ELECTRONICS NOTEBOOK

Wave Propagation and Reflection

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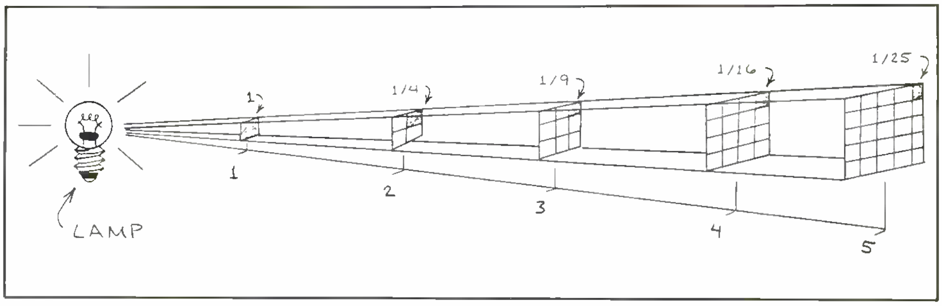

Fig. 1. Illustration of the inverse square law.

Electronic circuits that emit or detect energy are subject to several very important physical laws that you should know about. Typical energy-emitting circuits and devices include radio transmitters, infrared (IR) remote controllers and audio speakers. Typical energy-receiving circuits and devices include radio receivers and lightwave and microphones.

Some of the physical laws that affect energy sources and detectors can be very complex. Fortunately, some of the basic laws that determine how energy waves are projected and reflected are simple. I like to think of these as geometrical laws.

Even though the geometrical laws that control energy distribution are very simple, they are often overlooked when energy-emitting and energy-receiving circuits are designed. It's particularly easy to overlook these laws when the energy being emitted or detected is sound outside the range of human hearing or invisible radiation, such as ultraviolet, infrared and radio-frequency waves.

This time around, I'll explore some of the basic geometrical laws that very much affect the operation of circuits that emit or detect energy. I'll also present some experiments you can perform to test their validity. First, however, let's pause for a brief analysis of why these laws are so important.

Light, Sound & Radio Waves

The intensity of the light waves reflected from this page that permit you to read these words is determined by two principal parameters. The first is the intensity of the light source that strikes the page and the distance the source is from the page. The second is the distance of the page from your eye. Other parameters that determine exactly how much light enters your eyes include the diameter of the pupils of your eyes, the clarity of the air and stray light reflected from walls and even your own body.

The intensity of any sound waves you happen to be hearing as you read these words is similarly affected by the circumstances of your surroundings. The chief parameters that control the intensity of what you're hearing are the sound level at its source and the distance from the source to your ears. Sound-reflecting objects, such as flat walls, tables and even this page you're reading, may boost or reduce the intensity of a sound you hear.

Sound-absorbing surfaces may reduce the intensity of what you're hearing. Or they may absorb sounds within a particular frequency range so that you can better hear sounds that are at other frequencies. Temperature, motion and relative humidity of the air may also have an affect.

Are you listening to a radio as you read these words? The intensity of the electromagnetic waves received by a radio or television receiver is also very much affected by the power of the transmitter and the distance of the transmitter from your radio receiver. Atmospheric ducting effects and reflections from the ionosphere, buildings and aircraft in the vicinity and may alter the intensity of the signal.

Several physical laws apply to the distribution of energy in each of these examples. The most important is the "inverse square law."

The Inverse Square Law

The inverse square law holds that the intensity of an energy wave is inversely proportional to the square of the distance of the wave from its point of origin. For example, if the distance of the wave from its source is 3, the intensity of the wave is 1/9 ($1/3^3$) the intensity of the wave at a distance of 1.

While its name and definition may at first seem rather intimidating, the inverse square law is very easy to understand. You can even perform some simple experiments to test and verify it.

Figure 1 is a pictorial representation of how the inverse square law works with a bare light bulb. This drawing can also be applied to a radio transmitter or sound source. We could also take into consideration all the light emitted by the lamp. But it's easier to consider a square crosssection of light projected outward.

