 2.0 W/m^2. How should a second polarizing filter be arranged to decrease the intensity to 1.0 W/m^2?



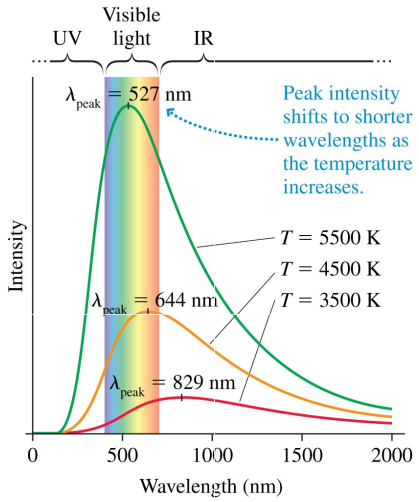
The Electromagnetic Spectrum



A radio wave has a frequency of 100 MHz. What is the wavelength, and what is the energy of individual photons?

Now, do the same calculations for a gamma ray of frequency 3.0 x 10^{19}?

Thermal Emission Spectrum



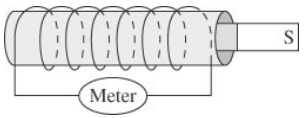
$$\lambda_{peak}(\text{in nm}) = \frac{2.9 \times 10^6 \text{ nm} \cdot \text{K}}{T} \qquad (25.22)$$

Wien's law for the peak wavelength of a thermal emission spectrum

Additional Clicker Questions

A bar magnet sits inside a coil of wire that is connected to a meter. The bar magnet is at rest in the coil. What can we say about the current in the meter?

A. The current goes from right to left.
B. The current goes from left to right.
C. There is no current in the meter.



Answer

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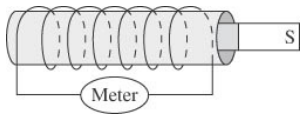
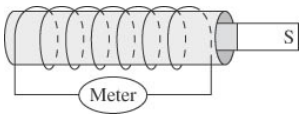
C. There is no current in the meter.



Additional Clicker Questions

A bar magnet sits inside a coil of wire that is connected to a meter. The bar magnet is pulled out of the coil. What can we say about the current in the meter?

A. The current goes from right to left.
B. The current goes from left to right.
C. There is no current in the meter.



Answer

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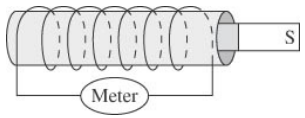
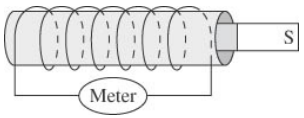


Additional Clicker Questions

A bar magnet sits inside a coil of wire that is connected to a meter. The bar magnet is completely out of the coil and at rest. What can we say about the current in the meter?

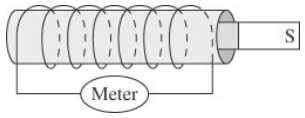
A. The current goes from right to left.
B. The current goes from left to right.
C. There is no current in the meter.



Answer

A bar magnet sits inside a coil of wire that is connected to a meter. The bar magnet is completely out of the coil and at rest. What can we say about the current in the meter?

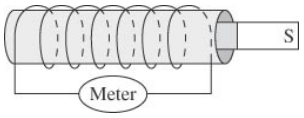
C. There is no current in the meter.



Additional Clicker Questions

A bar magnet sits inside a coil of wire that is connected to a meter. The bar magnet is reinserted into the coil. What can we say about the current in the meter?

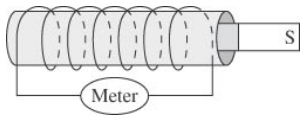
A. The current goes from right to left.
B. The current goes from left to right.
C. There is no current in the meter.



Answer

A bar magnet sits inside a coil of wire that is connected to a meter. The bar magnet is reinserted into the coil. What can we say about the current in the meter?

B. The current goes from left to right.



Additional Clicker Questions

A typical analog cell phone has a frequency of 850 MHz, a digital phone a frequency of 1950 MHz. Compared to the signal from an analog cell phone, the digital signal has

A. longer wavelength and lower photon energy.
B. longer wavelength and higher photon energy.
C. shorter wavelength and lower photon energy.
D. shorter wavelength and higher photon energy.

Answer

A typical analog cell phone has a frequency of 850 MHz, a digital phone a frequency of 1950 MHz. Compared to the signal from an analog cell phone, the digital signal has

D. shorter wavelength and higher photon energy.

Additional Clicker Questions

A radio tower emits two 50 W signals, one an AM signal at a frequency of 850 kHz, one an FM signal at a frequency of 85 MHz. Which signal has more photons per second?

A. The AM signal has more photons per second.
B. The FM signal has more photons per second.
C. Both signals have the same photons per second.

Answer

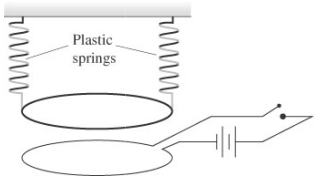
A radio tower emits two 50 W signals, one an AM signal at a frequency of 850 kHz, one an FM signal at a frequency of 85 MHz. Which signal has more photons per second?

A. The AM signal has more photons per second.

Additional Examples

1. Two metal loops face each other. The upper loop is suspended by plastic springs and can move up or down. The lower loop is fixed in place and is attached to a battery and a switch. Immediately after the switch is closed,

   A. Is there a force on the upper loop? If so, in which direction will it move? Explain your reasoning.
   B. Is there a torque on the upper loop? If so, which way will it rotate? Explain your reasoning.



Additional Examples

2. The outer coil of wire is 10 cm long, 2 cm in diameter, wrapped tightly with one layer of 0.5-mm-diameter wire, and has a total resistance of 1.0 Ω. It is attached to a battery, as shown, that steadily decreases in voltage from 12 V to 0 V in 0.5 s, then remains at 0 V for $t > 0.5$ s. The inner coil of wire is 1 cm long, 1 cm in diameter, has 10 turns of wire, and has a total resistance of 0.01 Ω. It is connected, as shown, to a current meter.
   a. As the voltage to the outer coil begins to decrease, in which direction (left-to-right or right-to-left) does current flow through the meter? Explain.
   b. Draw a graph showing the current in the inner coil as a function of time for $0 \le t \le 1$ s. Include a numerical scale on the vertical axis.