

A Monochromatic Light Source Emits 100 W Of Electromagnetic Power Uniformly In All Directions. (a) Calculate

Understanding a Monochromatic Light Source Emitting 100 W of Electromagnetic Power

A Monochromatic Light Source Emits 100 W Of Electromagnetic Power Uniformly In All Directions. (a) Calculate the various physical parameters associated with this light source. This question is fundamental in the study of electromagnetic radiation, optics, and physics, providing insights into how energy is distributed and how to quantify properties like intensity, flux, and radiation pressure.

In this article, we will explore the principles behind monochromatic light sources, the significance of uniform emission, and the detailed calculations involved in understanding the behavior of a 100 W electromagnetic source radiating in all directions. We aim to clarify the concepts with step-by-step explanations, formulas, and real-world applications.

Fundamentals of Monochromatic Light Sources

What is a Monochromatic Light Source?

A monochromatic light source emits electromagnetic radiation of a single wavelength or frequency. Examples include lasers emitting a specific wavelength or certain spectral line emissions from atoms. Such sources are essential in scientific experiments, optical communications, and various technological applications because their predictable wavelength allows precise control and measurement.

Uniform Emission in All Directions

When a light source emits energy uniformly in all directions, the radiation is said to be isotropic. This means the electromagnetic power is distributed equally across the surface of an imaginary sphere surrounding the source, leading to symmetrical radiation patterns.

Power and Energy Considerations

The total power emitted (in watts) quantifies the energy flow per unit time. For a 100 W source, this implies that 100 joules of energy are emitted every second, spread uniformly over the entire surface area of a sphere that encompasses the source.

Basic Principles and Formulas Involved

Surface Area of a Sphere and Power Distribution

Since the energy is emitted uniformly in all directions, the surface area of a sphere at a radius r from the source is:

$$A = 4\pi r^2$$

The power per unit area, or intensity I , at a distance r from the source is:

$$I = \frac{P}{A} = \frac{P}{4\pi r^2}$$

where:

- P is the total power emitted (100 W),
- r is the distance from the source.

Electromagnetic Wave Intensity and Related Quantities

The intensity relates to the electric and magnetic fields of the wave. For a monochromatic wave:

$$I = \frac{1}{2} \epsilon_0 c E^2 = \frac{1}{2} \frac{B^2}{\mu_0} c$$

where:

- ϵ_0 is vacuum permittivity,
- c is the speed of light,
- E is the electric field amplitude,
- B is the magnetic field amplitude.

Calculations for a 100 W Monochromatic Light Source

Let's now proceed to the specific calculations based on the given power emission.

1. Calculating Intensity at a Given Distance

Suppose we want to find the intensity at a certain distance r . For example, at $r = 1$, meter :

$$I = \frac{P}{4\pi r^2} = \frac{100\text{ W}}{4\pi (1)^2} \approx \frac{100}{12.566} \approx 7.96\text{ W/m}^2$$

This value indicates how much power per unit area the observer would receive at one meter from the source.

2. Determining the Electric Field Amplitude (E)

Using the relation between intensity and electric field:

$$I = \frac{1}{2} \epsilon_0 c E^2$$

Rearranged for (E) :

$$E = \sqrt{\frac{2I}{\epsilon_0 c}}$$

Plugging in the known constants:

- $(\epsilon_0 = 8.854 \times 10^{-12}\text{ F/m})$,
- $(c = 3.00 \times 10^8\text{ m/s})$,
- $(I = 7.96\text{ W/m}^2)$:

$$E = \sqrt{\frac{2 \times 7.96}{8.854 \times 10^{-12} \times 3.00 \times 10^8}}$$

Calculating the denominator:

$$8.854 \times 10^{-12} \times 3.00 \times 10^8 = 2.656 \times 10^{-3}$$

Then,

$$E = \sqrt{\frac{15.92}{2.656 \times 10^{-3}}} \approx \sqrt{5994} \approx 77.4\text{ V/m}$$

Thus, at 1 meter, the electric field amplitude is approximately 77.4 V/m.

3. Magnetic Field Amplitude (B)

The magnetic field amplitude relates to the electric field via:

$$B = \frac{E}{c}$$

$$B \approx \frac{77.4}{3.00 \times 10^8} \approx 2.58 \times 10^{-7}, \text{ T}$$

This magnetic field is extremely weak but measurable with sensitive instruments.

4. Radiation Pressure and Force

The radiation pressure (P_{rad}) exerted by the electromagnetic wave on a perfect reflector is:

$$P_{\text{rad}} = \frac{2I}{c}$$

At 1 meter:

$$P_{\text{rad}} = \frac{2 \times 7.96}{3.00 \times 10^8} \approx 5.31 \times 10^{-8}, \text{ Pa}$$

This pressure is negligible but significant in precise optical systems or in space physics.

Implications and Applications of These Calculations

Designing Optical Systems

Understanding the intensity and field amplitudes enables engineers to design lasers, optical fibers, and communication devices that operate efficiently and safely. For instance, knowing the electric field at a certain distance helps prevent accidental exposure.