Let's assume that the light from a bare flashlight bulb has an irradiance of 100 microwatts per square centimeter at a point 1 meter from the bulb. According to the inverse square law, the irradiance at 2 meters will be $1/2^2$ the irradiance at 1 meter, or 1/4 of 100 microwatts/cm^2, which factors out to 25 microwatts/cm^2. The irradiance at 3 meters will be only $1/3^2$ that at 1 meter, or ⅑ of 100 microwatts/cm^2, which now factors out to 11.11 microwatts/cm^2.

Table 1 shows what happens to the irradiance of our imaginary flashlight bulb out to a range of 10 meters. The values given in the table are plotted in graph form in Fig. 2. From the values in the Table and Fig. 2 graph, it is readily apparent why the signal from, say, a LED transmitter falls off very rapidly at first and then decreases much more gradually as it's moved away from the receiver.

Thus far, we've looked at how the inverse square law is supposed to work under ideal conditions. In the real world,

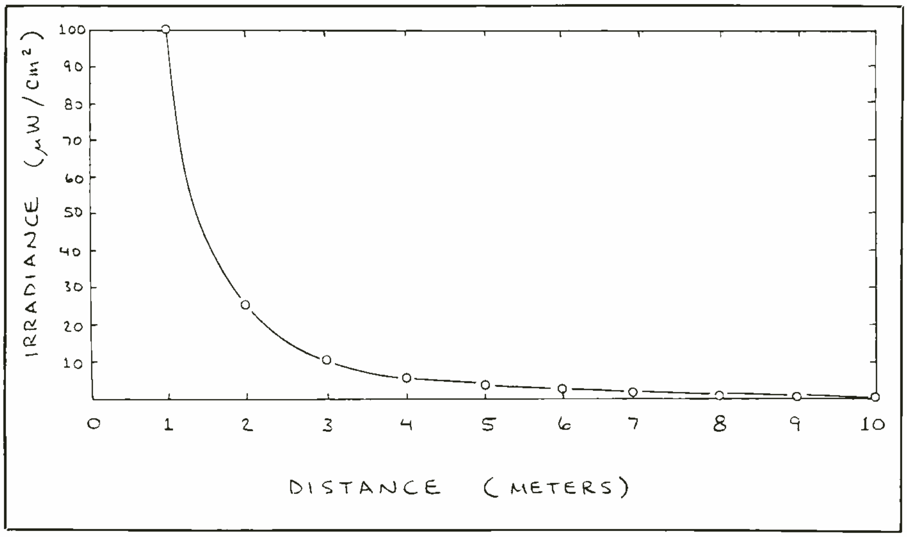

Fig. 2. Plot of the predicted irradiance from a small lamp.

many factors—often unsuspected ones—can alter the shape of the theoretical curve shown in Fig. 2. For example, the size of the source should be as small as possible. Generally, the size of the source should be at least one tenth or smaller than the size of the area being considered at the first measuring point (1 in Table 1). If the size of the source is any larger than this, the inverse square law will not hold true until the distance from the source becomes great enough to rule out the error.

The inverse square law will not necessarily hold true for energy waves that are projected as a beam. If the beam is very uniform and fairly broad, the law may hold true. However, if the beam is very narrow, the law will not hold true. This is the case with beams from most lasers and highly collimated light sources.

Testing the Inverse Square Law

You can test the inverse square law with the help of a light meter and light source. The success of your test will be determined by your care in performing the measurements. The light source should be as close as possible to a point source. An incandescent bulb with a clear glass envelope is a good choice for the light source. Absolutely no light other than that from the source must be allowed to strike the light meter's detector. Even light from the source that's reflected from its base and nearby objects and then back toward the detector will distort your measurements.

To meet these requirements, you should conduct your test in a darkened room. All reflecting objects should be moved away from the detector's field of view. If this isn't possible, cover these objects with a diffusely reflecting black cloth. Also, you should wear dark clothing for the same reason.

If you don't have a light meter, you can make a suitable substitute from a silicon solar cell and a multimeter. The meter should be able to measure currents as low as tens of microamperes.

You'll obtain even better results with the circuit shown schematically in Fig. 3. Use a silicon photodiode or small-area silicon solar cell for the sensor. The operational amplifier should have a low input bias current and low offset voltage. For

Table 1. Irradiance Figures for an Imaginary Flashlight Bulb

Distance (meters)	Ratio ($1/d^2$)	Irradiance (μW/cm²)
1	1/1	100.00
2	1/4	25.00
3	1/9	11.11
4	1/16	6.25
5	1/25	4.00
6	1/36	2.78
7	1/49	2.04
8	1/64	1.56
9	1/81	1.24
10	1/100	1.00

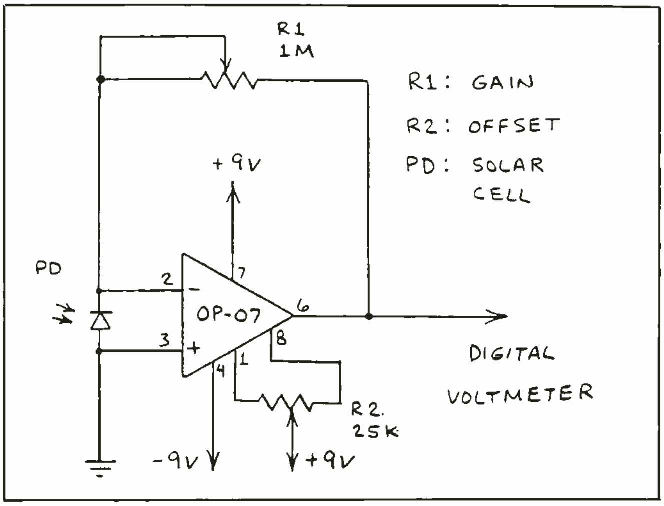

Fig. 3. Schematic diagram of a simple light-measuring circuit.

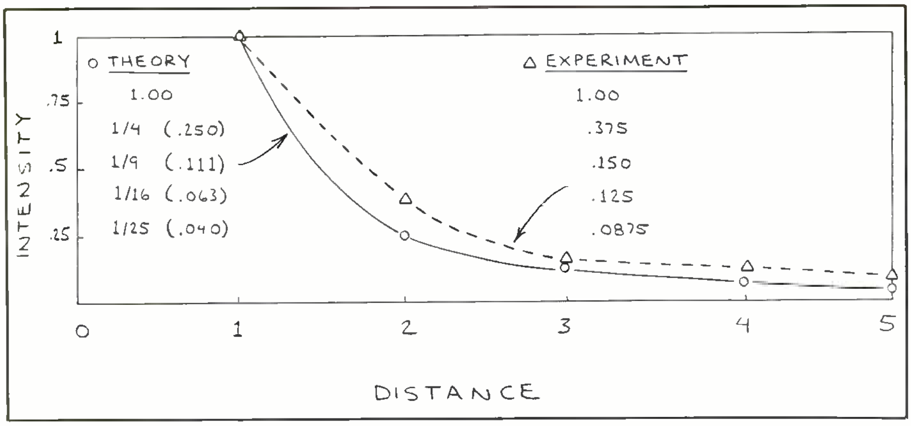

Fig. 4. Plot of an experimental test of the inverse square law.

Table 2. Lambert's Law Predictions for a Perfectly Diffuse Reflector

Angle (degrees)	Cosine	Reflected Intensity ($\mu W/cm^2$)
0	1.000	100.0
15	0.966	96.6
30	0.866	86.6
45	0.707	70.7
60	0.500	50.0
75	0.259	25.9
89	0.017	1.7

best results, especially at very low light levels, use a high-quality op amp like the OP-07 or OP-77 from Precision Monolithics or an LM607 from National Semiconductor. These and other precision op amps will yield much more accurate results when the photocurrent falls to very low levels. However, be sure to adjust the OFFSET trimmer to give an output of 0 volt when the solar cell is dark.