Remote Sensing and Measurement

Remote sensing technologies rely on these calculations to interpret received signals. Knowing how electromagnetic power disperses allows for accurate distance and object detection.

Safety Considerations

High-power monochromatic sources require safety protocols due to their potential to cause thermal

damage or eye injury. Calculations of intensity and field strength inform safety standards.

Scientific Research and Spectroscopy

Precise knowledge of electromagnetic emission aids in spectroscopic analysis, enabling scientists to identify materials and study atomic transitions.

Conclusion

A monochromatic light source emitting 100 W uniformly in all directions exemplifies fundamental electromagnetic principles. Through systematic calculations, we determine the intensity at various distances, electric and magnetic field amplitudes, and radiation pressure. These insights are vital across scientific, industrial, and safety domains, showcasing the importance of understanding electromagnetic radiation's behavior.

By mastering these calculations, professionals and students alike can better design experiments, develop technologies, and ensure safety when working with high-power optical sources. The principles discussed extend beyond theoretical exercises, influencing real-world applications from laser manufacturing to space exploration.

Further Reading and Resources

- Principles of Electrodynamics by David J. Griffiths
- Optics by Eugene Hecht
- Online simulations of electromagnetic wave propagation
- Standards from the International Commission on Non-Ionizing Radiation Protection (ICNIRP)

Understanding the propagation of electromagnetic waves and their properties remains a cornerstone of modern physics and engineering, empowering innovations and ensuring safety in our increasingly connected world.

Frequently Asked Questions

What is the total power emitted by a monochromatic light source that emits 100 W uniformly in all directions?

The total power emitted by the source is 100 watts, as given in the problem statement.

How do you calculate the intensity of a monochromatic light source emitting 100 W uniformly in all directions?

Intensity is calculated by dividing the total power by the surface area of a sphere with radius r : $I = P / (4\pi r^2)$.

If a monochromatic light source emits 100 W uniformly in all directions, what is the intensity at a distance of 2 meters?

Using $I = P / (4\pi r^2)$, with $P=100$ W and $r=2$ m, the intensity is $I = 100 / (4\pi \times 4) \approx 100 / 50.27 \approx 1.99$ W/m².

What is the significance of the monochromatic nature of the light source in these calculations?

The monochromatic nature means the light has a single wavelength, which simplifies analysis related to spectral properties but does not affect the power or intensity calculations directly.

How does the power distribution of 100 W uniformly in all directions affect the irradiance at different distances?

Irradiance decreases with the square of the distance, following the inverse square law: $I \propto 1/r^2$.

What assumptions are made when calculating the intensity of a point source emitting 100 W in all directions?

Assumptions include the source being a point source, uniform emission in all directions, and no absorption or scattering in the medium.

How does the wavelength of the monochromatic light influence the energy per photon emitted by the source?

Energy per photon is given by $E = hc/\lambda$, so the wavelength determines the photon energy; shorter wavelengths mean higher photon energies.

Can the 100 W power be directly related to the number of photons emitted per second?

Yes, using the photon energy $E = hc/\lambda$, the number of photons emitted per second is $N = P / E$.

What is the importance of knowing the power and emission pattern when designing optical systems using this light source?

Knowing the power and emission pattern helps in calculating illumination levels, designing detectors, and ensuring proper coverage in optical applications.

If the wavelength of the monochromatic light is 500 nm, what is the energy of each photon emitted by the source?

Using $E = hc/\lambda$, with $h = 6.626 \times 10^{-34}$ Js, $c = 3 \times 10^8$ m/s, and $\lambda = 500$ nm (5×10^{-7} m), the photon energy

is approximately 3.97×10^{-19} Joules.

Additional Resources

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Introduction

In the realm of optics and electromagnetic theory, understanding the behavior of light sources is fundamental to numerous applications—from telecommunications and laser technology to astrophysics and medical devices. One intriguing scenario involves a monochromatic (single wavelength) light source radiating power uniformly in all directions. Suppose such a source emits 100 watts of electromagnetic power isotropically—that is, equally in every direction. This scenario provides a perfect case to explore key concepts such as intensity, flux, and the characteristics of electromagnetic radiation.

In this article, we will delve into the problem of calculating the intensity of the light at a given distance from such a source, unravel the physics governing electromagnetic radiation, and clarify the significance of each step in the calculation. We aim to present a comprehensive, yet accessible, guide for students, professionals, and enthusiasts interested in optics and electromagnetic theory.

Understanding the Key Concepts

Before diving into the calculations, it's essential to clarify the foundational concepts involved:

Electromagnetic Power and Its Distribution

- Power (W): The rate at which energy is emitted by the source—in this case, 100 watts.
- Isotropic Radiation: The emission of energy uniformly in all directions, forming a sphere around the source.
- Intensity (I): The power per unit area (W/m^2), representing how much energy passes through a given area perpendicular to the direction of propagation.
- Surface Area of Sphere: The area over which the power is distributed at a given radius, calculated as $4\pi r^2$.