You can use a common 741 op amp in the circuit in Fig. 3 if precision isn't absolutely necessary. All connections will remain the same, except for the OFFSET trimmer. Connect this trimmer to the negative supply rail.

The photocurrent from a silicon photodiode or solar cell is linear over a wide range of incident light intensities. The output voltage from the op amp in the Fig. 3 circuit is equal to the photocurrent times the feedback resistance (R_f). Therefore, the output voltage from the circuit in Fig. 3 is linear with respect to the intensity of the light falling on the detector.

Figure 4 shows the measurements I made of the intensity of a bare flashlight bulb out to a distance of 5 feet. For this experiment, the detector was a small solar cell. The gain of the amplifier was set to give an output of 1 volt when the lamp was 1 foot away from the detector. There was no need to calibrate the system in terms of absolute sensitivity since the amplifier's output is almost perfectly linear. Therefore, the measurements are relative with respect to each other.

Superimposed on Fig. 4 is a plot of the intensity of the lamp as predicted by the inverse square law. As you can see, the theoretical curve is displaced downward from the experimental curve.

There are several possible reasons for the difference between the predicted and actual curves shown in Fig. 4. The chief reason, however, is probably due to the first measurement point being too close to the lamp. Light reflected toward the detector by the lamp holder probably caused most of the error at the first measurement point.

Another possible error source is the requirement that the source dimensions be small with respect to the distance between the source and detector. These factors are why manufacturers of calibration lamps specify a minimum separation distance between a lamp and a detector before the inverse square law can be applied with any reliability.

While light was the energy source for this simple test of the inverse square law, keep in mind that the same principle applies to sound, radio waves, ultraviolet radiation, x-rays and so on. The same kinds of errors also apply. In the case of sound, changes in the transmission medium, which is usually air, can cause major errors. For example, layers of warm and cool air can channel or disperse sound waves, thereby greatly altering the sound received by a microphone. Major problems can also be caused by reflections from nearby surfaces.

Reflected-Energy Waves

When a wave of energy strikes a surface, the energy that isn't transmitted through or absorbed by the surface is reflected away from the surface. You can better appreciate what happens to radar beams, radio waves, sound waves and beams of light if you understand some simple principles of reflectance. There are two principal types of reflection: diffuse and specular. Some reflectors have both diffuse and specular properties.

Diffuse reflectors reflect or scatter an oncoming beam away from their surfaces in the form of very broad beams. Specular reflectors, on the other hand, are like mirrors; they reflect an oncoming beam of energy with little or no change in the beam's divergence.

The surface of a diffuse reflector is rough in comparison to the dimensions of the wavelength of radiation that it reflects. The surface of a specular reflector is smooth in comparison to the dimensions of the wavelengths it reflects.

As an example of the above, the surface of this page you are reading is rough in comparison to the wavelengths of visible light. Therefore, this page is a very good diffuse reflector of light. On the other hand, sound waves are huge compared to the roughness of this page. Therefore, when this page is perfectly flat, it's a good specular reflector of sound waves.

Figure 5(A) shows how light is reflected from a perfectly diffuse reflector. The reflection of light from a perfect diffuser follows Lambert's cosine law, which holds that the intensity of a ray of light reflected from a diffuse surface varies with the cosine of the angle the ray makes with an imaginary line normal (perpendicular) to the surface of the reflector.

Table 2 shows what Lambert's law predicts for a perfectly diffuse reflector that is illuminated by a beam of light perpendicular to the surface of the reflector. The reflected intensity in the light level is a constant distance away from the point at which the incoming ray strikes the reflector. The reflected intensity is found by multiplying the intensity at the normal angle (0 degree) by the cosine of the angle of the reflected ray.

In my work to develop various kinds of infrared travel aids for the blind, I've found that many surfaces come close to being perfect diffuse reflectors. Good examples are some fabrics, wall paper and surfaces coated with flat paint.

Figure 5(B) shows how light is reflected from a perfect specular reflector. If the surface of the specular reflector is perfectly flat, the reflected beam follows three laws:

(1) The angle of the reflected ray is equal to the angle of the oncoming ray.

(2) The oncoming and reflected rays lie in the same plane as an imaginary normal line extended perpendicularly from the surface of the reflector.

(3) The divergence or spread of the reflected beam is equal to that of the oncoming beam.

Most mirrors are made by applying a thin film of aluminum or silver to the back of a sheet of glass. Therefore, these so-called second-surface mirrors have two specular reflecting surfaces. The front surface of the glass acts as the first reflector, while the reflective coating applied to the rear surface of the glass functions as the second reflector. This means that second-surface mirrors will reflect an oncoming ray of light as two parallel rays. This effect is magnified as the mirror is tilted with respect to the angle of the oncoming ray.

Many natural and artificial surfaces exhibit both diffuse and specular reflectance properties. Consider what happens when light strikes the shiny surface of a leaf or a freshly waxed car. In both cases, the waxy surface of the material is very smooth and partially transparent. Since the surface is very smooth, it functions as a specular reflector. The tissue or paint below the wax usually has a rougher surface and functions as a diffuse reflector.

Figure 5(C) illustrates how an object can exhibit both specular and diffuse reflectance. In the real world, the reflections can be much more complicated than is shown in this simplified drawing. For example, if the specular front surface has a thin coating of dust, it alone will also produce both a specular and a diffuse reflection. Too, the diffuse reflection from the second surface can be altered in various ways as it passes through the front layer of specular reflecting material.

It's interesting to note that changing the shape of a specular reflector can cause it to simulate a diffuse reflector. For example, a flat sheet of polished metal is a specular reflector. Bending the metal into a cylinder will cause an oncoming beam of light to be reflected as a broad, diffuse (spread out) beam.