Wavelength and Frequency

- Since the source is monochromatic, it emits light at a specific wavelength (λ), which relates to its frequency (f) and the speed of light (c). However, for the purposes of calculating intensity at a distance, the wavelength specifics are not directly necessary unless we delve into photon flux or spectral properties.

Step 1: Visualizing the Emission Pattern

Imagine a point source emitting light equally in every direction. The emitted power (P) is spread over the surface area of an expanding sphere centered at the source:

$$\text{Surface area of a sphere at radius } r: \quad A = 4\pi r^2$$

Since the emission is uniform, the energy passing through any unit area on this sphere per second (the intensity (I)) is:

$$I(r) = \frac{\text{Power passing through area}}{\text{Area}} = \frac{P}{4\pi r^2}$$

This fundamental relation allows us to calculate the intensity at any distance (r) from the source, assuming no absorption or other losses.

Step 2: Calculating the Intensity at a Given Distance

The problem does not specify a particular distance, but for illustrative purposes, let's calculate the intensity at a distance of 1 meter from the source.

Given Data:

- Power, $(P = 100, \text{W})$
- Distance, $(r = 1, \text{m})$

Calculation:

$$I(1, \text{m}) = \frac{100, \text{W}}{4\pi (1, \text{m})^2} = \frac{100}{4\pi} \text{ W/m}^2$$

Calculating the numerical value:

$$I(1, \text{m}) \approx \frac{100}{12.566} \approx 7.96, \text{ W/m}^2$$

Thus, at a radius of 1 meter, the intensity of this isotropic, monochromatic light source is approximately 7.96 W/m^2 .

Step 3: General Expression for Intensity at Any Distance

The derived formula can be generalized for any distance (r) :

$$I(r) = \frac{P}{4\pi r^2}$$

\]

This relation illustrates the inverse-square law—a foundational principle in physics stating that the intensity diminishes proportionally to the square of the distance from a point source.

Implications:

- At $(r = 2\text{ m})$:

$$I(2\text{ m}) = \frac{100}{4\pi (2)^2} = \frac{100}{4\pi \times 4} = \frac{100}{16\pi} \approx 1.99\text{ W/m}^2$$

- At $(r = 0.5\text{ m})$:

$$I(0.5\text{ m}) = \frac{100}{4\pi (0.5)^2} = \frac{100}{4\pi \times 0.25} = \frac{100}{\pi} \approx 31.83\text{ W/m}^2$$

This inverse-square relationship emphasizes how the energy becomes more concentrated as you move closer to the source.

Step 4: Considering the Wavelength and Photon Flux (Advanced)

While the primary focus is on intensity, for monochromatic light, it's often insightful to understand how many photons are arriving per second per unit area.

Photon Energy:

The energy of a single photon:

$$E = hf = \frac{hc}{\lambda}$$

where:

- $(h = 6.626 \times 10^{-34}\text{ Js})$ (Planck's constant),
- $(c = 3 \times 10^8\text{ m/s})$ (speed of light),
- (λ) = wavelength in meters.

Photon Flux:

Number of photons per second per unit area (Φ) :

$$\Phi = \frac{I}{E}$$

Suppose the monochromatic light has a wavelength of 500 nm ((5×10^{-7}) , m):

$$E = \frac{6.626 \times 10^{-34} \times 3 \times 10^8}{5 \times 10^{-7}} \approx 3.97 \times 10^{-19} \text{ J}$$

At 1 meter, with $I \approx 7.96$, W/m^2):

$$\Phi = \frac{7.96}{3.97 \times 10^{-19}} \approx 2.00 \times 10^{19} \text{ photons/m}^2\text{/s}$$

This calculation provides a sense of the photon flux density, which is crucial in applications like photodetectors, laser-matter interactions, and quantum optics.

Step 5: Practical Applications and Limitations

Applications:

- Optical Communications: Understanding how intensity diminishes with distance helps in designing efficient free-space optical links.
- Laser Safety: Knowing the intensity at various distances ensures safe exposure levels.
- Astrophysics: Estimating the brightness of distant celestial objects involves similar principles.

Limitations:

- Real-world sources are rarely perfect point sources; they may have directional patterns.
- Atmospheric absorption, scattering, and divergence can alter the intensity distribution.
- Monochromatic sources are idealized; in practice, most emit over a spectrum.

Conclusion

The scenario of a monochromatic, isotropic light source emitting 100 W of power offers a clear illustration of fundamental electromagnetic principles. By understanding the inverse-square law and the geometric distribution of energy, we can accurately determine the intensity at any distance from the source. Such calculations are indispensable across scientific disciplines, enabling precise control and measurement of electromagnetic radiation.

In summary:

- The intensity at a distance (r) from an isotropic source with power (P) is given by $I(r) = \frac{P}{4\pi r^2}$.
- At 1 meter, the intensity of a 100 W source is approximately 7.96 W/m^2 .
- The photon flux depends on the wavelength and can be computed to understand the particle nature of light.

Understanding these principles not only deepens our grasp of electromagnetic theory but also enhances our ability to innovate and optimize technologies that rely on light and radiation.

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