A flat sheet of aluminum foil is a spec-

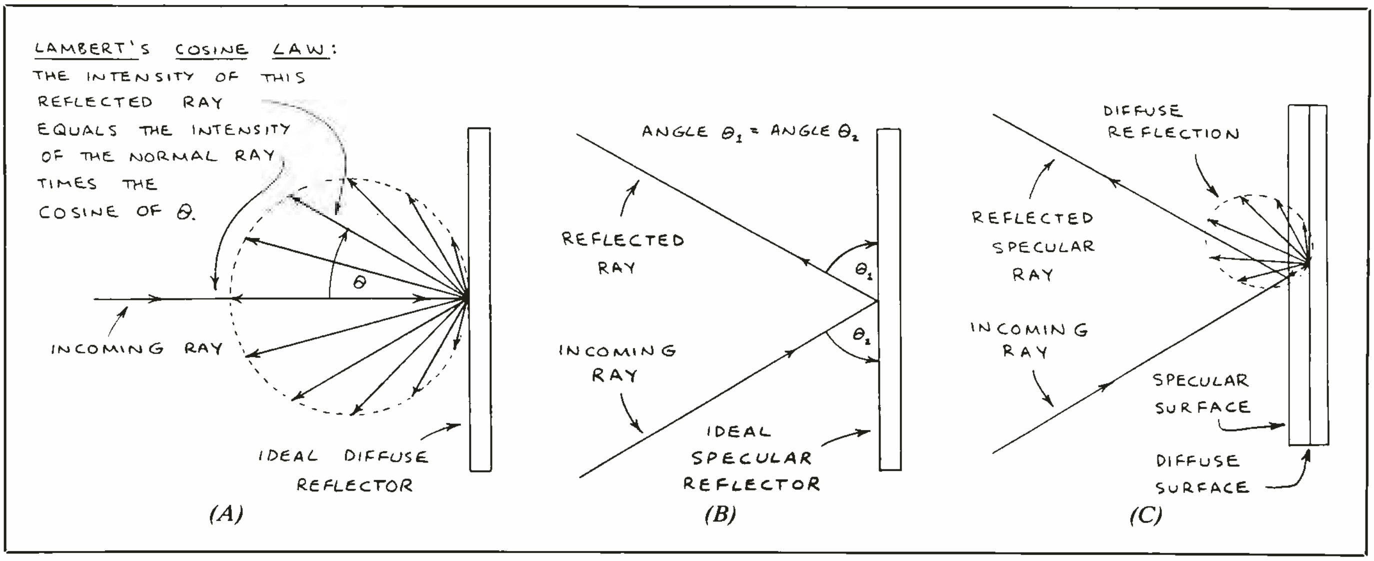

Fig. 5. Illustrating the reflection from (A) a diffuse surface, (B) a specular reflector and (C) a combination of the two.

Table 3. Diffuse Reflectance for 3M Nextel White Reflectance Coating

Angle (degrees)	Cosine	Measured Intensity (μA)	Error (%)
0	1.000	84.0	.0
5	0.996	83.5	– 0.216
10	0.985	82.0	– 0.883
15	0.966	80.0	– 1.422
20	0.940	75.0	– 5.246
30	0.866	70.0	– 3.923
45	0.707	56.0	– 6.066
60	0.500	40.0	– 5.000
70	0.342	26.0	– 10.499
80	0.174	12.0	– 21.554

ular reflector. If you crumple the foil and then open it back into a sheet, it will simulate a diffuse reflector. Of course, the reflected light won't have the uniform energy distribution of a true diffuse reflector.

Thus far, I've applied the principles of reflectance to only waves of light. Yet the reflectance of energy waves greatly affects every aspect of life as we know it. In the ultraviolet spectrum, for example, most things are very poor reflectors. Therefore, if we could see only UV radiation, we would live in a drab world of grays and blacks.

Stealth aircraft technology uses radar-absorbing coatings and structures to minimize radar reflections. Sharply angled structures, such as wing roots and engine intakes, are carefully contoured to minimize specular reflections. These steps greatly reduce what is known as the aircraft's radar cross-section.

Auditoriums must be carefully designed to avoid unwanted "hot" and "cold" sound sots caused by specular reflections from flat surfaces. This is accomplished by means of sound-absorbing acoustical tiles and curtains.

Look around you. You'll see countless examples of how your perception of the environment is very much affected by diffuse and specular reflectors.

Testing Diffuse Reflectors

Since the wavelengths of sound and radio waves are so long, it's difficult to make tests of diffuse reflectance in a small space. Light waves and microwaves have much shorter wavelengths, making diffuse reflectance tests very easy to perform.

The easiest way to test the diffuse reflectance of a surface at visible-light wavelengths is to illuminate the surface with the narrow beam from a helium-neon laser. Place a small light detector a fixed distance away from the surface and measure the power of the reflected light. Thereafter, repeat the measurement for various angles.

I've conducted diffuse reflectance tests against wood, concrete block, tar paper, magnesium oxide and other surfaces. Table 3 shows the measurements I made of the diffuse reflectance of a coating of 3M Nextel white reflectance coating. The Error column gives the difference in intensity between the measured and predicted intensities for a perfect diffuse reflector.

Even though the error becomes fairly large at high angles, the error is almost negligible at small angles. Consequently, this reflectance coating is an excellent diffuse reflector in most applications.

Going Further

While I've used light to illustrate the application of the inverse square law and the basic principles of reflection, be sure to remember that these laws also apply to sound waves as well as beams of electromagnetic radiation. An interesting experiment you can conduct is to test the application of the inverse square law to sound. For best results, conduct the experiment outdoors in a large field on a still, cool day. Place a piezoelectric tone generator on a tripod. Measure the intensity of the sound level over a range of distances and plot your results on a graph. When I conducted this test, my results agreed closely with the inverse square law.